Karl Terzaghi

The Engineer as Artist

Richard E. Goodman

Foreword by Ralph Peck

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ABSTRACT: After five years of research—reading and translating 82 volumes of Terzaghi's diaries, interviewing acquaintances, and perusing 15,000 letters, numerous essays, publications, and reports—Dr. Goodman has developed this biography of Karl Terzaghi, the father of soil mechanics. Foreword by Ralph Peck.

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...gradually I learned that even when it looked absolutely hopeless,
"the Master" Vigeland could always find a solution.
Thanks to his ingenuity alone it has been possible to do
the impossible. But exacting he is, and extremely demanding.

From a statement by wrought-iron craftsman Mikkelsen
concerning the great Norwegian sculptor Gustav Vigeland (1869–1943).

▼

▼

To Ralph B. Peck

A courageous, strong, and honest human being
whose teaching, writing, speaking, and practice of civil engineering
continue to light the way.

▼

Acknowledgements

Although the author never met Karl Terzaghi, a remarkably complete paper trail provided the opportunity to become very well informed about his life and thoughts. Fortunately, Terzaghi savored his words and saved them—not only in diaries, correspondence, manuscripts, and publications, but also notes, sketches, workbooks, memoranda, clippings, wine-bottle labels, and more. Much of this voluminous record has been preserved in the Terzaghi Library at the Norwegian Geotechnical Institute in Oslo, thanks to the farsightedness of its first director, Laurits Bjerrum, and the continuing stewardship of successive directors, including Kaare Hoeg and the present leader Suzanne Lacasse. A series of librarians developed this collection, including Unni Oiseth, Margareth Grini, Guri Rollum, and Wenche Enersen, the current custodian of the Terzaghi Library at NGI. The author was highly privileged to visit the Terzaghi Library four times, the first when Laurits Bjerrum read him remarkable diary excerpts, and the last three from 1993–1996 to pursue research for this book. He feels very fortunate to have received every opportunity to study the collections, pester the librarians and engineering staff, and almost take root in Oslo, thanks to appointment as a Terzaghi Scholar, with financial support for living expenses.

In addition to materials at the Terzaghi Library, the author was extremely fortunate to acquire from Karl's daughter Dr. Margaret (Peggy) Terzaghi-Howe the opportunity to read through Terzaghi's personal diaries (some 82 handwritten volumes) and a number of old, personal letters that had been stored in the attic at "Bear's Corner" in Maine. Through her help he was also privileged to review many of Karl Terzaghi's photographs, slides, and movie films, and the correspondence files of Ruth Terzaghi. In addition, through the kindness of Leo Casagrande's son Dirk, he reviewed correspondence in the office of Casagrande Consultants in Arlington, Mass. Professor Gerald (Jerry) Leonards provided correspondence, reports, and manuscripts from Professor Gregory Tschebotarioff, which had been left in his care at

Purdue University. J. Barry Cooke offered his personal correspondence and files of Terzaghi articles. Later, Walter Ferris provided an opportunity to read his carefully compiled set of notes for Terzaghi's Engineering Geology 260 at Harvard (which Mr. Ferris taught after Karl's retirement). Others, including Harald Lauffer, Charles Ripley, and Professors Laurie Richards and Robert Schiffman, provided additional items of correspondence.

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Most helpful advice and information was provided in a series of interviews with Terzaghi's colleagues, friends, and family. Professor Ralph Peck provided a great amount of information on the circumstances of their collaboration and friendship over the last 24 years of Karl's life. Professor Peck also suggested candidates for interviews. Charles Ripley, with his colleagues Cyril Leonoff and Mark Olson, reflected on their engineering adventures with Karl Terzaghi, during an inspiring two-day trip with the author to visit many of Terzaghi's job sites in British Columbia.

The wealth of personal data and historical perspective was increased by helpful interviews with J. Barry Cooke, and Professors Alec Skempton, Gerald Leonards, Robert Schiffman, and Leonardo Zeevaert. The author also profited from discussions with Karl's son Eric Terzaghi, his grandson Sergei Terzaghi (a practicing geotechnical engineer), Henry Grace, Elmo di Biagio, Jack Forester, Dirk Casagrande, Erna Casagrande, Carla Maria Casagrande, and Professors Heinz Brandl, Nilmar Janbu, Reint de Boer, Ralph Fadum, Richard Jelinek, Gordon Prescott, John Christian, Kemal Ozodogru, and William Judd.

Fortunately it was possible for the author to visit some of the places in Austria where parts of Terzaghi's story unfolded. Terzaghi's relatives Grete Byloff, Elizabeth Puchwein, and Werner Byloff showed him the rooms where Karl lived and visited in Graz. Members of the Vandalia Corporation proudly showed their house in Graz and allowed him to photograph the Terzaghi pictures on display (and gave him a quick lesson in the art of dueling). Professors Gunter Riedmüller and Wulf Schubert gave him opportunity to sample academic life in Graz by appointing him as a visiting professor at their (and Terzaghi's) college, the Technische Hochschule in Graz; while visiting in Graz, Library Director Dr. Karl Stock arranged to locate Karl's report cards and some of Wittenbauer's published theater pieces from the Graz Technische Hochschule's library and archives and supplied the picture of Professor Wittenbauer reprinted here. Mr. Ivan Vrkljan guided the author on a trip through the Croatian karst. Prof. Brandl, the current holder of Terzaghi's position at Vienna Technische Hochschule, showed him Terzaghi's offices, teaching rooms and laboratories and some of the original soil testing devices maintained there as well as important relevant reports and publications of his institute.

Finally the author is pleased to thank those who helped in the business of research and writing. Ulrike Makurat and Helmut Lewis helped him to improve his knowledge of German and Sieglinde Wegener Gisholt helped him to decipher old letters that had been written in Gothic German script. Professor and Mrs. Rainer Poisel and Professor Dobroslav Znidarcic provided information about Austrian and Yugoslavian history. Anni Pendl obtained photographic copies of portraits borrowed from Grete Byloff. The author is grateful to his brother Arnold P. Goodman, literary agent, who generously offered expert counsel. Finally the author wishes to acknowledge and thank his wife Sue who listened to and criticized drafts of the manuscript read to her in their retreat at Mendocino, California.

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Foreword

As the reader of this book will discover, it was my privilege to work for and with Karl Terzaghi for much of the last 30 years of his life. Certainly no other person, with the possible exception of my father in my precollege years, had as great an influence on my professional career as Terzaghi, and I came to feel that I knew him well. He was a tough taskmaster, he expected and demanded much, but he was patient and constructive in his criticism. Above all, he had the ability to make every endeavor on which we cooperated become a new voyage of discovery in what we now call geotechnical engineering. He created a sense of excitement that heightened as the job or project continued. He made me feel that I was a part of the development of our profession. Over dinner, after a day of technical work, he would discuss the state of some aspect of soil mechanics, the contributors to the work, the open questions, the blind alleys, the likely roads to progress. He was in touch, in person or by correspondence, with everyone serious about the subject, and he encouraged my independent thoughts about the merits of the work and the workers. Those were indeed stimulating evenings , and through them I came to feel that I knew not only the work but those who carried it out. We struggled over parts of "Soil Mechanics in Engineering Practice" to the point that I (and probably he) was frequently disheartened, but still I felt we had a mutual problem and that eventually we would find a mutually satisfactory conclusion. We became at times exasperated with each other, but never did he become angry. It was a remarkably stimulating relationship to me, and he made me feel as if I were a key player far beyond the reality.

So I came to know him. Yet, as he often would talk about his earlier experiences, I also knew that there was a half-century of his life about which I knew almost nothing except for an occasional reference or anecdote. I knew he had a deep philosophical questioning, that he had been a challenge to the authorities in his college days, that he had a tempestuous personal life before he met Ruth, with whom he found personal and intellectual fulfillment. I knew only bits and pieces, wondered how they combined to make such a remarkable man, but could only wonder.

Then came this book. I am confident that nobody, not even Arthur Casagrande or Ruth, knew Karl as Dick Goodman has come to know him. Through his interviews, his study of Karl's reports and letters, and especially through his heretofore untranslated and unread diaries, Goodman has come closer to the real man than anyone else ever did. As the reader will see, Terzaghi was one of a kind, to the great benefit of civil engineering and, indeed, of mankind. The reader will be fascinated by his personality, his approach, and his accomplishments - as indeed was I, who thought I knew him.

If the reader wonders whether this book can possibly be an accurate reflection of Terzaghi's life, I can say only that the account of that part of his life that I knew, those last 30 years rings true. Further, the accounts of those occasional glimpses that I saw of Karl's earlier life, as disclosed in some of his writings and reminiscences, also ring true. Goodman's is a totally consistent picture of the man as I knew him; it is safe to say that it is a totally consistent picture of the whole man. I certainly know Karl Terzaghi immeasurably better, and appreciate him immeasurably more, after reading this book.

Ralph B. Peck
June 15, 1998

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Prologue

Professor Karl Terzaghi advised the civil engineering students at Harvard that "engineering is a noble sport... but occasional blundering is a part of the game. Let it be your ambition to be the first one to discover and announce your blunders.... Once you begin to feel tempted to deny your blunders in the face of reasonable evidence you have ceased to be a good sport. You are already a crank or a grouch."

If civil engineering was a game, Terzaghi had a right to lay down the rules, as he had invented and established much of the ground work. He is known as the father of soil mechanics. But he never signed his reports as a soils engineer; he was a "consulting engineer" who tried to see the whole of a problem, beginning with geology, and ending with measuring behavior during and after construction. He developed a mechanics for soils because it was needed, just as Isaac Newton had developed the calculus to empower his studies in physics. Terzaghi was a pioneer in showing how to make dams, buildings and other structures safe even though founded on soils. This required that there be a science of soil mechanics, as well as an art of soils engineering.

Before Terzaghi came along, very impressive structures of all kinds had been built for centuries out of stone, concrete, iron and steel, and timber. The architects and engineers had found ways to make them sturdy and safe and to achieve their intentions, *most of the time*. But all of these works were founded on earth and there the safety was less assured. There was much guesswork since engineers did not understand this material and their collective experience was not universally comprehensible. So there *were* blunders, many of them.

The problems with soil as a foundation were complex and quite different from those of all other structural materials. The sand or clay that may comprise the foundation of a dam or a building had been placed there by natural processes that no one was around to observe, and then all but the uppermost layer remained hidden from view. Thus, one could never be absolutely certain of what was there, how it was layered or otherwise arranged, and what its consistency might be.

But there was yet a worse problem. Even if a soil's consistency at the start of a job could somehow be demonstrated to be satisfactory, it could not be certain that it would remain so. For many soils readily transform from a coherent to an unsafe state by the mere action of water within their pores. The soil grains have little actual bonding force holding them in any kind of stable structural arrangement. When water that fills the spaces between the grains somehow acquires an internal pressure, the grains tend to simply lift off one another and float apart. Thus the mere application of pressure to a soil, as from the rapid placement of a fill over the surface, can convert it from a solid into almost a liquid, sometimes with catastrophic consequences. By discovering the mechanisms at work and developing engineering methods to control them, Terzaghi made it possible to achieve safe results in all kinds of soils. Then soils engineering took its place as a legitimate technology, now known as *geotechnical engineering*.

The story of this development in the mind of Karl Terzaghi and its evolution under his hand is uplifting. Here was a solid thinker, intensely focused, with meticulous logic, who also loved and appreciated nature. He had keen ability to describe what he observed; he was a mountaineer, a geologist, an observer, a listener. But also, he was a wonderfully expressive writer and conversationalist, in three languages. His travels as engineering consultant took him virtually everywhere, and, wherever that might be, he became the spirit of every gathering and the spark of every group. And he wrote it all down, in letters by the tens of thousands, in diaries, in essays, and reports, and memoranda, lecture notes, and books and articles, virtually all of which survived three wars. His method was to learn from every situation, and every person. He told those young students at Harvard, "Very few people are either so dumb or so dishonest that you could not learn anything from them."[1]

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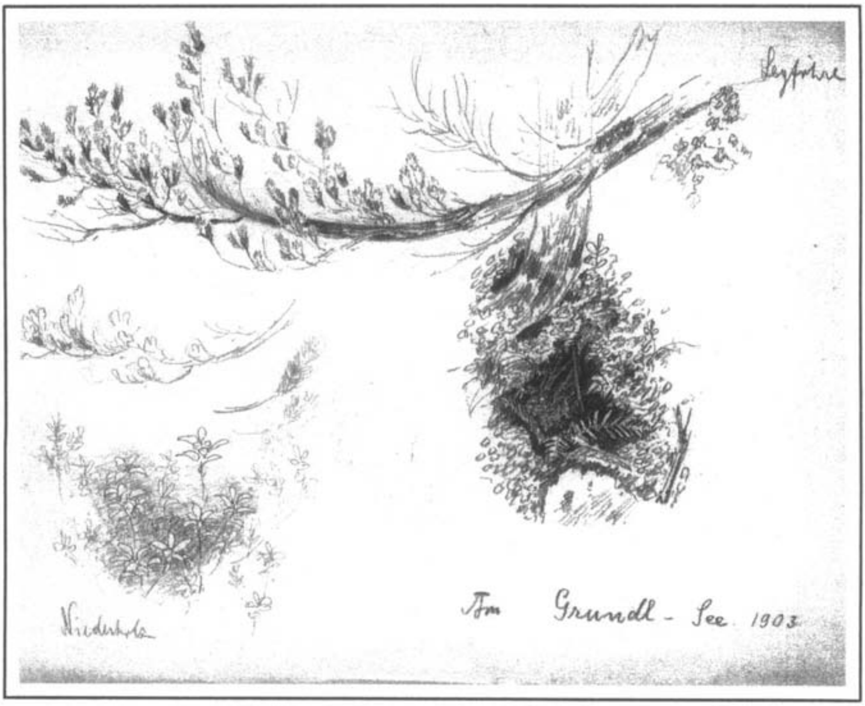


Firs and blooming underbrush at Lake Grundl.

1
The Roots of Genius 1883▾1906

Karl Terzaghi's roots are embedded in the great Austrian Empire, which in the mid-nineteenth century stretched from Krakau to Venice, from Transylvania to the Dalmatian coast. His grandfather, Pietro Antonio Terzaghi, born in 1805[1] in Lodi, Lombardy,[2] was a career officer in the Kaiser's army. In 1854, having attained the rank of Major, with more than 31 years of continuous military service and decorations for valor, he was awarded by Kaiser Franz Josef I membership in the aristocracy with the title *Edler von Pontenuovo*. The honor was conferred in perpetuity to the major, his son Anton born in 1839, and all descendants.[3]

Karl Terzaghi was born October 2, 1883, the first child of Anton and his wife of one year, Amalia Eberle. Lieutenant Colonel[4] Anton von Terzaghi had been assigned five years earlier to command an infantry battalion in Prague, after service in Italy and then Prussia. Although we now firmly link Prague with the Czech Republic, it was then very much a part of the Habsburg Empire, ruled by Franz Josef as Kaiser of Austria, and King of Bohemia and Hungary. Prague was in fact Austria's second center of German art and culture, where Mozart's greatest operas had premiered.

Amalia, fourteen years younger than Anton, quickly became pregnant again and less than a year and a half after Karl's birth had given birth to Ella. Karl and Ella had a good place to play in the garden of their large, old house on Thungasse from which, over the tiled rooftops, one glimpses a high wooded hillside with only a church and a tower to mar the natural landscape rising above the city. A tunnel-like passage led down into Thun's palace garden; Thun's gardener became "my special friend and took me off and on through the tunnel into his impressive signeurial domaine."[5] Karl's intense curiosity as a young child became apparent when he stuck his head so deeply inside a toy barn that it had to be dismantled to spring him free.[6]

The life in Prague was brief, for upon Anton's retirement the family resettled in Graz, the main city of the Austrian state of Styria. Then on New

Year's Eve (Sylvester Abend) of 1890, when Karl was all of seven years old, Anton died.

Karl had been named after Amalia's father Karl Eberle, a successful and well-to-do mechanical engineering graduate of the Vienna Technical University. Anton and Amalia could not have known how important grandfather Karl would prove to be in little Karl's development: with Anton's passing, 67-year-old grandfather Eberle became the head of the Terzaghi household. Karl Terzaghi later described him as "an experienced and very energetic engineer of the old school ... whose strong, lucid personality and upright masculine character strongly influenced my development until I reached maturity."[7] At almost 70 years of age he was appointed General Director of an international banking consortium, for whom he went into the service of the Austrian tobacco industry, and succeeded, under great difficulty, in organizing tobacco manufacture in Romania.

The family's new home in Graz was a large, handsome three-story block in a newly developing section of town only a short walk from the opera house, the market place, and the city park. Most significantly, it lay on the corner directly across from the Civil Engineering Faculty of the University of Graz. The massive edifice of the Technical University and the Terzaghi block alongside were imposing features of the landscape, there being almost no other neighboring structures.

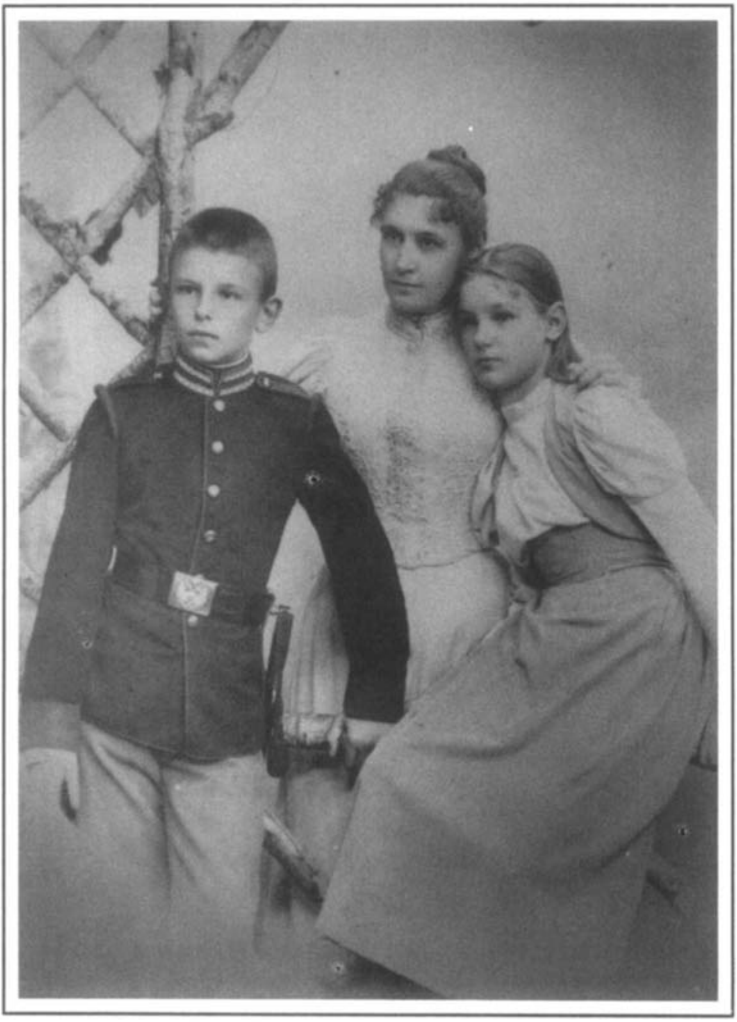
As young Karl had descended from a military tradition, it was taken for granted that he too would become a career officer and so, with grandfather's blessing, in 1893 in his tenth year, he was sent off to military Unterrealschule,[8] in nearby Guens (now Koeszeg, Hungary). It was Karl's early ambition to apply later for admission into the Imperial Royal Navy. He was happy in the masculine atmosphere of the military school, with controlled learning conditions and a Spartan accommodation. The officers made Karl feel that they liked him very much, and helped him to adjust.

Nevertheless, in the second year at Guens, Karl began to feel he was not right for a military profession. He kept this, at first, entirely to himself, although at one point he was nabbed by the sergeant of the watch as he and a friend emerged from a well-planned escape route that surfaced in a manhole outside the tunnel walls.[9] Karl then got on with his studies of geography, which he had found exciting as a small boy. He was especially stimulated by polar exploration, a flame that was heightened by the visit to his school of the Arctic explorer Julius von Payer, and Karl determined to become a polar adventurer. Karl spent time with a vivacious, gifted boy named Hans Kalbacher, and their mutual passion for geography cemented a close friendship. "We ordered books and catalogues from around the world, drew maps, and worked on wildly varying technical problems including underwater construction, flying machines, and so forth."[10]

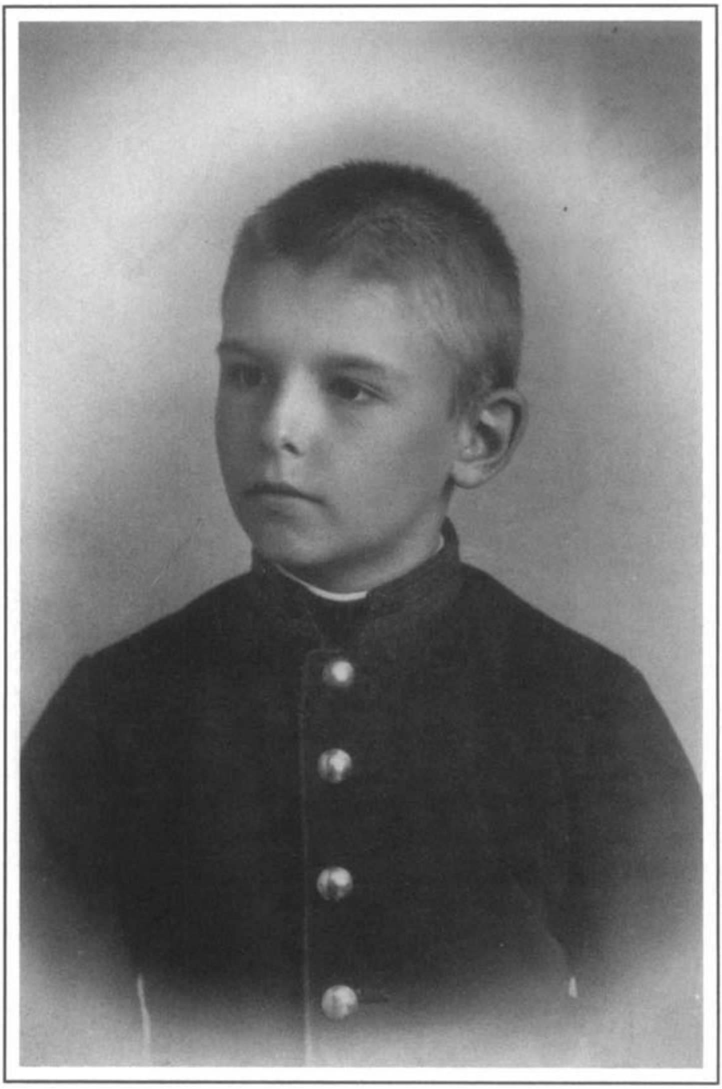
Karl's father, Antonio Terzaghi.

Karl's mother, Amalia Eberle Terzaghi.

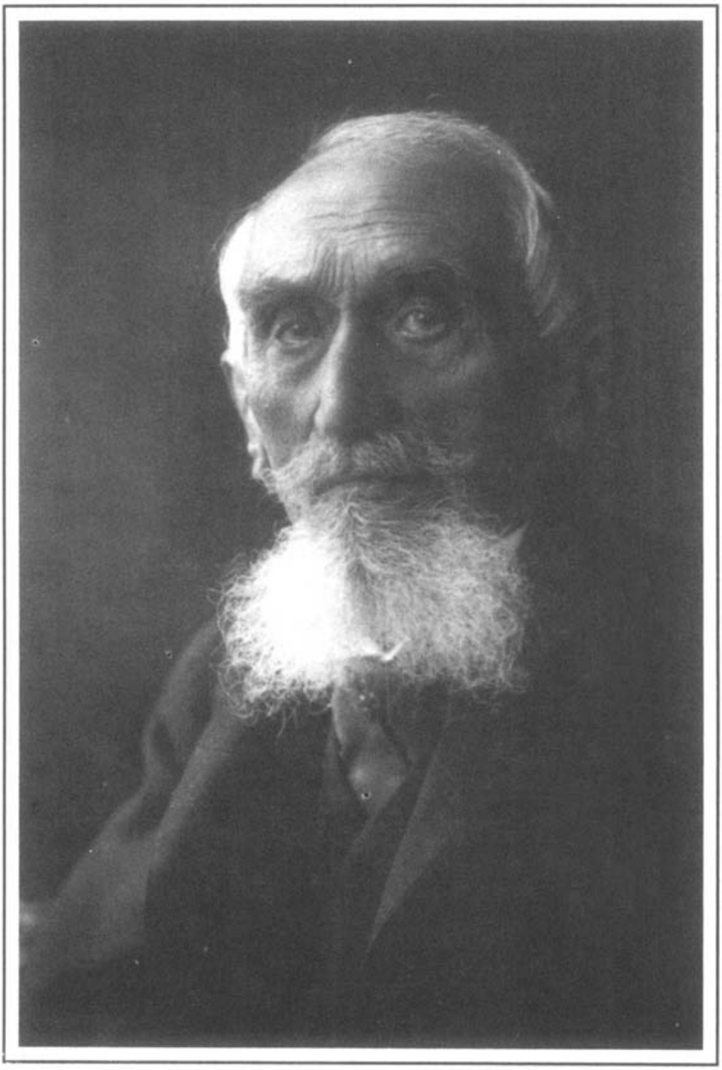
Karl as a toddler, circa 1886.



Karl at age 14 with his mother, Amalia, and sister Ella in 1897.



Cadet Karl Terzaghi at age 14.



Karl's grandfather, Karl Eberle.

As time went on, Karl drifted away from his friend's persistent interest in technology in favor of his own fascination with theory, particularly astronomy. He tried to develop a physical apparatus simulating the solar system. Although Karl had not yet studied trigonometry, within a half year he had succeeded in working out for himself the laws governing the rising and setting of the sun.

At the age of fourteen, Terzaghi advanced to the Military Oberrealschule in Maehrisch-Weisskirchen (now Hranice, Czech Republic). This was a year of personal discovery for Karl in which he became disenchanted with geography as a mere description of places, while his fascination with astronomy evolved into a passion for mathematics. His earlier clumsiness with arithmetic passed into uncommon facility with geometry and algebra, and he was acknowledged to be the best of the 150 students in these subjects. When in February of 1898 a sickness, badly handled by military doctors, confined him to bed for four months, he entertained himself with geometry problems.

Young Terzaghi had discovered he much preferred science to "mindless soldier games". He made application to the Imperial Royal Marine Academy but was denied on account of "a slight eye defect."[11] Karl then decided to abandon his present military path. This did not happen without opposition from home, but he patiently persisted. Furthermore, he developed "an extensive thirst for knowledge", seeking to discover the purpose of human existence through the study of religion. The question of "the evolution of all things began to storm within."[12]

So in the summer of 1898 the young philosopher prepared himself for the entrance examination for the nonmilitary Landes-Oberrealschule in Graz, simultaneously continuing his religious readings "including the Bible, which set me brooding over newly awakened doubts and concerns until I didn't know what to think." In spite of his philosophic confusion, he did manage to pass the entrance examination and matriculated into the sixth-year class at Graz where he immediately became inspired in natural sciences by Professor Hoffer. He craved and devoured the books recommended to him—Darwin (which brought him some trouble with the school authorities), Haeckel, Hertzog, Boelsche, Ratenhorst on evolution, embryology, taxonomy, marine algae, mussels. It is no wonder that he received the highest possible grades in this subject. He also excelled in descriptive geometry, and performed well, though not at the top, in all other subjects.

His enthusiasm for learning persisted through his second and last year at the Landesrealschule, and he graduated at the age of seventeen, with honors. In the summer he conducted his own excursion in natural science in the high Austrian Alps, armed with a geology pick and exuding confidence in his own preparation. "There was no field of natural science in which I had not at least turned the pages of a relevant work."[13]

Seeing how Karl loved the out-of-doors, his grandfather advised going on to the Technical University in Graz to study civil engineering. Simply because the advice came from the older generation, Karl spurned it and elected instead to study mechanical engineering, because it seemed the most rational branch. He preferred to develop according to his own fashion and not according to the opinion of the elders.[14]

As Karl prepared himself for the start of college, he reflected on the "beautiful foundation" he had achieved from his military roots. "Both physical and spiritual development require the same basis—as a first step having both feet planted firmly on the ground. For the spirit to be strong, the body must become tough, courageous, defiant and firm as iron. The ideal preparation to acquire a sharp, multi-faceted spirit is not the distorted picture of cold feet and a hot head but a body in shape. The soonest as possible I am out in the high mountains and rock crevices to test my courage and strength."[15]

Karl continued to pit his strength against the mountains at every chance throughout his college years, but the academic resolve started to wither. When he came to realize that the lectures in mechanical engineering were purely professional, whereas he had been consumed by a flame for rich and wide knowledge, he lost his inner drive completely, fell into line with the robust *Vandalia* fraternity, skipped most of his lectures, and admitted to knowing his professors only by name.

To Terzaghi, the best of the lectures were like sermons, while others "tasted like French fried potatoes which have been heated, served and rejected ten times in succession.... One of the scholars, a man whose mere name attracted many students from foreign countries, always appeared in the lecture room with his face looking as though the mere presence of the audience was a personal insult."[16] Admittedly students were not required to attend the lectures but only to pass the examinations at the end of the second and fourth years. To prepare for the examinations, they bought the lecture notes from poor students who thus financed their education, and then crammed during the last available weeks. Karl tested the system by preferring to attend only the first and last lecture of any engineering course, since it was hard to get out of the room once the session had begun.

However, he did take advantage of the scientific and humanistic courses offered in the various other faculties of the university about the town of Graz, including philosophy, experimental psychology, art history, plant physiology, astronomy, and especially geology. And with Bohemian friends he inhabited the coffee houses and Gast Gartens into the small hours of morning, discoursing and arguing on the plays of Strindberg and Ibsen, the essays of Emerson and Carlyle, and the economic theories of Karl Marx and Henry George.

"The stream of assorted information which rushed into my system produced spells of unbearable mental indigestion, because it did not satisfy my craving for an answer to the ultimate and crucial question: what is the meaning of our life? Therefore the periods of frantic search alternated with others during which I did nothing but drinking, rioting, and duelling. These periods lasted sometimes for weeks in a stretch. I became a frequent customer at the pawnshop, debts accumulated and more than once I landed at police headquarters as a result of disorderly conduct.[17]

The "dueling" he mentioned was a treasured, old rite of Vandalia, and many other "Corporations". With the vital parts of the face guarded, each combatant standing in a fixed position swung a "schlaeger" with a honed edge, attempting to cut his opponent about the fleshy part of the face. In some cases the victor and vanquished would not even wash away their facial blood until the proud group picture had been snapped. It was said that some even applied salt to perpetuate the scar. Many Austrian gentlemen carry a conspicuous scar, termed a "Schmiss", from this bonding test of manhood; Karl's was on the right cheek, extending for some 3 cm. horizontally forward from his strong jaw line.

Wild exuberance from young academics was fairly expectable and almost legitimate in these days, and the police were not too bothered by it. The effect on the individuals varied. Some became heroic surgeons, many "turned into painfully respectable citizens of the Main Street type, and a few have perished in the gutter."[18]

At Vandalia, on the first floor of a dark interior in the medieval section of Graz, there were occasional dinners attended by alumni, where the songs and revelry of identically hatted brothers continued a camaraderie with peers of university and society. At one of these events, Karl found himself seated beside a professor of applied mechanics, Ferdinand Wittenbauer, whose name Terzaghi recognized as belonging to one of his teachers. When asked why he failed to attend lectures, he responded that he would rather read "the prescriptions" for himself. Wittenbauer wisely agreed it might be so and then challenged Karl to do one better and go read the original sources of these prescriptions; in particular he recommended Lagrange's *Analytical Mechanics* in the original French.

Terzaghi took the bait, consulted the book, and found in it the excitement of discovery. Author Wallace Stegner wrote of a Doppler shift for the observer of events and ideas, whereby the pace and excitement of events sound so different when they are approaching than when they are receding.[19] In this case, the high pace of developing ideas of Lagrange's mind offered Terzaghi, for the first time, the "unforgettable revelation" of "science in the making", and he became ensnared in the "depth and lucidity of spirit of its author."

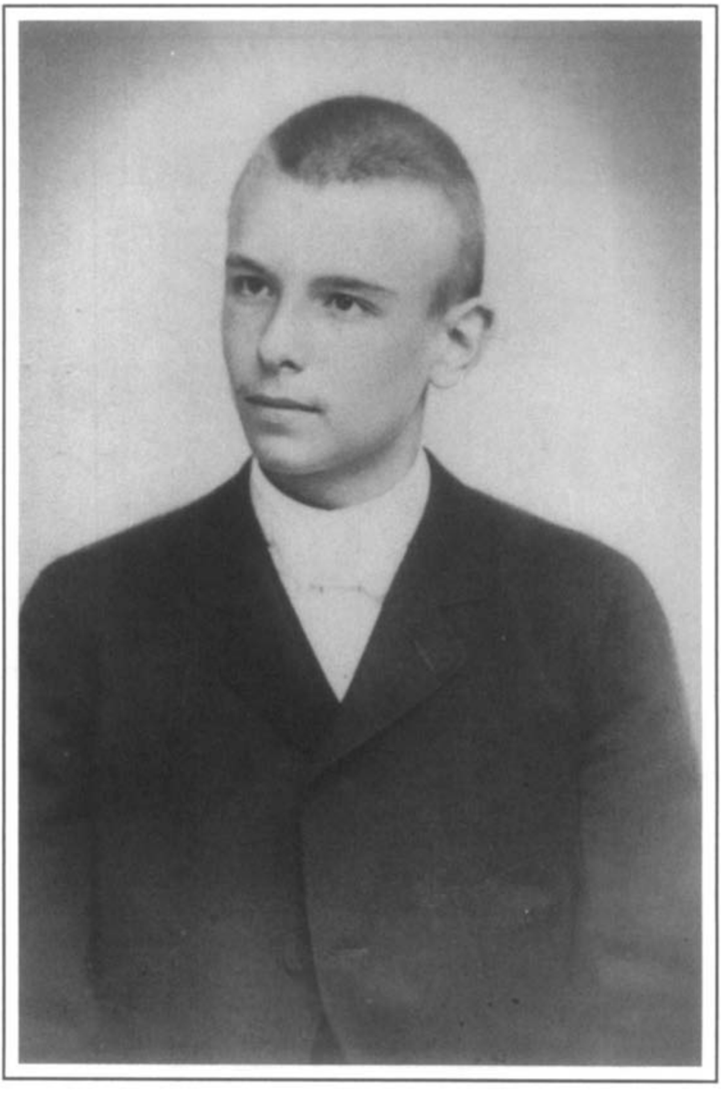
Ferdinand Wittenbauer, born in 1857, was no ordinary university professor. A bronze plaque and relief in the Technical University commemorates him as Teacher, Researcher, and Poet. He was not just a famous professor of theoretical and applied mechanics, whose discoveries and publications in graphical dynamics had made it possible to replace idealized methods of analysis with graphical techniques vastly improving the design of transmissions and other real machine parts. Wittenbauer was also a highly regarded, if not controversial, poet and playwright, whose works performed on the stage in Graz and Vienna exposed political, social, and cultural issues of the times amid intimate portrayals of student and university life.[20] Austria-Hungary was a community of many language groups and, as various national movements began to emerge, there was much opportunity for humor derived from stereotypical figures. Among other biases, he was anti-church, antisemitic, and strongly pro-German.

Young Terzaghi was fascinated by the rare and remarkable professor who could create at a significant level in two extreme poles of human experience. In turn, Wittenbauer must have admired Terzaghi's deep probing brain and thirst for ideas. Being a fraternity man himself[21] he could understand, but not agree with, Karl's misguided pranks. Wittenbauer continued to gently guide Karl to other original sources. "The conversations associated with his manifold suggestions introduced me into a realm of thought which I never could have entered otherwise. My teacher became my fatherly friend and confessor." This built for him "that inner world which for me represents my university education. The University itself, and the colorless mass of inert knowledge offered in its lecture rooms hardly count."[22]

Wittenbauer's gift with words enabled him to recognize the same in Karl, so that when the young man asked him to read his manuscript "Social injustice in modern society"[23] he proceeded to do so. The professor was impressed. He asked Karl if he might not prefer to become a writer and introduced him to editors of periodicals.

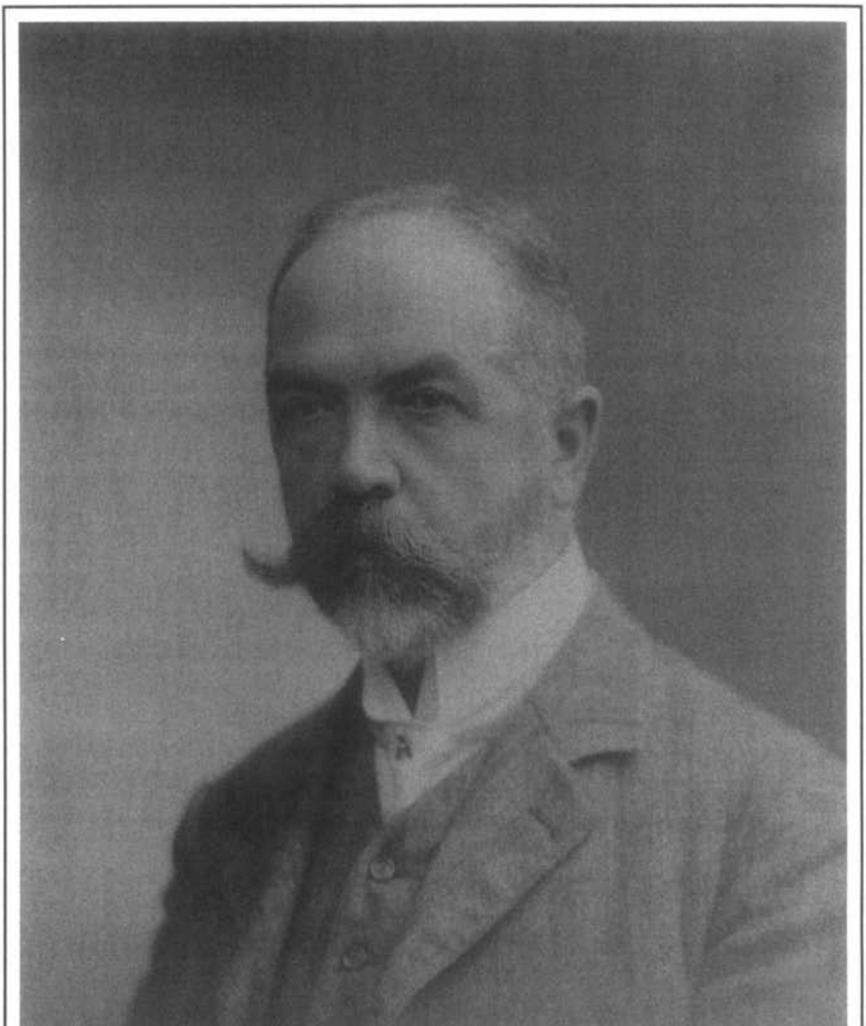
A year later, Karl got into deep trouble on account of a prank that led to his assailing and abusing a policeman from a tree in a city park. The incident amused readers of the front page of the Graz newspaper. When the obviously entertained judge acquitted the defendants, the police were so enraged that they appealed, which landed Karl and his cronies in jail. They carried on further there and the unruly behavior led to further discipline ("because we had bribed the jailer and turned our sojourn into a noisy and jolly party").[24]

This party became serious when Karl's expanding police record was brought to the attention of the faculty, who were ready to expel him. But eloquent Professor Wittenbauer came to his defense. In the entire history of the Technical University of Graz, he told them, there had been only three expulsions: Tesla, Riegler, and another. Afterwards, Nicola Tesla revolution-



Karl as a young college student, 1900.

The members of the fraternity ("Corporation") Vandalia about 1901.
Karl is second from the left in the back row.



Professor Ferdinand Wittenbauer. (Photograph courtesy of Prof. Karl Stock, Head Librarian Emeritus, Graz Technical University.)

ized electrical technology with his invention of the AC motor; Riegler created the steam turbine; and the third developed into a leading church architect of Germany. The faculty, Wittenbauer concluded, is not good at choosing candidates for expulsion. And so Karl squeaked by.

Despite all these shenanigans, Karl managed to excel in both the two-year and the four-year state examinations in mechanical engineering. These are strenuous tests extending over an entire week, and including special as well as general achievement, with written and oral segments. Karl's scores included many "excellents", a great number of "very goods", and only a few that were merely "good". In each examination period he was rated "very accomplished", corresponding to "honors".

Karl had actually attended courses in geology during his years at university, from three different professors, and he made every hiking and climbing trip into the high mountains an adventure in field geology, with detailed, flowering notes in diaries and essays. This is what he really loved—the joy of observation and discovery in free nature—and he anticipated work as a mechanical engineer with misgivings. This feeling of discomfort stayed with him throughout several months after graduation in 1900, when he served as a trainee in the engineering works in Andritz. He came to the conviction that he would not be satisfied with the work as a mechanical engineer and resolved to switch into civil engineering, as had been recommended from the start.

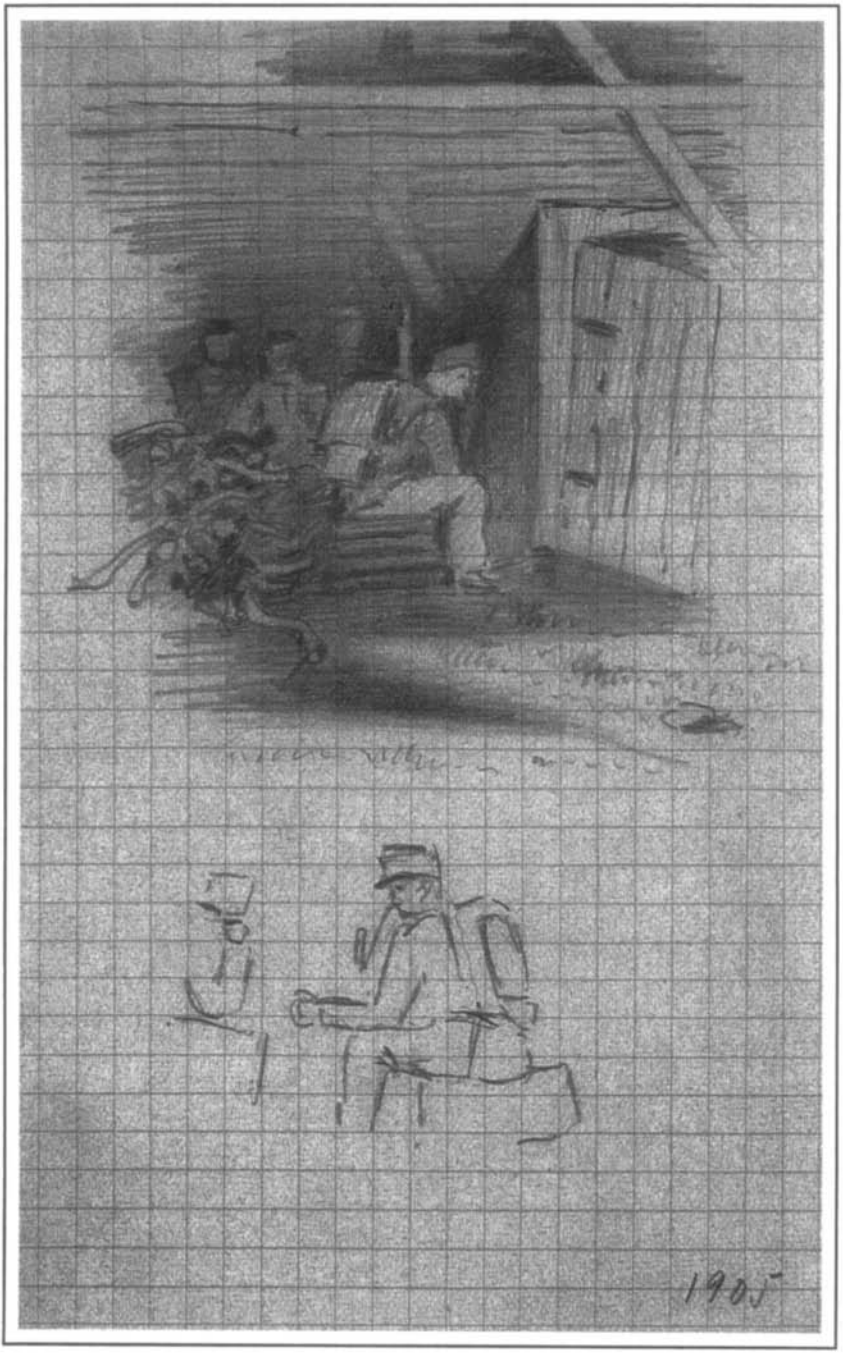
However he had first to satisfy his compulsory one year's military service, in an infantry regiment. This must have been slow for Karl, with long nights on watch, idle time in the barracks, and "a long detention in the Guard House."[25] His repertoire of subjects for miniature pencil sketches expanded from landscapes, trees, and plants to include military themes. As sketching could hardly merit all his free time, he turned his hours of waiting in a useful direction by undertaking the translation into German of a popular manual on field geology by the director of the British Geological Survey, Archibald Geikie. He succeeded in publishing this work in 1906, with a forward by his geology professor at Graz, V. Hilber,[26] who noted that hardly any activity is more important to geology than observation.

Terzaghi was not satisfied in mere translation; he prepared a new edition to extend the work where British horizons had been meager, namely in describing karst features (such as caves and sinks) in limestone country, and the features to be found in glaciated country. British examples were replaced by Austrian illustrations. And Terzaghi improved the chapters on mineralogical analysis and the rock-forming minerals. "Thus the book lost its local English flavor without sacrificing the exemplary English clarity."[27] Terzaghi, at the age of 22, offered this work to spur German-speaking youth to see and learn for themselves, thus to catch the excitement of geology, rather than having to imagine it from stale, lifeless facts.

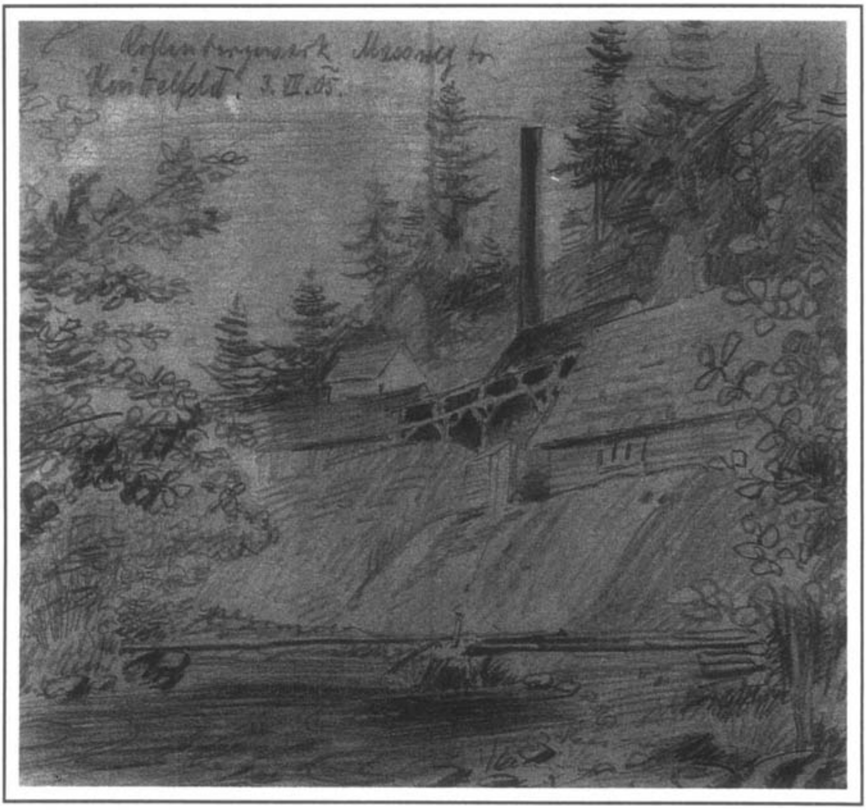
Since Karl was resolved to switch out of mechanical engineering, his grandfather granted permission for another year at the university in Graz, at the end of his year in army service. Karl combined further study of geology with courses in railway and bridge engineering at the Technical University. During this year he published his first research paper, aided by a grant from the Steiermark Natural Science Society, on the marine terraces of southern Styria.[28] The paper contains sketches of the landscape and a geologic map of the more or less horizontal layers of soft, Tertiary marl, clay, and loam.

Although he went about this geological field work with ability and pleasure, it did not meet his expectations as a way of life. There was no real action and no important outcome, whereas he wanted "to lead and take chances".[29] The opportunity to do precisely that arose with an offer to serve as a geologist on a trans-Greenland expedition, which he immediately accepted. Unfortunately for him, in the summer of 1906 Karl severely injured his knee in a mountain climbing accident in the Alps, making it impossible to go.

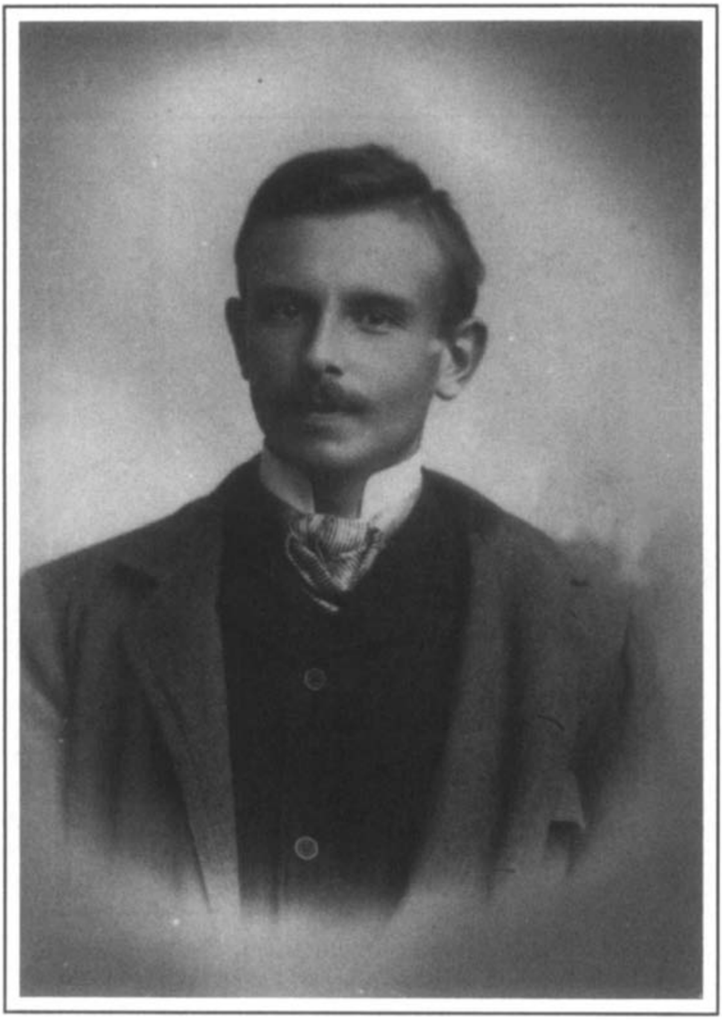
He opted then to apply for a job in civil engineering, where at least he could work in engineering geology and maintain contact with his "beloved science".[30]



The emptiness of Austrian army life, 1905.



The coal mine at Knittelfeld, 1905.



Engineer Karl Terzaghi at age 23 (1907).

2
To Work in Europe 1906–1912

Karl Terzaghi had finally settled on civil engineering as his profession and quickly found a challenging position. The firm Adolf Baron Pittel, Vienna, a specialist in concrete design and construction, took him on as a junior design engineer. Although Karl worried about his lack of qualifications, his degree in mechanical engineering must have seemed fitting for the firm's purposes as they moved into the relatively new field of hydroelectric power generation.

Terzaghi worked hard to fill out his education by reading, and listening, particularly to the stirring young engineers of the company. To his surprise, they were equally stimulated by the new knowledge he brought to them, not so much in mechanical engineering as in engineering geology. The planning and construction of a hydroelectric power station mean sorting out data about stream flow and settling on suitable sites for dams. They must be of the right height to hold reservoirs sufficiently large to supply a constant stream to a power plant throughout the year. The water from the reservoir has to be conducted by a surface canal, pipeline, or often through a tunnel, and then down into the powerhouse at high pressure by means of a shaft or steep pipe (termed a "penstock"). Finally the water leaving the powerhouse has to be safely returned to the river. The planning for all these features is greatly dependent on geology.

But when they occasionally consulted an expert geologist, guidance was not necessarily helpful. In one job the expert predicted that they would find good rock at shallow depth below the dam site and improving tunneling conditions as they progressed into the mountain. Actually an adequate foundation could be obtained only after a very deep excavation, and the tunnel rock deteriorated as they advanced. When confronted, the geologist "only laughed and said: 'If I knew for certain what was inside the mountains I would not be the director of a geological survey, but the richest man in the world.'"[1]

It quickly became apparent to engineer Terzaghi that the engineering staff was looking to him for guidance with respect to geology in their hydroelectric design problems. "The grounds were very soon obvious. Nearly all the technical difficulties, accidents, and miscalculations in the sphere of activity of the enterprise were traced back, in the last analysis, to geological circumstances which the engineers knew nothing about or had learned too late."[2] It was not considered usual to drill borings at sites of structures in order to investigate the subsurface. But even when the soil and rock characteristics were exposed to view, the engineers seemed to lack any approach for making use of this information in going about their design work and were often faced with unpleasant surprises during construction.

Soon after Terzaghi joined Pittel they were attempting to build a dam in Tirol on a stream channel filled with coarse cobbles and boulders. The normal way to place the concrete foundations sufficiently deep for a dam on a streambed was to isolate sections of the foundation soils, one after another, by creating box like walls of steel. This was accomplished by driving overlapping sheetpiles—flat rectangular steel sheets equipped with lateral interlocks. Ground water was then pumped out of the interior of the steel-sided box, and a stable excavation could be dug from within the box to permit concreting at the base of the dam. One section after another was to be completed in this way until the dam stretched all the way across the river.

Pittel had trouble, however; they simply couldn't drive the sheet piles to the required depth through the bouldery stream sediments, and the walls and open base of the protective box leaked badly so it couldn't be pumped dry. The foundation had to be concreted under water using an expensive technique. When the concrete placement was completed and the reservoir filled, water began to stream vigorously through the foundation. Then, suddenly, the dam burst.

This case troubled Terzaghi considerably for nobody seemed capable of explaining how to avoid such a failure in another place. The mode of failure was known by name—"piping"—but no one understood how to assure safety against it.

There were other, somewhat similar, difficulties in 1907 as Terzaghi directed the construction of a power station with a dam and tunnel, in the town of Waldegg. In this site, a temporary embankment of earth—a "cofferdam"—was to be built to divert the river and isolate a portion of the stream bed so that the concrete could be formed and poured in a large open pit. But when they tried to pump the open pit dry, water leaked into the excavation through the soils under the cofferdam faster than it could be pumped out. Terzaghi observed that the spaces between the coarse stones of the subsoil that are usually filled in naturally with sand and silt were essentially open, permitting water to move unhindered through the ground. The only way the job could be done was to bring on a dredge to excavate the work area through the soils from below the standing water, all the way down to the bedrock surface.

At the time of this engineering error Terzaghi learned about a worse case from 1897 in Salzach, Austria, where it proved impossible to pump out the foundation work area and the entire project had to be abandoned after heroic attempts.

Karl was also troubled by the methods he saw being used by government engineers to forecast the settlement of structures. It seemed like little more than guesswork. The prediction of tunnel driving conditions in an Alpine hydrotunnel in fractured limestone, and the design of a lining to hold water pressure presented other severe frustrations.

Whereas Terzaghi was learning mainly about the profession's inadequacies in dealing with soil and rock construction, he was gaining self-confidence as an engineer. He learned how to manage workers and to run a construction job, and became adept in design and construction of steel-reinforced concrete structures. At the age of 25 he was assigned to take charge of design and construction for a gypsum silo, in Siebenbuergen, then with constructing a factory in St. Pölten, and a hotel in the resort at Semmering. "For the money that my quick growth in experience had cost the enterprise, they had now an experienced construction director of the first rank."[3] He wrote up these experiences as contributions to the Austrian journal of concrete and steel.[4]

Terzaghi began to imagine spending a comfortable lifetime with this firm. But he could not overcome his fundamental restlessness, especially when confined to a drafting board in Vienna for the winter. When he learned about the Dutch colonial army's campaign against rebelling tribes in Borneo, Karl decided to join this action and applied for a commission. Fortunately a better opportunity emerged first, in Croatia, and, as he had already half committed himself to learn more about engineering geology, Croatia seemed a better direction to take. It was there he went in the first days of 1909.

Croatia's "Dalmatian Coast" along the Adriatic south from Trieste, Austria's only seaside, held alike ports of fishing and commerce, and celebrated watering places of the wealthy with deluxe hotels and palaces. In contrast, the interior of Croatia to the east was a rocky, hilly country inhabited by peasant farmers. Geologically it is known as "the Croatian Karst", etched over millenia in the great thickness of soluble limestone formations. The karst includes hundreds of thousands of "sinkholes" where the ground has collapsed into underground caverns, and broad shallow lakes filling "dolines" where continued subsidence has created broad basins. Rainfall runs into rock fractures or sinkholes and disappears underground, some reappearing over the craggy divides as springs. As it is a steep land with ample rainfall, there is hydroelectric power potential. Thus the French

"Enterprise Generale des Constructions" thought to form "Adriatique Electricite" to develop a major project.

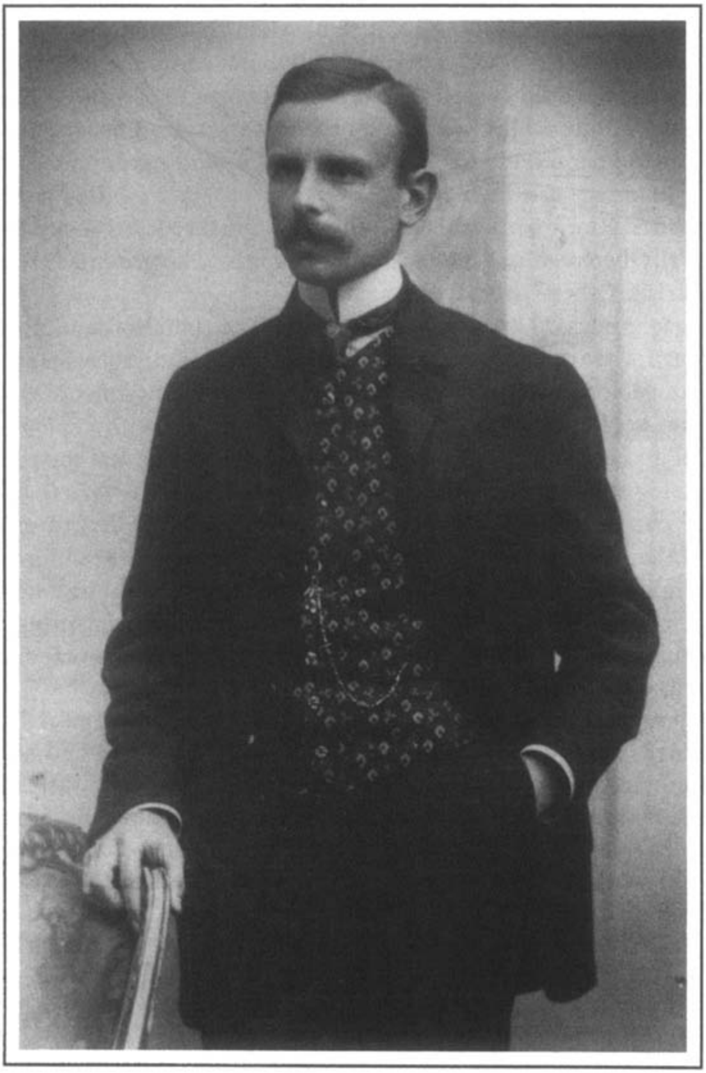
Terzaghi was drawn to this project by the opportunity to collect geologic data and have free rein to use it in engineering planning. But it was also a chance to explore an exciting, rough new landscape. His headquarters was Fiume, (now Rijeka) on the coast; his base was the village of Otocac at the end of a doline basin across the very steep Velebit Range, reachable only by a tough mountain road. The project plan was to divert the Gacka river near Otocac into a tunnel some ten miles long through the Velebit Mountains to a powerhouse on the coast at Zengg (now Senj).

The landscape became both his work place and his hobby. He was responsible for measuring the streamflows, surveying the topography and relevant geology, and preparing a plan to harness the power potential with reservoirs and tunnels. He also took private pleasure in attempting to decipher the geological picture as he tramped back and forth across the region. Whether a stormdriven winter karst or a summer beech forest with birds and bears and deer, it was to him a marvelous wilderness. He described this excitement in a letter to Professor Wittenbauer: "All the beautiful and terrible things that nature could offer were assembled before me." [5] These included gigantic hills, massive precipices, wild ravines, jagged limestone cliffs, and craters. He marveled at the extraordinarily vivid colors and the expansive views over the seacoast. "It is difficult to imagine times more rich and enjoyable."

But at the same time he worried about the engineering dangers of cavernous limestone, and the Technical Director "who not only lacks solutions to karst problems but, even worse, doesn't even know there are any." It was a gamble to plan hydro works in such a terrain for there was no assurance that a dam would hold water or that a tunnel would transmit it. Even estimating the annual discharge of streams was a puzzle. The Gacka River rose from springs in the rock at one end of the Otocac basin and disappeared into sinkholes at the other end. The project called for blocking sinkhole outlets of a periodic lake and converting it into a permanent reservoir.

It was a landscape so unlike his native Alps. Unlike the rushing brooks of his youth, "the waters of the karst come eerily, noiselessly ... [and] the streams flow through the sad plains between fantastic rock formations in the greatest monotony, without waves, without obstacles, without energy when the going is good, and disappear noiselessly as they had appeared."[6]

It was also a land of turmoil, Croatia being the farthest outpost of Austrian empire at a time of mounting nationalism among Serbs, Slovenians, Croats, and Bosnians. Austria-Hungary directly governed the coastal strip, but granted semi-autonomy to the Duchy of Croatia in the east. The independent Serbia intended to acquire Ottoman Bosnia but Austria preempted them, and ignited their hatred, by itself annexing the state, just a few weeks



Karl Terzaghi, age 23.

before Terzaghi began his first reconnaissance of the entire project for the French enterprise. Thus he moved among a divided and volatile populace. As well as a geology hammer on his belt, he wore a Browning pistol, which he asserted was "the highest authority in a Serbo-Croatian dispute". He called the region "our European Central Africa".[7]

After a while he began to find fault with the populace. "I have the firm impression that the Maker has not only botched up the long profiles of streams but the people as well."[8] Later, in retrospect he wrote, "The sea is truly beautiful like a blue wonder, but it washes a dead coast ... And the lifestyle of the people is just like the land. Man and nature are in perfect harmony. The race can be blamed for its own misery ... Dilapidated, half-decayed huts. Run-down mills and their owners brooding away the days apathetically between puddles and dungheaps ... The ground is fertile for political crisis. Otherwise, not much more."[9]

Terzaghi puzzled over the local geology to the point of sending a paper to a scientific journal, partly because of an intense disagreement with a Hungarian geologist who accompanied him on a walking tour of the reservoir region.[10] Nevertheless, he asserted that working with geology in the context of a practical engineering project had quieted his zeal for pure, academic geology. The field geologist expostulates with only sparse data and lacks the chance the miner and the engineer have to drill and excavate. Moreover, he claimed that water-power engineering and not reinforced concrete design had now become his "true domain", even though he was to perform one last job for his old employer in Vienna (instrumenting a reinforced concrete silo he had designed for them in Mannersdorf) and then continue to work in that field for some time.

He got permission to hire an assistant, and recruited by means of Prof. Wittenbauer. To his embarrassment the man proved unsuited and had to be terminated, inspiring Karl's adroit sarcasm. The assistant was "entirely incompetent technically but at any rate interesting, a puzzling mixture of immeasurable self-confidence and childish timidity and clumsiness. What he has taken in his hand is, in a short time, bungled, ruined ... He has linked up a new way of teaching engineers ... Time heals all wounds and can transform the dumbest engineer into a source of stimulation and instruction."

The work was hard and the hours were long. In the winter he worked out of an office in the city of Fiume assembling his data and preparing his plans and reports. There he could also enjoy boating and a good number of "cultured parties", in contrast to the routine at Otocac where his social activities consisted of regular visits to the brothel "lying first with this and later with that beauty."[11]

Alongside his assigned work, Karl explored the origin of the landscapes. He was particularly curious about the formation of extensive depressions, termed "Polje". His observations gave birth to a theory that led to a controversial publication.[12] Forests were gradually sinking, he thought, due to the chemical decay of the underlying limestone by their organic acids. As the forest sank, it came closer to the water table; when the tree roots had descended to the ground water surface, the trees died to be replaced by marsh, whereupon the subsidence ended. The depressions were thus "fossil images of former ground water tables". This idea was strongly rebutted by geologists attached to the idea that the subsidence of Poljes came from the collapse of subterranean cavities. But four years later noted geomorphologists Penck and Lehmann independently expressed support for Terzaghi's novel concept.[13]

By July 1910, Terzaghi's plans had been completed, but construction could not begin for half a year or more. He happened to leaf through a volume of the manual of reinforced concrete that dealt with water works and read over and again reference to works in North America. While he was vegetating in Croatia, big engineering was going on elsewhere. He snapped to a decision to become part of it. He would resign his position and head to New York.

The first part of this scheme went ahead, and very quickly. As he began to pack up the room he had occupied for a year and a half, with its "indescribably beautiful" view over the Adriatic, and later as his steamer departed, he was gripped with nostalgia. "I have never suffered nostalgia and have only a weakly developed sense of family" but it was different with colleagues and friends with whom he had shared storm, heat, and worries through the months and years and on whom his profession depended. However, he was on his way to America to see dams and reservoirs, entirely commanded by a deep longing to travel. He was becoming, as he later described himself, a nomadic engineer.

Returning to Austria he quickly acquired "a stately number of recommendations from the best circle of Viennese reinforced concrete engineers." If it didn't work out in America, he had an offer from his French company to help them with a hydro project in the Chilean Andes. Then, someday, he would return through China and India. "The world is round."[14]

But his yearning ambition to go to America did not survive the news of a construction emergency in Russia. A friend working with a Russian contractor, J.J. Lorentzen & Sons, on a big bank building on Nevski Prospekt in downtown St. Petersburg, reported that the construction of the foundation had been bungled and the contractor had no clear idea how to remedy the initial mistakes. There were penalties for delay in completing the contract. Terzaghi immediately offered to direct the project, and within two days was on his way to St. Petersburg to arrive on June 1, 1911.

He was taken from the train station directly to a working breakfast and on to the job. Fix it at any price he was told. Just how was up to him.

The building commission had stopped the work until they had received and reviewed new plans and specifications. It quickly became obvious why. All around the perimeter of the excavation pit was a retaining wall that had been placed to hold back the river sand, peat, and mud beds that form the subsurface of this part of St. Petersburg. But it wasn't doing its job. Quicksand was flowing like a liquid through various gaps in the sheet pile wall that encircled the foundation excavation; as a result the neighboring buildings lay damaged, some perilously. The concrete pad was half poured. Steel girders lay rusting. "My first impression fastened on me a dumb headshaking, almost sphinx-like facial expression."[15] Then he stopped feeling sorry and got to work.

Or tried to work, in the face of "haphazard methods" and "concentrated incompetence".[16] He was bombarded with unfamiliar impressions. In the main office, a dozen uniformed engineering assistants chatted, smoked, drank tea. Calculations and plans were in confused disorder. The "single point of light", a German engineer, "sat with resigned countenance waiting for better times." Terzaghi said "thank you" and retired to his room, where he drank tea and smoked up his last Austrian cigars in hope of inspiration.

After three days, he moved forward with a dynamic plan that would not only get the job on track but reduce its cost by 30%. He fought it through at the building commissioner's office, over the objections of "experts", and had the work restarted within a week of his arrival. There was but slight interruption for his first all-night celebration with a Russian contractor. The work was put back on schedule and completed on time with a workforce of a thousand on day and night shifts.

Under Terzaghi's Austrian style the office became quieter, the consumption of tea declined, and a few Russian engineers were exchanged for imports from Norway and Croatia. The economic outlook began to seem bright, not just for the bank building but for contracting work in general. He could imagine planting roots here.

St. Petersburg in 1911 was a very different milieu from Vienna. Efficiency was low, and corruption was accepted. The bitter competition for the St. Petersburg engineering market, being waged by Lorentzen & Sons against Danish and German firms, could be won only by gaining the confidence of higher authorities, unaided by any sort of political action. Terzaghi learned "to get to know the mentality of the clients" and quickly cement personal friendships with the right people, "always to link practical with psychological considerations."[17] Thus his professional and personal affairs were "interwoven". This made it hard to leave.

He was asked by Lorentzen to organize a branch office in Riga and take charge of projects there. This included industrial buildings in the Baltic provinces and construction of a castle for an uncle of the Czar. He also enjoyed parties with "merciless, impudent Champagne"[18] and "the brighteyed Riga maidens who, without moral restrictions, and expenses paid, answered the call of nature".[19]

As Fall passed into Winter, Terzaghi found the land brutal, ever foggy, with sunless sky.[20] It was time to move on with his plans for travel in America, and then on to China. To responsibly separate from Lorentzen & Sons he needed a dependable replacement. He nominated Otto Fröhlich, whom he had previously brought to St. Petersburg from Berlin. On the surface, Fröhlich seemed to be following Terzaghi through life. Born two years after Terzaghi, also in the Czech part of Austria, Fröhlich was likewise a graduate of the Technical University of Graz, and also worked in Fiume, under Terzaghi. He was no genius, but to Terzaghi he was a systematic engineer and a man with clout. Otto Fröhlich was accepted, and Karl Terzaghi was off, on December 7, 1911.

During Terzaghi's six months in Russia he had evolved novel graphical methods to solve specific questions concerning the design of industrial tanks. It occurred to him that he could write this contribution in the form of a thesis and obtain a doctorate, which might help him to gain acceptance in his travels. He wrote to the Technical University of Graz and found a willingness to cooperate. With an essentially completed work in hand, he obtained the date of January 16, 1912, for the doctoral examination ("Rigorosum") in Graz. The event was attended not only by a significant number of faculty members but by a large group of students, anxious to learn if this famous fraternity man was in fact a real talent or a charlatan.[21] He passed the examination with acknowledged distinction and was "promoted" to "doctor of technical Sciences". For grandpa it was the realization of his greatest wish; both were greatly moved as they embraced.[22]

Terzaghi's dissertation made quite an impression on Professor Theodor Pöschl who saw it as an opportunity to advance his own status and subsequently arranged with Springer Verlag to publish it as part of a comprehensive coauthored work. Together they succeeded in elaborating the new methods in a compact book "for students and engineers and for use in construction offices".[23] The first part presented analytical solutions, using a novel mathematical approach;[24] the second presented Terzaghi's new graphical techniques. In an unkind mood Terzaghi wrote to Wittenbauer that his coauthor was good enough to edit the work and prepare the appendix but for not much more.[25] This could not have been true since both parts of the book received highest honors in a review written by Otto Fröhlich for the Austrian Society of Architects and Engineers.[26]

In his short stay in Austria, Terzaghi worked on enlarging his dossier of introductions and recommendations to help unlock the engineering world in America. He also enjoyed amorous associations, not only continuing his corporeal relationship with his new sister-in-law, Olga Byloff,[27] but adding, begrudgingly, a mysterious short affair stimulated by advances from the wife of a colleague. At this age Karl was immensely appealing to women, with a handsome face with a cropped moustache and straight brown hair kept fairly short and neatly groomed. He had a slim, manly figure and upright posture. But even more appealing was his expansive, articulate personality alive not just with tales of adventure but with treasured knowledge of literature, art, and music and a passion for ideas. He loved women, literally with body and soul.

In February of 1912, Dr. von Terzaghi said farewell to his family and friends in Graz and rushed towards disillusionment in America. He went to learn, and in that he did succeed.

3

Ambition in America 1912

The long train trip across the Alps to the top of Germany allowed Karl a chance to visit engineers and friends in Munich and Hamburg. He was delivered to Hamburg in a Prussian railway director's private sleeping car; apparently his pattern of interpersonal networking, learned in Russia, was being honed. On February 13, 1912, at the Hamburg America line at Cuxhaven, armed with US immigration advice that anarchists and polygamists would be denied entry to the United States, he boarded the magnificent steamship *America*.

In first class, the life on board was that of a fashionable resort. Every morning he enjoyed the gym, "with improvised horses helped by small electromotors to simulate a fast trot, a slow trot, or walking";[1] the menus offered "astounding richness" (he kept a log of the meals), and a daily newspaper came to the ship by Marconi Telegram.

The accommodations and food were indeed first class but the passengers, he suggested to his grandpa, were not, as "the majority are American, only a few women, and a damn lot of Jews."[2] Karl quickly befriended a wealthy German-American industrialist, Mr. Plant, owner of the largest North American pharmaceutical company. Among his many connections, Plant was a personal friend of the director of the US Geological Survey. Terzaghi could not have appreciated what a lucky break this would be.

He also greatly enjoyed playing chess with "a marvelous old man, tall, with a belly, missing the tip of his nose, and with numerous dueling scars."[3] This was none other than German-American millionaire Schoelkopf, who counted among his possessions the Niagara Falls power development.

He found the majority of the American travelers uninteresting. But there were two who were—Mrs. Eden and Mrs. Adams, who found entertainment in the Graz conversation of their "little Doctor". He, in turn, enjoyed being between Adams and Eden in Paradise,[4] expressing astonishment in the apparent freedom of American wives.

The arrival in New York on the night of February 27, after nine days, seemed so overwhelmingly disorganized that Karl included reference to it in a travel essay he sent to the Vienna newspaper.[5] "Hardly had I left the pier than I was carried away by the irresistible 'forward march' which rules all American lives. This pace grips me and paralyzes me at the same time. The brain works faster than it would like, unintentionally punishing the muscles." He was highly impressed with the Astor Hotel, which seemed like a European palace, except for his room with a view of the light well. "People obviously have so much to do here that they don't spend time on details."[6]

Compared to the Astor, the clean boarding house he found in a brownstone building at 111 West 76th street was quiet and surprisingly hospitable thanks to the landlady and her elder clientele. Although "the absence of oysters, lobsters, pineapples, smoking, and dollar princesses in a puritanical boarding house" at first caused him to feel embarrassed and strange as the only European, he began to see that "cooling off from my dissolute Petersburg lifestyle may be charitable to health."[7]

New York surprised Karl with its boundless vitality, smoke-free air, and much beauty coexisting with the ugly monotony of endless brick facades. As an engineer Karl found the great steel buildings and long-span bridges truly remarkable, as well as the public transport system that took one at trivial cost over the vast extent of the city along logical routes. Equally unparalleled in his European experience were the intensity and ferocity of traffic and the absurd din of it all. "Here there is life, albeit of a ruthless kind."[8]

To carve his way in this strange place he ought to have a more American look, so he shaved off his moustache, purchased a new Derby, sighing at the expense "as winter sighs at the equator" and paid his first visit: to the "Steel and Concrete Company". The street address (Park Row 1222) led to a block of a hundred offices and ten elevators, which were always full and ever in a hurry. He tried getting off at each floor and asking if there were an engineer there, to deaf ears. Then he tried to phone. The "super Gods" were protected by chattering secretaries. He found no sentimentality and no admittance. "I felt like a Bengal Tiger trying to gain entrance."

After several days of effort, he managed to cross the threshold of I.G. White, a leading international contracting company. The Chief Engineer was struck by his references, experience, and publications and opened up the possibility of a profit-sharing position in their London office. If this doesn't work out, he encouraged Terzaghi to keep plugging as his ambitions in America seemed well-founded. But just in case they weren't, Karl started to learn Spanish.

He discovered the headquarters of the American Society of Civil Engineers, reached by a friendly walk through green Central Park with its social squirrels. At the lunch room he befriended a young Viennese man who had somehow managed to "overcome his aversion to America". In the library of the ASCE Terzaghi found a great number of helpful technical books and began to spend long hours there. From his reading and conversations he quickly concluded that theory serves little purpose in American civil engineering. There is good use, however, for books on plant administration, organization of construction sites, and so forth, in which they are well ahead of Europe.[9]

In his education and early experience, Karl had been drawn into the field of reinforced concrete design. His significant doctoral dissertation advanced reinforced concrete engineering practice, and he had designed, constructed, and instrumented important structures. But he was not inclined to seek a position in that field in the United States, for two good reasons. First, he had little regard for the commercial orientation he discovered in American practice. In Europe "they brooded over every crack. Here they order a reservoir the way you order a winter coat," and it is achieved with only primitive calculations. The only "engineering" utterly required is inspection; the contractor organizes everything. The whole field has degenerated into a trade like shoemaking or fish-mongering due to the American manner of "pure salesmanship".[10] This was "the land of materialism, the antipode of Russia."[11] Second, he was still excited about engineering geology.

The reason so much seemed to be going on in North America was the massive water resources program enabled by Teddy Roosevelt's Reclamation Act of 1902. The plan called for 60 dams, some with almost unprecedented height, and many miles of irrigation canals, mostly in the arid west. The management of the project was entrusted to a new agency, the U.S. Reclamation Service, associated with the Department of Water Supply, Irrigation, and Water Power of the US Geological Survey. The significance of engineering geology to the success of the plan was recognized from the outset. If anywhere on the planet there was an opportunity to gain practical experience in engineering geology, thought Terzaghi, it was here.

Karl had a trump card in his shipboard friend Mr. Plant. He reminded him of the offer of introduction to his friend Mr. Clark, the head of the Geological Survey. After an opulent luncheon with oysters, strawberries and Bordeaux wine, Terzaghi was presented with the letter he needed. He started almost immediately for Washington, D.C.

The architecture of New York's Penn Station, the utter democracy of the one-class rail system, the idea that wild Indians had lived barely a century ago along the route traversed, the Negroes and Chinese in the dilapidated section of Washington through which he walked with his valise—all this was intoxicating to the impressionable visitor. The crowning impression was the image of the domed colossus of the capitol rising from the heterogeneous mass of houses; it was almost too much for his European eyes.[12]

Washington was professionally more welcoming than New York. He was received warmly by Mr. Clark who supplied him with exactly what he needed, a letter of introduction to F.H. Newell, Head of the US Reclamation Service. Although beneath him in the hierarchy, Newell directed an essentially independent organization.

Terzaghi was warmly received by Newell. The mature, round-faced man, with bright blue eyes, listened attentively as Terzaghi explained Austria was just starting to build large hydroelectric plants and therefore was anxious to profit from American experience. He did not flinch when Karl told him he was going to write an article for Austrian engineers and that what he wanted most to learn were the construction mistakes and their geological causes. He was promised vigorous support, including help with travel itinerary and complete background information. Newell started by writing a letter of introduction for Terzaghi, instructing all his construction staff to cooperate in every way. He also introduced Karl to comfortable accommodations at the Cosmos Club, where the regulars at lunch spark the scientific ferment of America.[13]

Since the trip would include visits through western wilderness, Karl sent a letter home asking for immediate shipment of his horseback-riding outfit. He was expansive. "If all goes according to plan I will be able to become a specialist in dams and one of the best professional engineering geologists in the German community."[14] He also wrote to the Austrian Society of Architects and Engineers inquiring about a grant, which he saw as a good investment for Austria. The trip would cost about $1,000 over three months. Just in case that was not forthcoming, he wrote a detailed proposal to his grandfather arguing the economic soundness of his expedition.[15] The Western U.S. seemed an immense engineering geology laboratory to supply the empirical data he was lacking.

Karl remained in Washington for a week studying materials about the projects he was to visit and writing his proposal to the Austrian Society of Architects and Engineers.[16] He accumulated additional documents to study over the next month, and would start out from New York early in May. Upon reaching San Francisco, he would then have to make a choice, whether to go to work for I.G. White in London, or go home by way of South America, ultimately to start up a firm in Austria that could take advantage of his unique and soon-to-be-vast experience.

But Karl had unfinished business in New York; he had to receive an unhappy and frightened Olga Byloff, who was pregnant with his child. He

Olga Byloff, circa 1911.

had known this prior to his departure from Europe and promised to take care of it, somehow. His moral code allowed no other response, especially since she was the sister-in-law of his own beloved sister Ella.

On the night of April 2 he trekked to a distant Brooklyn dock to greet her in a downpour of rain and emotions. They spent the month together, facilitated by a compassionate landlady. Karl took a day job as draftsman and evenings and weekends they toured and talked. He still loved her laugh, and the way she expertly and tenderly played the piano, and her free spirit, which was half to blame for her trouble. But he was not interested in marriage, a state completely incompatible with his near horizons, and Olga might not be his true choice in any event. He told her she would be better off if she could marry—someone else.

Karl confided his problem to an Austrian colleague in Boston who arranged an appointment for Olga and Karl with the General Consul of Austria. The Consul put them in the hands of the Sisters of Joan of Arc who listened, and went to work on her behalf. Within a short time they had a solution for her—a trip to Mexico and a position there with the wealthy Ramos family, owners of a plantation near Mexico City; the three children were about to lose their mother to terminal illness and an educated, compassionate woman was urgently needed as governess. Karl met Mr. Ramos, who was in New York on business, and quietly concluded a formal contract by means of which Olga would be cared for and employed and presumably could have her baby sent out for adoption. In return Karl gave his written promise that they would one day be married. He became legally engaged to Olga, although there was no assurance that this was more than a charade. His love had been but a tender moment a year before. It was all but a chapter in his book of life. Now he was a nomad who missed and needed nobody and wanted only to work.

Karl was delivering Olga to a strange land and household in a country on the verge of civil unrest. He honestly believed Mr. Ramos to be honorable, fine, and caring. The Consul assured him that the fighting in Mexico had been exaggerated by the newspapers and in any event it was limited to the north, 1000 kilometers from Mexico City. Olga was relieved with the arrangements, at first, but suffered over the idea of parting forever with her baby. But then, resigned and tearful, she boarded the train and let her arms separate from Karl's. A bystander, observing the tender scene, commented "They are very nice, these last minutes!"[17]

Karl could now resume his study of the construction reports and plans provided by the Reclamation Service for the water developments and power projects he was to visit in the western states. It took time for he wanted to really digest this material before embarking. He also spent time writing two articles to send to the Vienna newspaper, one on skyscrapers of New York and the second on the sinking of the Titanic.[18] On the eve of his departure, in a fury of packing, he received a long letter from Olga. She was having second thoughts and wanted to change the plans, presumably to keep the baby. Karl felt dizzy, frightened. He prepared an agitated reply at midnight bidding her most urgently not to wreck her young life (as well as his). Several months later he wrote to an in-law that he did not wish to discuss Olga as the subject caused him pain. She was terribly unhappy, saying she had been consigned to hell and the civil war insufferably delayed correspondence.[19]

Karl left on the fifteenth of May, 1912, for Washington, D.C. He dined with Director Newell at the Cosmos Club and inhaled stories of the pioneering construction work he was about to visit, most of which had commenced construction in 1911. His three-month itinerary started with flood-prevention work along the Mississippi at New Orleans, then onward, among other destinations, to Angel Dam on the Rio Grande, Roosevelt dam in Arizona, the Yuma irrigation project on the Colorado River, the Los Angeles Aqueduct, the Truckee-Carlson Project, Kachess Dam and tunnels in the state of Washington, the Boise Project including Arrowrock Dam in Idaho, and the dams on the North Platte in Wyoming.

Terzaghi expected New Orleans to be wonderful, and it was. There seemed to be something in the atmosphere, in the character of the city, and in the land that is reckless and compelling. And to think that this was made in what was once a notorious den of yellow fever. But New Orleans proved even more interesting than he had imagined, for the Mississippi was in the early stages of a major flood that had forced a widening breach in the levees. Everything that Louisiana possesses comes from the Mississippi, he wrote in an essay for the Vienna newspaper[20] and it can all be taken away by a major flood. Levees that protect the banks for a thousand miles upstream from the mouth of the river are vulnerable and the damage from a major breach would cost as much as another Panama Canal.

Terzaghi arrived on the fourth day of the breach, when the break in the levees had lengthened to 400 meters. He saw two hundred cubic meters per second of river water charging turbulently like a mountain torrent into a temporary pond endangering the western plantations and the homes of 60,000 persons. He lengthened his stay to report like a correspondent at a battle, as 500 prisoners filled sand bags and an engineering brigade used pile hammers and earth-moving equipment in a desperate attempt to build dikes to quiet and eventually stem the flow. "A force of ten on the ropes on either side hoisted the ram-rod up; then blow followed blow under the monotonous sound of the negroes' songs. The sun burnt hot on the tooth-baring, sweating faces and it was something to see the majestic muscles of the black men working."[21]

It had taken 36 hours to reach New Orleans and now 48 more took him to the U.S. Reclamation Services' Angel Dam office at El Paso. This was Terzaghi's first visit to an American desert, and the contrast between flat dry uplands and precipitous canyons evoked a geo-literary essay for the Vienna newspaper.[22]

The next stop was Tucson, Arizona, to see a desert pump station and then on to the remarkable Theodore Roosevelt Dam, a high masonry structure near Phoenix in the spectacular Salt River Canyon. Terzaghi was particularly interested in the way seepage water from the reservoir could be seen to collect and flow along the network of natural rock fractures ("joints") and emerge in springs over a length of a kilometer on both banks downstream from the dam. He concluded there must be high pressure in the water within the joints under the canyon slopes. In these dry canyon walls of bare sedimentary rock, one could observe directly what in Austria could only be inferred. There were more phenomenal rocky walls to be studied in his horseback trip down into the Grand Canyon (twice) with an Indian Guide.[23]

A surprise of a different kind confronted Karl at the site of the new town of Chandler, Arizona, which then consisted of eight tents, a wooden barracks, and a foundation excavation in the midst of an empty desert landscape 15 kilometers from the outskirts of Phoenix. The excavation, he was told, was for a hotel and the wood building comprised the "city offices", containing a physical model of what would be constructed and an official, clad in spurs, "attempting to clarify the unheard of advantages of the city to be... The shady side of this swindle can easily be imagined."[24] There was apparently shady gold to be gained from the gullibility of Americans.

Although it may have seemed shady, Karl began to appreciate that there was money to be made here, and it fueled his interest in marketplace economics. America had a different economic base than Europe, where people were rewarded according to the respect their position or title accorded. Here engineers earned perhaps $70 a month in their first ten years of practice or possibly $150 if willing to work in "fever ridden Mexico", while the construction shift boss takes home $200 per month and the superintendent $400. "The treasures are so rich that even the most primitive can be sufficiently elevated, the enterprisers along with the laborers. In the United States, he who takes up and holds onto an engineering profession is an idealist; thus the surprising solidarity of American engineers in the midst of swindling pirates. Their joy in their work is all they have."[25]

He wrote that "the easy acquisition of riches from the west does not lure me."[26] But he was fascinated nevertheless, especially as the cost of the trip looked to exceed his thousand-dollar estimate and the Austrian Society of Architects and Engineers had finally communicated their disinterest in funding his engineering geology research. This fascination was even intensified on reaching Los Angeles where shady promoters tugged at the skirts of fantastic population growth—from 50,000 in 1890 to the current 250,000—and the waterworks were being planned to serve a population of one million. The desert irrigation works were nourishing remarkably fertile farms, and the wealth displayed in the shops, dwellings, gardens and vehicles would shame a fine European city. "The whole is like a dream."[27]

In San Francisco, Karl bumped into a tall, New York banker he had met on the train to El Paso. He quickly learned that the man was planning to get rich in a land speculation scheme in southernmost California near Mexicali, by buying up land and reselling it after planting Egyptian trees. Water rights were the only unknown. Terzaghi just happened to have in his pocket the data on the flow of the Colorado River for the previous ten years and, upon studying it, agreed that there ought to be sufficient water for such a project. At the man's invitation, he agreed to travel back to Mexicali and, for a modest fee of $100, prepare a report on the water availability of different land parcels.

The banker provided a rail ticket and Terzaghi eagerly applied himself to the project, studying the land registry books for potential land purchases. He saw much evidence of "dirty stuff" in the transactions of speculators all along the border. At the end of the week, he prepared a report with data and calculations, concluding with a recommendation not to proceed with the scheme. He sent his invoice along with the report and "with that my lusting entrepreneurial banker disappeared from the scene"[28] without paying his bill.

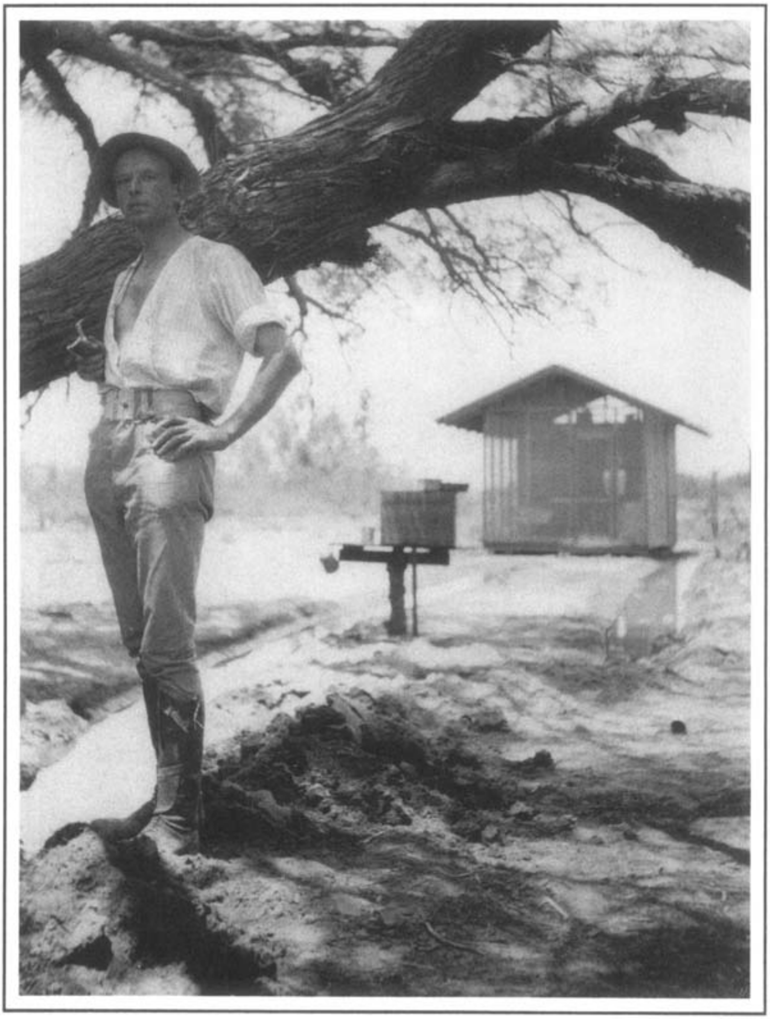
Upon awakening to the sad fact that he had been taken, Terzaghi vowed to turn his new knowledge to advantage. Thereupon he wasted another three weeks. A US Agricultural Experiment Station had established that date palms would prosper in the Coachella Valley, an undeveloped valley hotter than the Sahara and blessed with artesian water. Terzaghi learned that an 85-year-old prospector, succeeding in growing dates on his own large tract in the Coachella Valley, had rejected an offer of $35,000 for his farm from the Southern Pacific Railroad. Terzaghi visited him and applied all his powers of persuasion in an effort to enlist him as a partner in a romantic impulse to engineer a managed date farm. It was a complex deal involving money, land, and participation by three other men: the head of the agricultural experiment station, a civil engineer who owned 200 contiguous acres, and a publisher. Terzaghi's input was to consist of money (no doubt to be coaxed from his grandfather) and his expertise supervising the drilling of artesian wells and construction of irrigation works. All appeared to be moving towards consummation, until the venture collapsed in disagreement over the value of the civil engineer's land. Thus he closed the

Los Angeles chapter of his life, "a good bit wiser about people and business."

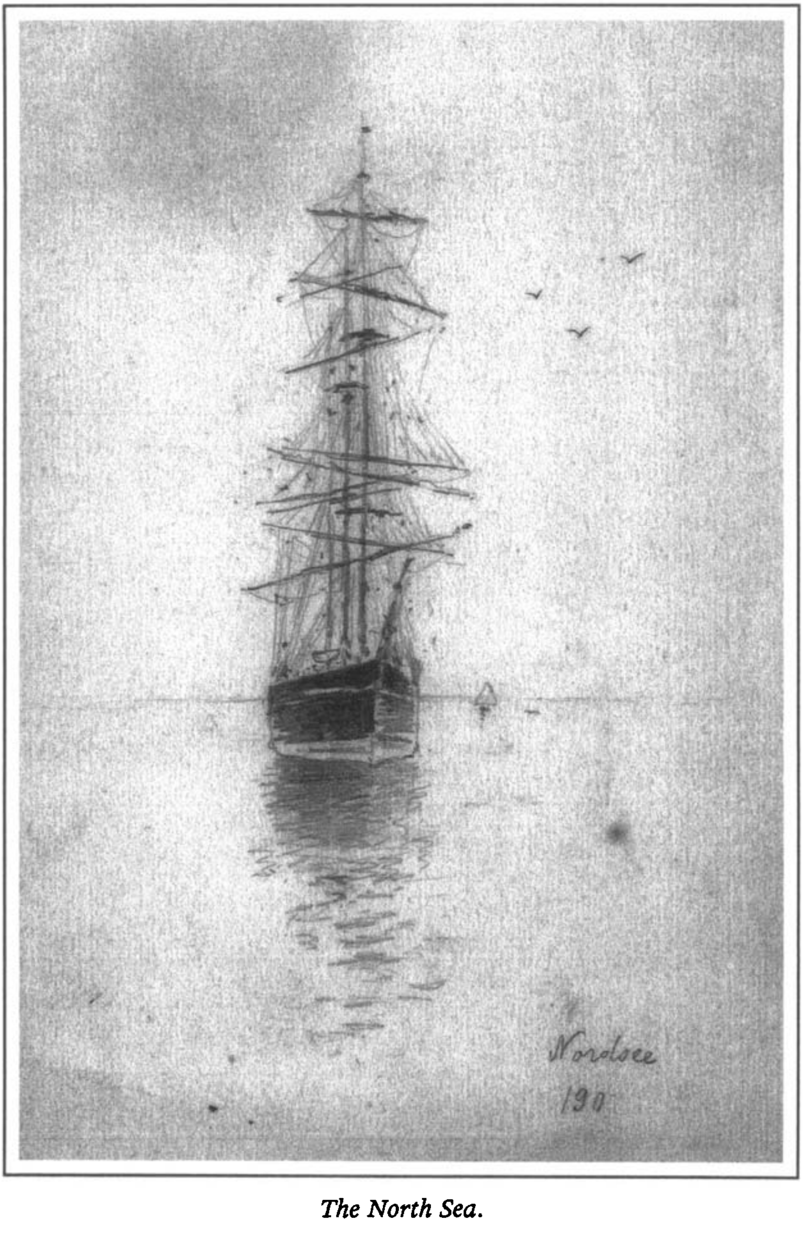
His trip continued, back to San Francisco, to Lake Tahoe and an irrigation project near Carson City where he saw for the first time the process of "grouting", in which cement mortar is pumped underground through boreholes to plug the cracks in rock and make it more watertight. He then proceeded to Lahontan dam at Great Salt Lake, Strawberrry and Spanish Fork Dams, in Utah (where he talked with workers from Otocac), Uncompahgre Valley excavation near Grand Junction Colorado, Pathfinder Dam and Buffalo Bill Dam in Wyoming, and finally Yellowstone Park, arriving on September 8.

Karl had always loved the colors of nature and it could therefore be understood that Yellowstone simply took his breath away: unforgettable sites, unheard-of colors. He spent a joyful week there, including the great adventure of a fifty-kilometer horseback ride over the continental divide, alone, through a fierce snowstorm. Yellowstone had been a dream destination for Karl even as a boy. Its geysers, canyons cut into volcanic rocks, and great variety of unusual rock colorations brought out an effusion of description and love as he wrote a birthday letter to his 89-year-old grandpa.[29]

Crossing the continental divide on horseback was both a physical and emotional high point for Karl. Now began the descent.



Terzaghi as a would-be date farmer, Coachella Valley, California, Summer of 1912.



The North Sea.

4
From Personal Depression to War 1912–1915

As Karl continued on his itinerary he began to lose self-confidence. His illusions had been blown away like Autumn leaves.[1] His future was unknowable and his resolve weakening. Perhaps the trip had gone on too long. He found himself being propelled from one project to another without any real personal involvement and began to miss his responsibilities in Russia. There at least one could have a drink with the men, something forbidden on Reclamation projects.

He spent his 29th birthday on a tenting trip by horseback near Kachess Dam, Washington, ruminating on whether his next destination ought to be Argentina or Peru. By the end of October the long list of projects had been visited, and his accumulated notebooks yearned for some sort of analysis. But the "fossils" at the Austrian Society had denied him funds, and he couldn't afford the period of pensive study, much less a voyage to South America. He needed to earn some money.

At the end of October, he went by steamer from Portland back to San Francisco, following leads for an engineering job. His experience and now enlarged knowledge of western construction ought to have made it easy for him to join a challenging project. But the only offers he received were for static office jobs. "I therefore stuck my academic credentials in my pocket and took a situation on the construction of a government lock on the Columbia River."[2]

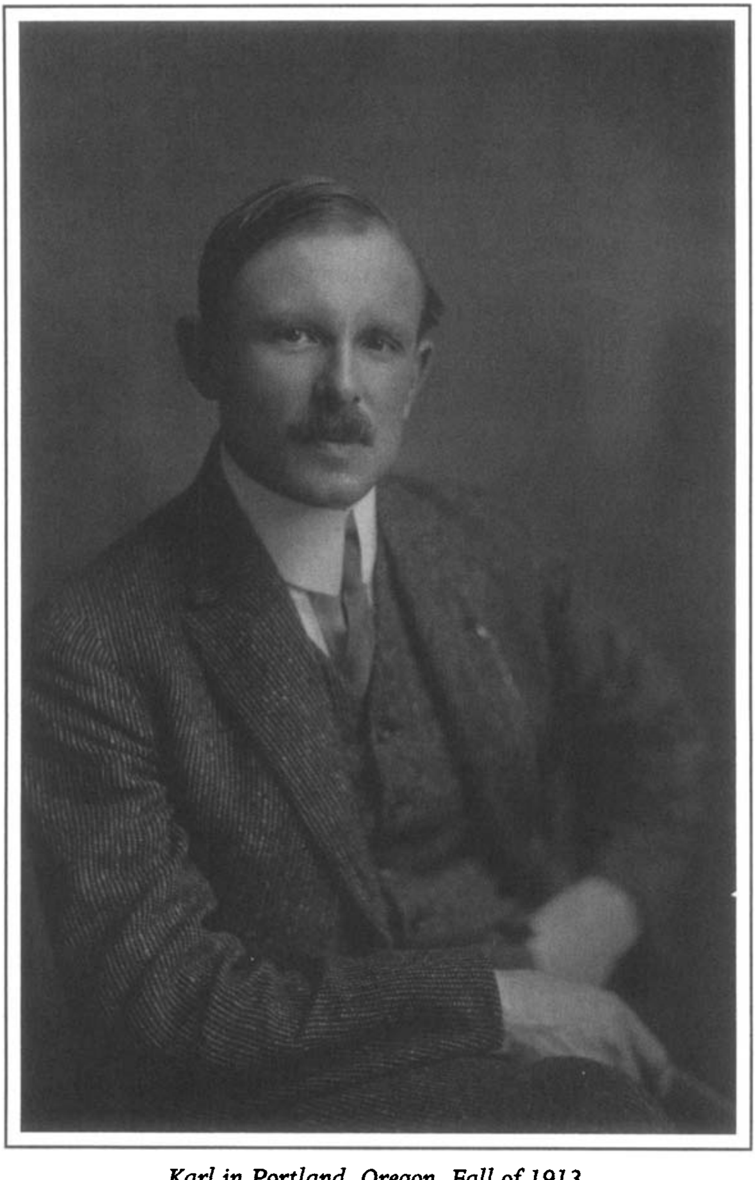
This was challenge of a different kind—digging, operating equipment, drilling, blasting; it was heavy work, noisy, violent, exhausting, and dangerous, with undisciplined men of much lower station, having little intellect, and even less ambition. The job was the construction of Celilo Locks on the great Columbia River of Oregon. Navigation on the Columbia was interrupted at Celilo Falls, which stood at the head of Big Eddy rapids, an 8-1/2 mile long, narrow stretch of turbulent water. All passengers and goods heading upriver had to be unloaded at The Dalles and transported over land around the rapids and falls, then reloaded onto boats for the continuation of the journey. Thus at the turn of the century a bypass canal was planned, unfortunately necessitating excavations up to 100 feet deep through very hard basalt. Construction began in 1905 on what proved to be a ten-year project.

Terzaghi found himself working in a deep rock cut "pecking at the dreaded monster like swallows on the walls, dangling from ropes between heaven and water."[3] He was in excavation division number 3. The men called him "Charlie". Rough and unbookish as the work indeed was, it did provide a real education. Working with the drill, nose against the rock, Terzaghi learned to observe each fracture in the rock and to weigh its potential hazard. "The work has a different aspect from that of the engineer who simply aims a level at the place where I have been drilling for two months."

It is natural that he would feel the inadequacy of his academic education in such an environment. For this work, he found his military education more beneficial for "of all human activities, engineering most resembles waging war." The military prepares its personnel adequately for war but the engineering schools, thought Terzaghi, decidedly do not. They have lost touch with the art in concentrating so much on the science. From the other men—lumbermen, adventurers, and prospectors from Alaska and Nevada hoping to earn enough to equip new prospecting expeditions—"I learned more about drilling and blasting, in a short time, than I would have learned in the course of a year of consulting professional comrades."[4]

The hardness of the rock called for experimentation with the relatively new art of blasting. But the rock would not give up its secrets and the experiments had never ceased over the seven years of the project. To blast rock, one first drills holes to a certain depth, loads the explosive in the holes, together with electric or heat-sensitive blasting caps and detonating wire or thermal fuse wire, and then sets it off. Sometimes the blast was ineffective in breaking the rock; other times the rock was torn up well beyond the intended limits. Occasionally the detonator failed to ignite the explosive, and every now and then it would shoot prematurely. The last was the misfortune that landed Karl in the hospital, with severe burns. He had neglected to have his injuries treated and came close to losing his foot. He would not be able to continue his work on the Big Eddy Project. On December 21, he returned to The Dalles to get his belongings and say farewell to a unique chapter in his American experience.

He spent a rainy Christmas feeling lost and abandoned, wanting to work and unable to do so. In January after a day of intense depression and



Karl in Portland, Oregon, Fall of 1913.

discouragement, he wrote of only two avenues: "to redouble my self-trust; or have a nervous breakdown... Small gaps in self-confidence quickly expand and breach. The question of where it will lead has an unequivocal answer. Disbelief in your own self-worth gives way to self-disgust, leading to alcohol and shipwreck."[5]

His concern about alcoholism was no doubt fostered by an article he read in Portland's *Morning Oregonian* of December 29, 1912, about the death of a hobo, Max von Bülow, destroyed by drink and dismembered by a train in the desert near Reno. This unfortunate lad was German, from a noble family like his own. Karl was inspired to write: "In these men is the spirit of the wandering Jew aroused? Or are they gagged pioneers who had despaired in hoping to reach their dreams of marching through to paradise on the other end of the continent? Or are they fleeing from the terrible desert inside them."[6]

It was the beginning of an outpouring of feeling, in essays, diary fragments, and letters. On a scrap of paper in the midst of a stack of loose diary pages of this period is a list of nineteen nontechnical essays he had written, mostly unpublished.[7] Had he thrown in the towel on engineering and decided to try to make a new career as a writer?

His prose was richly worded, carefully constructed, and thoughtful, whether written in German or English. It described, for the most part, impressions from his American travels—scenes, images, dialogues. Most was interesting and informative, but heavy, humorless, and moralistic stuff unsuited to an American readership. He was not much interested in promoting its publication in America, pointing accusingly, in a very Austrian fashion, to the "ethnic and esthetic codes of the soul of Jewish journalists. They prefer trite chatter about 'actual' events that meander through the interest areas of the subscriber base."[8] He did plan to use these materials, ultimately, in a longer Austrian treatise about his experiences.

One of the sketches, "Then and Now," unfolded the tragedy of the Columbia Gorge's Indians at the hands of development. "There where the Columbia in mighty cascades plunges between the black cliffs of The Dalles, the raging water eddies around an almost forgotten cemetery of an exterminated Indian tribe."[9]

He was moved, and later disgusted, by the commercialism of actress Sarah Bernardt's visiting performance in Portland. "That was not an actress miming the death of the lady of the camelias; that was an inexpressible death that happened before our eyes, with the life fleeing with undiminished sorrow of love from a yearning, desiring and despairing woman.... Hardly a minute passed when the curtain was raised and on the stage there appeared a womanly mistake, armored with greasepaint. With a fresh soprano, she warbled an American popular tune to the full house, and without protest and without murmuring in indignation, like a herd of satiated house pets, the audience then had to endure a speech about how the U.S. Chewing Company was so pleased with the death scene."[10]

In an essay called "Sunday Thoughts," Terzaghi lashed out at America's blind commercialism and "the industrialization of pleasure." "From the little house on the other side of the street a pleasant tenor voice and a mandolin began a Neapolitan song. I became gripped with homesickness for the first time in my life with such elemental force. I forgot Portland and Main Street, forgot the whole heavy-as-lead melancholy of American Sundays when the scourge of the tireless idolatry of 'good business' is allowed to rest and the poor slaves don't know where to begin in their short span of freedom. I found the way back to the urgings of my old, distant neglected homeland."[11]

Terzaghi was now quite expert with dynamite and had personal motivation to respect its dangers. Perhaps his depression called up a tendency towards paranoia when he wrote in the Vienna Tagespost that careless handling of dynamite in New York harbor, which has been reported by the press, is a deliberate conspiracy by greedy contractors to blow up New York. Then they could profit from its reconstruction.[12]

Terzaghi used this introduction to inform the general readership how dynamite works. It is a convincing tutorial that demonstrates, above all, the author's brilliant capacity to teach. He writes that he is smoking a cigar, and after a half-hour the aromatic fumes have completely filled the room. Had this same combustion process occurred in one second, it would have been properly called an explosion. We turn something with no more heat energy than that of a cigar into our strongest and "most dangerous agent in the fight against inorganic nature", merely by adding something to make all the ingredients burn at the same time. And then he proceeded to describe the history of trials and disasters that led to the present manner of accomplishing that.

By March, 1913, his outlook was no healthier as he confided to Professor Wittenbauer that his previous smugness with position and rank had completely vanished. "I have lost my best thoughts about the engineering profession and am full of disgust for all hypocrisy. I am living through the most miserable times of my life, without work, innerly torn, and filled with doubts."[13] His only friend was his pen.

On an excursion to a local tavern, Karl struck up a conversation with an architect. Discovering that the man needed help in structural design of the complex curved shapes of a church cupola, Karl prepared a memorandum on the subject. This succeeded, finally, in landing him a job. He found himself working as a foundation engineer in construction of tall buildings downtown and for factory structures of Portland Gas & Coke Company along the banks of the Willamette River. He also participated in experiments for soil excavation using a powerful water hose, termed a "hydraulic monitor."[14] Terzaghi was later able to put this new technology to work in Russia and elsewhere.

This activity raised his spirits from the depths. In November, 1913, he could claim his "courage is fresh and bold ... Here in a hard land and in hard times I have learned thoroughly from friends and foes and the country has made me abandon the milder, fairer and more understanding man I was when I arrived in New York two years ago."[15]

Karl had not given up hope of profiting from his American excursion, not just by writing, but through the advances he had expected to achieve in engineering geology. As an engineer in Vienna and then through his Croatian and Russian work, he tried to find a system to forecast the behavior of soils and rock foundations of civil engineering structures. The lure of America was, at least in part, that it could greatly expand his base of information on the connection between geology and engineering construction. Now he had at his disposal the data from a great number of cases, in many different rock and soil settings. The data included reports of investigations, maps, plans, and specifications, written descriptions and anecdotes of difficulties in construction, and notebooks full of his own observations. Moreover, from his exhausting note-taking in the New York library, he had encapsulated a great deal of background data, which at the time he thought ridiculous but now seemed of inestimable value.[16]

With spirits on the rise, he intensified his efforts to systematize and analyze all this material. Sadly, it proved a discouraging effort, and Karl began to conclude he was following a wrong path. The geologic data about the different sites varied from one geologist to another, but one factor was common: each investigator had attempted to describe the earth materials using only geologic terms. Unfortunately, the names geologists give to different rocks and sediments have developed mainly from a scientific curiosity about the *geologic origin* of these materials, whereas he was aiming towards discerning differences in their *engineering properties*.

If one describes a material, for example, as "alluvial sand" and does not report how densely its grains are packed together, the properties of the material could vary between enormously wide limits. It might or might not be able to bear the weight of a heavy structure. It might or might not permit successful dewatering of a foundation using sheetpiles. The whole premise for his trip was flawed, and the entire effort was going to fail. It was time to move on.

Terzaghi still harbored the ambition to visit South America, but he elected to return first to Graz where a friend was negotiating a hydropower development opportunity in Argentina. But a severe downturn in the Argentina economy terminated these plans abruptly.

Ironically, it was the Austro-Americana Steamship *Argentina* that Karl boarded on December 9, 1913, to cross back to the old world. This 9,300-ton ship, with a speed of eleven to thirteen knots, required three weeks from New York to Trieste. With only four passengers in first class, he had time to write a protracted philosophy of science, economics, and ethics, concluding that mankind was on the verge of an entirely new epoch.

Soon after his arrival, he found out what kind of new epoch it would be. His initial efforts to organize a consulting company with two friends had to be aborted in June as Austria went to war against Serbia. By July, the entanglements of allies had created the divisions of a world at war. Terzaghi discovered his commission notice under the Christmas tree at the home of Olga's parents, the Byloffs. He was called to active duty as Oberleutnant.

Terzaghi assumed the role of leadership naturally and was quickly assigned considerable responsibility in organization and training. He was to have been in charge of one of four 250-man brigades forming an engineering "Land Storm" battalion charged with building fortifications and roadways at the front. Although the men were a rude, untrained labor force, he was able to establish order among them, whereas the other three brigades seemed to him to remain undisciplined. "So now I am reassigned as Landstorm Commander of all four brigades, that is of 1,000 men."[17]

Somehow, he still found time to write. The philosophical questions he had pursued aboard ship now had a new perspective. He had looked to his Europe as the source of culture and rational thinking, which he saw as placing it on a higher moral plane than America with its crassly commercial orientation in all institutions. However, the immoral acts of Europe's leaders and the quick public support reaped by blatantly fictitious propaganda seemed to him wholly primitive and would very likely result in the ruination of all cultural institutions. Karl began to wonder whether the supposed sophistication of European culture might prove to be, like Europe's alliances, nothing more than a house of cards, a sham, a morally bankrupt invention of journalists. Even Mexican Indians and Chinese Coolees can distinguish fact from fiction.

Karl was beginning to sound like a pacifist as he wrote: "If we succeed in destroying the beasts of Russia and France, who will rescue us from the beasts within us?"[18] We are called to mount more courage than our enemies, but the capacity for courage is common amongst savages; it proves nothing for rational, cultured beings to display courage. The end result of too much courage will be the reduction of civilization's rich forest to a waterless, treeless desert.

Yet there was a side to this man that seemed to thrill to the sport of war. Years later he revealed at least some sympathy with the martial spirit of his ancestors in posing the hypothetical question: what manner of death could be more honorable than on a field of battle in a valiant cause among colleagues one admires?[19] On visiting the Smithsonian Art Gallery in Washington in 1927 and lingering over a painting depicting fierce hand-to-hand battle, he confided to his diary that "battle scenes have a violent, fascinating beauty", bound by the passion of blood.[20]

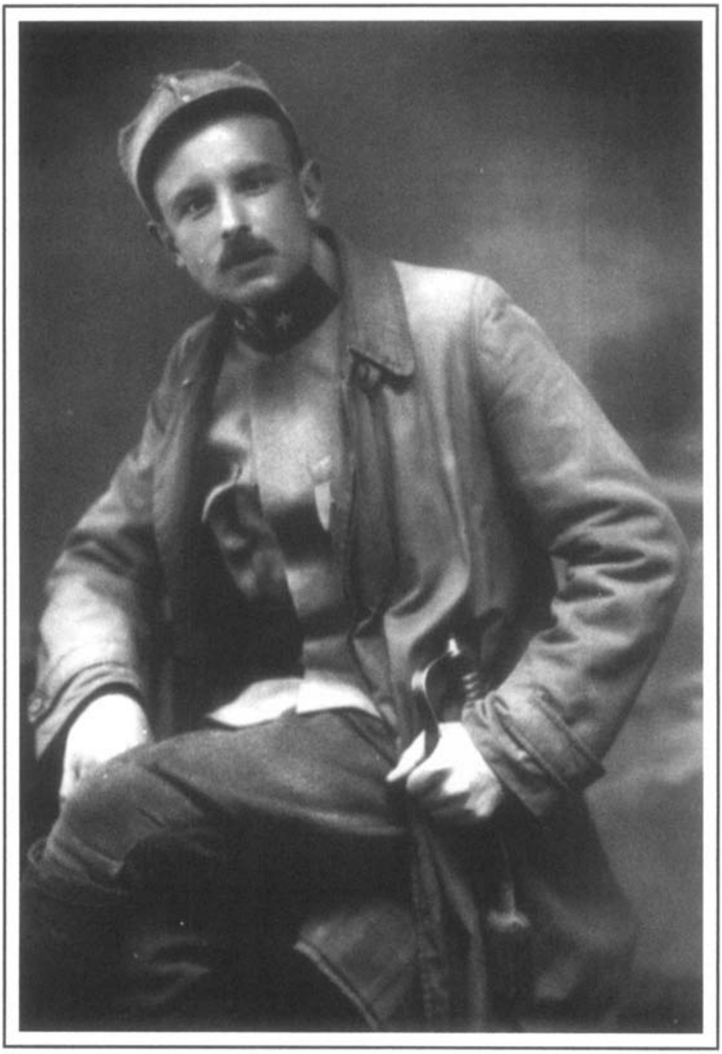
Both of these persona were combined in the Karl Terzaghi who traveled down the Danube, through Hungary, to the Serbian front in the early days of 1915. The one continued to write philosophy in his diary. The other displayed steel nerves amid artillery bombardment. It could be said that an apparent fearlessness was his constant characteristic, as exemplified by the following incident.

On September 21, 1915, Terzaghi rode out on horseback to study possible routes in rolling terrain near Semlin, Serbia. He so appreciated the wonderful morning weather as to forget the nearness of the enemy. As he approached a company of Austrian infantry marching towards him, an artillery shell exploded in the midst of the column, and more followed. The infantry unit scurried for cover; unnerved and irrational they seemed to look to Oberleutnant Terzaghi for guidance. He determined to set an example of strong nerves, and the faces of the troops showed they were innerly strengthened. His horse had been hit and was bleeding from the shoulder but Terzaghi led the animal to safety.[21]

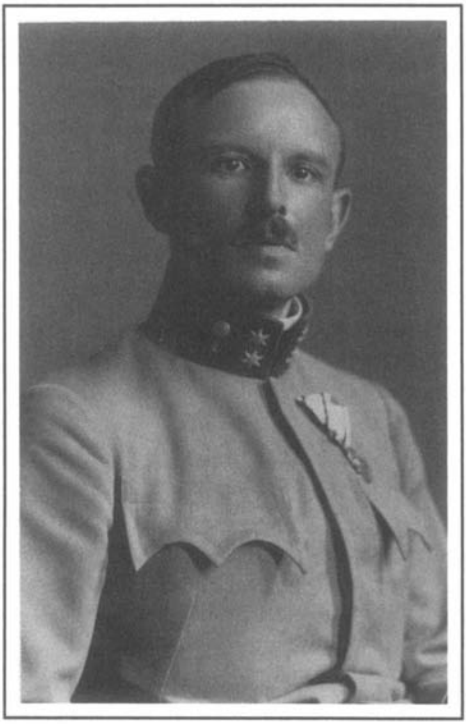
Terzaghi had been sent to the Serbian front as an engineer for an infantry unit, to supervise the construction of trenches and fortifications, as well as transportation routes, communications, and bridges. He had strong convictions how the work ought to be done and understandably fell into conflict with one of the commanding officers, a Major whom Terzaghi characterized as a neurotic and a notorious alcoholic. The Austrian army was foundering on the Serbian front because of lack of materials and men, and poor supervision. Terzaghi's outspoken criticisms created a tense conflict between them which proved a "source of inexhaustible outrage." His situation improved when the drunken Major rowed himself to an early demise in the bed of the Danube. Karl celebrated by taking a furlough in August, to be with Olga in Hungary. His passion was reignited in days of sunshine and love that caused him to forget the fertility of their relationship and the depth of harm it could enact.

Warfare tended to be waged by moving from one fixed position to the next. To establish these holding positions, the combatants constructed some 25,000 kilometers of trenches and protected passageways over the duration of the war.[22] The Germans and Austrians tended to be the more precise and demanding in the execution of these works, often providing extensive semi-underground facilities. Thus engineering officers like Terzaghi were vital.

From an engineering point of view, the Serbian front was especially difficult, and Terzaghi's knowledge was tested. The Austrians moved



Oberleutnant Karl Terzaghi, 1916.



A portrait of officer Terzaghi, 1916.

through Hungary into Serbia along the course of the Danube River, whose valley is underlain by soft river sediments and loess (wind-blown silt). Here the water table tends to be high, and the groundwater fills up any open pit, often to within less than half a meter below the surface; therefore, deep open trenches as on the western front were often not practical, but even construction of other types of works for fortification and communication required considerable drainage work. Terzaghi wrote that one had to be careful to dispose of the drainage water harmlessly as the earthworks, made of dried silty mud, would fall apart when inundated, almost as sugar cubes dissolve in coffee.

Terzaghi took interest in the high levees, extensive ponds, and pumping systems that allowed cultivation of this area in peacetime; it all reminded him of the Mississippi delta. Once he got caught up in a job, even a war, he had a capacity to retain engineering focus, and scientific curiosity, without a great deal of concern for his client's purpose.

In August, 1915, the Austrians were joined by units of the German army. Terzaghi was impressed with their "exemplary discipline and organization." They were led, he observed, by brilliant officers—brave, honorable, and self-assured—and, unlike the Austrians, they did not build barriers of excess privilege between themselves and their men. In contrast to the "professional" German approach, the Austrian system seemed to Terzaghi to be one of "mindless activity, corruptive reciprocities, and general mistrust that poisoned the atmosphere between officers and troops." It was no wonder that their campaign against Serbia languished for fourteen months.

When the Germans arrived, the momentum changed. A carefully conceived plan for a dynamic offensive was executed in early October, 1915. After four days of incessant artillery bombardment, the troops moved out successfully, crossing the Sava River on pontoon bridges erected under fire, and swept over Belgrade.

The divided psyche of Karl Terzaghi continued to struggle with the equations of war. The senseless hurt inflicted on these industrious and attractive Serbians seemed to him a coffin nail for the Dual Monarchy, not just for its bodyparts but for its very heart. On the other side, the boy who had dreamed of becoming a polar explorer seemed exhilarated in marching by night through "seemingly unexplored territory" as he traversed the abandoned defenses. To his son, he remembered years later: "The siege of Belgrade and the capture of the city on October 9, 1916, were spectacular military events I shall never forget. For three days and nights the heavy guns sputtered fire and steel and paved the way for the final assault."

In his unhappiness with the Austrians in the stalemate of July, Terzaghi had written secretly to his old military schoolmate, Hans Kalbacher, asking about leads for a transfer from his "soul-destroying work". Kalbacher returned that there might be opportunity with the new air force, a possibility that Karl found tempting. He signaled his friend to do what he might. It bore fruit, for on arrival in Belgrade, on October 28, Karl was informed by his Major that he had been urgently requested by the war ministry to depart at once for a new assignment at Aspern Air Field near Vienna.

Terzaghi was thankful to be out of the engineers corps and, hopefully, out of combat. War and technology, like fire, are stimulating in their primitive stages, he wrote, but degenerate in their eventual achievements.[23]

5

Return to Intellectual Life 1915–1918

With his posting as commandant of the experimental airfield at Aspern, Terzaghi had returned to intellectual work. His long descent into depression, disillusionment, and the senseless labor of warfare was over, and he could apply the full weight of his abilities on his job. His was the responsibility to promote the development and production of the airplane as a weapon of war.

The Austrian airplane industry was vitually nonexistent in 1915, producing only four to five planes per month, as compared with 350 to 400 from Germany. Terzaghi was put in charge of the group investigating performance of all aircraft, including those captured from the enemy.[1] He assumed responsibility as organizer and manager to stimulate the creation of new fighting aircraft and see that they were suitably tested at Aspern.

Terzaghi devoted himself to the assignment with fire and arrogance. On arriving at Aspern, he accumulated as much information as he could glean from interviews with pilots and technicians and from his own study of aircraft technology. There were forty aircraft of various manufacturers in the hangars when he arrived. He went on field trips to learn about the problems and opportunities in airplane manufacture, as well as about fuels, communications, and navigation. And he met with advisory scientists to propose research and development projects.[2]

As a manager, Terzaghi experienced the frustrations of dealing with what he perceived as Austria's corrupt and backward bureaucracy. But he took great interest in the work of the test pilots and made close friends there. Although his work was on the ground, it is reported that he sometimes took the controls in the air.[3] "We tried to proceed in a few years from the primitive types of airplanes to larger and more elaborate ones," with "shocking manifestations".[4] For as expectable with accelerated development of aviation in a time of war, there were fatal accidents. Karl was deeply affected by the human tragedy.

The summer of 1916 saw three giant events in Karl's personal fortunes. He married, derived an inheritance, and became a college professor.

Shortly before he arrived at Aspern, Karl had learned that Olga was again pregnant—from their tryst in Hungary. This time there was no way out. Although Karl was troubled that he was the victim of some kind of "foul play", Olga held a "trump card" from their agreement with Mr. Ramos in 1912.[5] In May, Olga gave birth to Karl's daughter Vera, and one month later they married. "I knew it was a daring experiment," he wrote, "but I wanted to do my best to provide the child with a home."[6]

On August 2, at the age of 93, his grandfather, Karl Eberle, passed away, leaving Karl and his sister Ella significant inheritances, the amount of which his grandfather had previously revealed. Karl regretted that he had never let himself express the deep respect and affection he held for this man, who had so influenced the progress of his development. "He was the most sensitive, loving, discerning, and understanding friend one could possess."[7]

Then, in late summer, Karl began a new life as professor in the Royal Ottoman College of Engineering in Constantinople (Istanbul). In this it could be said he became a part of Austria's diplomatic effort to stay in the good graces of the Ottoman Empire, which though declining in stature and size still controlled the gates of the Black Sea through the Dardanelles and the Bosporous Straits.

All the major European participants in the world war—Austria, Hungary, Germany, Britain, France, Russia, and Italy—had interests to protect in Turkey. The language of the Imperial Ottoman School of Engineering was French, which was Istanbul's language of engineering and culture. At the start of the war, Terzaghi's old French employer in Croatia, Adriatic Electric, was preparing to construct an 8,000-kilometer road network in Asiatic Turkey. The British, historical colonialists of the region, were well represented among the populace; they were active in export/import trade. Russia was vitally concerned with naval passage through the Dardanelles as this was her main commercial maritime outlet to the world.

The Germans held the lead in influencing Turkish affairs, including day-to-day governance. Moreover, Germans were major industrial developers; at the start of the war they were in process of building a railway from Berlin through Constantinople to Baghdad, as well as roads in European Turkey. "The Germans did strenuous, efficient, productive work" but, in contrast to the Austrians, who simply gave to the Turks as a mother gives to a child, the Germans "were inconsiderate enough" to demand a fair Turkish participation in the work.[8] Thus, the Germans were not liked by the populace.

Nevertheless, of all the diplomatic offensives in Turkey, Germany held the inside track in 1915. A German general, Liman von Sanders, led the Turkish army, while two German battle cruisers were stationed at Istanbul.

(Germany circumvented international rules of belligerency by pretending to have sold the ships to Turkey.[9]) In October, 1914, Turkey formally aligned herself with Germany and the Central Powers.

All Turkish students of engineering and military programs were expected to obtain a part of their education in Germany. As an intellectual competitor of Germany, Austria made a bid towards wooing the Turks in the person of Graz's distinguished professor of hydraulic engineering—Philipp Forchheimer. In 1914, Forchheimer, who had taught hydraulic engineering at the Royal Ottoman College from 1891 to 1892, was sent to Constantinople to be the College's Dean of Engineering.

Forchheimer's mission, and vision, was to reorganize the Royal Ottoman Engineering University toward the best European models. His method in part was to bring intellectual lions to its faculty. Prof. Forchheimer had been highly impressed with Terzaghi's intellect during Karl's graduate studies at Graz and had supported his successful ambition for the doctorate. It was in that spirit that he had written to Karl Terzaghi back in the summer of 1915 to ask if he would be interested in becoming a professor in Constantinople, to lecture on roads and foundations. And thus Karl became a diplomatic pawn "selected to modestly remind the Turkish government of Austria's existence."[10] The receipt of this letter on the front lines on the Danube, August 15, 1915, was a source of joy to Oberleutnant Terzaghi, and he had replied immediately to encourage Professor Forchheimer to proceed.

Forchheimer then recommended the appointment to the Austrian Consul General in Constantinople, who succeeded in interesting the Turkish Minister of Foreign Affairs, largely because of Karl's experience in the United States (for Turkey was planning its own water projects in arid Anatolia). It was not until August 15, 1916, exactly one year after the receipt of Forchheimer's invitation, that Terzaghi was officially relieved of military service at Aspern to proceed to his new assignment in Turkey. Curiously, it was once again the person of Otto Fröhlich who assumed Terzaghi's responsibilities, now as his successor at the airfield. Forchheimer later told Terzaghi, "I knew that you have brains and originality. That's why I asked for your transfer, but I always thought that you were an adventurer and a spendthrift. Now I discover to my surprise that you can concentrate and work."[11]

Terzaghi arrived in Constantinople by train on September 12, with his initial lecture notes in the French language already prepared but very little idea of what to expect and his fate "as uncertain as the future of Europe."[12] He was surprised and struck by the "radiant beauty" of the Constantinople region.

In short order, he was taken to the "office" of the Turkish minister of foreign affairs, Prince Abbas Pasha, to execute his employment contract.

The Ottoman experience was a new world. Led through marble corridors into an enormous, sparsely furnished marble room with oriental carpets, he found the Prince awaiting him together with a high public official, as in an operetta. "Ah, Monsieuer Terzaghi, what news do you bring from Vienna?" "Not much," Terzaghi replied, "We are training our stomachs to be modest." The Pasha wanted to know whether American science was superior to Europe's. Terzaghi replied that the Americans have more money but "we have more ideas."

But his visit to the engineering college was expectably disappointing. Founded as the Ottoman School of Artillery in 1807, it became public and broadened its outlook towards the end of the nineteenth century.[13] The faculty he met seemed to have no concept of engineering research, the funds and facilities were lagging, and the students seemed unsuffused with the self-confident energy he associated with students in Graz.

Even so, the opportunity to teach was for Terzaghi the intellectual chance he had yearned for. By organizing his thoughts about geology and engineering, he could reopen the search for methodology in relation to foundation engineering, the lure that had driven him to America and converted him into a nomad. He put great energy into his work and by November had prepared two books of French lecture notes on road construction and railway engineering, "risen like the bird Phoenix out of the cigarette ashes."[14] Prof. Wittenbauer obliged by sending him more cigarettes and cigars.

Having thus discharged his teaching burden, he now applied himself into the organization of "a soils engineering book on a geomorphologic foundation." The idea of this work was to discuss the work of engineering construction in a geological context. "I grouped the difficulties together that are common to earthworks in alluvial plains, sand abrasion plateaus, lava plateaus, plateaus of other kinds, hills, denuded rock masses, mountain country, and high mountains ... The intended output of these attempts is the fulfillment of a wish that I had for a year."[15] In March, he concluded that the last six months had been one of the most productive periods in his life; it was "a harvest" and now he has a clear plan for foundation engineering in mind.[16]

The Pasha's interest in Terzaghi was fuelled by Terzaghi's knowledge of the workings of the American Reclamation Act, acquired in his pre-war study trip to the United States. And so his advice would soon be sought on the feasibility of Turkey's irrigation schemes. Terzaghi applied himself to this charge and, in a long article that he published in a Turkish newspaper, we can read his conclusions. Terzaghi counselled Turkey to prefer small, well thought-out and economically viable pilot schemes rather than politically appealing showcase attempts to open up vast dry areas to new agricultural development. "Today every farmer in the [American] west knows that the reclamation act did not work the magic that had been expected.... The irrigation problems in the United States show how complex these problems are and how difficult it can be to overcome them. The pioneers of previous centuries merely speculated in water projects and neglected the engineering details. The American government made the opposite mistakes, seeing the irrigation of the semi-arid regions as merely an engineering, hydrologic and geologic problem, as expressed by the engineering staff. The difficult points of irrigation lie neither with respect to financing nor with the technical details but in colonization of the land. An excellent engineering solution is a requirement for success but does not guarantee success."[17]

Terzaghi's happiness in Constantinople was enhanced by his relationship with Prof. Forchheimer. An expert on bridges and railways, the former professor at Aachen and Graz was an experienced engineer and a brilliant engineering mathematician. His contributions in applied hydraulics were of particular interest to Terzaghi, for the movement of water in soils was obviously going to be important in the theory of foundations. Forchheimer was a pioneer who mobilized a mathematical analogy between the well-known solutions to heat flow in solids and the movement of water in porous media. This transformed the field of groundwater and laid the stage for Terzaghi's further developments in soil mechanics.

Professor Forchheimer was also a "sensitive connoisseur of the country" who took a hobbyist's pleasure in the architectural heritage of the Byzantine capital. Karl soon became equally passionate about historical architecture and thereby found the means to "counteract the restlessness" he felt from the narrow circle of his professional duties.[18]

In 1917, Terzaghi was able to reflect once more on the data he had acquired in the United States and his rationale for its apparent inadequacy. The purely geological description is not a sufficient basis for making engineering decisions. He had seen this in Portland. He set out to enrich his manuscript on engineering geomorphology with original formulations to describe the movements of slides from clay banks, and the loads on tunnels passing through clay masses. Then he focused on the question of what additional information would be needed to describe adequately the behavior of soils under engineering loads.

He searched through the English, French, and German literature of civil engineering back to 1850 during occasional return visits to Europe, but, rather than obtaining insight into the performance of soils, Terzaghi grew increasingly frustrated and disappointed. The development of the professional literature showed the human capacity for observation being replaced, after about 1880, by theorizing with idealized assumptions, unsupported by "interest in observing and describing the whimsical manifestations of the forces of nature." Theories were postulated without adequate presentation of the evidence on which their validity could be asserted. Failures were attributed not to errors in the postulated basis for design as much as to the perverseness of nature, for "once a theory appears on the question sheet of a college examination, it turns into something to be feared and believed, and many of the engineers who were benefitted by a college education applied the theories without even suspecting the narrow limits of their validity."[19] Terzaghi felt so unhelped by the product of his library research as to prepare a paper on the shortcomings of published engineering literature.[20]

To treat soils as engineering materials would require knowing how they deform under different kinds of loads. Expressing this quantitatively would require developing apparatus for soil tests and advancing theories to convert the results into values of fundamental soil properties. Terzaghi decided to begin a methodical investigation in this vein, starting with sands, one of the most important components among the variety of soils in nature.

He began with the question of the forces transmitted by soil onto retaining walls and structures, a classical problem of civil and military engineering, and fundamental for the construction of earthworks, fortifications, tunnels, harbor structures, and so forth. Hypotheses on earth pressure against retaining walls in use at this time derived from the Scottish professor Rankine (1857) and the French mathematician Coulomb (1776), who had obtained their theories by assuming soil could be represented as an equivalent solid material. Terzaghi referred to this assumption as a useful working approach but essentially "a fundamental error" which "developed into an obstacle against further progress as soon as its hypothetical character came to be forgotten by Coulomb's successors."[21]

Furthermore, Coulomb and Rankine had both ignored deformations of the soil or the wall in deriving their theories. The deformations of the soil had to be important to the solution of this problem, because the interaction between a wall and the soil behind it obviously depends on the relative movements of each.

So Terzaghi elected to "start again from the elementary fact that the sand consists of individual grains" that would shift their relative positions under load. Such a material is too complex to reveal its truths from idealized theory, although several, including Terzaghi, had tried.[22] He was convinced that the problems of earth pressure could only be solved by conducting experiments, "and that we ought first of all to learn the physical facts of earth behavior."

He looked around the college for basic equipment that might be adapted for such experiments. There wasn't much to be found. The inventory of his laboratory space consisted merely of kitchen utensils, empty cigar boxes, scraps of steel, and an antique balance acquired from a bazaar. Furthermore, he had no budget for experiments and an inadequate reference library. Nevertheless, he managed to work with the bits he could acquire, including significant contributions purchased from a locksmith he had befriended in the city.

The first question he took up was what would be the horizontal pressure at a given depth below the surface of a layer of sand. If the sand behaved like a liquid, the horizontal pressure at any depth below the surface should be exactly equal to the vertical pressure due to its own weight overlying that depth, because an ideal liquid has no shearing strength, that is, no resistance to distortion. On the contrary, a sand has shearing strength, and therefore its horizontal pressure at rest should be smaller than the vertical pressure at any depth.

Terzaghi fashioned a thick-walled box from wood and filled it with sand in a reproducible manner to a certain density. To establish the vertical pressure was easy: simply weigh the sand. To obtain the horizontal pressure without modern measuring equipment required ingenuity. Between one of the walls and the sand fill, Terzaghi placed three flat steel strips covered with paper. One of these strips was rigged to a string so that it could be pulled across the wall; the string was affixed to the laboratory balance in such a way that its tension could be measured. An indicator was provided to reveal the onset of relative motion between the sand and the steel strip. By pulling on the string he could cause the steel strip to slip past the sand. The tensile force in the string is required to pull the strip past the sand because of friction between the two, and, at the moment of initial slip between the sand and the strip, this tension force equals the maximum friction force between the sand and the wall. The normal force of the sand on the wall could therefore be calculated by introducing the known friction coefficient. Terzaghi succeeded in independently measuring the friction coefficient. Thus, he was able to establish the horizontal pressure of sand against a wall at any depth.

The results determined that the ratio of horizontal to vertical pressure in the sand, at rest, was 0.42. This was checked by using the steel strip embedded in the middle of a mass of sand, first with its flat side vertical to measure the horizontal pressure, and then with its flat side horizontal to measure the vertical pressure. The results were the same and remained so regardless of the density of the sand.

Now he was ready to determine the force on the wall if it were allowed to move under the horizontal pressure of the sand. This is one of the fundamental items the design engineer requires. Ingeniously using alternately rollers and sliders along the bottom of the wall, he measured the horizontal force on the wall with and without horizontal friction. From the difference between these results, he determined the magnitude of the friction force on the base of the wall and thus, by introducing the friction coefficient, could determine the magnitude of the vertical force on the wall. Now, for the first

Terzaghi's earth-pressure apparatus at Royal Ottoman College of Engineering.

time, engineers had a proper basis for assigning the direction of the soil force on a retaining structure.

In this way, Terzaghi succeeded in achieving fairly precise measurements for different amounts of wall movement, both when the wall moves away from the sand (the "active" case) and when it is forced towards the sand (the "passive" case). The experiments were carried past the elastic condition of undisturbed soil into the region in which the soil was slipping within itself along surfaces of shear. He was amazed by his success at fitting a general parabolic law to the data connecting wall soil displacements with the value of the wall pressure ("passive pressure"). Terzaghi continued a frenzied pace with some hundreds of different wall tests over three months, covering varying wall angles, backfill densities, and backfill geometries.

On January 21, 1918, Terzaghi presented a short lecture to the mathematical society in Constantinople setting out the ideas of his new theory. Friction was not the only (nor even the controlling) factor in dictating forces of sands against walls; it was rather the whole stress/strain behavior of the soil and the wall that had to be considered, just as with other engineering materials. Prof. Forchheimer seemed to understand his thinking so well that he feared Karl had told too much in public, at a formative stage.

On June 22, Karl was booked for a thorough presentation of his work. He suffered over the presentation; there was too much material and it was so new in his head that he could not give it the proper perspective. He forgot to discuss certain important points and spoke too fast. Even so, afterwards one esteemed professor said that hearing his lecture was like hearing about the voyage of Columbus. Forchheimer's silence worried Terzaghi, but later, in private, he congratulated him for making an important and fundamental contribution. In the next days, Terzaghi's experiments were moved into a better space.

The work was published in 1919.[23] Its summary in English a year later in the *Engineering News Record (ENR)*,[24] together with a paper on surface friction sent to the *Physical Review*,[25] were the first events in Terzaghi's discovery by the English-speaking, non-German-reading, world.[26] This unknown Austrian teacher in an obscure Turkish college was declaring his approach to be fundamentally more sound than Rankine's well-known earth-pressure theory. In an editorial preface, the *Engineering News Record* declared that characterizing earth as an engineering material is "the outstanding research problem in civil engineering" and that Terzaghi's article "heralds the opening of an avenue of progress." They fully understood that his research was "starting from the beginning" in order to develop scientific knowledge based on the real behavior of the material.[27]

In retrospect, in the 1930s, Terzaghi observed that his later experiments at M.I.T. with highly refined, large-scale equipment confirmed "all the essential conclusions" of his Constantinople experiments, which were made with such primitive apparatus, "proving the old adage that research results depend not on the perfection of the equipment but on the truth of the proposition.... The simpler and cheaper the apparatus, the better it expresses the purpose and accordingly one can gain insight into a process being investigated, approving or rejecting and postulating anew, without wasting time and money. Costly, sensitive instruments belong to the situation where one already has a clear hold of the natural phenomena and where there is value in obtaining refined numbers. When one begins experiments with costly apparatus, he becomes a slave to that apparatus and the experiment, rather than serving to establish the truthfulness of a valuable idea, serves merely to establish a fact—but never to establish a law."[28]

Caught up in the excitement of discovery, Terzaghi was becoming content in Constantinople. While proud to learn from Prof. Pöschl that he was being considered for a position as professor of hydraulic engineering in Prague, and also quietly pursuing an academic position in Austria,[29] he was really happy in his work. Under the difficult conditions of a wartime economy, heavy teaching load, and limited facilities, he had taken the approach "persevere or perish"[30] and was succeeding against odds. "How time flies if one tracks the secrets of nature and how difficult it is to advance in the undisturbed virgin forest."[31]

He also found the time to interact with engineers and geologists. He went on frequent geological field trips with geomorphologist Walther Penck, and petrographer Bruno Sander, both later to become giants of geological science. He reportedly carried out a study of commercial clay sources and investigated possible exploitation of oil shales by foreign investors.[32] He also became involved in soil investigations for a possible bridge or tunnel crossing of the Bosporous.[33]

The life in Constantinople was thus fascinating, but difficult. Olga showed little enthusiasm for his long hours away from home and seemed to have no sense of the need to be frugal. This drove Karl to despair, and in his diary he started listing the many women he had known as if to reinforce the misery of his bad luck with Olga. But he loved the way she played the piano and was confused about his true feelings. So was Olga, who began a relationship with another man but refused to allow him to address her in the German familiar "Du". Baby Vera did not seem interested in contributing to his serenity at home. On the other hand, he knew he was lucky to be living out the war in peaceful circumstances, and admitted to himself that he had "unleashed a storm in a water glass".[34]

Outside the water glass, there was a real storm raging, as witnessed by the sight of hungry Turkish soldiers on their way to the front in tattered uniforms, the figures of starving civilians, and the corpses of those executed for desertion or "crimes". The most ugly story was that of the poor Armenian civilians who had been forced out of their homes by General Saunders, and abandoned by the roadside or dragged off as slaves for the military. In mid-1915, 1.2 million Armenians allegedly were forced by the Turks to march into the Syrian desert, with insufficient water or food. By the time of Terzaghi's residence period in Turkey, the genocide had given way to occasional murders and cruel massacres, including crucifixions and burnings.[35] Within his immediate sphere, aerial attacks by the British to sink the two German cruisers in the Bosporous were answered by antiaircraft guns, and cannonading of Turkish forts by the Russians occasionally brought home the sounds of battle.[36]

Against the backdrop of human misery, Terzaghi found the time to complete a series of essays on culture, development, and civilization, which he entitled "Folk-Culture or a civilization of foreign races?",[37] extending an essay he had shared with Professor Wittenbauer in 1914, entitled "Old and New World". He submitted the manuscript to publisher S. Fisher in Berlin, proudly dedicating it to Professor Wittenbauer as its content had clearly sprung from their relationship. This volume has not been located anywhere among Terzaghi's papers. Terzaghi hinted at its contents when describing to Wittenbauer his obsessive conviction that German culture must be purged of foreign influence to prosper in an authentic Germanic way. This is an old and recurrent theme of German philosophy and literature, as in Hans Sachs' triumphant closing aria of Richard Wagner's overpowering opera *die Meistersinger von Nürnberg.*

Wittenbauer's strong influence on Terzaghi's "cultural" views cannot be doubted when Terzaghi writes subsequently to extend thanks for accepting his dedication. [38] "We have been linked for almost two decades," he observes. "You dislike Rathenau because of his Jewishness, which enters into all his works; this is the same spirit that transformed the German language. I am immune to such influences since one can change his clothes but not his hide."

Terzaghi was encouraged from the favorable reception accorded his ideas by a German colleague attached to the German public relations office at Constantinople.[39] But the Berlin publisher rejected his manuscript, with "very adverse criticism", not so much for its content as for its "shop-worn" presentation. [40] Terzaghi considered attacking the critic but was urged away by the public censor. Although embarrassing to him, the stillbirth of this work was probably fortunate in view of the later distortion and misuse of similar philosophies by the Nazis.[41]

In mid-August, 1918, Terzaghi received notice from the Ministry of Education that his period in Turkey was over and he should now report back to Vienna. He was crushed at the thought of interrupting his work. With his own money he set out to Vienna to visit the ministry. Trying to communicate the importance of this work to the Hofrat with whom he finally achieved audience was utterly unsuccessful, and he began an endless series of waits in Austrian bureaus, all in vain.

This visit allowed him time to reflect on his marriage, which called forth some seventeen love letters to Olga reaffirming his role as husband. He visited his home in Graz to find his Mama skinny like a skeleton; in this island of peace in a mad world he climbed with nostalgia to a childhood summit and he reacquainted himself with some fraternity cronies, whom he found a bit wiser. In Vienna he visited a series of friends, including hydraulics Professor Schaffernak at Vienna Technische Hochschule. Schaffernak informed Karl that he had lost the competition for the chair at Prague because they viewed Terzaghi as a traveling researcher, rather than as an engineer. Throughout the period in Vienna, Karl continued to work, late into the nights, on his earth-pressure manuscript.

As the summer wore on, the war finally moved towards its end. The British and French landing in Salonika resulted in the defeat of Bulgaria, which agreed to armistice on September 29, 1918. Karl was dining with Fröhlich in Vienna on the day the Bulgarian front collapsed. The pessimistic and very worried "sly fox" was devising strategies for Terzaghi to get his family to safety in Odessa. But Karl seemed to be somewhere else, prompting Fröhlich to state: "This is the most memorable evening I have lived through and all you think about at this time of world history is your earth pressure theory." Karl finished his manuscript by working all that night, mailed it off, and then boarded the 7 a.m. train. It took him through Bulgaria, and masses of deserting soldiers, arriving only ten hours late in Constantinople .

Ironically after some nine weeks of frustration, and the expenditure of 3,000 crowns, Karl obtained his permission to remain in Turkey soon after arriving back in Constantinople. It took the intervention of the German Consulate.

Events were moving rapidly now. On October 4, 1918, the Turkish cabinet resigned and three collaborators of the Germans fled, later to be murdered. Soon thereafter, the British, advancing north from Jerusalem, succeeded in cutting the German railway line to Baghdad, effectively ending Turkey's fight. The Pasha surrendered on October 30, and the final armistice in Europe was signed on November 11. When the British fleet sailed triumphantly into Constantinople and anchored in front of the Palace on November 13, it was a spectacle that Terzaghi told himself he would never forget, as he tried to imagine the unknowable yet to come.

6
The Invention of Soil Mechanics 1918–1923

Forchheimer and Terzaghi were now nationals of a defeated nation and were soon put out on the streets as Turkey tried to posture itself with the victorious conquerors. Without income, and with savings being depleted by insane inflation and black-marketeering, Terzaghi was hard-pressed to provide for his family. The times were terrible, with civic anarchy and wide-ranging banditry. In this hour of great difficulty, help appeared from an American source. Tiny Robert College, originally a missionary school, had widened its horizons and was now teaching science and engineering. They had an immediate opening for an instructor in thermodynamics and gas technology; however, it was not certain that they could obtain permission to hire an Austrian.

Although he could not count on obtaining a residence permit, and must teach a subject that was hardly up his sleeve, Terzaghi applied eagerly, and accepted a temporary post. He did have a degree in mechanical engineering, and, if the salary was less than he had obtained in Russia in 1911 and the teaching load enormous (by contemporary standards), he was in no bargaining position. So Karl Terzaghi switched his lecturing language from French to English and became a faculty member at the American Robert College.

He knew the college and its engineering Dean, Lynn Scipio, from several cordial visits in the previous two years. Terzaghi was much impressed with the integrity and resourcefulness of this remarkable mechanical engineer, a man who had, among other things, designed and inaugurated a flour mill to provide bread in the community when the uprooting of Armenians deprived Constantinople of its bakers.

Forchheimer too found temporary employment on the instructional staff at Robert College. This was not the outcome Forchheimer had foreseen on an earlier visit to Dean Scipio, the day after the United States entered the war in 1917. Forchheimer at that time imagined Americans would be forced to leave Constantinople and the college would have to shut down. He had come to propose that his Royal Ottoman College take over Robert College rather than have the Americans just abandon it. Scipio invited his Austrian visitor to discuss it cordially over a cup of tea, but Forchheimer refused abruptly, saying that they were now officially enemies and should not fraternize. The Austrian, however, was willing to accept Scipio's offer to remain as caretaker "since engineers were usually not interested in political matters."[1]

It was a pale replica of the former haughty Dean who now returned to beg an interim appointment, because his age precluded travelling back to Austria in mid-winter. When Scipio said he'd speak to President Gates, "the expression that came over his wrinkled old face was indeed touching."[2]

Robert College was located in Bebek, a small community north of Constantinople along the western, European bank of the Bosporous Straits, part way along its straight path from the Sea of Marmara to the Black Sea. It stands in a commanding topographic position with magnificent vistas of water and hills. In a driving rain on December 9, 1918, Terzaghi made the trip to Bebek by steamer and wagon and moved into a small, unheated corner room in the attic of a college building. On December 12, Robert College President Gates went himself to speak with the British authorities about Terzaghi's exceptional qualifications and, after "a stiff battle with the High Commissioner",[3] obtained a temporary permit for Terzaghi to remain, but only until January 20, 1919. So on December 18, Olga and Vera joined him, and they moved into a house rented for them by the college.

He spent the whole Christmas period preparing the lectures for his five courses: irrigation, water conservation, theoretical hydraulics, reinforced concrete, and gas machines—seventeen hours per week in front of classes. He surprised himself in the ease with which he rediscovered the spirit of thermodynamics. He added new material in excavation, well-drilling, and earth dams and tried to work out practical examples. The class sizes were tiny: three in irrigation, two in water conservation, eight in hydraulics, one in reinforced concrete, and four in gas machines. The students were put to hard work and some complained.

Terzaghi quickly discovered the students were largely unprepared in mathematical and scientific fundamentals, the underpinnings of engineering. Unlike European students, they had manual dexterity and experience operating cameras, tools, and equipment, but no idea of construction, and they could neither draw nor calculate. Worst of all, they seemed to possess little imagination.

Nor was he pleased with the system of education. There was too much manual work and the "incredible stupidity" of overreliance on generalizations from textbooks with hardly an interest in new ideas. Teachers should avoid introducing generalized rules, he asserted, because such technical simplifications are the products of long experience and should remain the personal property of the originator. The students are asked to parrot back rules they are taught without comprehending basic principles, with "a prayer meeting mentality". In short, the American engineering education system earned a bad grade.

When the end of his temporary visa period arrived, the British Commander informed President Gates that Terzaghi could continue to remain in the country only if he would swear he harbored anti-German feelings. Terzaghi refused to allow that he did, but he was quite willing to agree not to advance any German propaganda during his stay at Robert College. If that gesture wasn't sufficient to appease the British, then he would pack up and go. With this reply they left him alone.

By late February he found his lectures going so easily that he could return to writing and research, even though he would have new courses in engineering geology and masonry structures in Spring. He planned articles for his developing syllabus on engineering geology, which dealt with weirs on permeable soils, quicksand, evaluation of clays for embankments, economics of boreholes, and construction in limestone. The first subjects, concerning the action of water in sands, under dams or in excavations, had puzzled and challenged him in his Vienna work ten years earlier and again in Russia. In February of 1918, at the Royal Ottoman College, he had initiated experiments on the origin of quicksand phenomena, but then diverted himself into earth pressure against walls. He would resume this area of inquiry.

Forchheimer's work on applied hydraulics would be the place to start studies on quicksand, but it seemed "a mathematical jungle".[4] To help him extend Forchheimer's work specifically into the physics of dam foundations on sands, Terzaghi tried to enlist his old mentor's direct participation. Forchheimer, however, declared he had little interest in practical applications of his theory and no personal capacity to retain observed facts about actual behavior. "He cannot remember that which is not achieved through logical thought.... Had he a better technical memory it would not have been necessary for him to derive a theoretical approach."[5] Yet it was Forchheimer who first recognized the analogy between flow of electricity and the flow of water, and thereupon adopted the electrical physicists' graphical "flownet" method to solve problems in practical hydraulics. Terzaghi was teaching these methods to his class.

Application of Forchheimer's flownet to the problem of a dam on sand demonstrated that the hydraulic force of water was directed upward as the water emerged downstream from its journey under the dam, through the foundation. The upward-seeping water would oppose the self-weight of the sand grains and decrease the force with which they pressed against each other. If the water force became equal to the sand's self-weight, some of the finer particles would tend to lift off one another and could be eroded. Under a dam the erosion of particles at one point would rapidly lead to the creation of a hollow, termed a pipe, with the occasionally witnessed outcome of a complete emptying of the reservoir and destruction of the dam, as well as of any downstream structures.

A pioneering work by Bligh from 1910[6] in use by design engineers at the time, reported that piping could be prevented by keeping the length of subsurface flow greater than a fixed multiple of the water head[7] retained by the dam. This fixed number was reported as a function of the type of soil, increasing from about five for bouldery sand and gravel to eighteen for fine sand and silt. But this could hardly be correct, Terzaghi deduced, because piping initiates at the point of highest vertical hydraulic force of the emerging seepage water in the downstream part of the dam, and that could occur at different Bligh numbers according to the layout of the work and the lateral variations in subsoil properties.

With a small grant from Robert College, Terzaghi began to establish a research laboratory for his experiments, scrounging parts from here and there, including the college dump. He wanted to observe the changes in water permeability of soils as the upward hydraulic force increased.[8] This force, he showed, was directly proportional to the quantity of flow per unit area (the "flux") in any section and inversely proportional to the permeability of the soil. Forchheimer's flownet enabled the former to be calculated everywhere under any specific dam structure; therefore, the determination of permeability values for sand would complete the specification of the system. Above all, he wanted to observe the physics of the initiation of piping.

Terzaghi's experiments showed a clear result. As the upward hydraulic force was increased through a column of sand, the quantity of percolation would increase proportionally (in accordance with Darcy's law) until the upward hydraulic force became equal to the submerged weight of the column of sand. Then the flow would immediately and dramatically increase while the sand underwent a complete change in its fabric, acquiring a very loose grain packing. In other words, the structure of the sand had rearranged itself automatically into a looser and much more permeable fabric in order to reestablish hydraulic equilibrium between the weight of the sand and the now much smaller force of the flowing water.

Terzaghi subsequently constructed model dams, of various shapes, and observed the effects of gradually raising the water level stored behind them. As the water height increased, a critical height would be reached at which sand on the submerged surface at the toe of the dam would appear to "boil" as it suffered erosion of fine particles; shortly afterwards, a tunnel would be eroded completely under the dam, and the reservoir would summarily wash through it—a classical failure by "piping". This critical height was perfectly computed from the hydraulic flux and permeability at the worst point along the seepage path, which was usually at the downstream toe of the dam.

Terzaghi conceived the idea of preventing the development of piping by providing a heavy filter at the critical location. This would consist of a blanket or mass of pervious soil, over which was to be placed a weight of additional soil backfill. The higher permeability of the drainage filter mass would reduce the upward hydraulic force, while the overlying weight would simultaneously increase the downward resisting force.

Terzaghi had completed the theoretical part of the work with pervious soils in the first week of March, 1919, and then began applying it to canals. He was delighted with the way Forchheimer's theory had brought order and meaning to observations. "Theory", he wrote, "is the language by means of which lessons of experience can be clearly expressed. When there is no theory, as in earth construction, there is no collected wisdom, merely incomprehensible fragments."[9] In his new laboratory he successfully measured "the permeability of quicksand" in mid-May and by August, 1919, he felt that there were no puzzles yet to be unraveled, just the factory-like production of specific results. Yet it was not until 1921 that he completed tests of the weighted-filter concept. This proved so perfectly effective in preventing piping that Terzaghi committed himself to trying it out in practice and fostering its use by engineers. He worked with his engineering friend in Vienna, Joseph Pfletschinger, and together they obtained a patent in 1922. After some difficulties, he learned from Pfletschinger, in December, 1923, that the weighted filter would indeed be built into a dam in Gratwein, Austria. The site at Gratwein is noteworthy because the foundation of an old dam in the same stretch of the river had to be constructed with compressed-air caissons on account of the high permeability of the coarse-grained alluvium. With Terzaghi's filter, the construction of a foundation using caissons charged with compressed air was avoided, with significant savings.[10]

In March, 1919, buoyed by his initial successes with hydraulics of sands, Terzaghi returned to his old dream and planned out an ambitious set of additional experiments. The aim was to define the properties and behavior of soils quantitatively, in order to supplant engineering guesswork by logical and systematic procedures of applied engineering science. To the extent that boreholes and test pits and geological inference could decide what soils were present, his new applied science should make it possible to evaluate all the relevant properties through tests and allow an accurate forecast of soil deformations and safety as part of the design for any engineered structure.

His main interest now turned towards clays, which remained mysterious. As a first step, he thought it should be necessary to determine the proportion of clay in any soil, for the binding action of the clay would be foremost in determining the soil's properties. The decisive factor for stability must be connected with the water content of the clay mass and its changes with load. He initially saw the function of the water principally as displacing soil material and therefore weakening the total mass, but he suspected there may be complicated chemical interactions between the water and the clay particles. Thus, he resolved to study colloidal chemistry along with his experiments.

Terzaghi apparently had a sudden burst of inspiration in planning for his new experiments. "Sitting in a mood of depression on a piece of rock outside Robert College," related Laurits Bjerrum, "...looking out over the Golden Horn, he suddenly visualized what was needed to obtain a rational approach to the problems involved in earthwork and foundation engineering. He realized that progress depended entirely on the development of testing equipment and methods which could give a quantitative measure of the mechanical properties of the soils involved. On some sheets of paper he listed a number of possible ways of testing soils, made sketches of the equipment needed, and suggested how the results could be interpreted. These sheets of paper represent the birth of soil mechanics." [11]

As related to Prof. Wittenbauer: "At the beginning of March I put together a planning document on what needed to be done regarding the strength and physical properties of clays in order to place earth construction on a scientific basis. My plans were ambitious ... and I doubted that I would be able to answer all the questions that I had posed."[12]

Regardless of the engineering application, thought Terzaghi, all loose, uncemented sediments owe their properties to the forces acting between the grains at points of contact. The experiments must elucidate the nature of these forces. The forces stem from pressure of self weight, and chemical action of water in contact with the grain surfaces. It will be important to study the friction of mineral grains, and the viscosity and surface tension of water, which creates capillary forces due to the air/surface boundary in the small intergrain conduits. Very fine clay particles will also have chemical bonding forces between contacting clay particles. Thus, Terzaghi began the study of soil physics.

Without sophisticated equipment, he contrived a way to study the mechanics of friction between mineral surfaces. If a pair of glass slide plates are placed in contact, colored rings appear. These "Newton's rings" arise from the interference of light around contacts at high points where microscopic particles had been deposited at random on the sliding surfaces. The very tiny heights of these contacting points could be measured by observing the change in the spectral color caused by pressing the plates together, which could be calibrated with a microscope stage. Terzaghi later used this phenomenology, with help from Dean Scipio, to construct a fine extensometer to measure small displacements in other experiments.[13]

He was well aware that the properties of the soil mass would depend heavily on the proportion of void space in the specimen and the degree to which the pores were filled with water. The void proportion, in turn, was obviously increased or reduced with change in the magnitude of the intergranular forces. In one of those famous sheets of paper of March 19, he sketched a fundamental apparatus in which he could both measure permeability and monitor the pore volume change on changing the external pressure on a specimen.

The device, which would now be said to encompass a combined *oedometer* and *permeameter*, would consist of a rigid tube inside of which a short, circular cylindrical soil specimen could be loaded or unloaded axially without permitting any change in its diameter. By attaching a hydraulic standpipe connected to the water in the base of the specimen, he could also establish an initial water-pressure difference across the specimen; this would allow him to determine the permeability of the soil from the rate of decline of the water level in the standpipe as the water was allowed to flow through the specimen.

Terzaghi's purpose in devising this apparatus was to measure not only the permeability of soils, including clays, but the change of permeability accompanying change in the volumetric proportion of voids in the sample. The latter could be expressed in a variety of ways, including the *porosity* (ratio of pore volume to total volume), the *void ratio* (ratio of pore volume to the volume of the solid particles), and the *water content* (ratio of water weight to the total weight of grains, or to the total weight of the specimen, grains plus water). Simple formulas connect porosity, void ratio, and water content.

Terzaghi at this point was beginning to understand from his experiments with quicksand that the force of water percolating through a specimen could suddenly neutralize the forces between the soil particles and bring about structural collapse. He probably inferred that a reduction in the intergranular forces was a continuous development accompanying increasing seepage force. He may have also made the further logical inference that intergranular forces are similarly reduced even without actual flow simply by increasing the static water pressure in the pores of the soil. And perhaps he even foresaw the logical connection that a continuous reduction in intergranular force would cause a corresponding continuous reduction in strength. Whether or not he pictured all this in 1919, his experiments little by little led him to all these fundamental conclusions.

The construction of the apparatus was started in the Greek locksmith's shop on April 6. It took only a week to manufacture, although this wasn't nearly fast enough for Terzaghi. In early May he was trying to work out clay handling and testing procedures but became highly frustrated with repeated system failures and confessed that working with clay provided more of a riddle than he had anticipated.[14] He tried to find the source of the difficulty by observing the clay in a microscope borrowed from a reluctant professor; this gave absolutely no help. But by May 23rd he was excited by some success in the lab.

He started with a viscous soup of clay and water in a glass cylinder centered over a smaller, short bronze ring. He placed a filter paper on top of the clay surface and a layer of clean sand above it. Under the weight of the sand and its self weight, the clay slowly compressed. He then loaded the sand filter with a cup filled with lead shot and the clay shortened some more. He now transferred the clay sample within the basal bronze ring into the oedometer and continued the loading in increments up to the highest pressures of interest in engineering construction.

For each increment of load, Terzaghi monitored the shortening of the clay sample with time. The rate was quick at first and then tapered off to approach a final value. At last he could report the modulus of elasticity for a clay, or any soil. This property, determining the amount of strain caused by application of an increment of stress, is fundamental for engineering with steel and most structural materials, and now it could be presented for a soil. This had been one of Terzaghi's prime goals.

The shortening of the specimen corresponding to a certain amount of pressure was now indeed determinable by his experimental procedure, but this shortening occurred only after a delay of time. What caused this delay? It eluded him until March, 1920, when he discovered that the permeability of clay decreased markedly when the gradient driving waterflow across the specimen was reduced. This meant that, like sands, an increase in gradient of flow would bring about an increase in permeability. It could suggest that the intergrain forces were decreased when the seepage force was increased as if the clay were behaving like sand. It could also imply that water was tenaciously held between the clay particles by bonding forces. "I was so exhausted that the discovery evinced little joy."[15]

No wonder he was exhausted. He was almost simultaneously running his tests on clay, conducting tests on silty sand, investigating friction between mineral particles, initiating experiments to measure the shear strength and compressive strength of soil, conducting further experiments on the permeability changes in quicksands, and still developing measurements of the at-rest pressure in sand layers. Procuring samples was time consuming, and could be dangerous in this time of lawlessness. He was working very long days, too busy to read the paper, and lying awake at night excitedly trying to understand what he had measured by day. As he wrote to Prof. Wittenbauer in summer 1919, "after six weeks of continuous failures with twelve-hour days, my luck seemed to turn and since then I haven't run a single test that didn't meet the desired objective. After this I worked with the clock on the table so that I could conduct four or five series of observations simultaneously and at the times of my intense activity these were stretched out to where my nightstand was loaded with specimens to be read at six-hour intervals."[16]

Furthermore, despite increasing research assistance from Robert College, his expenditures for books and correspondence, and what he interpreted as Olga's utterly uncooperative spirit in not holding down household expenses, forced Terzaghi to attempt to increase his income. He consulted for a Borax mine, and the Golden Horn Steamship Co., but found difficulty in obtaining other commercial engineering opportunities. But he did succeed in interesting Engineering News Record in accepting a string of articles[17] in return for good remuneration once editor F.E. Schmitt recognized "their sensational character".[18]

It was not just money that drove him to search for consulting activity but his basic restlessness and desire for professional involvement outside the college. When his close friend Prof. Terbini informed him of a serious problem with foundation settlements in a power plant along the shores of the Bosporous, he decided to go after the company to retain him for this was a clear opportunity to try out some of the fruits of his research in an urgent, professional setting.

The company, Société Anonyme Ottomane d'Electricité, operated the Silighdar power station, founded on a stony sediment underlain by soft clay. Since its construction in 1913 it had suffered up to forty centimeters of settlement, and the machines began to suffer premature wear. Terzaghi convinced himself that the cause of the settlement was excess pressure in the pores of the soft clay, and he longed to be allowed to work on the problem. But the general director, M. Haussens, was not of a mind to engage a local engineer and completely ignored his overtures.

On his own initiative, encouraged by the power plant engineer, he had already invested four weeks of his time studying their problems and had identified the source of the excess pore pressure as piling of coal heaps near the plant, operation of a heavy gantry crane, and excavation of a five-meter-thick shale bed nearby. Terzaghi determined that attempts to improve the foundation by driving sheet piles through a rubble bed had accelerated the differential settlement, presumably by creating drainage opportunities for the excess pore pressure in the mud. Although he had already prepared his report, he now worried he wouldn't get paid, or receive encouragement to continue.

He suffered over this indignity throughout the Christmas period of 1920, and then in the start of the new year he decided to more or less camp on the general director's doorstep. Having previously left his report, he now deposited a letter saying he would require only a modest sum for his work as he was using the opportunity to showcase his new methods. After four hours of waiting outside the office door, Mr. Haussens finally emerged and caved in to his insistence.

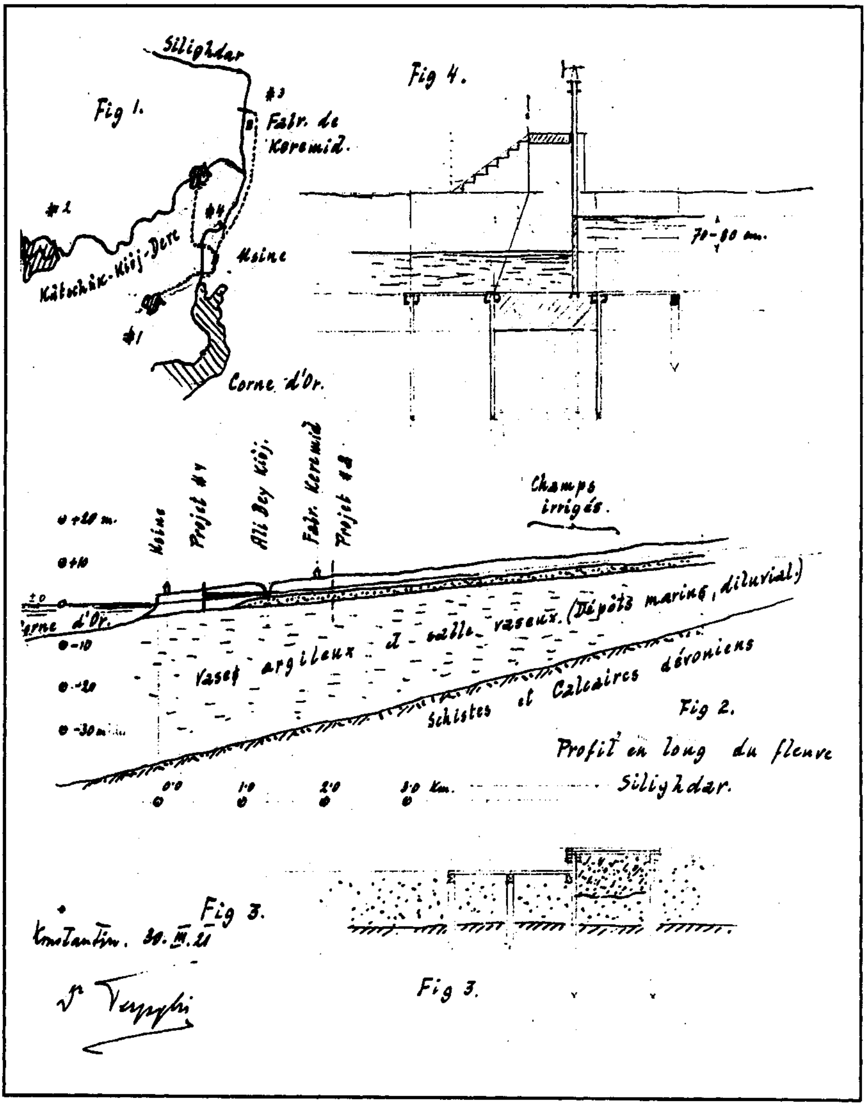
Immediately, Terzaghi was treated more kindly, asked to lecture on his methods, and even invited to present his opinions in the head office in Brussels. There he argued that it was dangerous to found the structure partly on end-bearing piles and partly on friction piles because the foundation would fail in bending.[19] Furthermore, the friction piles were useless and would not reduce the magnitude of settlement. His stock with the engineers went up when the latter proved to be true.

In the following months he completed an impressive array of assignments for Silighdar, involving not only soils and engineering geology studies, but steel and reinforced-concrete design, economic analysis, hydrology, and hydraulic engineering. He studied sources for a new water supply for the plant, designed and reconstructed a new crane foundation to be supported by piles, incorporated a re-leveling device for the crane rails, and finally designed and directed the construction of a new quay that required a dangerous four-meter-deep excavation by dredging. The latter was demanding because the expected differential soil displacements were so large as to threaten any rigid waterfront structure; piles to halt the soil movements were too expensive. He carried through an innovative solution using temporary supports of wood that would be replaced by reinforced concrete after the deformation from dredging had tapered off.

In this work Terzaghi displayed his complete understanding of the need to deal with excess water pressure in the clay, a concept that he had so recently discovered in his laboratory. The irony is that he learned via correspondence in 1939 that the large settlements of the plant foundation were probably due in the main to pumping from the water wells whose existence during the early life of the plant he had not uncovered.[20]

By the end of 1920, Terzaghi began to feel that he was on top of things. His "Poe-esque detective novel"[21] with clays was drawing to a close, and he was engaged in practical applications. He summarized what he had learned in research, "the fruits of four years in twelve pages" as an article to be published by the Austrian Society of Engineers and Architects, partly due to the help of his friend Professor Fritz Schaffernak in Vienna.

In this paper, among other things, he clearly demonstrated that he now understood the reason for the delayed compression of clay in his oedometer when an increment of load was applied. Under the heading "Hydraulic equilibrium of clays" he wrote that a clay mass is in hydraulic equilibrium if its water content corresponds throughout to its external pressure. This happened when the water content eventually reached its final value after application of a load increment in his oedometer. "Because



A drawing prepared by Terzaghi to support his discussion of potential sources of industrial water for the Silighdar power plant, Societé Ottoman d'electricité in Turkey, March 1921.

of the small permeability of clays, the attainment of equilibrium was achieved, however, very slowly."[22]

This was an important statement. Its mathematical formulation could not be far behind. But Terzaghi struggled to obtain that and, as he struggled, everything seemed to be going for naught. On April 30, 1922, he wrote in his diary that all the questions he had presented to himself were answered and the solutions are eminently satisfactory but one disappointment follows another. His initial work on earth pressure was forgotten by the world in the hustle and bustle of the Armistice.

The *Engineering News Record* articles had been sidetracked because the editor found them too theoretical. In his defense, Karl wrote that his study of all the relevant papers *Engineering News Record* published in the last year present either unconvincing or incorrect conclusions and are not useful. We must direct attention not alone to phenomena but to what lies behind them.[23]

So much troubled him. He had attempted to collaborate with the Swedish agricultural scientist Atterberg on the states of clay, but the collaboration failed. (Terzaghi was using Atterberg's concepts in his own work.[24]) Furthermore, his summary paper in the Austrian Society of Architects and Engineers seemed never to materialize. The installation of a weighted filter in a dam, with Pfletschinger, had run into trouble. Despite his enormous attainments, he was becoming discouraged. Then on March 15 he received notice of the death of his great mentor and friend Professor Wittenbauer. "It is as if a curtain rises for me and opens on a new world, a world I can not touch but only feel."[25]

But he had the remarkable capacity, with his diary, to serve as his own psychiatrist. After listing all these setbacks, he added that nevertheless he should retain his courage. After all, he had experienced the joy of discovery. And that is sufficient reward.

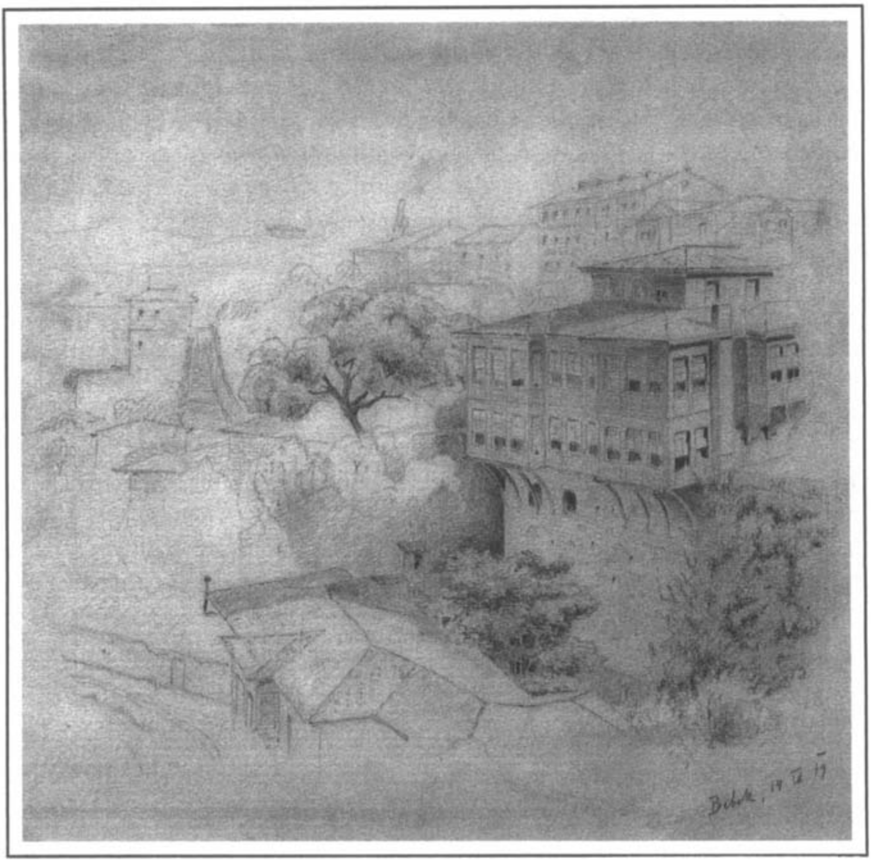
The joy of discovery was carried a step further in the first days of October, 1923. By this time he was collecting his new system of soil mechanics in the writing of a book manuscript: *Erdbaumechanik auf bodenphysikalischer Grundlage,* which could be translated roughly as "Earthwork mechanics based on the physics of soils". He fully understood now that the addition of an increment of external pressure to a clay resulted in a temporary increment of water pressure of equal magnitude. The soil's intergrain contacts would feel no increment of force until the pore pressure began to dissipate. When the water pressure in the soil's pores had a value u, and the external pressure had a magnitude p, only the value $p - u$ was effective in causing force between the grains. He called this quantity "the pressure acting in the solid phase of the clay". Today it is known as "the effective stress".

The understanding and working of this relationship is one of the most important elements of modern soil mechanics. As Terzaghi's shear strength experiments clearly indicated, the magnitude of the effective stress governs the strength of soils and therefore the safety of slopes and foundations. [26] The notion of effective stress is equally fundamental in relation to predicting settlements and lateral motions of soils under foundations, embankments, and other applications. Terzaghi's effective stress principle may be considered the unifying premise for much of the subsequent work in this field.

To predict the effective stress at any time was the problem Terzaghi had set out to solve. He understood the physics well. The addition of an external pressure causes an immediate increase of pressure within the water-saturated soil pores. This establishes a gradient of pore water pressure that tends to drive the water out and so the water content decreases, causing the clay to compress. But because the permeability of clay is so small, this takes time to happen. The physics of clay compression was similar to that of the closing of a door cushioned by a viscous shock-absorber to prevent it from slamming shut.

He had been unable to make headway on formulating this physical behavior until he thought to study the books on the mathematics of heat conduction.[27] This suggested to him simplifications that led to derivation of a differential equation completely analogous to the well-known diffusion equation governing the time-dependent flow of heat in solids. His theory of "one dimensional consolidation", as it came to be known, was another application of the diffusion equation, with water pressures in place of temperatures. He might have gotten this help directly from Forchheimer, who had made much use of this analogy, but the professor had long since returned to Austria. Wittenbauer had also left him, and now Olga too.

Bebek, 1919.



Bebek, 1919.

7
Developments in Turkey 1922▾1925

Relations between Karl and Olga ranged between wild extremes. He loved her, but was completely at odds with her carefree, irresponsible nature, and they had frequent arguments, invariably about money. While they were married, he remained essentially faithful, in body if not always in spirit. But as soon as they parted, the romantic reemerged—with old flames and new ones, deep emotional partners, or friends for the while. It was as if he had suppressed an intense physical longing through all the six years as family man.

The final argument happened amid the tense backdrop of large events. The Turkish nationalist forces were reported to be driving on Constantinople. The Moslem people became agitated, and the Turkish army clustered around the city. Because there was real concern of a massacre of all foreigners, diplomats were ordered to send their families home, and an American destroyer set anchor in the Bosporous near Robert College, with marines to guard the college entrance.[1] Evacuation plans were being laid, with the battle between the British and the Turks likely to occur on about September 27, 1922.

Olga suggested to Karl it might be a good idea for her and the child to take up temporary residence in Graz with Karl's sister Ella and her husband (Olga's brother). Karl thought it a typically inconsiderate Olga proposal to invite herself with child into a small home in impoverished postwar Austria for a prolonged stay. And he wrote a letter to that effect to his mother on the 22nd of September.

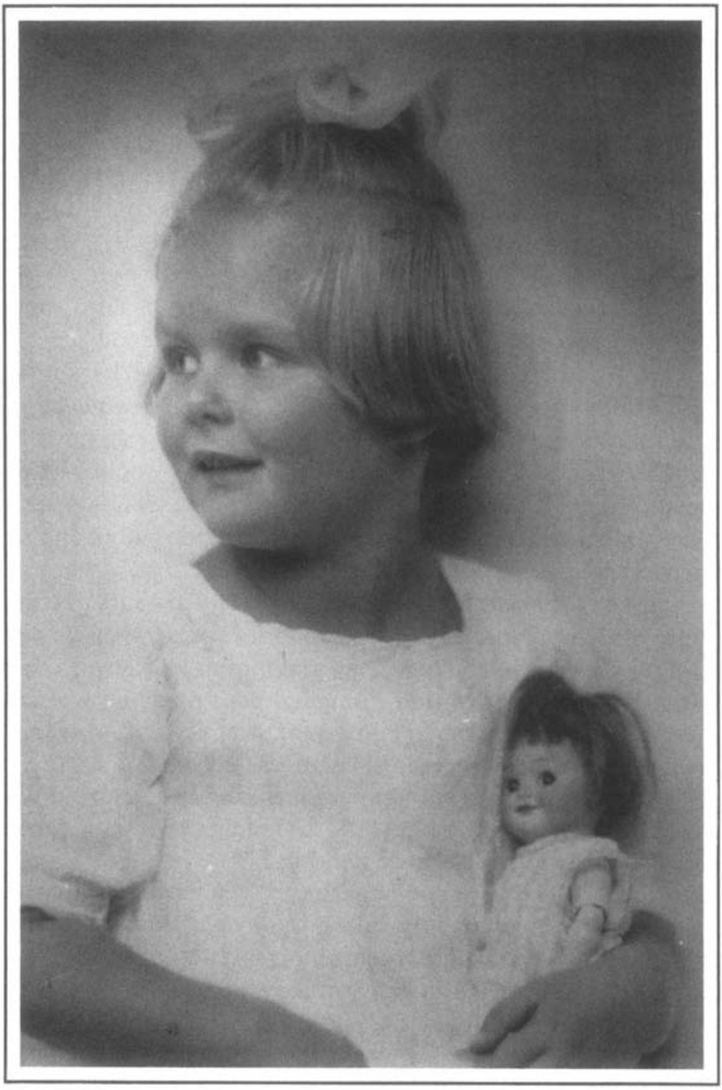
Olga found and read the letter, screamed at Karl, called him a barbarian, and raved through the night. They both knew it was time to separate. That was not so easy. The railway was fully booked with Greek refugees from the fall of Smyrna to the Turkish nationalists, and the Greek and Italian embassies in Constantinople were besieged with requests for emigration. He was able, however, to book Olga and Vera on a steamship, the *Adria*.

At the moment of departure for the docks, on the 26th, Olga sobbed, and, when Karl saw Vera's teddy bear on the sofa, he too lost his control. They embraced richly for a full minute, and the tears flowed. Then Karl moved out, took a room in the College, and energetically resumed the writing of his book *Erdbaumechanik.*

Robert College at that time was closely watching the event that threatened Constantinople. Both President Gates and Professor Hussein Bey became involved in the political negotiations. The nationalists were generally feared for extremism, but their leader Mustafa Kemal had a reputation of incorruptibility and ardent fervor for democratization. Terzaghi remained a doubter and pessimist. His main fear was the spread of Bolshevism, which, in the wake of war and discontent, seemed a real threat to corrode the way of life throughout Europe. He worried that the Bolsheviks would try to carve up the world jointly with the pan-Islamists, Turks among them. Horror stories and rumors of Bolshevik underhandedness circulated widely, and generally the blame was pointed towards the Jews, wherever they were. Terzaghi recorded from a British paper "it is sad to see where the three darkest powers in Germany emanate: Judaism, atheism, and anarchy—three names for one thing."[2] Subsequently the same paper reported that the entire German socialist party, the majority party of the people, is in Jewish hands, and Terzaghi wrote it down.

Indeed, Turkey never settled into an easy existence at any time of Terzaghi's residence there. For siding with Germany in the world war, the Ottomans lost four-fifths of their territory, some given to Greece as reward for having joined the allied cause; Constantinople, in particular, was offered to Russia, together with the Bosporous and Southern Armenia. However, in the grips of revolution, Russia had struck a separate peace with the Germans, and the offer was reneged. Constantinople instead became a divided city under the joint administration of the occupiers—France, Italy, England, and the United States. The French and the British argued, and in time France and England signed separate accords with the Sultan and eventually departed.[3]

The rearrangement of national borders, confirmed in August, 1920, with the Treaty of Sevres, was bitterly opposed by a budding nationalist movement under Mustafa Kemal. The Kemalists declared themselves free of the Sultan's authority and set up their own army and a government in Asiatic Turkey, at Ankara. At this time, Terzaghi was downtown, late in the evening, waiting for a tram. The silence suggested there would be none. Then a distant noise approached as a thousand spirited people carrying flags and torches paraded and danced towards him. "Then a second horde came, then a third." He hired a driver to take him to Bebek but on the way had to cross similar mobs, one of which danced wildly and threateningly



Karl and Olga's daughter, Vera.

around his car. The next day he learned it was the spontaneous celebration of the nationalists' proclamation of independence from the Sultan.[4]

The Kemalists fought against and defeated the Greek army, chasing the Greeks entirely out of Asia Minor, reportedly inducing a bloodbath as they sacked Smyrna (now Izmir). They had acquired large military stores and now prepared for battle with the British, who had brought their Mediterranean fleet into the Sea of Marmara. But in October the British capitulated. They felt themselves too weak to hold Constantinople, and, at Mudania, signed an agreement with the Turkish nationalists under Mustafa Kemal.

The accord of Mudania was confirmed in the second treaty of Lausanne, in 1923, which formally ended the border-grabbing after the Armistice of 1918 on terms favorable to Turkey. Obviously so, expressed Terzaghi, because the Turks were represented by real fighters Mustapha Kemal and his aid Ismet Pascha, while the diplomats of European nations were represented by politicians. "Mustapha Kemal stood for a purpose plainly known to him and to his people. This plan was backed up by an army ready to fight because it was a fight for existence, while all the other governments had first to consult their finance departments for finding out whether the costs of a fight for the ideals of humanity would be a profitable investment, or not."[5] Both President Gates and Professor Bey attended that conference, the former as advisor to the American delegation, and the latter, now a general, as a representative of the new Turkey.

Terzaghi's enjoyment of the political wisecrack led him to copy topical humor into his diary, especially in the euphoric expansion of his psyche following Olga's departure. The bumbling and internal bickering of the allied occupiers, and its generalization, provided considerable inspiration. For example: "The French think, in all naivete, that revolution is the path to progress for mankind and their enemies are the enemies of culture; in equal naivete the British think all progress of mankind is associated with their imperialistic pursuits; the Germans lack the tendency for imperialism—German wars don't change the status of the world."[6]

He wrote: "If you have one Englishman, you have stupidity; two Englishmen, a Society; three Englishmen, a great people. With one Prussian you have nothingness; with two Prussians, an organization; and three Prussians, a military might. With one Russian you have a genius; with two Russians, confusion; and with three Russians, a public scandal."[7]

Terzaghi was often puzzled by the mind of the Turks, whom he called "orientals". "They have something we can't quite grasp," he entered in his diary. He later analyzed the differences.

"There are two possible ways of approaching truth: by blindly believing the truth of the revelations embodied in sacred books, or by skeptic, philosophical inquiry. And there are two possible ways of taking care of our material needs: by ascetically reducing our requirements down to the most primitive needs; or by developing our means of production. The attitudes mentioned second ... lead to development of brilliant, startling civilizations ... but at the same time they kindle in our souls the spark of insatiable desire—desire for domination, for knowledge, for wealth. There is no limit set to desire. The more we get the more we want and the game is apt to lead to absurdity, to self-destruction ... The attitude mentioned first leads to wisdom and to perfect inner harmony ... but at the same time, this attitude leads to a state of stagnation, killing every incentive for material progress. The bent towards assuming this attitude of peaceful resignation seems to slumber in the soul of every genuine Near East Oriental ... Our state of mind compares with the oriental one as bubbling wantonness of youth compares with the resignation of old age ... They cannot imitate each other without the risk of becoming ridiculous."[8]

On New Year's Eve, 1924, to have a new experience he visited the home of an Afghanistani sheik whom he had met by chance. The meal was graciously served. He heard tales of continuous suffering and undeserved misfortunes, and observed in the sheik's conduct a perfect, childlike submission, "a state of perfect peace and inner harmony which, if any, deserves the name of Wisdom ... I wondered which one of us has chosen the better part, the old man or I? I myself, entangled with soul and body in occidental conceptions of life, who cannot believe, because I want to know—the spirit of inquiry leading to eternal dissatisfaction—or the old man, a picture of what humanity might have been before it was expelled from paradise."[9] The answer was obvious for inquiry was the light in Terzaghi's spirit.

Karl Terzaghi's teaching at Robert College was often challenging, even troublesome, to some of the students but his extra-curricular talks were uniformly admired. He was famous as a skilled and highly entertaining, and uplifting speaker. He spoke with a slight accent and the occasional misplaced preposition that revealed his Germanic roots, but his choice of words and logic in English constituted prose of an order higher than what students were often likely to hear. His breadth of knowledge and ideas reflected a penetrating curiosity and intellect, which brought him to read widely and to attend almost every visiting lecture, be the topic scientific, political, sociological, philosophical, or literary. He also mined the life stories and points of view from worthy visitors while lingering over the dinner table and dutifully recorded the highlights in his diary.

His first general lecture, to the freshman class on April 4, 1919, dealt with problems of agriculture. In December, he spoke on the planning for a bridge across the Bosporous. The next April, he addressed a full house in the college's general assembly hall on "religion, science, and life". An American visitor told him his trip to Robert College would have been justified if only to hear that lecture, which he considered a "landmark in the history of the college".[10] This talk must have particularly pleased President Gates who later told Terzaghi that "without God's help such an institution as Robert College could not exist."[11] Karl confessed his opinion of that attitude years later: "The continuous personal intervention of God in the lives and fates of us lowly parasites populating a third-class planet of His Universe gets decidedly on my nerves ... [It is] unbearably arrogant."[12]

While religion and prayer meetings bored Terzaghi, he thought often about the limits of science and the need for something more. "Science gives us every information about the mechanism of a piano but none whatsoever about the man who has invented it, on the organization of the factory, on the man who plays on it, and about the purpose of the music. This science is strictly confined to the inert, or driven part of the universe. The driving impulses are forever beyond the field of scientific conception and without these driving impulses the universe could not possibly be anything but a shapeless chaos of energy and of construction-material without any constructive tendency in it."[13]

In his 1923 lecture, "About Life and Living", Terzaghi stated, "Science is a shorthand system, invented for the purpose of accurately expressing a maximum amount of experience by a minimum amount of letters, and not for the purpose of solving the riddles of the Universe. The poetic conception of science attempting to unveil the mysteries of Nature to find anything that looks like an ultimate cause was smuggled into the mentality of the lay public by the Newspapermen."[14]

One of the contemporary issues in science that greatly interested Terzaghi was Wegener's thesis that the continents of the earth were in motion.[15] In December of 1924, he spoke on "the drifting westward of the American continent" to the newly formed Robert College Technical Society. His clear enunciation of the geophysical and geologic arguments, supported by drawings on the blackboard and a model, communicated the certainty of this hypothesis at a time when most academics considered it to be poppycock. In reviewing this material, Prof. Herbert Einstein was "amazed" to find how close he came to putting together the whole picture of *plate tectonics* which was not advanced as a unifying hypothesis of earth geoscience until the late 1960s.[16]

Terzaghi's address to the students "About life and living" exalted the joy of creativity in preference to materialistic objectives.[17] The supreme record of living is the study of history but history records results, not life itself. It deals mainly with successful outcomes and ignores lives that failed to have a positive impact. "The one thing you can be sure about is that you have to fight, and fight bitterly, because the world is dominated by the law of inertia and the chances are that you lose out." And society that applauds a winner is disinterested in the greater number who are not.

But yet it is much more exciting, he observed, to participate in the attempt to win than to stand by and watch. The process of thinking and realizing, with its attendant fears and depressions and heights, is itself "living", whatever the odds. And the process of conceiving and achieving physical realization of the concept is the truest "beauty" that exists. Passionate enthusiasm is the driving force and the goal is less exciting than the quest. "To develop a thought into a finished, visible entity is as stupendous a marvel as is the transformation of a seed into a tree. While trying to develop the thought into a visible shape, the builder passes through the whole scale of human emotions, hope and fear, enthusiasm and depression. His strenuous mental efforts open fields in his mentality, whose existence he hardly suspected.... And after the feat is accomplished ... the toiler may relax for a while and joyfully contemplate the achievements of others, until the increasing internal pressure starts him on a new dash towards the unexplored. That is life.... The vaster the scope, the more passionate the effort, the more intense his love for what he tries to achieve, the more a man has lived."

This clearly autobiographical statement reflected Terzaghi's earlier expression to Professor Wittenbauer that "there are men who value their own unselfish passionate urgings more highly than a comfortable, safe career". He takes a moral from Wittenbauer's taming of his youthful wild energy: "A torrential stream which marks its path with destruction is a potential blessing because sooner or later that stream can be harnessed and turned into a source of benefit."

Terzaghi realized that not all people are equally endowed with the powers to blossom as creative thinkers. Those who are fortunate in their endowments would do better than to force on others the products of their creativity, but rather find a way to have them experience for themselves "the boundless joy of creating."

Just what constitutes happiness was the subject of a talk entitled "The Way to Happiness" which he presented in March, 1924, at the home of Mrs. Edwards near the campus in Bebek. The Edwards were benefactors of the college, and their home became a cultural center on numerous occasions. Terzaghi asserted that our strivings lack value unless they achieve "an increase in the intensity, the variety, and the refinement of our mental reactions and of the stability of our minds." This is the source of true happiness, and it can be recognized in the face of one who possesses it, as one encounters so frequently in paintings from past eras. But in modern art the faces lack the spirit of happiness. Our life is too fast; unassimilated facts lie within us like an undigested meal.

He argued that humanity has made the worst use of every gift it has received. "The religion of love served as a pretext for the most cruel persecutions, The pure thought of the early French philosophers led to the terrible chaos of the French Revolution and the philanthropic dreams of the German theoretical socialists to the obscure tyranny in Bolshevist Russia. The century of science and invention ended with the most destructive war of history and in spite of 1,900 years of Christian tradition the States as acting persons proved to be on the moral level of Stone Age brutes." This stems from application of the law of selection, which "leads to the survival of the most clever, most reckless, and most hypocritical. There seems to be no fox-hole left for the freedom of will.... The validity of the fundamental laws provides that the fear of perishing and the desire to succeed dominate all the other instincts."

"The very moment you overcome fear and desire you leave the domain governed by the law and you become free." In this spirit Terzaghi left his hearers with three rules to promote internal happiness, all of which contradict the laws pointing toward external success: 1) do not avoid suffering but welcome it as a way to augment your strength, 2) disregard market conditions and give your best effort no matter what and never produce something that is worthless even if the market says to do so, and 3) try to combine "the inflexible firmness of the man of action with the sensitivity and spontaneity of the artistic mind."

Less than two weeks later Terzaghi spoke at the alumni dinner for Robert College Founders Day, and two months later he was back full of humor for a talk presumably about "Geology of the Bosporous." It was a charade, another attempt to sermonize, this time under the facade of a scientific subject. He admitted frankly that his engineering students prefer sitting in a dentist's chair to hearing about geology. But he has personally greatly enjoyed geology and especially trying to decipher the geology of the Bosporous region. "If you want to get as much joy and satisfaction out of life as I do, you must have a Bosporous of your own—something to which you abandon yourself wholeheartedly without any reserve ... If you don't feel everyday the trembling joy of life, which is the inevitable manifestation of an unbroken personality residing in the center of a small world of its own ... then I claim it is not worth the coal to keep your boilers under steam."

All this heady, self-assured optimism and determined righteousness was a product of Terzaghi's enormous pride in having succeeded in working out a mechanics of soils. In that spirit, and excited to emerge from his hiding place in Turkey after years of strenuous achievement, he traveled in April of 1924 to Delft, Holland, to participate in the International Congress on Applied Mechanics. There he presented his theory of consolidation, with experimental results, quantifying the time rate of compression of saturated clays.[18] The great and famous were there—von Karman, von Mises, Southwell, Prandtl, Griffith—and they applauded his accomplishment. Prandtl, who reminded Terzaghi of Prof. Wittenbauer, told him: "Your lecture, Herr Colleague, was marvelous; extraordinary simplicity and clarity of the basic ideas. It pleases me that it was in Delft that the entirely new concept of the physics of clays was expressed."[19]

He had read, in October of 1920, about the work of a committee of the American Society of Civil Engineers (ASCE) concerned with the physical properties of foundations and techniques for their measurement. At the time this frightened him, consumed him, and the idea that he would be upstaged before publishing his enormous work "followed me night and day". He immediately sent a detailed letter to the committee chairman, Allen Hazen, explaining what he had done and hoping for some sign of recognition. He felt that his future depended on this letter, but, despite an unhelpful reply from Hazen, he and his work survived.[20] Now at Delft he learned more about the work of this committee as well as a parallel activity in Sweden—a geotechnical commission formed to solve problems of landslides along the Swedish State Railways, where one landslide alone had taken 41 lives.

Through discussions at the conference and continuing correspondence thereafter, he informed himself fully about the activities of these two working groups. He discovered that neither had accomplished much more with respect to physical properties of soils than their mere description. He felt lucky to have discovered these formal committee activities when he was already well along in his own research for "at the initial stage I would not have dared to take a part in this competition with those who had all technical means at their disposal while I myself had to work without help and with the refuse from a locksmith's shop."

"Subsequently it was easy to see that all the advantages were on my side." He had come to the subject through his personal experience in construction, and he was not constrained by someone else's proposals. "I had nobody to blame for the arduous work but myself ... under the blessings of freedom. I was compelled by the scarcity of available means to view experiments merely as a means to aid intense mental effort." He had proceeded from working hypotheses, to tests designed to affirm or deny them, and on to final experiments planned specifically to help work out a comprehensive theory.[21]

As if writing the book that summarized all his research achievements (not to mention simultaneously teaching and public speaking) were not enough, Terzaghi continued to engage in considerable consulting at this time. He had his Belgian clients and a new one, Azaria Company, for whom he was working on plant and mill foundations on the shores of "The Golden Horn", in the Constantinople area. The foundation problems were horrible; Azaria's grain mill site was nothing more than a thin bed of rock fill floating on the surface of a bed of "liquid mud" that was eight to ten meters thick. The water content of the mud was above Atterberg's liquid limit, meaning it was essentially in a liquid state in the ground and could support only a minuscule pressure—0.05 kilograms per square centimeter.

He convinced the owners that the planning already started would lead to catastrophic failure and insisted on stringent modifications. There were no sheet piles that could take the lateral thrust needed to hold the mud in place under surface loads. The permeability was so low that it will almost never strengthen by itself. The owners had to rearrange the building layout to achieve virtually uniform pressure and keep all structures away from the edge of the property, where the mud is even weaker. Piles would have had only illusory benefit unless they reach at least 24 meters in length, and then each cannot be expected to hold more than about seven tons. He told them that if they go against these recommendations, they go against nature.

Because many structures function safely along the shore of the Golden Horn, some on primitive foundations, he was anxious to determine why this site was so inferior. His sleuthing revealed that the particular site was not located atop the actual ancient sea bottom, but overlies a mud that had been deposited only recently (geologically speaking) in a bay created in Byzantine times. The bay was caused by Byzantine fills out into the sea, and the soft deposits were subsequently filled over by man.

He completed the *Erdbaumechanik* manuscript in April of 1924, and, as soon as early copies became available, he sent them to his friends in Austria and America. Then he waited for a tumultuous reception. It seemed, however, not to come, and he remembered his advice to Fröhlich from 1920: "He who conducts scientific work with the expectation of receiving appropriate remuneration for his efforts, or at least proper recognition, belongs not in a college but in a lunatic asylum."[22] He felt forgotten but contented himself that Spring follows Winter.

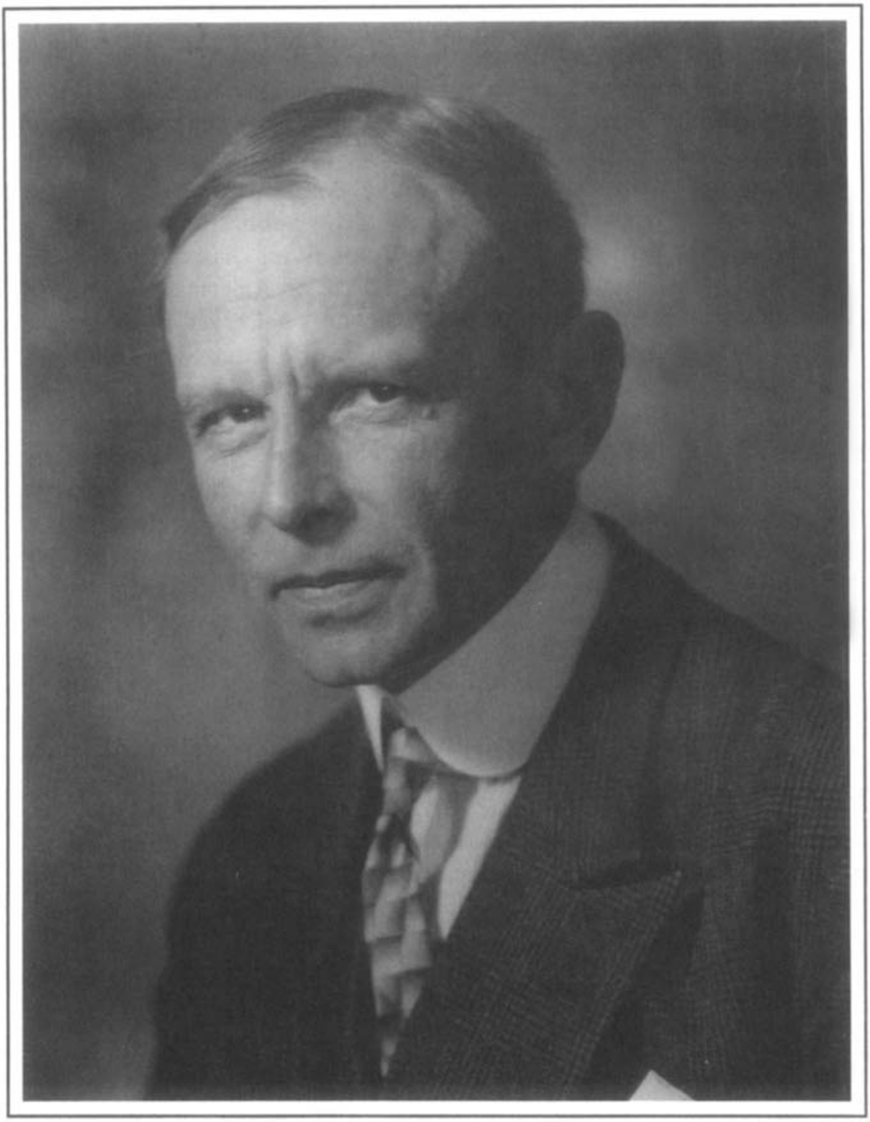
In his Foreword to *Erdbaumechanik,* Terzaghi pointed out the paradox that structural engineers would hardly think of working without a knowledge of their structural materials, whereas foundation engineers have hardly any scientific basis at all for their work, except for a few simple relations for sands. His intention was not to delve into pure theory, which had made no real mark on the subject in two hundred years, but to develop a semi-empirical science based on observed behavior. This book has no antecedent. He said it plainly. He staked his claim.

In the Introduction, he wrote that decisions in earthwork engineering have been based principally on "engineering instinct". [23] But judgment from this source dies with the individual. Engineering instinct often fails. In point of fact "the earthwork designer is today hardly better equipped with respect to the tasks of earthwork engineering than the bridge designer was with respect to the construction of bridges at the time when engineering mechanics did not yet exist as a science."

He waited impatiently for the reviews to come in. His heart sank when the post was barren day after day. Then they started to arrive: a favorable review from his friend Bruno Sander[24] and another from engineer Max Singer for the prestigious Austrian Society of Architects and Engineers.[25] Others followed from Switzerland, Czechoslovakia, and Germany—from construction, mining, and waterworks publications. When *Engineering News Record* published a glowing, leading review by noted engineer George Paaswell, entitled "A New Soil Mechanics",[26] he was so happy that he uncorked his last bottle of fine French champagne. He chalked it up as a victory with respect to the ASCE's Foundation Committee.[27] Paaswell was highly satisfied that Terzaghi chose "to wipe the slate clean" as far as classical theories are concerned. He admitted that it contains much that is speculative and controversial. Prof. Hilgard noted Terzaghi's "exceptionally fine gift of observation."[28] Another said it deserved only the warmest greeting by engineers.[29] Two reviewers said it would become indispensable.

In the wake of the unfolding success of this publication, the American engineer John R. Freeman, unknown to Terzaghi, purchased copies of *Erdbaumechanik* and sent them to a wide circle of American engineering acquaintances, including faculty at M.I.T. where he served in an advisory capacity.[30] Dean Scipio had told Dean Potter of Purdue about Terzaghi's work, but nobody at Purdue could imagine he would fit in there. Dean Potter sent Scipio's letter on to President Stratton of M.I.T.[31] Meanwhile, from his new home at the University of Vermont, former Robert College professor Paul Dike learned of an opening at M.I.T. and, with Karl's blessing, wrote there with a strong statement of Karl Terzaghi's exceptional qualifications. Professor Charles Spofford, Head of the Department of Civil and Sanitary Engineering, then wrote a carefully worded invitation to Terzaghi on May 15, counselling that only cooperative persons, capable of working under a Head of Department, need apply.

Terzaghi had been on tenter hooks ever since receiving Dike's intelligence and thus was greatly relieved finally to get Spofford's telegram of June 27: "Twenty five hundred dollars for the academic year. Considerable free time." A pitiful offer, he thought, "nevertheless a pathway to freedom after eight years in quiet seclusion".[32] They wanted him to develop a graduate course in foundations and soil mechanics.[33] He accepted immediately and drank up one more bottle of champagne.



Karl Terzaghi, 1926.

8

Fulfillment and Recognition in America 1925–1929

In an expansive spirit, Karl set off for his return to America on July 18, 1925. He was not needed at M.I.T. until mid-September, so he organized a long itinerary, sufficient to say goodbye to the old world while exploring some more of the new.

He bid farewell to Vera (and Olga) and family in Graz, visited with Forchheimer in Vienna, and toured laboratories at Karlsruhe before an extended stay in Paris. The stately buildings and art museums, promenades, restaurants and, especially, night clubs of Paris rewarded him. He found the city pulsating with life and light. The show at the Moulin Rouge with "almost naked women, beautiful legs and perfect breasts in a background of refined harmony" whetted him for more, so, right afterwards, when a nicely dressed man asked him how to find a certain address in Montmartre, Karl suggested they search for it together. They found themselves in an elegant apartment, with marble statues and murals, whereupon a double door opened to reveal a dozen young girls, music, champagne, and an erotic theater piece in a mirrored hall, all of which cost him almost twice his daily hotel bill.[1]

Suitably reinvigorated, Karl crossed from Boulogne to New York to open a new stage in his development. If he felt any stage fright, it evaporated on his first reglimpse of New York with its "atmosphere of concentrated activity". It is the flow of happening, not remaining in one place, that grants happiness.

One of Terzaghi's goals in forsaking his hideout at Robert College was to open new engineering connections. He hit the target immediately in New

York, for awaiting him at the ASCE headquarters were George Paaswell, structural engineer for the City of New York, and Lazarus White, foundation engineer and renowned underpinning contractor.[2] Karl made a quick and enduring friendship with each of them that deepened with years.

Paaswell told Karl that in preparing his review of *Erdbaumechanik,* he had studied the book for four months, not skipping a section because it was all new. White said it would be a good investment for his company to buy out Terzaghi's book and dump it in the Hudson River because it tells too much to the competitors. They painted an optimistic picture for him: if he would publish his lectures on foundation engineering and teach at Columbia he would surely draw a crowd of a thousand. F.E. Schmitt of *Engineering News Record,* whom he met shortly afterwards, also suggested a lecture series at Columbia and told him he would be able to influence the research results of the whole country if he would settle in the U.S.A.[3] They were looking for him to lead their fight against a "wall of prejudice" that American practitioners have against invoking fundamental principles in foundation engineering.

This was the message Terzaghi dreamed of hearing. On arrival in New York, he had asked himself, "how could I establish the validity of the theory so firmly rooted in my brain under the mighty economic pressures of this economy?"[4] He now knew there were powerful men ready to back him.

"Now I have a chance to look at you," Schmitt said at dinner. I thought you to be a very young man but I see you are getting bald. You are not physically strong. Fifteen years ago you just drifted in to look around but "now you return as a mature man for the harvest."[5] You must publish, he advised, but not simply to be printed; your mission is to convince.

Together they laid out a series of articles for *Engineering News Record* that would impart some of the message of *Erdbaumechanik* tailored to the American reader. The resulting eight articles were published in November and December of 1925 and subsequently reprinted as a short book, *Principles of Soil Mechanics,* in 1926.[6] The appearance of the first in the series was accompanied by an editorial about this new "science of soil action ... of far-reaching value to the practical man".[7] An editorial accompanying the last article pronounced his work "epoch making" and called for a collective effort to carry it forward. "There is room for all the workers whose interest and desire for discovery may be awakened by the evident potentialities of the new subject."[8]

This series constituted the first comprehensive treatment of soil mechanics principles read by English-speaking engineers. Among those who reacted was Daniel Moran, a resourceful consulting engineer with limited theoretical knowledge who had developed a primitive soils laboratory in his own house.[9] Moran wrote that Terzaghi's work was "without doubt the greatest step yet made."[10] On the other hand, Prof. J.H. Griffith of Iowa State College wrote a long letter trying to defend a piece of soils history for himself and casting some clouds over the utility of Terzaghi's findings, whereupon Terzaghi replied that Griffith may have read his work too hastily.[11]

More irritating was an attack on the concept of large capillary forces existing within clays by Thaddeus Merriman, Chief Engineer of the New York City Board of Water Supply and a Director of ASCE.[12] Terzaghi was often frustrated in attempting to explain capillary forces to engineers, but this letter he found "poisonous". He replied immediately with what he termed "a masterpiece in the field of insulting engineering". When the letter appeared in print with gentle tone and educational spirit, the products of F.E. Schmitt's editing, he was disappointed, until colleagues started congratulating him on his "christian spirit". He later confessed to Schmitt: "I learned my lesson then and there."[13]

From New York, Terzaghi had visited Philadelphia and then Washington, D.C., touring the Bureau of Public Roads, Department of Agriculture, and Bureau of Standards. Thus, when he arrived finally in Boston on September 7, he had a good idea of what was going on in research and consulting work with respect to soils throughout America. There was a vast amount of undigested data from scattered energies. But at least the European-type paralysis, from the existence of an old establishment, was absent. He concocted a comprehensive plan to make M.I.T. the national center to collect and direct human energy for soil mechanics. He would plan to train men in observation and interpretation, participate in every paper and every project, install the foremost laboratory, and maintain collections of soils and soil data through continuous contact with the contracting world.

Intoxicated by this grandiose conception, he made his entree with his new employer, Professor Charles Spofford, and was summarily deflated.[14] To Terzaghi, Spofford was a man without passion, lacking initiative, with little expression in his round face and speaking in empty phrases. Terzaghi became miserably depressed, with nothing to look forward to in Cambridge and homesick for Constantinople. The weather was gloomy.

He perked up quickly, however, as the intelligentsia began to discover in him the ideal guest—fascinating, cultured, a raconteur but also a real listener, and so handsome. His public lectures on Turkey and the Near East were immensely well received—"the audience was breathless".[15] At another occasion his talk was met with "cheers, applause and very friendly glances from the younger set of ladies". He quickly became a prime find for the Cambridge elite at play. His new friends, Prof. and Mrs. Tyler, invited him to poetry readings, plays, and musical evenings, and Mrs. Tyler tried to line up prospective women friends. German Consul Baron Kurt von Tippelskirch, with noble German roots, squired him to gatherings and lectures on political philosophy, especially concerning the future of Russia. Although falling short of Terzaghi's expectation as a leader, the Spoffords proved generous hosts, and, among other places, took him to Congregationalist events, while the Tylers brought him to mystical meetings of the Theosophical Society.

There were numerous public lectures in the college and communuity, often followed by a late dinner at the University Club, the Twentieth Century Club, the Cosmos Club, or an upscale home. Karl usually managed to be seated close to the speaker and entered freely into the discussion. There were painters, poets, musicians, philosophers, political analysts, and many scientists and mathematicians. In this whirl of stimulation, he was seldom alone, always involved, and ever curious.

He was invited to weekends at country homes, to encampments at New England lakes, to seaside cottages. "One weekend in the open makes stronger ties than a dozen in the city."[16] He was taken to a Chinese restaurant "and learned to eat with two sticks". Throughout his stay at M.I.T., he was continually discovering, in unexpectable quarters, "living beings ... with creative imagination and genuine hospitality".[17] But seldom at a faculty colloquium, after escaping from one of which he wrote in his diary: "Professors, America's third sex!"

He took advantage of every opportunity to socialize with the distinguished science and engineering faculty and visitors at Harvard and M.I.T.—Lindgren, Bryan, Mather, McLaughlin, Bragg, Penck. He particularly enjoyed trips with the geologists for they shared rich gossip about distinguished geologists he knew personally as well as bits of humor like the following: A wife, speaking through a medium to reach her deceased husband, asked if he were happy. The husband: "Very happy—even more than when we were together." The wife: "Otherwise how is it in heaven?" The husband: "I'm not in heaven."

He loved the anecdote related by foundation engineer Charles Gow. A well-known engineer had protested against placing a load on sand, preferring to put it onto clay. Why? Because thirty years earlier he had placed a building on sand only to watch it settle one foot. What was beneath the sand? "I don't know."

It was the time of prohibition, and a man like Terzaghi, who so enjoyed his whisky, was well provided wherever he was, on the job or in town. This sometimes necessitated clandestine excursions to seedy districts, as for example when he shared a drink with a convivial sculptor. For this they went up some narrow steps past a barber shop, through an empty room with four dummies propped at a card table, through a soft drink salon, down a narrow corridor and finally into a "private office". Paaswell had told him, with sarcasm, that you can learn where to get whisky from the cop on the corner. He might have added, or from any engineer.

Unfortunately, the personal satisfaction he was gaining in Cambridge society was not matched by developments at the college. On their first meeting Spofford had agreed it ought to be possible to find $5,000 to support creation of some lab experiments. On looking around at possible locales and equipment to borrow, his opinion of civil engineering at M.I.T. took a dive. The facilities were "abominable".

Although he found Spofford impenetrable, in contrast President Stratton seemed to be a gentleman of action.[18] This proved to work against him for Stratton quickly took action, vetoing award of funds for a laboratory until Terzaghi could show results. This absolutely enraged Terzaghi. "Cynical ignorance. No boat until you have crossed the river." To him, the institution was hollow.

Terzaghi's persistence finally triggered a presidential invitation for a detailed proposal of support for a continuing program in soil mechanics and foundations and a detailed list of the equipment that would be needed. As part of the proposal, Terzaghi's lectureship appointment would be extended beyond the contracted one year and he would become an Associate Professor, that is, a regular member of the faculty. Despite a quick submittal of everything requested, President Stratton returned the proposal with more questions, and Spofford failed to stand up in its defense. Terzaghi laughed at M.I.T.'s reputation as a premiere institution. "An old fool of an autocratic disjunction at the head and not five yards vision in his advisors."

In the first eight months at M.I.T., without any research support from the Institute, he could hardly have been expected to produce much in the way of research. But in April, having obtained a modest grant, his productivity climbed. He developed a refined oedometer (which he called a device for measuring compressibility, swelling pressure, and permeability of clays in one test). He laid the basis for a quick method to evaluate permeability of sands in the field by simply recording the rate at which capillary moisture would move visibly through the pores. He measured physical behavior of sand/mica mixtures. He was most proud of experiments in collaboration with chemical engineering professor Lewis concerning the swelling of a pure colloidal substance—gelatin—as a model for clay; he had theorized that clay swelling and shrinkage were essentially elastic deformations caused by clay's affinity for water, and this was a new, competing idea in physical chemistry.

In this short time his publication record was already prolific. In addition to the eight *Engineering News Record* articles, he had made an indelibly strong mark on the Boston Society of Civil Engineers with a talk and paper on how his fundamental analysis of soil physics immediately benefited the foundation engineer. Colored with experience from the Azaria consultation in Constantinople, this struck home, and earned him a prize from the Society.[19] After this lecture, Allen Hazen congratulated Spofford for having secured the services of such an expert. Paaswell and White came up from New York to hear it, White saying he would not hesitate to go all the way to Constantinople to hear the Doctor. In discussion he was called to set forth a blueprint for the quick development of soil mechanics in engineering practice; Terzaghi returned to the podium and did just that, to the awe of the large audience.

Soon afterwards his work on gelatin was presented to the National Symposium on Colloid Chemistry and published in its proceedings.[20] Inquiries of various kinds were now arriving from as far away as Shanghai and Russia. On January 20, 1927, he presented a paper entitled "The Science of foundations—its present and future" to the ASCE Structural Division in New York, whose publication earned him the high honor of the Norman Medal.[21] In inviting discussion from his friend, engineer Arthur Shaw of New Orleans, Terzaghi wrote: "The paper should merely serve the purpose of opening the outlet gates." It certainly achieved that, with printed discussions by nineteen engineers, filling 136 pages of the society's Transactions.

Terzaghi's correspondence with Arthur Shaw also opened an outlet to his feelings about the place of theory in civil engineering.[22] "Theory—and even very rigorous theory—is required for training and developing our capacity for correctly interpreting what we observe; but, at the same time, with theory alone we could not accomplish anything at all in the field of earth work engineering, and the more plain facts we can accumulate, the better. I always lose my temper with people who think they have grasped the very core of the substance after they have succeeded in representing some artificially simplified phase of it by means of complicated triple integrals; while, at the same time, they have forgotten how the soil really looks. Keen observation is at least as necessary as penetrating analysis, and, since you obviously have this rare gift, anything you could tell would be of value. Most of the engineers I know are incurably blind."[23]

Despite Terzaghi's notable successes in advancing the practice of civil engineering, M.I.T. seemed incapable of understanding his success and unwilling to invest in him. This corroded his thoughts, evoking, as usual, self-analysis. He took it out on his diary. "Remember", he wrote, "every pioneer work has been accomplished in spite of resistance.... Work and don't despair! Fight and suffering is the human lot. Nothing to be envied in those who cowardly back out, to occupy the easy chairs at the price of their souls. Don't forget that each new idea is a public offense!"[24]

But what he perceived as paralysis in high places continued to eat away at him. To save himself, he stiffened his resolve and found a *modus vivendi*. There is no use in plotting revenge. "Disregard what is ugly or undesirable—don't look at the smokestack."[25]

The free expression of wrath penned in Terzaghi's diary allowed great restraint and patience with his tongue. This paid off. For, in a convivial meeting, President Stratton offered to allow Terzaghi to present his proposal to the M.I.T. advisory committee of prominent engineers including John R. Freeman.[26] After circulating copies of *Erdbaumechanik* at his own expense, the energetic benefactor Freeman had just presented $25,000 to the Boston Society of Civil Engineers with the suggestion that they use some of it to translate Terzaghi's book into English.[27] By April, Terzaghi received authorization for some purchases. And this greatly changed his whole outlook.

Moreover, various consulting jobs had started to flow to him from firms associated with M.I.T. advisory committee members Knowles and Modjeski, as well as from Spofford's Boston company, Fay, Spofford & Thorndike. The City of Cleveland sought his help on the design of pavements and road subsoils, and the State of New Hampshire asked his advice on dam construction materials. He obtained a public service assignment to advise concerning foundation settlement for new buildings at M.I.T., which provided a laboratory assistant and a very modest budget for lab operations. And he succeeded, through his appointment as research advisor to the Bureau of Public Roads in Washington, to obtain the services of his own research assistant at full government salary. This position was extended to a shy, 24-year-old Austrian engineer named Arthur Casagrande.

Casagrande, whose roots like Terzaghi were in the Italian part of the Austria-Hungary empire, had sought opportunity in the United States only to end up as a steel detailer and draftsman for Carnegie Steel in New Jersey. On a visit to M.I.T. to apply for a position in hydraulic engineering, he met Terzaghi by chance in Dr. Spofford's office, and the two countrymen were introduced. When the conversation switched to German, and Casagrande figured out to whom he was speaking, he felt lucky because, he confessed, he had been reading *Erdbaumechanik* and had some questions.[28]

Terzaghi had just agreed to guide foundation studies for a bridge across the Mississippi at New Orleans. The site was underlain by very loose sand, with various options for bearing horizons among the lower soil layers; the selection of the final foundation elevation and its design would hopefully show off Terzaghi's scientific approach, premised on the measured physical properties of subsurface samples. Terzaghi arranged for the core samples to be tested under his direction at the Bureau of Public Roads Laboratory in Washington, since he would be spending most of the summer there.

He offered Casagrande the job to conduct these tests as his assistant, earning in the process the opportunity to learn Terzaghi's methods and those of the Bureau of Public Roads, and $40 a week for four to six weeks. While awaiting completion of the test apparatus and arrival of samples from New Orleans, he could spend time checking Terzaghi's reinforced-concrete design for the foundation of a pumping facility in Lynn, Mass.[29]

Arthur Casagrande became Karl's frequent companion in Washington. Together they walked the monuments, parks, and gardens and talked of life in Austria, music, art, the Vienna Technische Hochschule, and common acquaintances. Arthur had been a violin prodigy as a child and loved classical music.[30] He went on to study hydraulics with Karl's friend Professor Fritz Schaffernak in Vienna. Terzaghi greatly enjoyed Arthur's company, finding him a good observer who reminded him of home. He offered fatherly advice and took an interest in his future, finally deciding to recommend that the Bureau of Public Roads send Arthur to M.I.T. as his research assistant, to begin in November, 1926. Their research would attempt to develop an engineering classification of soils.

As Terzaghi came to know and appreciate Arthur Casagrande, he found him to be an indefatigable and brilliant worker with very high standards. But he was shy and stubbornly silent in front of strangers, unable to adapt himself to American ways. He tended to be highly pessimistic and unenthusiastic. Arthur felt his courage and self-confidence buoyed by the nearness of Karl and was very grateful to him. "Whatever I am and become, I owe to you," he later told Karl when their four years together in America approached its end.[31]

Casagrande had a coworker in the laboratory, Terzaghi's doctoral student, Glennon Gilboy. Gilboy worked initially on properties of sand with varying amounts of mica, and then settled down on the problem posed by hydraulic fill. An embankment could be constructed by sluicing sediment that was transported to the construction site through a hydraulic pipeline. The impervious central core of the dam would be made by creating a quiet pond in which silt and clay particles would gradually settle out. But how fast would such a core densify and build up strength? Would it remain semi-liquid for a long time and therefore leave the embankment in an unstable condition; or might it dry and crack, damaging its function as the impervious center of the dam? This critically important evaluation could be addressed with the new theory of consolidation. Terzaghi therefore eagerly grasped the opportunity to obtain and test undisturbed samples from a shaft driven through the core of Germantown Dam in Ohio. Gilboy ultimately made this work into a doctoral dissertation.[32] All of Terzaghi's initiatives in research at M.I.T. and the driving force behind his teaching sprang from real needs of the engineers constructing roads, dams, and buildings.

The students must have been inspired by this dynamic, well-connected professor, but at first some were quite lost by his theory and complained. Spofford then recruited Alberto Ortenblad, a Brazillian student with a mathematical background, to attend his class and report back regularly. Ortenblad was quickly unmasked and confronted by Terzaghi, whereupon he confessed not only that he was a spy, but that he had thoroughly enjoyed the lectures. He subsequently adopted a problem in consolidation theory for his doctoral dissertation.[33]

Terzaghi was conversant with the needs of the profession from his rapidly enlarging experience as an engineering consultant. Fortunately, the teaching load was relatively light—courses in soil mechanics and in foundations in the first year, and subsequently another in engineering geology. Although these courses were well attended (fifteen to thirty students), conditions were sufficiently flexible to permit adapting class meetings to his consulting itinerary.

The preponderance of his consulting work was related to dams and dikes on sand and gravel foundations. In almost every case he was able to recognize and use the geological history of the site to find an optimum engineering solution, which he crafted by meticulous attention to design details as the subsurface became exposed during construction. Schmitt had expressed pleasure in Karl's willingness to modify his editorial opinions. But such flexibility was absent on construction jobs if he believed he had seen what others had missed. One engineer complained: "Doctor, you're a hard man to convince."

The site of Granville Dam near Westfield, Mass., presented a real question of feasibility. The subsoil was an almost continuous sea of highly pervious sands and gravels. Would it even be possible to build a reservoir here? The engineering geology report by W.O. Crosby had said it would not. Terzaghi showed that the sands and gravels had been deposited in an ancient glacial delta. He argued for digging 35 test pits, from which he ran 96 permeability tests, and, using these results with his geological stratigraphy, he worked out the variation of permeability throughout the site. This yielded calculations that showed the situation was probably tolerable but that some of the reservoir might have to be lined; however, the decision to line could await the first reservoir filling.

In doing this Terzaghi exposed a philosophy of site investigation that stood by him for the rest of his career. "Due to the absence in nature of perfectly uniform soil deposits, no reliable forecast of the actual quantity of seepage loses will ever be possible. Hence the problem does not consist in computing a definite seepage quantity but in utilizing the available, inadequate evidence and the geological data for estimating the most unfavorable possibilities."[34]

The site for Chicopee Dam, Mass., also inspired a resourceful geological analysis related to potential leakage, but, in addition, he had to address real danger of piping. Terzaghi affirmed this visually, supported by analyses of the proportions of different grain sizes composing the sand ("mechanical analysis"); it was found to be principally comprised of grains in a narrow range of fine sand sizes with a complete absence of fine silt and clay. His field work quickly turned up quicksand at some natural springs, and during the construction period "sand boiling" troubled the excavation for the new outlet tower.

Not far away, four years previously, a dam with a central concrete core wall like that planned for the new structure had washed out, releasing a devastating flood.[35] Terzaghi analyzed the remains of this structure and affirmed it had failed by piping. Thereupon he guided the designers and constructors to a safe outcome.[36]

In Hartford, Conn., an industrial area along the river was to be protected from floods by a series of dikes. The immediate subsoil was a nonpervious silty sand, and at depth was a thick layer of laminated glacial clay ("varved clay"). But beneath these was a nonsilty sand that could transmit river water through the foundation of the dikes and defeat their purpose. By analyzing the time lag between high stages of the river and consequent high stages of water in wells, Terzaghi worked out the permeability of the sand and designed a method for cutting off flow with pumping wells and sheet piles.[37]

His consulting for a power dam in Michigan showed a mature geological sleuth at work in the cause of engineering.[38] His quick reconnaissance of the site negated the results of all the previous investigations. These had failed to resolve the structure and morphology of the site sufficiently to present any coherent model. He demanded and obtained new borings and, from these results and his field and library work, put together a detailed geological history and the dam's context in it. This led to the conclusion that the selected location for the structure was unacceptable because the sheet piles would have to be placed through mudstone layers that did not require them and would not be able to reach down to pervious sand layers that did. He essentially replanned and redesigned the entire project.

In 1926, M.I.T. studied building settlement in planning new structures on their campus along the floodplain of the Charles River. Terzaghi's help was sought; in fact, John R. Freeman had urged Terzaghi's appointment at M.I.T. partly because of the insight he might be able to provide on this matter. Settlement of some existing buildings had been blamed on the

Karl Terzaghi at Chicopee dam site, 1926.

compression of peat and compressible silty fill beneath them. The engineering geologist, William O. Crosby, had specifically ruled out any explanation involving a known deeper layer of blue clay, because that layer was stiff.[39]

Although lamenting the fact that M.I.T. had provided funds to build only one consolidometer, Terzaghi showed that the blue clay held considerable excess water due to incomplete consolidation. While the clay had such a low permeability that the rate of consolidation settlement would be tolerably slow, its high water content made it very soft, allowing it to flow plastically from under a foundation at constant water content; this mechanism could not be stopped by driving piles. In view of the very slow rate at which the clay would stiffen as the excess pore pressure gradually drained, he suggested simply designing new buildings to accept considerable differential settlement.[40]

In 1927, Terzaghi consulted on the foundations of the Bank of Commerce Building in Houston and argued against using piles, protesting they could have no benefit. Raymond Concrete Pile Co. argued that piles would densify the subsoil by compacting it. But the pile driving to date, explained Terzaghi, had caused the ground between piles to heave upwards eighteen inches. This occurred, he maintained, because the soil resisted any change in its moisture content; therefore, it would not become denser.

Subsequently, he wrote a beautifully clear exposition of the causes of building settlements for a law suit concerning a building in Detroit.[41] In this report he instructed how to distinguish between settlement due to gradual drainage of pore water in clays ("consolidation settlement") from that due to displacement of the walls of foundation excavations ("lost ground" settlement). This was a clear case of lost ground settlement, he argued, and the culprit was the shortcomings of the site investigation.

In February, 1928, Terzaghi received an invitation from the research director of United Fruit Company to visit Central America. They thought he might be able to advise on irrigation of banana plantations, and on how soil permeability influences selection of forest land for clearing. Such a trip seemed to Karl like an escalation of life's adventure into a completely new region. So in June he took a steamer to the Panama Canal and on to Costa Rica, where he studied soil movement problems affecting their coastal railway. He toured extensively, finding parallels in the poverty and living style of peasants with those in Hungary and Roumania.

A foolhardy side trip was made by horseback in the rainy season, against all advice, to the summit of Poas volcano. He stayed "overnight" in a grocer's mud hut in San Pedro and at 1:00 a.m. started up the difficult trail, abandoning the horses only at the crater rim. "At the bottom of the huge depression, steam jets rushed out with noise like a huge factory. The wind blew the smoke to and fro, occasionally exposing a small quiet elliptical lake of deep green colour.... Intense smell of hydrogen sulfide." Instead of departing they climbed 100 meters down the very steep slope into the crater, finally giving it up on account of the increasingly noxious smell. An intense rainstorm that turned the trail into deep mud accompanied the party home, where they arrived feeling heroic but exhausted.[42]

Returning to Panama to study the great landslides in the notorious shale along the canal, he was invited on a new adventure: to accompany a small geological expedition up the Chagres River to a new dam site in jungle karst.[43] Sightings of snakes and alligators triggered the most hair-raising stories from his travel mates, and made the overturning of his dugout canoe all the more memorable.

In Honduras and Guatemala, the fearless adventurist went on his own to study how clay formations and volcanic strata control the regional distribution and flow of groundwater. His field travels took him all the way to the border of Mexico, partly on muleback, where his wanderings were cut short by intense amoebic disorder. It took a month in the United Fruit Company Hospital in Quiriga, Guatemala, before he could manage the long trip home to Cambridge.

In the mountain of mail that awaited his almost four-month absence was an opportunity to become director of the test facility for waterworks and ship construction in Berlin, and an invitation to the World Engineering Congress in Tokyo. In December, he went to Chicago to discuss the Gray's Island pulp and paper mill in the state of Washington, which was experiencing colossal and unexpected settlement. His comprehensive report four months later, the first of many he would eventually produce for Simons Engineering, forecast the rate and amount of future settlement almost exactly.[44]

In that same Fall of 1928, Terzaghi was called by New England Power Co. to advise on the design of a long retaining wall, up to 180 feet high, that was to function as part of Fifteen Mile Falls Dam on the Connecticut River. This structure, to stand astride the Vermont/New Hampshire border, presented a tough problem for the designers. The Vermont side was underlain by good rock but the New Hampshire side by an ancient valley cut 40 feet into the bedrock surface and subsequently filled by pervious, glacial outwash sands and gravels.[45] Thus the Vermont part of the dam could be a conventional concrete weir on rock but the New Hampshire side would have to be an earth embankment.

The owners thought to construct a wall to divide the two dissimilar parts. But they quickly found that the design of a wall completely across a dam, in order to form a steep side to a complete earth dam section, is a very complicated affair, perhaps beyond the state of the art in 1928. Since the earth dam needs to have flat side slopes whereas the concrete structure has very steep or even vertical slopes, the earth dam is far wider than the concrete one. So the wall that separates them acts, for most of its length, as a free-standing retaining wall, but one that is under enormous potential load due to the weight of wet soil behind it. The loads on the wall depend partly on the pressure of the water filling the pores of the soil, and this varies dramatically and continuously over the wall's length. For Fifteen Mile Falls, it was easy to show that a conservatively designed wall would be unaffordable, while one that was too skimpy might cause failure of the dam. They called in "the Doctor".

Dr. Terzaghi proposed large-scale soil-loading tests, to refine knowledge of earth pressure under the conditions to be faced. He wanted to know precisely not only the magnitude of the forces exerted by the soil on the wall but their location and orientation. He asked for $16,000 to build a 37-cubic-meter, reinforced-concrete earth-pressure testing chamber at M.I.T. and a special building to house it, which required 75 piles to support its weight; the project eventually suffered an almost triple cost overrun, but the potential savings were far greater. A 120-ton sample was taken from the site and shipped the 200 kilometers to the campus. Terzaghi assembled a research team with Arthur Casagrande, Glennon Gilboy, and later Donald Taylor, and in mid-May the experiments began, to continue for five months.

This was a chance for Terzaghi to confirm his earth-pressure work of 1917 with the finest modern facility in the world. But it was not thrilling to him at the time; he preferred discovery to development and, though pacesetting, this venture was essentially an engineering development—intellectually anticlimactic. It would also create a mountain of work at a very busy time. Nevertheless, he was proud when Spofford told him he believed it to be "probably the most outstanding test ever made in the field of civil engineering" and then told Paaswell that Terzaghi was a real scientist, never fixed by preconceived notions.[46]

The research with the earth-pressure test bin at M.I.T. permitted Terzaghi to design a daringly narrow wall that efficiently served its purpose. It saved the owners a bundle of money.

These long hours with his research staff and construction men were exhausting but wonderful for Karl. He loved to become acquainted with people, lingering over dinner or relaxing in transit. After entering their physical descriptions in his diary, he would record his gleanings about their roots and life experiences. He enjoyed bonding with rough men of the contractor's world. But although he lived essentially in a man's world and was surely as fearless and self-reliant as the toughest, Karl had another dimension that set him apart—a soft, sensitive interest in paintings, literature, flowers, ceramics, music, and especially nature. These were best enjoyed in the company of women.

As a result, and because he continued to be very appealing to women, he seemed to find great amounts of time for being in their company; so much so in fact that he confessed and complained to himself that "the most insignifcant female if well shaped and physically attractive has the power to disrupt and even overshadow true impressions produced by facing new and beautiful or deep phenomena."[47] He wanted to exile sex but was powerless to do so.

He needed the company of women to feel a whole person. They reciprocated platonically and, not a few, romantically. Several seemed to throw themselves at him. First, there was his young secretary, then Lilly, a real love and sharer and almost a wife. But that would be impossible, after the pain and cost of Olga. Miss X. was a sheer adventure, and Rosalie, a writer who was clearly the aggressor, offered a more intellectual adventure that yielded original poetry. Mrs. B., a bossy Russian wife with no compulsions, put a strong arm on him and dragged him off to the Wellesley Woods at night; when Arthur Casagrande received the confidence of an account of this woman's advances, he told Karl a female like that would make him feel impotent.

But Ruth Doggett was clearly different. He was knocked over by her and torn by the most severe personal dilemna. She was a doctoral student in geology at Harvard. Fittingly they met on a geology field trip in October, 1928. She subsequently sought his professorial advice about the steep slopes of coral reefs. Soon she became "Rufus" and within short his principal preoccupation, with penetrating eyes and a supple face, tender, a listener, very clever—he had never met any woman who was so stimulating to talk with and so restful to be with. The Tylers told him he should marry, which he thought to be out of the question. A lecture he'd heard at Robert College in 1922 had shown how perfectly impossible marriage was for a man like him. But he declared Ruth "the only type I could live with. A girl honestly and strenuously striving to build a world of her own, discriminating between argument and prejudice and wholeheartedly rejecting the prejudices. A wild little stray bird that settled on my window sill."

With European offers beginning to open up for him, and increasing irritation with M.I.T. tending to drive him away, the dilemma of "Rufus" made Karl's life choices even harder. Should he settle down with M.I.T.'s expected offer of full professorship or move on?

He had more or less come to an accommodation with Professor Spofford and had long ago decided against returning to Robert College. "I love that place as I love the places where I have spent my childhood ... I lived alone in a wonderfully animated world whose existence nobody else perceived", his best friends being "the tanks, levers, and scales in my little laboratory."[48] However, New England possesses almost equivalent natural beauty, not at the world's end but in the mainstream of western civilization. His life in Boston has constituted "fulfillment after extended preparation in the desert."[49]

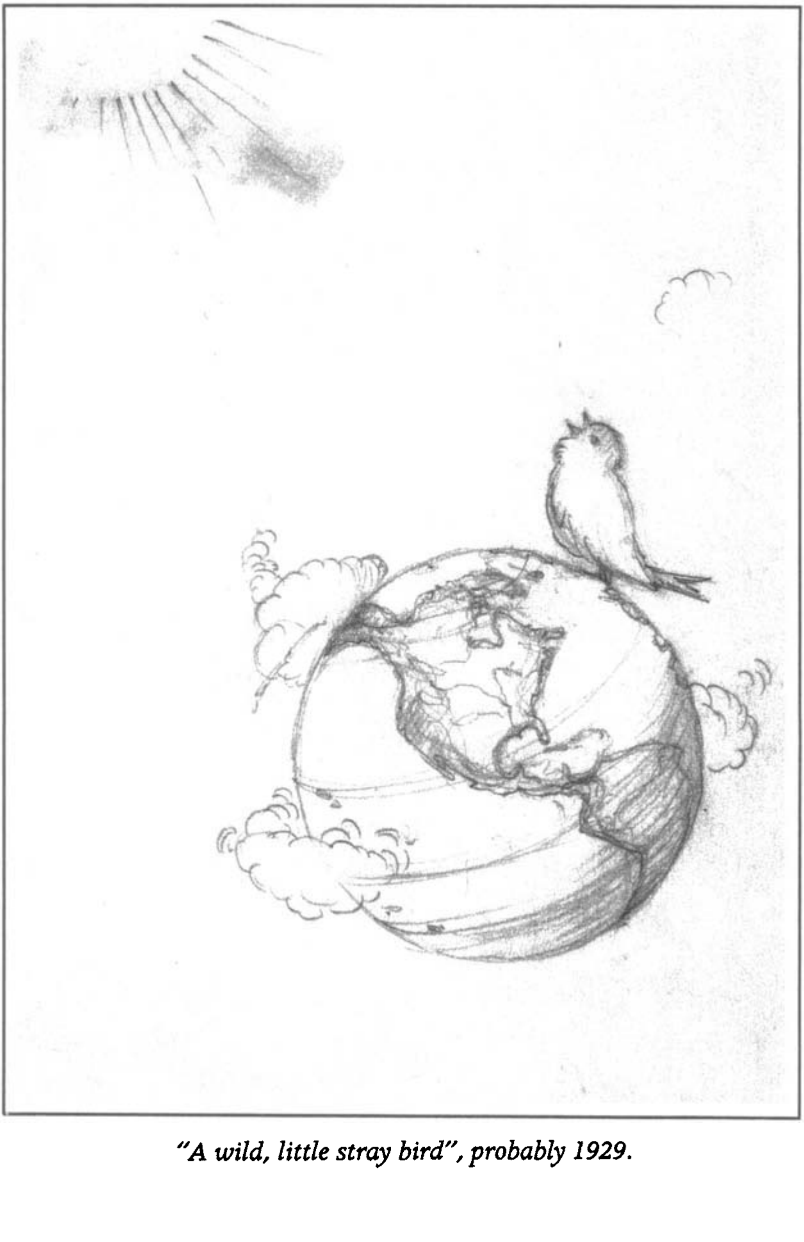
In March of 1928, Prof. Schaffernak wrote to ask if Karl was willing to accept a Chair at the Vienna Technische Hochshule.[50] He really had his gaze fixed on Germany, but thought Vienna could be an acceptable intermediate stop.[51] Although not poor, Terzaghi felt himself inadequately paid by M.I.T. and knew that Vienna would be far more generous. From Professor Harald Westergaard,[52] he learned that the great Russian mechanics professor Timoshenko had asked the University of Illinois for $12,000 only to end up at the University of Michigan for $6,000. It irked him that America so undervalued the intellect of universities and condemned its best minds to poverty. Six thousand dollars may seem a goodly income for 1928, but Terzaghi computed he should have at least $10,000 for a "tolerably comfortable existence."[53] In fact, through his consulting, he was earning at the rate of more than $23,000 by 1929. "I give five times more than I take and earn five times more than I need."[54]

Terzaghi's active consulting was bringing prestige and a bright future to M.I.T., but not everybody saw it that way. In particular, his consulting practice had made an enemy of the "idiotic president". President Stratton wanted him to forsake consulting fees and was spreading rumors that Terzaghi had taken a huge fee for the retaining wall experiments. John R. Freeman also worried that Terzaghi was too commercial.

So, when Shaffernak finally confirmed all in readiness for his appointment at Vienna, Terzaghi's vacillation reached a zenith. It would be wrong to accept. Europe was a corpse, and the universities were notorious for bickering and feuding. Spofford had offered him a title as Research Professor, and he was assured time to travel as far as Russia if he wanted. But Vienna would provide him with six paid research and teaching assistants, while M.I.T. was considering possibly giving him two. There would be many new contacts in Europe, and he could maintain the new ties to America through Casagrande and Gilboy. He finally decided for Europe, told Spofford, and then went to a swinging party with Ruth on a launch in the Boston harbor; when he returned home he cried.

It is surprising to think of a great engineer who freely offered rational decisions to his clients suffering so over his own decisions in life. The big perplexity in his equation was Ruth. How could he possibly leave her? He decided to cancel his summer plans for work with the Panama Canal Commission in favor of a vacation with Ruth in Maine. They canoed, he sketched, and worked, and loved as he had never in his life. When the time came to depart, they spoke of marriage but did nothing about it. Give it a year, he thought, and if I can't stand it I'll act.

And then he was off in triumph and tears to the top of the academic world in Vienna, a new Austrian hero returning from his conquest abroad.



"A wild, little stray bird", probably 1929.

9
At the Academic Pinnacle in Austria 1929–1935

On leaving America, Karl was treated with reverence by his New York friends. At dinner he spoke of the extraordinary open-mindedness he had seen in America and noted with pride that a large contingent of engineering progressives—in Washington, Boston, Pittsburgh, Providence, New York, San Francisco, and elsewhere—were now promoting scientific methods in earth construction. He accepted his friends' assertion that his acts and deeds had catalyzed this transformation. But he now appreciated that his effort, perhaps his whole thesis, was incomplete.

In a lecture to the American Institute of Mining and Metallurgical Engineering, in February, 1929, Terzaghi had cast a long shadow over excessive reliance on scientific investigations of a foundation site.[1] He wrote that "minor geological details", such as the precise location of water-conducting joints beneath a dam, are likely to escape even a systematic and thorough subsurface exploration. This was also true of subtle lateral variations in permeability within an apparently homogeneous alluvial deposit. Yet the presence or absence of particular arrangements of such features can cause life and death differences between foundation sites.

Engineers are overconfident, he concluded. They tend to believe that identically appearing sites should be able to receive carbon-copy structures. But one structure may succeed while its identical copy fails, a postulate that he supported with actual case examples. Recognition of this simple irony stayed with Terzaghi throughout his lifetime and called from him an artist's attention to the geological details actually exposed during the construction stage. On this basis, the elucidation of a scientific theory of soil exploration and soil mechanics could never be a sufficient basis for design and construction. His work would never be finished.

It was, nonetheless, a very satisfied and optimistic Karl Terzaghi who sailed from Brooklyn on October 4 (just three weeks before the collapse of the New York Stock Exchange). On board the SS *Bremen* as his sailing mate was Arthur Casagrande, who had accepted the commission to mastermind the setup of a new soil mechanics laboratory at the Vienna Technische Hochschule. As part of their bid, Professor Schaffernak and colleagues acquired funds and space to initiate a soils laboratory under Terzaghi's direction. With Casagrande's planning, enriched by a study tour of relevant research facilities in Sweden and Germany, this laboratory would prove to be a model for followers.

On arrival in Bremen, the two men took refuge from stormy weather, with a bottle of Liebfraumilch, in the Rathskeller. The colorful wall paintings depicted devilish Falstaffian mischief. To Karl, the crowds of drinkers seemed curiously closer to Falstaff's time than to the present. The great cathedral in medieval Bremen completed his return to "dear, old Europe". What America lacked was the fourth dimension—historical perspective—"the bridge which connects the past with the future." Without this bridge, life in America shoots by with great speed and without conspicuous landmarks.[2]

Rather than heading together for Vienna, Karl left his luggage in Arthur's care and began a trip through Hamburg and Berlin, on to Moscow, to consult with the Soviet authorities on the construction of a lock along the Don-Volga canal. The project was, no doubt, of considerable interest, because its route traversed soils that tended either to slide ("loess" soils) or expand (stiff clay) when moistened, or to readily conduct ground water, threatening gross leakage from a canal. But even more tempting was the chance to revisit Russia—the land that had once offered him the opportunity to lead as a young and dynamic individualist but which had subsequently frightened, and perplexed him with the rise of Bolshevism. He could not refuse this chance to examine the Bolshevist phenomenon first-hand.

After resuming his friendship with Von Mises in the professor's magnificent Berlin home, Karl was met by the finance attaché of the Soviet Embassy for a night flight to Riga, Latvia, about which Terzaghi wrote, the "nocturnal flight through space [was] the most perfect physical image of the creative efforts of our spirit." After a refueling stop in Königsberg they flew into a fierce storm. "The pilot reduced the elevation to hardly more than two hundred feet and the machine went up and down, as if all the laws of aerodynamics had lost their validity. The physiological effect of these violent movements on the passengers was ghostly. Within a short time, their stomachs were entirely empty. An Englishman suffered a heart attack and looked as if he was going to die. My Soviet companion, pale like a corpse, sweat flowing down from his forehead, started to undress, because he could not bear any external pressure. He thought he is suffocating. I myself remained unaffected merely on account of the enthusiasm I derived from observing the skillful maneuvering of the pilot. It was a real treat to watch him handling the desperate situation."[3]

This stoical, curious, and passionately adventurous Karl Terzaghi now applied his intellect towards trying to understand the causes, methods, and aims of the communist experiment. Its grip was immediately evident from the grayness of once sparkling Riga, and the news that his former employer, Lorentzen, had been jailed. At the railway station across the Russian border the crowd "seemed to have escaped from Gorky's night asylum".[4] Almost every railway station was crowded with peasants and beggars and women with babies, the faces haggard, no hats, no white collars, the dresses mostly torn and dirty. It was as if the population was in the grip of a state of unrest, possessed by an urge to move."

He learned that the country was in the control of the Communist party, numbering 1 million of a total population of 150 million, and composed principally of laborers and peasants; it demanded "unconditional obedience and obligatory poverty". To Terzaghi, the party had the characteristics of a religious sect, but its rules were enforced by intimate espionage and public denunciation. The original Communist plan of equal rights and compensation to all had been abandoned, as a failure, in favor of a program of state capitalism.

Russia's five-year plan of development, which reminded Terzaghi of the U.S. Reclamation Act of Theodore Roosevelt, called for unprecedented rapid industrialization and modernization to make Russia economically independent. Terzaghi thought his invitation to consult on the Don-Volga canal was but a pretext to lure him inside Russia in order to gain his help with main features of the five-year plan. The work was being prosecuted at the expense of the general welfare, under the defense that the country is waging a kind of war in order to create values.

Russian professionals and proletarians, he discerned, were in a paradoxical relationship. The professional was nominally in charge but could be pulled down without a hearing by the innuendoes of the laborers; likewise, the professor could be dismissed by the charges of students regardless of his scientific standing. The young were imbibed with the principle that financial wealth and individualism were both disgraceful. Peasants were being put to death by firing squads merely for defending the practices of individualistic farm operation.

Russia was conducting the absurd biological experiment, he observed, of forcing proletarian rule in a land where proletarians are a small minority of the populace. Thus, they sought to ruthlessly transform the population. They conduct an enormous engineering experiment "with a nation which has great gifts for pure theory, but probably less talent for practical engineering than any other nation on earth."

Terzaghi noted that every great revolution has started by overwhelming internal resistance to achieve a broader point of view. Maybe these poor devils are paying the bill for a future happiness, creating "new currents of history while we are merely dragged along by the existing ones.... Russia in 1929 lives in a state of war, as real and as bloody as our war of 1914. Hence we are not entitled to apply to our present state of Russia our standards of peace." In capitalistic countries, the industrialization created enormous wealth for a few industrial pirates. We, the arrogant foreigners, are living on the backs of those who suffered in previous generations.

"The capitalistic system means continuous economic warfare of everybody against everybody within the state and struggle for new markets outside the boundaries. The laborers are the soldiers. If their general is defeated, the soldiers have to suffer. To make sure of the sale of the products, the desire for buying the goods must be produced artificially by mass-suggestion through the channel of propaganda and advertisement. The consumer *must* be talked into buying, regardless of whether or not he is apt to derive a real benefit from the merchandise. As a result, we face the queer spectacle of vast populations spending most of their time in consuming the goods and the pleasures they buy. They *must* do it because this frenzied activity represents the very foundation of American prosperity." This leads to loss of capacity to use free time constructively. Happiness is possible only through consumerism, purchased "at the expense of their own creative capacities." This is called *raising the standard of living,*and competition in its pursuit leads to warfare with other countries.

With this remarkable analysis, Terzaghi could perceive state capitalism in a less unattractive light. Lowering the efficiency of all the production processes of the whole world puts more people to work, and there would be less production of unnecessary goods. Accordingly, the quality of life would rise in a real sense. The conflict for foreign markets would be suppressed, and there would be, in consequence, fewer wars. "Our attitude towards these problems is based on the assumption that high-grade efficiency and a continuous increase of the quantity of production is the *only one* desirable state of affairs. This assumption may be erroneous. And the cost is high—wars, periodic unemployment, and "degeneration of the creative capacities of the average individuals."

These events in Russia were abhorrent to Terzaghi; he was no apologist. But he thought that they might be understandable as happenings in a state of war. "If the enemy is confined to a territory beyond a barbed wire obstacle, it is easier to conduct a war with a semblance of decency than in case the enemy is scattered throughout one's own country." Waging war on one's own citizens in defense of a beneficial platform would be anathema to almost any true-blooded American but not necessarily to a free-thinking central European like Karl Terzaghi.

Karl eventually saw that this enormous experiment in Russia had failed. In a lecture in 1941, he commented on the stages of communism's decline into barbarism and the lesson we must learn to safeguard democracy. The initial result of any attempt to enforce an ideology, he said, leads to public indifference, inadequate commercial output, and abysmal standards of living for everyone but the ruling class. Thus the government can enforce its will only by brutality, liquidating the idealists who stand in the way. The end result is division of the nation into a small set of slave drivers and a vast set of slaves.

The best defense against this onslaught, he told the professional engineers, is in defense of our code of ethics and morals. "Nobody among us will doubt that the democracies are the legal guardians of one of the finest ethical traditions which humanity has so far evolved." But the failure of democracies fully to sustain this heritage has spawned ideological movements, as in Russia, that evolve into outright abolition of any traditional standards of decency. The most degenerate and dangerous element in society is a religious leader, supposedly a guardian of ethical tradition, who himself corrupts our ethical behavior. In contrast, the humble religious minister who lives by and teaches ethical heritage, and the laymen who will stand up in its defense, "are more beneficial in human society than an artist or a scientist with a brilliant name, because religion is wisdom and wisdom ranks higher than science and art."[5]

There was one face of Russia in 1929 that pleased Terzaghi: the willingness of his hosts to follow his recommendations for conducting large loading and field permeability tests for the Volga-Don canal design. While in Moscow, he presented lectures on soil mechanics to intensely interested audiences. He wrote to Lazarus White that "in spite of the inconveniences connected with life in Russia, they are very enthusiastic about their professional activities."[6] Terzaghi was applauding the Russians for passing a law requiring centralized soil sampling and testing, field load tests, and uniform recordkeeping on foundation performance for all Russian buildings. This was a measure he had advocated, without success, as a necessary step for improving the state of foundation engineering in the United States.

Karl finally arrived in Vienna on October 31, 1929. He was pleasantly surprised with the Vienna Technische Hochschule. He was responsible for but three lectures a week, with intelligent and motivated students and ample assistance. Moreover, his laboratory assistants had just received initial training from Arthur Casagrande. As a full professor, he was not required to maintain regular hours and was free to engage in consulting work, attend conferences, and so forth. The university proved generous in supporting his laboratory and research initiatives.

The Technische Hochschule was in a choice location, at Karlsplatz, in one of the city's attractive sections, near the opera house, state theater, and the historic city center. His fifty-square-meter office (four times larger than his office at M.I.T.), with an attractive view overlooking Ressell park, was quickly stocked with volcano-like stacks of reports and papers. The space for laboratories was ample and so convivial that Terzaghi preferred its seminar table as the place to work, and smoke, without interruption. His assigned space included a dedicated lecture theater, as well as a staffed machine shop.

Terzaghi held the Chair of "Hydraulic Engineering II" ("Lehrkanzel für Wasserbau II"). Because his predecessor, Professor R. Halter, had included foundation engineering among his lectures, Professor Schaffernak had been able to argue successfully for Terzaghi's appointment to this Chair. Terzaghi restructured the lectures to embrace foundation engineering, soil mechanics, and engineering for waterways but retained the title.[7]

Karl found the cost of living to be half of that in the United States and was able to rent and furnish a good flat nearby. He quickly settled into a delightful lifestyle, resuming his family connections in Graz, walking and skiing in familiar Alpine terrain, taking up the threads of old relationships, and cultivating a host of new ones in Vienna. The old world held, for him, a new world of professional contacts that he hastened to explore, while managing to keep one foot in the USA through his continued friendships with Arthur Casagrande, Lazarus White, and, of course, with Ruth.

Karl found the separation from Ruth to be "an extremely severe loading test of their relations" obliging him continuously to compare.[8] Despite G.B. Shaw's admonition that "love means over-estimating the qualities of one young lady to the detriment of all the others", an attempt at a new liaison with a singer, Paula, served only to intensify his surging desire for Ruth, culminating in his decision to marry. Consequently, Ruth appeared at the Cambridge City Clerk's office, at the end of March, 1930, according to Karl's plan, to obtain marriage licenses for the two of them. A newspaperman overheard the City Clerk lecturing Ruth to the effect that marriages in absentia could not be conducted on a Cambridge license and, concluding that such odd behavior from a European professor would be newsworthy, reported the event in the Boston Herald.[9] Their engagement was now public.

Undaunted, Karl appended the following postscript in his business letter of April 20 to Arthur Casagrande: "In the event that I have all the documents together in time, I have the intention to marry by proxy on May 12. I cordially request that, on the morning of that date, you call on Fraulein Ruth with a big bunch of roses and the enclosed ring, and then inform me of the event." Although this redesigned wedding was legal by Austrian law, there was yet another delay, and finally the proxy marriage arrangement was reprogrammed to shipboard while Ruth traveled to Europe. At the same time, Karl spoke the marriage vows in a civil ceremony in Graz. Each of them recited to a stand-in. Karl met his new wife in Zurich on June 7 and escorted her to Rotterdam for a honeymoon sandwiched between pile loading and pulling tests. Then they settled into their sixth-floor walkup apartment at number 2, Platz der Freiheit.[10]

Ruth became more than a wife to Karl, sharing in aspects of his work, frequent joint travel, and occasional subordinate consulting assignments. She was often to be found pursuing research of her own in his laboratory, concerning petrography of concrete and soils. In a sense, Ruth was replacing a little bit of Arthur in his life, as typist, errand-runner, organizer, etc., and a degree of perceived commiseration strengthened a bond between Arthur and Ruth, which evoked lighthearted correspondence and gift exchanges.

Arthur and Karl, meanwhile, exchanged long, informative letters with continued regularity. Karl was very fond of Arthur and highly impressed with the quality of his scientific work. He thus enjoyed continuing in the role of Arthur's confessor and protector, but exacted, in return, Arthur's obedient service as reviewer, informer, and intermediary. No wonder that, years later, Arthur chose to reprint a Terzaghi letter that praised him as a friend and a gentleman and assured him that fame would soon come his way, while in the next breath instructing him to distribute to various recipients the four enclosed envelopes.[11]

Karl thought Arthur to be the most gifted of his various disciples and was perplexed that he was so weak as to be floundering for lack of apparent recognition in the residue of the Terzaghi empire at M.I.T.. He confided to Lazarus White that "one of the first requirements to accomplish something in this world consists in maintaining one's enthusiasm and one's efficiency *in spite* of persistent lack of visible recognition."[12] Casagrande's problems were twofold: he could not satisfy his employer, the Bureau of Public Roads (BPR), and he was intensely jealous of Glennon Gilboy, Terzaghi's PhD, who had been appointed to the M.I.T. faculty in Terzaghi's footsteps.

Casagrande was continuing to pursue research at M.I.T. on classification of soils using Atterberg Limits and grain-size analysis, the structure of clay, and frost action in highway subgrades as a researcher under the employ of the BPR. They valued his work, but he couldn't seem to deliver final copies of reports and exhausted their patience in innumerable alterations. He was just too much of a perfectionist.[13] He obviously preferred designing equipment and making tests to completing reports.

Terzaghi attacked the Bureau of Public Roads for ignoring Casagrande's important results, for example, in developing an improved liquid limit measuring procedure and a vastly better hydrometer technique for grain-size determination; they preferred to retain outmoded methods, for diplomatic reasons.[14] He accused the Bureau of seeming to resent conscientious scientific work, preferring "sterile statistics" and unfounded hypothe-

A pile-load test, Rotterdam, July 1930 ses. "The motives for such resentment are obvious enough," wrote Terzaghi, "because a conscientious scientist must, by necessity, represent a disagreeable and disturbing element in a working organization. If he does his duty, he must be skeptical. He is always apt to find complications in things which appear to be simple to the others. He hardly ever considers any conclusion to be the last word about the subject and his presence troubles the atmosphere of cheerful optimism which is essential for 'pushing ahead.' Yet no steady progress can be achieved without patiently submitting to his incessant criticism.... A scientist of the type of Casagrande has the function of a fly-wheel, preventing the empirical men from shooting off on a tangent into the empty space of mere speculation."

Terzaghi thought it was time to publish a comprehensive book for the practitioner of soil mechanics and foundation engineering. But such a work would be deficient without a companion volume on soil investigations and testing. Accordingly he advised Casagrande and Gilboy to coauthor such a volume, asserting that it would propel their careers. With Terzaghi's departure, however, Gilboy found himself overwhelmed trying to carry on the range of activities expected of the heir to Terzaghi and understandably failed to begin the project. Unfortunately, when a Professor Crandall invited him to contribute ideas from the Terzaghi "school" to his developing book on pile foundations, Gilboy accepted, thinking that the book with Casagrande could be delayed somewhat pending progress by Terzaghi on his soil mechanics companion.

Arthur Casagrande, who lacked the time and temperament to write such a book on his own, reported to Terzaghi that he could receive no help from Gilboy as the latter was now committed to helping Crandall's publication project.[15] This elicited a fierce sermon from Terzaghi to Gilboy. When the terribly hurt Gilboy patiently tried to explain the full circumstances, he received a prompt letter of apology.[16] Any Gilboy-Casagrande collaboration became less likely, in any event, in September, 1932, when Arthur accepted a lectureship in soil mechanics at Harvard's School of Engineering and departed from M.I.T.

After this sad experience, it seems Terzaghi no longer tried to answer Arthur's every distress signal. When a German visitor at M.I.T. went home with privileged test data from Casagrande's laboratory and published it under his own name, Terzaghi wrote that he would confront the man and force him to publish a clarification. But when Arthur railed against Lazarus White, who as author of ASCE's foundation committee report had not cited certain Casagrande papers, Karl remained silent. And when Arthur Casagrande complained further that the same Lazarus White in a lecture at Harvard had countered some of his own recommendations on foundations, motivated only by his own selfish business interests, Terzaghi did not take up the chant against his friend.[17]

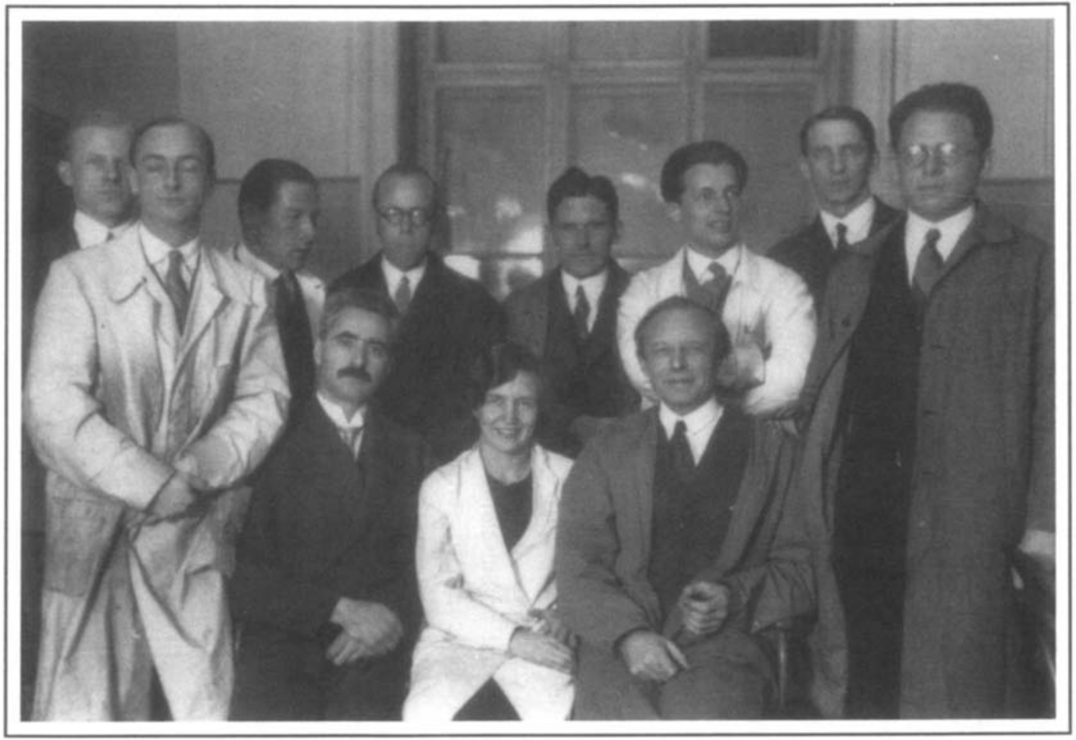
Arthur had a younger brother, Leo, also a graduate of the Technische Hochschule in Vienna and working in the field of civil engineering. In May, 1930, Leo took advantage of his brother's research position at M.I.T. to visit the United States and hired on as a research assistant in soil mechanics under Arthur's guidance. In 1932, when Arthur moved to Harvard, Karl brought Leo back to Vienna as his own assistant for soil investigations; Leo received a doctorate there in 1933 for work started at M.I.T. on seepage of water beneath earth dams.[18]

This no doubt fueled Arthur's interest in obtaining a doctorate himself, a possibility he first examined when the events of the depression started to make his future at M.I.T. appear uncertain.[19] Terzaghi was upset when Arthur lost his position with BPR as it provided a connection between academia and construction. Research in soil mechanics without such a connection, he wrote, "is as unthinkable as a medical faculty member without a clinic." He then proposed Arthur come to Vienna for a quick doctorate on the basis of work he had already completed at M.I.T., writing, "Your work has made such a favorable impression on me that with only a small effort from your pen you can satisfy the volume of statutes of the Technical University. You can thus earn the doctorate in your next visit to Europe without expenditure of time."[20]

Arthur worried about the doctoral oral examination even as he prepared to plan his travel, whereupon Terzaghi consoled him not to worry about having insufficient time to prepare. He, Karl Terzaghi, will be the chief examiner, which should lessen the ordeal. Furthermore, Fritz Schaffernak, Arthur's former professor, had promised to limit his questions to groundwater flow, a subject Arthur knows well.[21] The effort was successful and, in June, 1933, Arthur Casagrande received the Doctorate in Engineering Science for a thesis in two parts: "Investigation of the Atterberg Limits of soils" and "The Hydrometer Method".

The Casagrande brothers were two of the most notable degree recipients of Terzaghi's Vienna years, but there were many other students of stature, including Leo Rendulic, Juul Hvorslev, Wilhelm Steinbrenner, Hubert Borowicka (in structural engineering), Walter Bernatzik, and Richard Jelinek. Professor Schaffernak's son pursued his doctoral research in Terzaghi's lab.[22] Moreover, Christian Veder, Gregory Tschebotarioff, and several other distinguished engineers from abroad visited to learn Terzaghi's system for soils and foundations.

Terzaghi's broad academic reach was notably extended through a vast correspondence. Many academics and professionals wanted to hear his opinion, and von Terzaghi's Germanic diligence in answering all the queries kept him at his work table sometimes right through the night. Some, like M. Buisson, an official of the French industrial insurance company Veritas, seemed to be attempting to force from him a free correspondence course in



Ruth and Karl and the laboratory staff in Vienna, 1932; he wrote to Mama that it was "a funny little picture".

soil mechanics. As a theoretician, Buisson was fascinated by *Erdbaumechanik* and anxious to sort out his understanding of every mathematical detail, some of which he questioned. He invited Terzaghi to lecture in Paris and at various conferences, translated his works into French, and opened consulting opportunities for him, all the while absorbing knowledge of soil mechanics. As their correspondence went on and on, Buisson began to address Terzaghi as "My dear master". Ultimately, as if to serve as a graduation rite from correspondence school, M. Buisson informed Terzaghi that he was now going to collect his own contributions to soil mechanics in the form of a book. Terzaghi was not amused, writing that Buisson would surely become dissatisfied within five years in reading over the "undigested contents" of such a work.[23]

He seemed never to tire of travel, crisscrossing Europe to Holland, Scandinavia (as far as Spitzbergen), Russia, Italy, France, Germany, England (his first trip there) to lecture, attend meetings, and consult on construction projects, or just to visit. The Germans made him a member of their organization for soil mechanics research (Degebo), which he came to dislike intensely because of politics and intrigues between imperious members.[24] The Swedish consulting firm Vattenbygnaddsbyran appointed him as their soils consultant on impressive works throughout Scandinavia, the Baltic countries, and Russia, while his friendship with Italian engineer Giovanni Rodio brought him concentrated activity in North Africa.

Vatten's first urgent call to Russia asked Terzaghi to inspect the foundation for a large concrete weir under construction on the Swir River near Leningrad, between Lake Ladoga and Lake Onega.[25] The construction excavation was open when he visited the site in July, 1930, and the horizontal Devonian-aged claystones and sandy interlayers were well exposed. The foundation "rock" was seen to be fissured, and there was clear evidence of hydraulic connection between wells and the river levels. Furthermore, the underground hydrologic regime was artesian, the water flowing upwards.

He noted that the claystone beds contained interlayers of soft clay of a higher water content. The fact that the water could move vertically suggested to Terzaghi that the beds of soft clay within the upper clay unit could not be continuous, for, if they were, they must be as impervious as rubber diaphragms. However, careful geological mapping by Ruth on a return visit in August proved that the clay seams—which he argued had been formed by longtime application of relatively small shearing stresses under the advance of the continental glaciers—were truly continuous over the entire site. Because of the continuity and softness of these sheared seams, together with the high artesian uplift pressures, the designers were justifiably concerned about the possibility that the dam could slide along the soft clay layers within the foundation.

Two design solutions were considered for the Swir III dam. The state commission overseeing the project safety wanted a deep foundation, to be constructed by extending the concrete downward into a deep, excavated channel. Vatten proposed a shallow, flat foundation made wider with aprons upstream and down. Terzaghi's examination of the foundation rock exposed in the excavation had revealed that the fissures in the rock were easily widened by disturbance, even by groundwater movement, and by excavation work the rock was readily transformed into a loosened mass. Therefore, he vigorously opposed constructing a deep foundation; its excavation would expose more of the foundation to damage by loosening and for a longer time, reducing the shear strength even further and increasing damaging settlements. He checked the settlement predictions that had been based on laboratory tests, by ingeniously deriving compressibility data from the observed deformations of benchmarks in response to excavation and water pumping.

Additionally, Terzaghi worried that the higher seepage water flow rates at the greater depths of a deep foundation would promote piping in sand interbeds and in a sandy lower layer. Therefore, he insisted on the shallow foundation. To assure its safety, he examined in great detail the variation of sliding resistance with time for each of the four uppermost potential sliding seams, and helped Vatten to work out a detailed design with shear keys. His view prevailed. It is interesting to know that the Swir dam survived bombing in World War II.

Terzaghi had to make a hurried return to the site in March of 1935 when overzealous blasting to remove a cofferdam precipitated a slide in the upstream slope of the earth dam section, exposing its central core for more than 70 meters. The reservoir was full at the time and covered over with ice. He expressed himself delicately to avoid inviting criminal proceedings against any of the engineers and went straight to the emergency repair. Terzaghi had three slits opened in the ice and then sand was deposited through the water. Then, based on experiments conducted in the local laboratory by Vatten's engineer, Samsioe, he recommended tamping the floor of the reservoir with long wooden poles through holes in the ice. This increased the lateral support for the core by compacting the soil in place to form ribs of stiffer soil eight meters apart. A large peasant workforce was assembled to carry out this plan, saving the dam and averting a major catastrophe.

Giovanni Rodio's first invitation to Terzaghi occupied him from 1931 to 1934 in consulting for the design of Bou Hanifia dam in Algeria, a 160-foot-high embankment dam to replace one that had failed on the same stream. The subsurface was comprised of sandstone and shale, much fractured and folded, and containing beds of pervious, loose, fine sand and marl (calcareous clay). This assignment grew out of an overture to Terzaghi by

Giovanni Rodio promoting his company's expertise in grouting marl and clay. Rodio was a Swiss-educated, Italian engineer at the head of a large, international contracting organization headquartered in Milan. His expansive, outgoing Italian freespirit complemented Terzaghi's flair for repartee, and the two men became fast friends, meeting to plan and to relax together over the next three years in such places as St. Moritz and Adriatic coastal resorts. Together they celebrated Karl's fiftieth birthday, and on the same day mourned the passing of Professor Forchheimer.

Rodio became intensely interested in Terzaghi's work. He arranged to acquire and develop Terzaghi's patents (including a downhole water pressure sonde—the "Druckwassersonde"—that Karl had conceived and tested for White's New York Subway work in mid-1929). Also Rodio supported research work in Terzaghi's lab, including a successful effort by Ruth to find a superior grout mix. Under the supervision of Terzaghi's assistants, he inaugurated soil mechanics laboratories in Milan and Paris.

Grouting—the emplacement of cement or chemical binder in pores of soil or rock—was a subject known to Terzaghi from his visit to Nevada in 1912, but with which he lacked significant personal experience. If it could truly improve the properties of a foundation material in a determined and dependable manner, he could foresee many applications, and large potential profits. So he was enthusiastic about becoming involved.

Rodio wished to enter a competition for award of the Bou Hanifia contract and needed a man of Terzaghi's stature on his team to prove that his company's methods were superior and reliable. It would be very difficult to cut off potential leakage out of the reservoir through the pervious sedimentary layers. Such a cutoff would require both a concrete cutoff wall extending across the full width of the valley to a depth of eighty meters beneath the dam and a "grout curtain" almost two kilometers long, with a maximum depth of 130 meters to seal a narrow pervious ridge along a portion of the reservoir perimeter. Each bidder had to prepare engineering plans at his own expense; the winner would receive a substantial monetary prize (500,000 francs) by a French government commission in Algiers, and would probably be awarded the final job.

Terzaghi felt certain that attempts to build an impervious curtain by pumping fluid grout into the fractured shale and sandstone would be unsuccessful because there would be zones in which the grout simply would not be able to penetrate the tiny pores of the sand and fine cracks of the rock. To see what effect this would have, he investigated physical models of the pervious ridge made to simulate a 95% perfect grouting job, that is with 5% of grouting gaps. The model showed water flowing through the ridge almost as if it had not been grouted at all.

With this experience, Terzaghi lost confidence in a grout curtain as the principal measure and proceeded to design an immense graded filter, with a surface area of 40,000 square meters, in order to harmlessly collect the seepage water rather than try to stop it. A grout curtain was also provided, but just to diminish the leakage by closing the largest of the hydraulic passageways through the rock.

To keep ahead of the competition, he investigated the likelihood that they could also solve the design problem using their patented grouting methods. Rodio had two principal competitors—Francois Cementation Co. Ltd. and Siemens Bau Union. Siemens' process relied on quick setup of a colloidal precipitate at the points of contact between separate injections of sodium silicate and calcium chloride. Whereas the method worked in medium-grained Berlin sands, Terzaghi knew that it had failed in very fine-grained sand under the Palace of Justice in Cairo. He concluded that Siemens did not understand their product's limitations, for otherwise they would not have squandered their money in Cairo. Terzaghi then performed experiments establishing convincingly that the precipitate would not form below a certain rate of water flow through the soil and accordingly could not work in fine sand for which the flow rate was low, and in particular would not work at Bou Hanifia.[26]

Francois' patented technique introduced a mix of aluminum sulfate and sodium silicate into the ground. They claimed this material would serve to "lubricate" the walls of fine cracks and pores, facilitating the entry and travel of grout in the fine interstices of the rock and soil. Terzaghi performed an experiment that showed this assertion to be untrue. Much later, when Terzaghi worked with Francois Cementation, they admitted the term "lubrication" was Francois' invention to "lubricate his way through the patent office".[27]

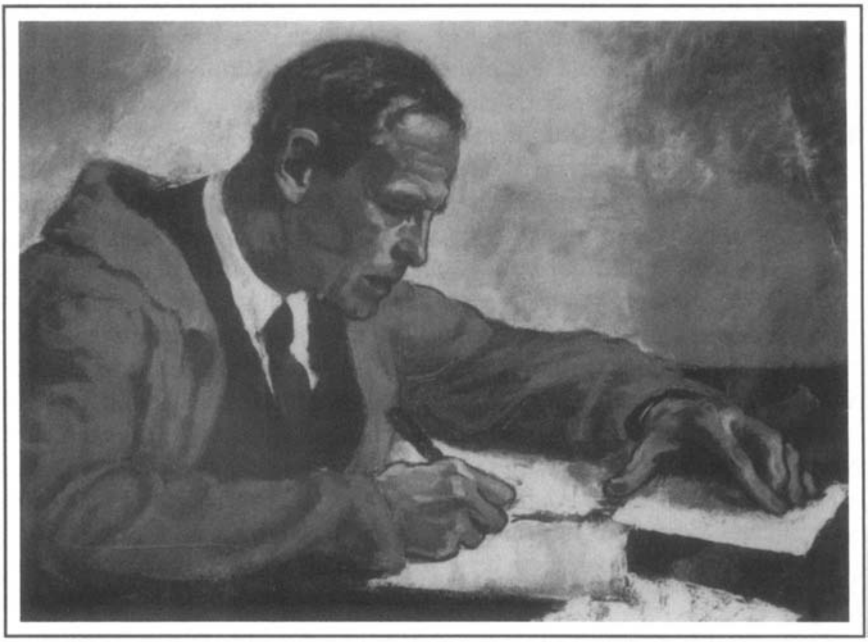
Terzaghi's design was based on the assumption that the dam would remain entirely safe despite inevitable imperfections in the grout curtain, whereas the two main competitors were so certain their grout curtains would be perfect that they omitted a second line of defense. The commission was swayed by his theory and experiments and awarded first prize to his design; subsequently, the Rodio organization was awarded the job. Years later Karl dared to confess to a colleague that "I was the only one among the competitors who had not yet had any practical experience in cementation [grouting]. Yet the experience did not help the competitors because they failed to draw correct conclusions from their observations. Instead of being a source of information their various mishaps were only a source of loss of capital."[28]

The sad irony of the Bou Hanifia experience was that despite his great victory on behalf of Rodio, Terzaghi was subsequently barred by Rodio's French subsidiary, S.E.C, from further participation.[29] His assistant, Gottstein, whom he had brought to Algeria to conduct prolonged field studies, was apparently too free in arguing in favor of Nazi ideas, which did not go down well among the French.[30] It became uncomfortable for Herr von Gottstein, and he soon found it necessary to leave, under the pretext of ill health. Shortly thereafter, Terzaghi himself was sacked. It seems that, in the ill wind of the Gottstein affair, the French misinterpreted or disagreed with the Germanic judgments of Terzaghi's reports and could not deal with his insistence on precise and speedy handling of his enumerated demands.

Terzaghi's dismissal from consultancy at Bou Hanifia was part of an unfortunate downward spiral in his relationships with Giovanni Rodio. The issue that steepened the descent, in the Fall of 1933, was a breach of confidence by means of which private information Terzaghi had shared with Giovanni found its way into a Swiss newspaper. Considering their enormous difference in personalities and styles, it is surprising their friendship lasted the three years it did. While they no longer interacted professionally after 1934, except for business concerning the International Society of Soil Mechanics, there lingered some genuine warmth between them for many more years.

Terzaghi was reluctant to accept consulting jobs unless they offered novelty or unusual aspect. But, as professor of foundation engineering, there were a number of Austrian jobs he felt obliged to accept as a public service. Since these assignments often afforded additional applications of soil mechanics in practical engineering work, the various small consulting jobs fed directly into his research work with students. For example, his theory of consolidation received a strong validation from consolidation tests he performed on the soft clay under the Bregenz post office, for which settlement measurements went back into the previous century. In a number of foundation design or correction jobs, with soft clays, peaty soils, and calcareous sands, Terzaghi worked in amazing detail to sleuth out the knowns and unknowns of the foundation geology, to design the best and cheapest foundation, and to specify its construction method. More than once his sharp observations and inferences settled old mysteries, as for example, the puzzling pattern of damaging settlements of a five-story block in Vienna; Terzaghi established the pattern of deformation, conceived a theory, and proved it by producing a map from 1890 showing the building had been placed directly over the edge of a former clay quarry for a brick factory.[31]

In 1934, he advised on foundations for the massive national museum building to be constructed in Krakow, Poland. The foundation contained acid groundwater so deep piers or piles could corrode in time. But the upper soil layers above the groundwater contain soft sand lenses so surficial foundations would settle nonuniformly and crack the building. Terzaghi insisted on excavating the upper layers and replacing them with compacted sand across the entire 2,500-square-meter foundation area. This raised the grade so that the cost of excavation and compaction was offset by shortening the above-grade foundation structures.



*Karl Terzaghi as painted by Harold Reiterer, mid-1930s.
The original oil painting was lost with the Terzaghis' household possessions, including their collection of valuable carpets, after storage in Trieste supposedly en route to America in 1939.*

The following year, Poland retained him again for the national museum in Katowice, which was to be a high building across the contact of different weak rock formations. Terzaghi had the designers lay out the museum with three separate structures, each founded independently on a homogeneous subdomain.

In December of 1932, the Ministry of Commerce and Traffic invited Terzaghi to serve as consultant, at no pay, for the design of the foundations of a new bridge across the Danube, to replace the first Reichsbridge from 1876.[32] The idea was to build a wider roadway on the piers of the old bridge, and the question put to Terzaghi was whether the increase in soil pressure could be accommodated.

He examined the old soil investigations, only to find the data incomplete and unusable. So he initiated an extensive new soil investigation, with help from Leo Casagrande, funded by the Ministry.

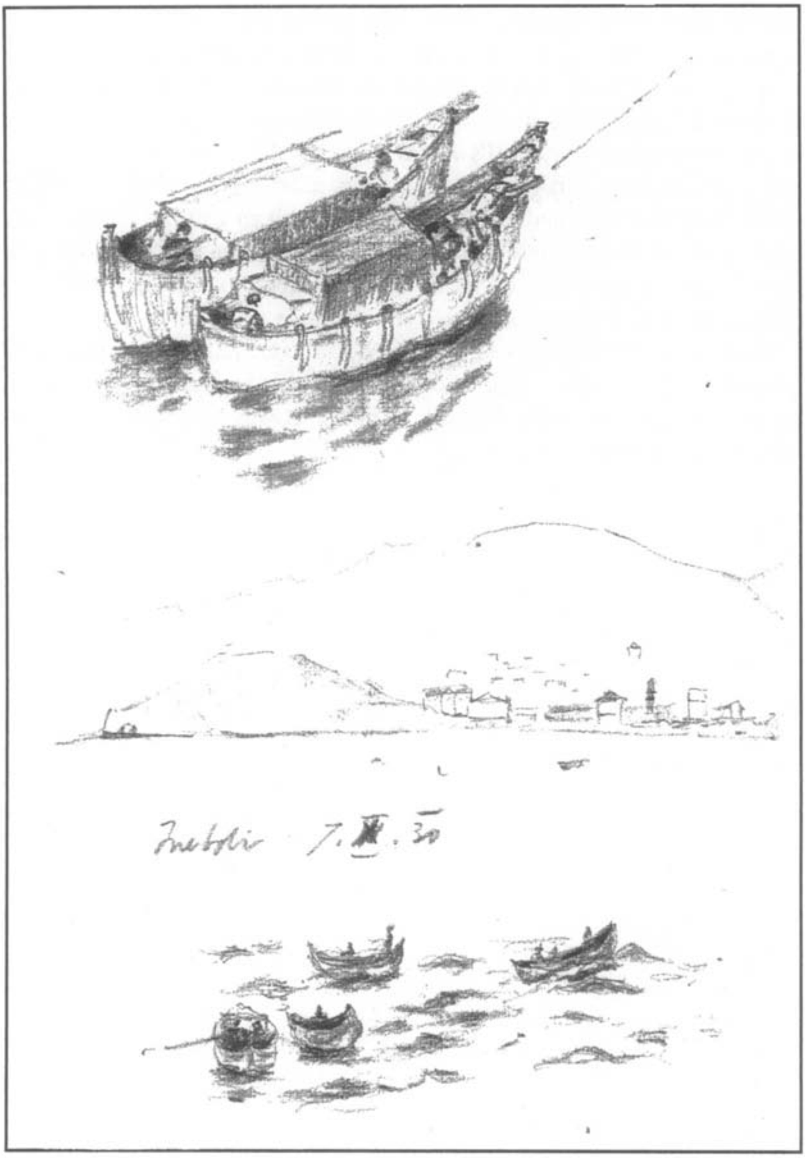
He asked how much settlement the old bridge had experienced, and was told there had been none. The bridge is underlain by clays and sandy clays, with occasional beds of fine sand, collectively known as "Vienna Tegel". Terzaghi could not believe that there hadn't been settlement and undertook to measure the differential settlement using a precise spirit level developed in his laboratory. With some assumptions about the original horizontality of specific members, he produced an estimate of the settlements of all the piers. On the basis of this information, together with the soil profiles, he determined the probable rates and amounts of remaining settlement and what these would become with the increased loads in comparison with the capacity of the bridge piers to deform. With some constraints, he gave his endorsement to the plan in a report of May, 1933.

The Ministry appointed a jury to select the designer based on submissions, but with only little attention to soil properties and entirely without soils representation in the evaluation of proposals. To Terzaghi's disbelief, without consulting him the Ministry selected a suspension bridge design. Terzaghi had investigated the foundation for essentially vertical loads, whereas a suspension bridge would apply horizontal loads. The settlement of the piers under increasing vertical load depends on the average compressibility of the layers whereas the horizontal slip of an anchor block depends on the worst shear properties of the weakest interbed.

The Ministry again tried to enlist Terzaghi's help, in January, 1934, but he refused, saying the project was unworkable. However, in December. he was prevailed upon by the contractors trying to build the bridge who pleaded for help in securing safe anchorage. He set to work with careful examination of the data. No new borings had been done for the question of anchorage. He found they had used a value of friction angle of twenty degrees to be applied to the base of the anchor block, whereas his report had given a value of sixteen degrees. Furthermore, the anchor block would not slide parallel to the excavated foundation surface as they had supposed, but along a weak clay interbed. Finally, and most importantly, the application of the anchor block's weight would show up initially as pore pressure in the clay pores, and the actual increase in normal stress would be much smaller for some time, perhaps years, than the normal force required to stabilize the bridge. He said the bridge would most probably collapse.

New investigations were conducted, with eleven borings in the footprint of the designated anchor blocks, and sufficient samples taken to determine the properties. Terzaghi's knowledge of the shear strength of the Vienna Tegel, and clay in general, had been substantially increased by the doctoral research of his student, the Danish-American Juul Hvorslev, and he was able to draw on this new knowledge in solving the Reichsbridge problem. The solution was effected using complex deep extensions of the concrete mass, designed to mobilize passive resistance.

Unfortunately, newspapers identified Professor Karl Terzaghi as one of the perpetrators of cost overrun. Consequently, his reputation was unfairly jeopardized as the heads rolled in the Ministry. It was not until April, 1937, that the record was set straight.



In the Urals, 1930.

10
Growing Discontent with Life in Europe
Mid-1930s

In leaving M.I.T., Terzaghi claimed to be seeking a quiet, more settled life in Europe. But that hardly accords with the workload he quickly allowed himself to acquire, with extensive consulting activities throughout Europe and North Africa, memberships in burdensome engineering committees in Europe and in the United States, and a vigorous research enterprise with students, visitors, and staff members. This prodigious activity yielded a continuous supply of new and developing geotechnical results that Terzaghi tried ambitiously to analyze and funnel into publications and books. Despite frequent ten- and twelve-hour workdays, an accumulating backlog of work awaited his finishing effort and began to weigh on his conscience.

This self-inflicted pressure began to rob him of lightness and joy and to convert him into an incipient tyrant, with high expectations of subordinates, and harsh judgments or haughty sarcasm for those who didn't measure up or threatened to break under stress. To Leo Rendulic, for example, whose heavy burden in a new position at Degebo prevented him from completing his pioneering triaxial compression tests on effective stresses in remolded clays, Terzaghi wrote, "you apparently don't have the required stuff to assert yourself. He who lets his self-esteem be dragged under, in the hours of deepest difficulty when he has run into a dangerous swamp, remains a fifth wheel on the wagon. It is not acceptable to choose the safest way and slog through along the path of least resistance.... It makes me sad to think that the good ideas in your head must wither since good ideas only have value when a firm will brings them to ripeness." Terzaghi then began to cry about how he had paid him for a year, how Rendulic had a moral duty to finish his work, how the time he had spent to help Rendulic was now lost and how "the final result stands merely as a serious deficit."[1]

He was no less imperious when Arthur Casagrande, asking to read his lecture notes on soil mechanics, received the following condition. "Please don't let them out of your hand as they contain much that is new and not previously published. Especially keep them, and the earth-pressure manuscript, away from xxxxx because when this good man, after strenuous effort, succeeds in understanding the train of thought of another, he attains the joy of discovery and imagines that he was himself its originator."[2]

When the results of the M.I.T. earth-pressure tests were finally analyzed, Karl prepared a series of twelve articles for *Engineering News Record*, including results of new experiments conducted in Vienna. But only five papers materialized in the 1934 publication, the subject being abridged by McGraw-Hill as too theoretical and detailed.[3] Terzaghi was deeply disappointed as he considered that this work brought together his ten years of experience in this field. He therefore decided to publish a translation of the entirety into German as a book "Earth pressure on semi-rigid retaining walls".[4] He obtained a publisher (Springer Verlag) and a translator in the person of a semidistinguished German construction official from Freiberg, Dr. Alfred Scheidig, whom he had hosted and supported as an academic visitor for a time at Vienna, and who had dedicated a book (on loess deposits) to Terzaghi "in honor and thankfulness". Terzaghi insisted on a liberal translation of his English articles into idiomatic German. But Scheidig's efforts were an embarrassment, showing that he understood neither the fine points of soil mechanics nor of English.

To save his reputation, Scheidig retained a helper at his own expense, without much improvement, and would not surrender his contract, nor Terzaghi's manuscript, until he had been paid 325 Marks. Terzaghi refused, saying the work was worthless, and his own loss was much greater—namely two years of work. The dispute raged for three-quarters of a year; finally Terzaghi and Springer decided to abandon the project. In the end of March, 1935, Terzaghi exhumed this project as the basis for a textbook on earth pressure, writing a new manuscript of 232 pages and 83 figures, as well as a rough draft of an additional 300 pages and 120 figures by May; but the work was never completed as such.[5]

Terzaghi did not originally offer to perform the translation himself for his earth-pressure book because he was inundated with about seven other book projects, in various stages of development from mere intention to working manuscript. They were a book with Bruno Sander on microscopic fabric analysis of soils, one on engineering geology; a second edition of *Erdbaumechanik,* a book on seepage problems, one on analysis of concrete dams, a treatise on mathematical solutions of the consolidation equation, with Otto

Arthur Casagrande, circa 1934

Fröhlich, and, his priority project, the preparation of a text on foundation engineering.

Terzaghi was close friends, from his Turkish years, with the petrologist Professor Bruno Sander, a back-slapping, hard-drinking field geologist known in geology as the originator of the study of "petrofabrics"—the textural and structural arrangements of rock elements as seen in microscopic sections. In good times together in the mountains and at Sander's home in Innsbruck, Terzaghi and Sander spoke about trying to apply Sanders' fabric study to natural soils. As a first step they exchanged books, but neither could make much progress with the other's and, in truth, their project for joint authorship was doomed from the start.

Writing a practical volume on engineering geology, on the other hand, had been Karl's ambition from the earliest days; in fact, it could be said to have been one of the aims of his trip to America in 1912. He began writing a syllabus on aspects of engineering geology for students while in Turkey. Then, during his last year at M.I.T., he contributed 250 pages as coauthor of a German textbook entitled "Engineering Geology".[6] This book had been well received, and Terzaghi was acknowledged as the source of its content of practical, state-of-the-art material.[7] But it could hardly be considered to represent the field of engineering geology, since Terzaghi's contributions were essentially a summary of contemporary soils engineering, not applied geology. Now, he proposed to mine those chapters for preparation of a book on engineering geology in English, to be coauthored with Professor Fred Morris at M.I.T.[8] This project went nowhere, but its spirit kept resurfacing.

With German hydraulics engineer R. Dachler, Terzaghi worked on producing a small book, "Seepage problems in foundations, embankment dams, and canals". He wrote to Arthur Casagrande that he intended to elaborate Forchheimer's theories of groundwater movement in a simple form for the engineer, and including "snatches from my Algerian practice".[9] Casagrande tried to discourage him from completing this project, arguing that it would prove useless without a proper introduction to soil mechanics. In 1934, he considered writing a short book in English on the stability analysis of concrete dams, consisting of reprints of three articles he had written on pore pressure in concrete under dams, together with example calculations and reference to German literature unknown in the U.S.[10] Again Casagrande dissuaded him, arguing that such a volume would be too narrow to merit publication in the United States.[11]

Bringing out a second edition of *Erdbaumechanik* had been on and off with Terzaghi for years, but until he could do so he refused to allow its translation into French, Japanese, English, or any other language. His self-critical attitude towards this work was summed up in a letter to John Wiley publishing company's vice president E.P. Hamilton in 1934: *Erdbaumechanik* "was in every respect the result of genuine, single-handed pioneering" he wrote. But it contains many defects: "intolerably lengthy discussions of phenomena which afterwards proved to be without any practical value, and hypotheses which later had to be discarded. In addition many facts of outstanding practical importance were not then known to me.... At the present state of my knowledge it makes me feel sick if I look at that book."

Erdbaumechanik was by this time out of date, and Terzaghi thought it would be misleading to contemporary authors trying to use it as a source. The Russians, who translated it without his permission, he asserted, deserved no better. A new edition won't appear until 1936 when the new findings will be completed and could be incorporated in it. "I do not consider anyone competent to write about the various subdivisions of this difficult and rapidly developing subject who has not done original and successful research in this particular line." Terzaghi proposed to split up the responsibility for writing the different chapters among those who are truly expert, including Arthur Casagrande. "I will retain for myself only those subjects in which my own research has been leading since 1925." He expected the English edition of this book to carry the standard for soil mechanics. "Together with Casagrande's treatise on testing, it will be the book for the schools and the laboratories."[12]

If Terzaghi was not committed to reforming *Erdbaumechanik* by himself, it was because he was really enthused about the writing of a major book on foundation engineering. Early in 1931, he sent Casagrande a table of contents for this work, saying that the source material was mainly at hand, and he expected to publish in 1932.[13]

He tried to focus on the writing of *Foundation Engineering*, taking working vacations in Hintertux, St. Moritz, Lugano, the Garda See, and on the Adriatic Coast at Villa Tartini to shut out interruptions. But consulting work stole his time, and depression in the Austrian economy caused political turmoil and reduced institutional support, denying him the chance to concentrate. At his instigation, his friend Lazarus White held out the possibility of an offer within a year from Dean Barker as professor at Columbia University with an annual stipend of $7,500. He replied, "This time-provision would suit me very well because I badly need time and leisure to finish my treatise on foundation engineering." These plans shifted to the idea of a sabbatical leave at Columbia in the academic year 1934–1935, where he would be able to put the finishing touches to the publication. But this did not happen.

To a friend, Professor Hornell in Sweden, Terzaghi wrote at the end of 1933 that his highest priority was to finish writing his book "about foundation engineering for the practical engineer. Its contents are intended as an antidote against the increasing tendency to over-estimate the value of purely theoretical work in this field. Its purpose is to give a sort of bird's eye view of the possibilities and limitations of research, and to embody a program for a rational coordination between the field and the laboratory. Working on that book gives me a real sportsman's joy."

He expected to have it finished by Spring of 1935, but the project became more complicated in October, 1934, when Casagrande asked how a reader of his book could understand it without reading first a primer on soil mechanics, including Terzaghi's earth pressure theory. Casagrande suggested it might be better for Terzaghi to write a two-volume work covering "soil mechanics and foundation engineering."[14] In the same message, Arthur informed Karl that certain academicians in the United States were proposing to author text books on soil mechanics: Dimitri Krynine, a Russian expatriate at Yale University; Gilboy at M.I.T.; and Prof. Housel from the University of Michigan. This really put gunpowder into his correspondence with his prospective publisher John Wiley & Sons for he did not relish the idea of someone other than himself—the founder of soil mechanics—being the first to elaborate its principles in print.

To John Wiley's Vice President he wrote: "The need for a textbook on soil mechanics undoubtedly exists. Yet those who are competent to write it unanimously feel that the psychological moment to prepare it has not yet arrived. Hence whatever is published now in that line will be of little value anyhow and out of date within a short time. Since Mr. Krynine has but little to his credit in this field, he cannot possibly produce anything but an abstract of the previous publications of others, particularly of my *Erdbaumechanik* whose obvious defects I have described.

"As to a text on foundation engineering, I know by personal experience what an immense amount of painstaking observation of full-sized buildings was needed before I could attempt a synthesis of theory and practice in this field. Mr. Housel, whose publications I know, has neither the habit of careful observation of buildings nor that skeptical attitude towards his theories which constitute the foremost requirement for learning something in this field. He is so energetically engaged in advertising his few little theories that he never finds the leisure to examine them carefully. Furthermore, his personal experience transcends neither the boundaries of the middle West nor those of a period of a few years. Hence whatever he may write about this subject cannot be considered serious competition."[15]

The crushing workload and distraction were of his own making, but the deteriorating economic and social conditions in Austria were not. After the World War, the government's printing of empty money to sustain social services and pay war reparations inevitably created a huge inflation. A loan was obtained with the support of the League of Nations, but the economic reform stipulated by the West to reduce inflation threw many out of work. The consequent popular disenchantment polarized the electorate into right-wing and socialist political parties, each of which developed large private militias outfitted by the residual armaments of the world war. A collision between these political armies in Vienna in 1927 produced ninety deaths, a sign of future instability that Terzaghi had mistakenly dismissed as "petty fighting" when he factored his equation on whether or not to return to Europe.

However, even with the beginning of the great depression in 1929, a professor on a fine state salary, newly married, and just rejoined with his national community, could remain for a time economically insulated and politically aloof. Thus, the Terzaghis were at first able to enjoy the social pace of jubilant Vienna, dining out frequently, entertaining at home, attending concerts, theater, balls, and masquerades, and holidaying in Alpine resorts. They were happy and involved, and untouched by the occasional misfortunes of the wider world reported by friends like Arthur Shaw, whose engineering activities in China having run virtually out of funds, was now actually considering moving to jobs in Russia rather than face certain failure in the States.

Terzaghi remained blissfully unpolitical and unaffected until "like a flash from heaven" in mid-October, 1931 he received a foreign exchange directive from the Austrian National Bank to report all his foreign assets and to declare all the wealth and property he had imported into Austria. What had transpired was the aftermath of Austria's attempt to conclude a trade agreement with Germany. France felt threatened by any Austrian/German concord and accordingly blackmailed Austria into revoking the agreement with Germany by suddenly withdrawing large sums from the Austrian Creditanstalt. This act not only forced an end to the Austrian/German accord, but it caused a change of government, led to an attempted coup by the right wing, and ultimately caused the failure of the national bank.

Most of Terzaghi's holdings were in overseas investments or had recently been imported from the United States. At this time, Lazarus White wrote that fifteen American banks had failed. Terzaghi thought himself very vulnerable and reported the events as "panic in the whole world" whose end nobody could foretell.[16] He read the newspapers with zeal and discovered that 212,000 people were newly unemployed in Austria at the same time as a magnificent 70,000-ton ocean liner was being built with unheard of luxuries. "No man should have the right to save at the expense of educating the next generation," he thought. He was fearful that the world was embarked on the path to a war more destructive than any heretofore, noting the sad development that "technology, only 100 years old, already threatens all mankind."[17]

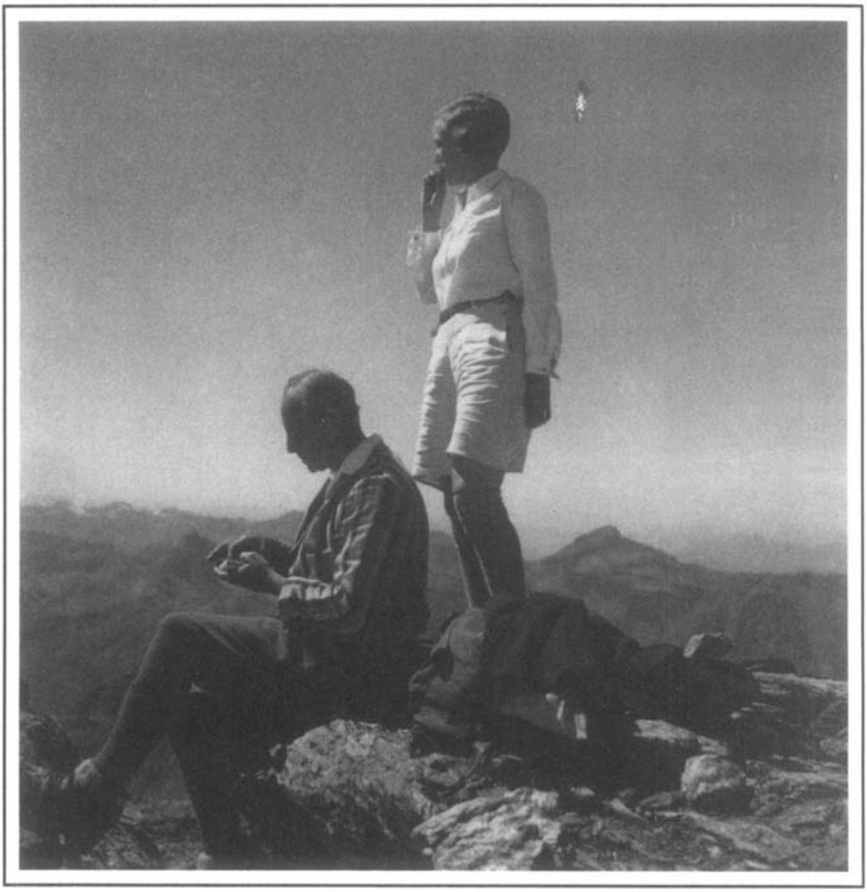
He planned immediately to transfer a large part of his savings deposits, to crate up his valuable possessions in Vienna, and possibly to move Ruth back to the United States. To Lazarus White, whom he asked for financial guidance, he wrote that his savings in New England banks "represent for us the only means to get out of Europe in case this continent is set on fire."[18] It was this alarm that triggered White's discussions with Columbia University.

At first he worked with Ruth to document all their assets in accordance with the monetary directive. Then he and Ruth concocted a plan to shelter their income through Milan, via his friend Giovanni Rodio. He asked Giovanni to receive and hold all his mail "and in no way send it on to Vienna lest it fall into the clutches of the authorities". He also decided to deposit all his valuable papers and reports with Rodio's affiliate in Zurich so that "in the event of the collapse of Austria, I can continue to work in Switzerland without further loss of time."[19] For the time being, Ruth would stay in Italy, at the resort they loved at Riva on Lake Garde. In the next weeks the Terzaghis traveled and maneuvered according to clandestine designs.

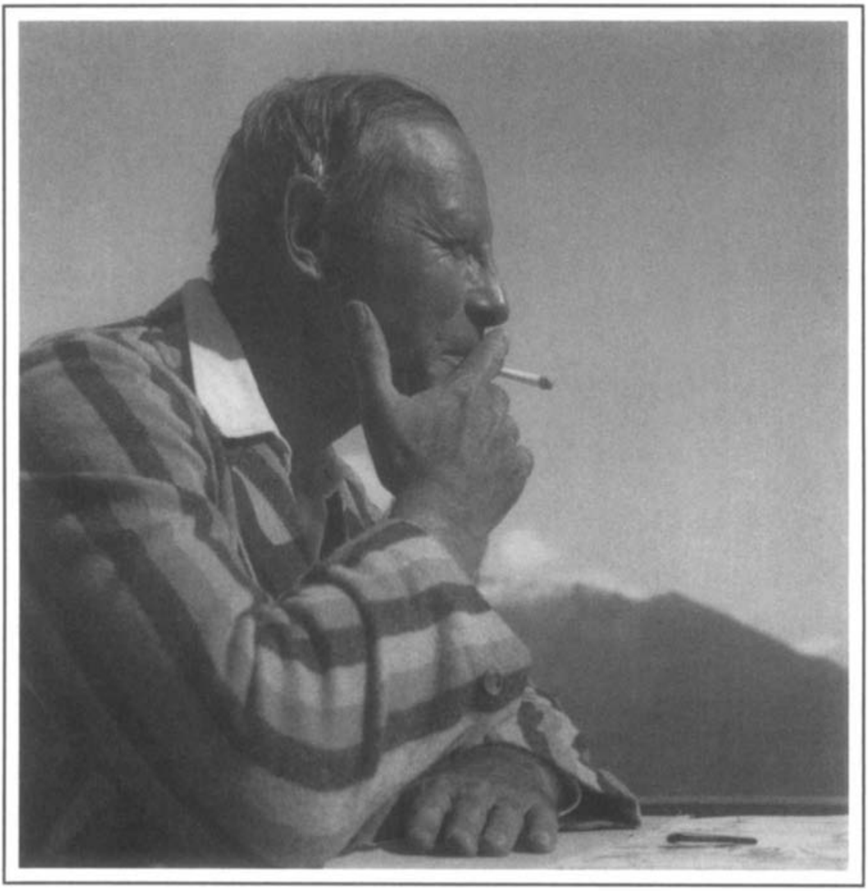
The explosion Karl feared did not materialize, and he gradually reclaimed his calm, although never again his joy with life in Europe. He considered Europe to be doomed and began laying the foundation to move, communicating his intentions to Lazarus White, John R. Freeman,[20] and Arthur Casagrande in the U.S., to Professor Hornell in Sweden, and others elsewhere. In addition to preliminary negotiations with Columbia University, he arranged an emergency post at Robert College, should it prove necessary to get out fast, noting that Turkey was ironically now one of the safest places in Europe.[21]

Continued unrest heightened the Terzaghi motivation to find a path out of Austria. The Austrian parliamentary government collapsed in March of 1933 and, with the support of Mussolini, a fascist Austria was quickly established, headed by Engelbert Dollfus. Encouraged by Hitler's rise to power in Germany, the Austrian Nazis began to gain members, including large numbers of university students, and Terzaghi's 17-year-old daughter Vera. Karl observed that the students at Graz were becoming fanatical. In June, a student leader at the Technische Hochschule in Vienna was arrested following the bombing of a Jewish shop.

On January 29, 1934, eighty students at the Technical University were arrested for participating in a Hitler commemoration day, the Nazi party having been outlawed since the previous June. Then, on February 12, 1934, supported by the right-wing militia (the Heimwehr), Dollfuss' supporters provoked a shooting war with the socialist militia (the Schutzbund), which led to the latter's destruction in just four days. Terzaghi recorded that young Nazis were smiling with contentment, just biding their time. There followed further suppression of civil liberties, establishment of political internment camps, and outlawing of the Communist and Socialist Parties; the latter was amazing considering that the Socialists had represented 41% of the electorate as late as 1930. The replacement of a divided democracy by a totalitarian dictatorship was surprisingly palatable to the bureaucracy, the mili-



A summit for Karl and Ruth, Summer of 1934 in Tyrol.



Terzaghi at Hintertux, 1934

tary, the Catholic Church, and the right-wing political machine of the former Republic of Austria.

Jewish professors in Germany and Austria began to flee, and Terzaghi learned from Von Mises, himself resettling in Constantinople, that 45 of them, including several Nobel Laureates, had taken positions in the University of Ankara. He might have wondered if he shouldn't go with them, although for different reasons. Karl was growing impatient with academia and longed to return to engineering practice. He wrote that scholastic inbreeding leads to "outrageous overestimation of one's personal achievements."[22] In Germany the whole field is full of little ignoramuses, many of whom will become members of the Academy of Engineering. As long as the academic profession offers complete independence it is a worthwhile address, but "the good times are over."

On July 25, 1934, a group of Austrian Nazis who had been expelled from the army on political grounds, attempted a coup which backfired but brought about Dollfuss' death. The Austrian Nazis escaped to Germany while Mussolini massed troops on the Italian border. Then, when Italy launched its aggressive war in Ethiopia in 1935, it came under attack from the League of Nations, and its ability to bolster Austria against Germany declined. Soon, Rome and Berlin moved into alignment. This left Austria's new dictator, Schuschnigg, with little defense against increasing tolerance of Nazification, and the inevitable 1938 union of Austria with Nazi Germany (the "Anschluss").

These political developments almost paralyzed Terzaghi's research operations in Vienna as several staff members were suspended for investigation of alleged disloyalty. This strengthened his resolve to leave. Arthur Casagrande was saddened that their "collaboration over the ocean" was coming to an end. He argued for them to see a bright side in the rise of German optimism. Arthur complained to Ruth that his acquaintances at Harvard were unfairly disposed against Germany, preferring to believe the lies of the newspapers rather than his personal reports (a plaint that he continued well into 1938). "The inhuman way in which the German Government is treating their Universities, Scientists and Science! Look at the mess they have over here! Here the so-called 'social sciences' which, indeed, enjoy little freedom today in Germany, have all the freedom to expand and their professors even are invited to run the government."[23]

Impatient with Harvard's slowness to advance him, Arthur told Karl that he was seriously considering moving to Germany, where he was already serving as a consultant, and where his brother Leo had become the Head of the Soil Mechanics and Foundation Division for the Inspector General of German Highways. Ruth countered that Europe is surely served by currents of disintegration stronger than the integrating force of optimism in Germany, especially when one considers Germany's meager gold reserves. She tried to convince Arthur that he was right to have thrown in with the raw, informal, but generous new world, with its history still to come and free from academic dogmatism.[24]

They were each reaching out to safeguard their crossing pathways to home. Ruth's way prevailed when, buoyed by his own promotion, Arthur subsequently committed himself to remain at Harvard. Now he began to concoct a scheme to bring Terzaghi back to the United States. Harvard was talking of transforming itself into mainly a postgraduate school and of dropping certain fields, for example mining engineering, in favor of those in which it could establish world preeminence. With Terzaghi as a cofaculty member, he believed he could convince Harvard that soil mechanics was one such preeminent field. Why not bring Terzaghi as a visiting professor for one year? He suggested that Karl could enlarge his somewhat limited salary with consulting work, "and when the year was up there would be the possibility, I would dare say the likelihood, that you would be appointed as Full Professor."[25] Terzaghi encouraged Arthur to pursue this idea and determined to take a leave from Vienna for the entire academic year 1935–1936.

Arthur's plan was endorsed by Dean Clifford and President Conant. To raise part of the money, they proposed to take advantage of the coincidence that Harvard would be celebrating its 300th year. Arthur conceived of the idea to hold a soil mechanics congress as part of the celebration, with Karl as president. Furthermore, Karl would be awarded an honorary doctorate.

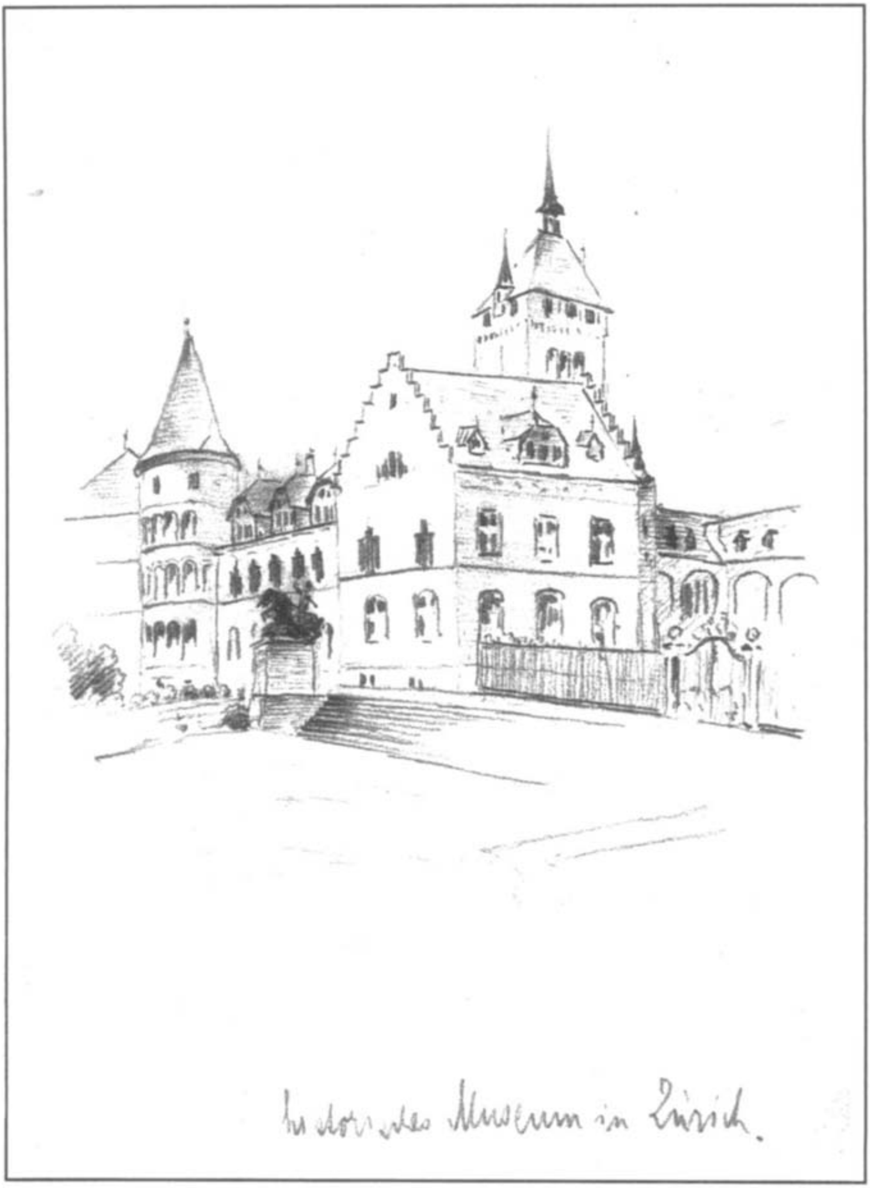
The honorary degree and the opportunity to preside over the meeting surely helped Terzaghi accept. At first he claimed to be fearful that the subject was too immature for an international congress, and worried that inevitable dissatisfaction would promote discouraging criticisms.[26] But, in short, he not only accepted the scheme but proposed to dedicate his book to the congress—originally to be on foundation engineering but now being called "soil mechanics".

He agreed to visit at Harvard. But the force compelling him to leave Europe for good must have been withering, for he wrote to Lazarus White: "Although I am sick and tired of the political conditions in Europe and although I would be delighted to join again the group of friends which I left in the States, I could not possibly consider reducing my standard of living to a level far below its present one."[27]

Perhaps he was feeling heady because the Germans had also invited him to be a visiting professor in Berlin. After much discussion, he now agreed to spend the Winter semester there before proceeding to Harvard in the Spring. Miraculously, once again he was able to arrange for Otto Fröhlich to carry on his existing responsibilities in his absence, now even to the extent of renting him his house and charging him to look after his daughter Vera who was also to live there in the interim. Fröhlich, at that time a civil engineer at the Hague, must have secretly hoped Terzaghi might not return, leaving him to inherit the Terzaghi Chair.

Terzaghi poured himself into cleaning up the loose ends of consulting and writing so that he could leave. By now his manuscript for a book on foundation engineering had divided itself like an amoeba, as Casagrande had recommended—volume one on soil mechanics, and volume two on foundation engineering. The first, effectively an introduction to earth pressure and soil physics, was to contain a chapter on shear strength that was now overly long and in its fourth draft. He had not dared to start a chapter on the stability of slopes in clays because his knowledge in that field was limited (or as he wrote to a Russian friend, "the empirical basis is not rich"[28]).

Providence struck, he must have thought, when he was called suddenly to investigate a developing slide along two kilometers of the German autobahn between Munich and Salzburg. "I had the pleasure to see exactly the type of slide whose data up to now had eluded me," in which a homogeneous, thick bed of soft clay was in motion under the weight of the highway fill. About 150 meters of embankment were damaged and a neighboring railway line was threatened; the administration was about to give up the whole stretch of highway. Terzaghi was "completely enthused about the results of this unintentioned experiment", quickly obtained permission to sink a shaft to obtain undisturbed samples, and put his laboratory to work. Germany might not be too bad after all.



The historical Museum in Zurich.

11

Two Zeniths—Berlin and Cambridge 1935▾1936

When Terzaghi made friends at the autobahn landslide, he did so in a big way. For that highway—from Munich to Salzburg—was being built at high priority so that Adolph Hitler would no longer eat dust on his frequent trips to his mountain house at Obersalzburg. Vitally concerned and there to meet him was Fritz Todt, the General Inspector of German highways, whom Terzaghi described as a forceful, active, clean-shaven man with a strong nose and a sarcastic bent.

That Todt was impressed with Terzaghi was evident a week later, October 27, 1935, when he was telephoned to come as soon as possible to Nuremberg. Todt wanted Terzaghi's urgent consultation on the foundation of permanent new structures for the Nazi Party's Annual Party Day Rally ("Reichsparteitag"). On Thursday, Karl took the night train and Friday morning was squired to Nuremberg City Hall, where a working group of architects, engineers, and officials, headed by the city engineer, architect Walter Brugmann, were waiting to explain the project.

He was staggered by the size, cost, and difficulty of building what amounted to a "party city" for only eight days use per year. The Reichsparteitag grounds had been conceived by Architect Ruif in 1929 around a Rathskeller table and sketched on a napkin in essentially its final form. The centerpiece was a great Athenian horseshoe stadium for 400,000 people, 240 meters long by 170 meters wide, with a foundation area of 60,000 square meters. There would also be a podium building 260 meters by 60 meters. It was all to be roofed, mainly with a huge steel truss bearing on ring walls 50 meters high.

There was also the March Field—so large that it contained a separate plot for army practice maneuvers—surrounded by grandstands to seat 160,000 in the center of which was to be a platform for dignitaries and a statue of a woman fourteen meters taller than the Statue of Liberty. The March Field was to open out to receive an avenue eighty meters wide and two kilometers long, down which tanks and goose-stepping troops in fifty-man rows would proceed on a surface of roughened granite slabs.[1]

This giant project, under the direction of "dictatorial architect Albert Speer",[2] was estimated to cost 300 million Marks; but that was not much of a deterrent to the sponsors[3] as it would be raised through special taxes in southern Germany, Hitler's stronghold of support. According to Speer, Hitler equated the cost to that of two battleships, and whereas ships would merely become scrap iron within a decade, this monument would stand for a thousand years.

This last was the chief source of Terzaghi's difficulty with the site. In his oratory, the Fuehrer had proclaimed a thousand-year Reich, and a thousand years must therefore be the useful life of this project. Terzaghi took it seriously. How on earth could it be achieved? His dilemma, and that of the architects, was akin to that of the modern nuclear power industry in trying to dispose safely of wastes that remain toxic for a very great period.

Terzaghi had just finished facing this same question on a consulting visit to Turkestan with VBB for the Mingechaur irrigation project. The Mingechaur scheme included a main dam about eighty meters high across the Kura River near Tiflis, a completely unregulated stream of great size. The Kura valley was cut through steeply dipping weak and erodible sediments, including "broken shales, clay, and strata of fine sand" and karstic limestone, fractured zones, and probably faults.[4] The problem was that the Swedish consultants imagined that an irrigation scheme like this would likely outlive its engineering creators, and therefore was not likely to be taken out for renovation after its life was over. To keep it safe for a very long time they would have to adopt a correspondingly long design life—say, 1,000 years.

But nobody was willing to assure that concrete could last for 1,000 years. Terzaghi insisted the dam could endure that long if constructed of natural earth and rock, but good workmanship would be absolutely essential. The Swedes worried this could not be guaranteed in a dam built by Soviet Russians. He thought an acceptable way to handle the design for the enormous flood spill was to make the outlet works of reinforced granite masonry filled with asphalt. But VBB doubted sufficient workmanship was obtainable; in fact, they asked him not even to mention his spillway idea. Take it out of the report and burn the letter, they told Terzaghi.

In Nuremberg, Terzaghi was dealing with German, not Soviet Russian workmanship. But the place presented even more difficulty than in

Turkestan. The site is underlain by about twelve meters of loose, stream sands over moderately permeable and compressible sandstone of the Keuper Formation. The sand would be likely to settle differentially by 2.5 centimeters, all of which could occur suddenly due to vibrations (the cause of a silo failure in Vienna in 1927 during a weak earthquake that produced only 0.2% of the acceleration of gravity). Therefore, the structures could not be founded on the natural sand.

It would ordinarily be quite straightforward to found the entire structure on piles or piers bearing in the rock, but not here for there was a strong throughflow of acid groundwater in the sand, made acidic partly by a high carbon-dioxide content in the pore water of the underlying sandstone.[5] Thus, the use of unprotected piles was out of the question; they would quickly corrode. The architects had planned to isolate the entire complex from the ground water with a complete watertight ring extending from the surface down to the rock; this ring would be wrapped in a double layer of copper separated by bituminous concrete, and backed up by acid-resistant brick.

Terzaghi objected strenuously, saying such a design was unthinkable. He offered calculations showing that the ring barrier would surely decay, but even if it didn't there would be sufficient underflow of water through the bedrock to resupply acidity to the water in contact with the foundation. And even if the ring held up and seepage through the bedrock were somehow prevented, diffusion of carbon dioxide from the bedrock's pore water into the "clear water" within the pores of the sand must, in time, make the latter acidic. Thus, within the design period, the piers would be destroyed.

Terzaghi offered a different solution, similar to the one he had pioneered in Krakow. Densify the sand, and then place the footings on the improved sand layer *above* the water table, where there would be no problem of deterioration; then the foundation might last 1,000 years. The sand could be densified by driving piles into it, or by running a new vibration machine invented by Professor Hertwig. Terzaghi predicted the void ratio of the sand would be decreased through pile driving by 6%, which he asserted would be a sufficient improvement.

There was a reluctance to change the design, so Terzaghi asked Todt if he might speak to higher authority. On Sunday, November 3, after two days of site visits, Terzaghi was taken on a tour of recent works for the autobahn, which were being rushed towards readiness for the 1936 Olympics. While inspecting a tunnel, a policeman approached to report that Todt had phoned: the Fuehrer wished to meet him at 5 p.m. at his private home in Munich.

Karl was driven quickly back to Munich where the Todts entertained him at their home until 7 p.m. when it was finally time to be received. Hitler was living on a quiet street, marked by a long line of cars. Terzaghi received the Hitler salute from two enormous guards in dark "death's head" uniforms, and waited in the entrance hall.

"In hardly a minute the Fuehrer appeared, young and elastic, dressed all in brown—a joyous, friendly alive face, with a domed forehead projecting strongly over his nose and his hair falling, uncombed over half of his forehead. His face was disturbed only by a soft, feminine mouth and an ugly little moustache. He excused his modest home, and led me into the reception room to a long, narrow table." Terzaghi recognized paintings by noted artists Stueck and Feuerbach.

Terzaghi referred to the problem of draining the terrain and likened the design requirement to that of a gun, whose foundation must not settle. If it is not right it must be changed. "Hitler laughed heartily." He listened as Terzaghi outlined his preferred scheme.

When Terzaghi spoke about his personal dislike of the granite selected for the architecture, Hitler came alive and waved his hands as he described the different beautiful types of stone he had seen in his life. He told Terzaghi that he had intended to become a stone mason but at that time could not afford the investment.

The Fuehrer then spoke with enthusiasm about the Party Day. He said it was "a beautiful family festival bringing together old friends and fellows of the struggle" and invited Terzaghi to participate.

"The entertainment lasted three quarters of an hour." Hitler walked Terzaghi into the lobby, introduced him to Mr. and Mrs. Goebbels, "and I departed from the Führer with a hearty handshake and thanks that I was brought to Nürnberg. My impression of this vigorous personality, full of fantasies, was strong and lasting. He spoke about every detail with expert, almost limitless, knowledge and unheard of memory."[6]

After several meetings, and correspondence extending well into 1936, Terzaghi's criticism was finally accepted, only to have Hitler himself propose an alternative approach. Terzaghi was able to convince Speer and Hitler that his way was better. Leo Casagrande wrote that "Herr Dr. Todt was pleased over your victory, that came about only through the uncanny perfection of your logic." In March of 1936, while Terzaghi was in the USA, a major pile densification test was conducted in which the Franki pile company drove eighty piles at the site. This caused the loose sand to increase in density by 10%, converting it into a weak sandstone.

The Terzaghis moved to Berlin on November 17, 1935, and he began his lectures the next day, at the University of Berlin in Charlottenberg. There were 300 persons attending, including many faculty, and engineers from the community, as well as Fritz Todt who made a warm introduction. Todt was also on hand for the last lecture on January 15th and presented Karl with a personally inscribed gift.

Long after Terzaghi had ceased to have connection with this friend, Dr. Todt rose in the Nazi administration, ultimately holding the equivalent of three ministerial positions: chief of technology, heading all road construction, navigable waterways, and power plants; minister of armaments and munitions, directly under Hitler; and head of the dreaded "Organization Todt" which was charged not only with building the western defenses (the "Western Wall"), shelters for U-boats on the Atlantic coast, roads in occupied territories from southern France to northern Norway and eastward into Russia, but also labor camps.[7]

Speer called him "one of the few modest, unassertive personalities in the government" combining sensitivity and candor typical of technicians. But the lure of Todt's portfolio must have been stronger than the pleasure of his friendship, for on February 8, 1942, Todt was killed in a suspicious plane crash, possibly arranged by Goering who coveted his ministries.[8] Albert Speer, not Goering, became Todt's successor, and his indispensable helper was Walter Brugmann, the architect who was Terzaghi's protagonist at Nuremberg. Like Todt, Brugmann was also killed in a suspicious plane crash, two years later.

The sabbatical leave in Berlin was Terzaghi's first extended residency inside Germany, and he was much impressed. Pumped up by Todt and Agatz, the head of Civil Engineering at the University of Berlin, as well as three former graduate students—Ernst Gottstein, Leo Rendulic, and Leo Casagrande—Berlin and German society were proving extremely cordial. He found the life in Berlin pulsating, the country rich with opportunities for work, and the populace good-natured and intelligent.[9] He introduced his daughter Vera to Todt and, at her request, arranged for her to visit with Nazi Party officials in Nuremberg, her Mecca as a rising young Nazi.

To Terzaghi, Germany contrasted strikingly with Austria, with her unemployment and old-world ways. "In Germany there was tireless, well organized activity, relative prosperity, and a significant population giving an impression of contentment. On patriotic holidays, the capital was teeming with joyful people. In Soviet Russia, I observed the sad figures going with joyless faces into 'Culture Parks' which contrast with the places where the working classes have to live. The elimination of the risk of a dictatorship of the proletariat and the abolition of unemployment are achievements that can not be too highly estimated."[10]

Could this be the same Third Reich described by the eminent Stanford scholar Gordon Craig, who was there at that very time? Craig wrote, "masterpieces of high German culture made a deep and lasting impression on me, but no more so than the many examples that I encountered of abuse of culture and, indeed, of inhumanity and barbarism. Munich, where I spent most of the early summer, was a beautiful city of broad boulevards and leaping fountains, but its charms were not enhanced by banners on storefronts that read 'He who buys at a Jewish concern is a traitor to his people!' or by the neatly lettered signs in the English Garden that said 'Jews are not wanted here.'"[11]

Craig continued, "It was all too apparent that the university, once a symbol of German eminence in the works of the mind, had fallen on evil days. A course on Richard Wagner that I had looked forward to with enthusiasm turned out to be an exercise in nationalism and Nazi propaganda, in which much more was said about Hegel and Hitler than about the composer and in which the argument seemed to be that Hegel had invented the state and Wagner had dreamed up things for it to do, but that their work had been meaningless until Adolf Hitler had given the substance of power to their visions." He goes on to describe hearing "floods of filth" pouring from a gross bully at a university lectern who "offered 'scientific' evidence of the predatory nature of the Jews.... The audience in the Aula was attentive and many took notes."[12]

At dinner with the Gottsteins, Terzaghi heard that "the Jews have greatly overestimated themselves. They should have learned from the fate of Rathenau. They should have kept quiet when their civil service was destroyed."[13] It is not surprising Karl failed to write any rebuttal into his diary, for such was not his custom. He only heard, absorbed, and recorded ideas and information and stereotyped people as a geologist classifies landforms or rocks. He held a negative stereotype for Jews, even as he respected Albert Einstein, Stephen Timoshenko, and his friend Lazarus White (and later Raymond Mindlin and the rising young star Nathan Newmark at the University of Illinois), and even as he recorded his friend Von Neuman's remark: "Germany was doing wonderful things for science in other countries by exporting their Jews; they should do as much for themselves."

If the Terzaghis were surprisingly insensitive to antisemitism, they did begin to worry about Hitler's intentions. In conversations at Christmas with Professor Franzius in Hanover, there was talk about the likelihood that the path of rearmament would lead to war; Franzius spoke ill of Hitler and the rabble around him and told him that war with Russia was now unavoidable. On seeing Leni Riefenstahl's film of the Nuremberg Nazi party rally, Terzaghi considered the impressive demonstration of long-barreled guns and aircraft to be "a threatening pronouncement of the Fuehrer and his soldiers."[14] He observed that the public was opposed to the Minister of Finance, Hjalmar Schacht, whom Hitler later called a saboteur of rearmament, Terzaghi noting that "the people talk but don't hear." Thus, when Fritz Todt independently proposed to help Professor Terzaghi obtain a well-paying professorial position inside Germany, Karl let it drop.

The purpose of Karl's Christmas trip to Franzius in Hanover was to learn details of a tragedy that had occurred in central Berlin in August. An excavation for subway construction collapsed underneath Herman Goering Street, killing twenty workers. The excavation was supported by lateral struts and roofed to carry street traffic over the top. Terzaghi was asked to help clarify the causes of failure for the litigation. Because he was preparing to leave for Harvard, he refused, but agreed to examine the documents. The first chance to do that was on shipboard en route to America in January.

He became incensed to learn that the government was building its arguments as plaintiffs on the basis of the old Coulomb theory of earth pressure, in which the loads on struts restraining the walls of a deep excavation are predicted to increase linearly with depth. But Terzaghi's theoretical work, experience, and publications showed convincingly that the lateral earth pressure of the earth against braces for open excavations increases only down as far as about the mid-depth of the excavation; with further depth the earth pressure on the struts actually decreases.

He felt as if his own work were on trial, and thus changed his mind about helping the contractors' defense. He worked like a devil throughout the whole trip, and for the entire first week after arriving in New York on January 24, 1936, finally mailing his report from Boston. But it was all in vain; Franzius passed away in March, before the trial was to begin, and despite a bombardment of telegrams, Terzaghi had to refuse any immediate return to Germany to take his place in the trial. Without his testimony to expose the fallacies in the official soils analysis, his clients became scapegoats for the state.[15]

Terzaghi could not possibly have returned to Germany; he was in the midst of teaching a well-attended course at Harvard, and he was preparing to be the main attraction of Arthur's International Conference on Soil Mechanics. Arthur had been planning this very carefully and working long hours with his committee on its organization. The two corresponded about details for more than a year.

They wanted delegates with practical experience and sought to exclude pure theoreticians. By carefully picking leaders to form delegations from all the important countries on the world map of the young field, Arthur and Karl assured a tailor-made success for this meeting. In their deliberations, they were each able to express opinions about suitable nominees throughout the world, or knew someone who could. For example, Terzaghi wrote: "Mr. A is a disagreeable fellow. In Germany all conceivable combinations of members of this profession are enemies with each other. Mr. B has the advantage of being removed from the warring parties but is one from the old school. Mr. C is an evil comrade and doesn't understand much."[16] Nobody challenged their authority, or if they did, they kept still.

They both wanted Terzaghi's student, Juul Hvorslev, to attend and to contribute two papers; he was nominated for both the Danish and American delegations. But the poor man had many problems: he had to complete his dissertation and defend it; he lacked travel funds and didn't know how to ask; he couldn't find any way to reduce his papers to fit the maximum length, and it would take longer to write a short paper than a long one; having to write in English would make his papers useless for his thesis; the typist could only come at night; he cut his finger badly; he had a bad cold; he got stomach trouble; he got a jaw infection—and more. In the end he did not attend, but did submit his thesis and passed the examination with honors. Hvorslev's reputation for bad luck was on Terzaghi's mind on an earlier occasion when he was to accompany Arthur and Karl on a walking trip in the Alps. "Is Hvorslev coming?" Karl inquired. "Yes." "Then I'm not going—it's going to rain." And it did; in fact it poured.[17]

The conference started with an event at Rockefeller Center in New York on June 19 and continued at Harvard where 200 stimulated participants convened for a week. Terzaghi decided to stay with other delegates in a Harvard dormitory, which provided his diary much ammunition about personalities of soil mechanics. He was a very active participant. There is no doubt that the conference was a great triumph—*Engineering News Record* called it "a milestone in engineering history"—and there was a consensus that Terzaghi's addresses, articles, and discussions across the entire discipline were its high-points.

Terzaghi's long opening address, entitled "the relation between soil mechanics and foundation engineering" was a brilliant act, transfixing its hearers with a great sweep, penetrating logic, and commanding delivery. He traced the roots of soil mechanics in failures that warned engineers they were "overstepping the limits of our ability to predict the consequences of our action." Early research efforts, like his own, were performed by isolated groups, and in the mistaken search for a science of soil behavior analogous to fields like bridge design. He called this stage "the period of unwarranted optimism".

"Unfortunately, soils are made by nature and not by man," he said, "and the products of nature are always complex.... As soon as we pass from steel and concrete to earth, the omnipotence of theory ceases to exist." Natural soil is never uniform. "Its properties change from point to point while our knowledge of its properties are limited to those few spots at which the samples have been collected." Furthermore, its properties are too complicated for rigorous theory, and approximate mathematical solutions are difficult for even the most common problems. "In soil mechanics the accuracy of computed results never exceeds that of a crude estimate, and the principal function of theory consists in teaching us what and how to observe in the field ... Hence the center of gravity of research has shifted from the study, and the laboratory, into the construction camp where it will remain."

He went on to analyze historic conflict between theory and reality and the unwarranted generalizations published and used before the first world war (and in thinking of the Berlin subway collapse, enumerating some that were inexcusably still in fashion). Soil mechanics was attempting to clean up the field by forging general methods for numerically evaluating soils and reliable methods for observing the behavior of structures, and by expanding analyses to include all the vital factors, which means expanding the investigation target into a sufficiently large volume about the work. "This inauguration of a new era of direct and intimate contact between the engineer and his structures alone would suffice to justify the time and labor invested in soil mechanics during the brief period of its existence."

One week later, despite having to sit through a closing dinner having neither alcohol nor tobacco, President Terzaghi glowed in addressing a closure to the delegates. They were engineers from twenty lands but F.E. Schmitt had divided them into three groups: practitioners who came to learn, project men involved in field tests, and laboratory researchers. Terzaghi addressed each in turn.

The practitioners, being asked to discard overly simple, ready-made formulas "are entitled to ask what they are going to receive in exchange for the lost treasures. The answer is simple. Soil Science offers medical service based on sound though very fragmentary knowledge, in exchange for the service of the medicine-man."

The engineers involved in field tests, to be successful, need to have knowledge of physics, but also "an inquisitive attitude towards the ultimate purpose of their tests. Otherwise investigation degenerates into a habit comparable to the pious act of an old peasant woman who was found absorbed in prayer, while kneeling in front of a mile-stone on a mountain road. When a passing tourist asked her which saint this stone represented, she replied, 'I don't know, but he is certainly good for something.'"

The researchers in their soils laboratories should resist the temptation to invent new theories until their results have been confirmed by full-scale behavior in the field. "Premature publication of a theory may force its author to defend his thesis as the philosopher Hegel defended one of his physical deductions. When a physicist of the experimental type who attended the lecture dared to claim that Hegel's statements were in contradiction with the observed facts, the philosopher proudly retorted, "The worse for the facts."

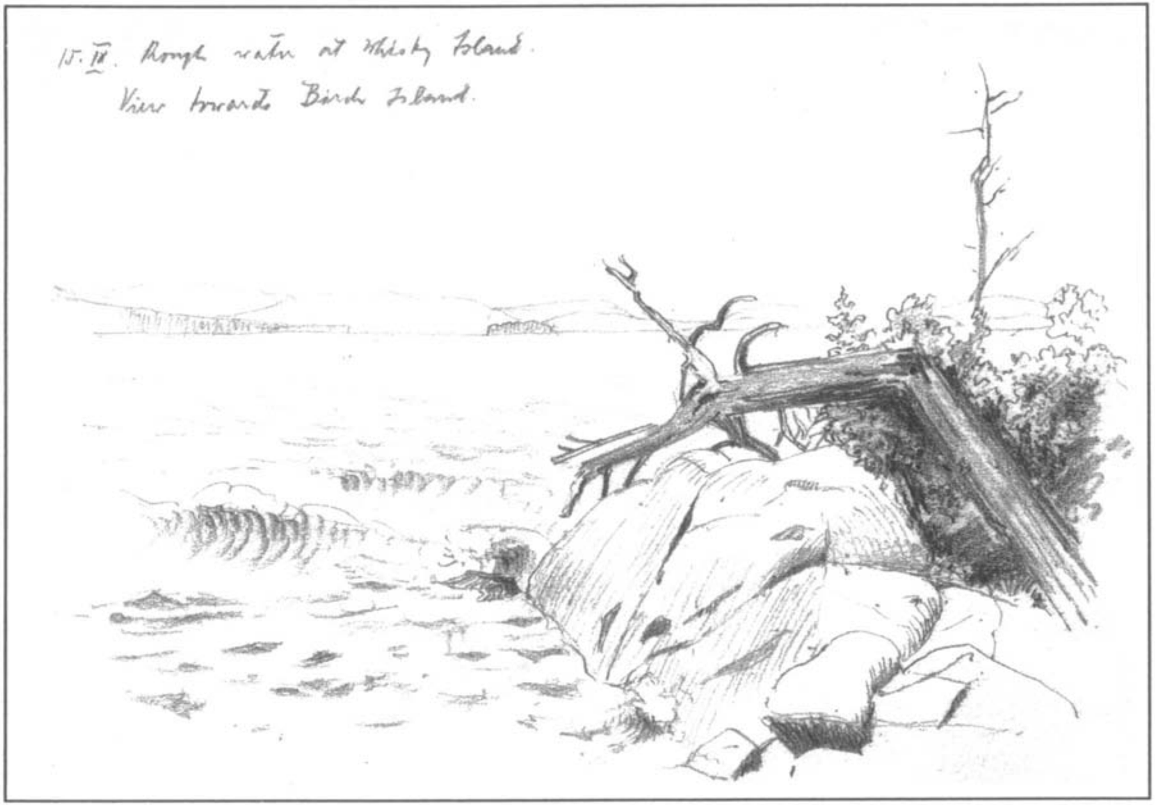
But Ruth topped this performance. At 8:30 a.m. on September 5, she gave birth to Eric Terzaghi, soon known as "Squeezix". As if to prove that this event would not transform his way of living, Karl embarked five days later on a six-week, coast-to-coast lecture tour and excursion. He could be excused for this aberration. The trip had been planned far in advance. More to the point, the whole idea of spending a sabbatical leave in America was to lay the groundwork for the family's permanent return. He had to discover for himself if this was really what he wanted to do.

Before his trip started, Arthur dampened Karl's hopes by revealing the extent to which the American depression had reduced chances to duplicate his Vienna living standard. Far from the conference opening a faculty slot at Harvard, its success was evoking jealousy from Arthur's colleagues, with a potential backlash against soil mechanics. Furthermore, opportunities for employment with the federal govenment were not bright. Federal construction was in the hands of the Army Engineers, the Tennessee Valley Authority, and the Bureau of Reclamation. The army engineers had grown tenfold under Roosevelt, but he said they followed the West Point mentality of engineering, working mainly from printed formulas. The T.V.A. seemed to want only concrete structures. The Reclamation Bureau was similar; their soils lab was just an arm of the cement lab, and there was little interest in progress. In any event, salaries were low everywhere, nothing equivalent to what he had in Vienna. As director of a new soils lab at Purdue University, Philip Rutledge was getting $3,200 per year. The top professor at Illinois might make $10,000.

It seemed to Karl that he would be going back to Europe to stay. But the lecture trip was on; it proved to be a magnificent excursion, a kind of replay of 1912 but always in First Class. Wherever he lectured, the reception was overflowing and greatly enthusiastic. The itinerary: Ohio with the Corps of Engineers; Chicago with engineer V.D. Simons; the University of Illinois with Prof. Harald Westergaard; Denver with the Bureau of Reclamation; Portland and Bonneville Dam in Terzaghi's own Columbia Gorge; Seattle and dams on the Skagit River; Moscow, Idaho, where the University campus reminded Karl of Robert College; highway geology from Grant's Pass to Sacramento; San Francisco and the new SF/Oakland and Golden Gate bridges; Stanford University; Los Angeles and big irrigation and flood control dams under construction; Cal Tech at Pasadena; Boulder Dam; and, finally, landslides near Cleveland.

At all the stops, he was lavishly entertained and personally escorted to the best attractions. At Illinois, where he gave three lectures and two talks, every lunch and dinner was an organized affair. In Seattle, his M.I.T. friend Dick Tyler, now Dean of Engineering at the University of Washington, took him to Mount Ranier, the Olympic Peninsula, and Grand Coulee, and invited him to talk to a gathering of friends on Soviet Russia (who refused to believe his negativism about Russian communism). Los Angeles' pioneer soils engineer R.V. (Cap) LaBarre, sent his personal car to San Francisco to bring Karl to L.A. by way of Yosemite and the Owens Valley. There were many dinner parties in his honor, including one hosted by Von Karman at his home in Pasadena. In Denver, a Bureau of Reclamation engineer "of the old school" first told a colleague, "That man is too darned theoretical," then told him again, later, "Why that man has ten times more experience than I have."

He returned to his family on October 19, and together they sailed away on October 21, 1936. "The departure was difficult," he wrote, "as if I had known what surprise was going to greet me in Europe."[18]



Moosehead Lake, Maine, 1929.
Terzaghi thought to make a "topographic, geologic, and jointing map" of Whisky Island during his vacation.

12

Soil Mechanics on Trial—The Nadir 1936–1937

Professor Wittenbauer had warned that the Austrian Ivory Tower was "an evil society". Karl Terzaghi discovered this for himself on November 24, shortly after his return to Vienna, at the Austrian Society of Architects and Engineers. As Prof. Tillmann, head of the Austrian delegation to the Harvard conference, completed an enthusiastic report on the proceedings, a scholarly appearing man with a dark moustache, Professor Paul Fillunger, arrogantly stood up in the front row to declare he held a different opinion of soil mechanics that would soon be stated. Terzaghi uttered some remark that brought general laughter, and that was that.

The promised statement came on December 3 in the form of a slanderous 47-page-pamphlet entitled "Erdbaumechanik ?", a thousand copies having been printed and distributed by Fillunger throughout European academic and engineering circles. It contested the correctness of the theory of consolidation, attempted to smear the name of soil mechanics, and most particularly to undermine the reputations of Karl Terzaghi and Otto Fröhlich, the recent coauthor with Terzaghi of a practical manual on consolidation theory.[1] Fröhlich, Terzaghi, all the assistants, Professor Schaffernak, and very soon the entire soil mechanics community became incensed against the errors, distortions, and vulgarity of Fillunger's tract.

The document made fun of the idea that estimating such a common occurrence as the settlement of a building warranted soil tests and calculations. The tests they perform belong in an agricultural station, not in an engineering department. Empirical factors like the coefficient of friction, which Terzaghi discusses, have been used for a long time by practicing engineers as crude devices to make rough calculations, and Terzaghi's juggling offers no advance, except to provide him a good income. Soil mechanics theory is nonsense. Next, Fillunger showed how a theory of consolidation ought to be formulated. He used a mathematical, rather than a physical, approach. The resulting differential equation was complex, and he did not suggest a way to solve it.[2]

On overcoming his rage on browsing this document, Terzaghi laughed that his "opponent" had so exposed his weaknesses.[3] Fillunger had been Terzaghi's opponent since 1933.

Paul Fillunger was born in the same year as Karl Terzaghi, the son of a railway engineer. He also received his education in mechanical engineering, but at the Technische Hochschule in Vienna. Before the first world war, he taught mechanics and materials in a technical school in Vienna,[4] and in 1922, he acquired his present position at his alma mater. He became a specialist in elasticity and plasticity theory, and was accomplished in mathematics.[5] Ironically, Fillunger also served at Aspern airfield during the war.

Starting in 1913, Fillunger became interested in the problem of formulating the upward force of water on concrete gravity dams. A gravity dam is designed to resist the horizontal thrust of the water in its reservoir by virtue of its own weight. If made sufficiently heavy, and correctly shaped, such a dam can neither slide on its base nor overturn about its toe. On the other hand, if the water underneath the dam exerts a large upward force ("uplift"), the weight of the dam is partly nullified, and the safety against sliding and overturning is lessened. Thus, the correct prediction of the uplift force produced by the water seeping under the dam is directly connected with dam safety.

Traditionally, this force had been calculated by assuming the dam had a horizontal crack of assumed dimensions at its base or in the concrete, in which case the upward force of the water in the crack could easily be calculated from well-known laws of hydrostatics. Fillunger argued that concrete is not a watertight block but a porous material whose inner pores hold and transmit water. From this perspective, he introduced a new formula for the calculation of uplift, one that yielded a considerably smaller uplift force and therefore made dams less expensive.

Having developed the effective stress principle for soils, Terzaghi was terribly interested in all work relating to prediction of water pressure inside the pores of soils, or porous solids. Since he was also a consultant on design and construction of dams, he was motivated to learn whatever he needed in order to design them to be safe. Therefore, when he learned that his colleague Professor Fillunger had published a method to compute the uplift force within concrete, based on the model of a porous medium, he felt motivated to read and understand it. Unfortunately, Fillunger's formula made no sense to Terzaghi; it could not be derived from any physical picture, and it seemed to give an unreasonable answer.

In a porous medium represented by a collection of solid grains and water-filled spaces, it follows from Archimedes' principle that if the pore water is in equilibrium (that is, if there are no excess pore pressures), the water decreases the wet unit weight of the medium by the amount of the unit weight of water.[6] This effect is called a "buoyant" uplift force, or simply "buoyancy". The buoyant uplift force in a porous aggregate is independent of the proportion of pore space ("porosity").

According to Terzaghi, Fillunger's formula prescribed that in concrete the buoyant force is measured by the product of the weight-per-unit-volume of the water, and the difference in porosity between that of the stone (the "aggregate") and the mortar (sand and cement) mixed with it.[7]

Suppose a concrete were made, reasoned Terzaghi, with its stone aggregate replaced by hardened lumps of mortar. Using Fillunger's formula, such a concrete when submerged in water would be calculated to have no buoyant uplift force at all, because the aggregate and mortar would then have equal porosities, making the difference in porosity values equal to zero. Now such a concrete is nothing more than mortar itself, and as mortar is a porous material, the Fillunger formula is giving a nonsensical answer. Furthermore, its mistake is on the unsafe side, that is it undervalues hydrostatic uplift and endangers dams. After the second attempt to communicate this to Fillunger, on December 10, 1932, he wrote that he had suffered "an unheartwarming debate with Fillunger, whose awkward, unworldly theory remains shrouded in unclearness and fallacies."[8]

Perhaps there was something about concrete that would make it behave differently than an ideal porous medium, thought Terzaghi. He derived the conclusion that the extent to which a concrete specimen would obey his effective stress law for strength would accurately measure the extent to which it would approach the ideal porous medium with respect to uplift force. With assistance from Rendulic and support from the Austrian Concrete Institute, he began a series of laboratory tests in 1933. These confirmed that the specimens of concrete almost perfectly obeyed the effective stress law and were therefore almost perfect porous media. He concluded that Fillunger's uplift formula was surely incorrect.[9]

Terzaghi considered it his "duty to establish the facts of the matter, taking the greatest possible care to spare the originator of the old theory".[10] Accordingly he wrote an article for publication but proposed to Fillunger that he read it first and suggest changes before publication. He also suggested that Fillunger prepare a rebuttal to be included with Terzaghi's point of view in a paper of joint authorship. But Fillunger became defensive, as he had done once before when his uplift formula was questioned by another.[11] Terzaghi noted "Instead of considering my offer, Fillunger rejected my arguments wholesale and used the publication of my work as the alarm bell."[12] Then, in November, Terzaghi wrote, "Fillunger is so stubborn about his mental confusion that he never will grasp it. He demanded, in friendship, on December 31 that I withdraw my work, or else he would shatter the air."[13] Terzaghi tried to reason with him again in February, 1934, in the midst of the short Austrian civil war, and was "fundamentally rebuffed".[14] So Terzaghi and Rendulic published their paper and a series of unfriendly discussions in print followed, the publisher warning his readers that he took no responsibility for what was said.

Paul Fillunger was obviously insecure, if not sick. He must have been jealous of Terzaghi, who waltzed into his Hochschule with a top salary and much fanfare and was given money to equip a soils laboratory. Terzaghi's challenge was a serious matter because Fillunger's uplift recommendations had been published a number of times and were being used in industry so that an admission of error would reflect badly on him; it might even raise questions about the safety of some existing dams. Terzaghi had not only challenged his work, but came from a neighboring chair in a different field to do so, infringing on "his turf", a practice that ignites sparks even in contemporary American universities. Fillunger must not have studied *Erdbaumechanik* very carefully for he misinterpreted steps in Terzaghi's approximate approach to the theory of consolidation. He had the mathematician's distaste for imprecise formulation, but then he was supposed to be an engineer.

Terzaghi, on his side, had acquired some misgivings about mathematics and mathematicians. He felt that their method of developing hypotheses in the mind leads one away from physical reality, weakens one's self-critical spirit, and destroys instincts about the real limits imposed by nature.[15] He liked to quip that "mathematicians should be kept in cages and fed problems through the bars", explaining that "mathematicians are usually undesirable members of engineering communities unless their function is strictly limited to that of calculating machines. They are fit neither for properly formulating the problems—which requires intuition—nor for adapting their findings to practical conditions—which requires judgement."[16] Later he described a mathematician as someone who could solve every equation but would fail to notice a misplaced decimal point. He continued, "Once every few months I get a manuscript full of differential equations describing a revolutionary discovery in the realm of theoretical soil mechanics for review and comments. I have composed a sort of standard letter for my reply and the manuscripts are tucked away in a fat file labeled "Nut House".[17] Thus, when Terzaghi referred to Fillunger as "a psychopathic mathematician", he may have been heaping insult on injury.

So in December, 1936, when Fillunger published his tract *Erdbaumechanik ?*, Karl did not take it lightly. It became clear that this was going to be, as Schaffernak announced, a war of life and death; he *must* act. Terzaghi and Fröhlich sought advice from their most trusted friends, railroad engineering Professor Orley, and hydraulics professor Fritz Schaffernak, and each went to work to draft a written reply. Karl proposed raising a suit of slander in the courts, but was advised against it, as a psychiatric defense could cloud its outcome. It would be better to bring the matter up through the faculty governing body—the Kollegium—charging that Terzaghi's professional standing, teaching, and research had been damaged by another professor.

An Austrian university at this time consisted of a relatively few chaired professors, each of whom was essentially a head of his own department. It was no simple matter to resolve a feud between two of them. At a stormy meeting, the Rector announced that disciplinary hearings against Professor Fillunger would begin. However, the first action of the disciplinary committee was to request that their work be joined by that of a special committee of faculty experts to evaluate the technical issues. The Rector agreed to appoint such a committee, with suggestions on its membership to be received from the protagonists. On December 23, the disciplinary hearings commenced under examining magistrate Dr. Goldberg, with a five-hour examination of Fillunger, who assured the magistrate of his high esteem for Karl Terzaghi and Otto Fröhlich.

Meanwhile, nasty rumors reaching Terzaghi's friends demonstrated that Fillunger's tactics were serving their evil intent. Terzaghi had recommended Otto Fröhlich for a faculty position in Prague; now the faculty at Prague, believing the smear, withdrew Fröhlich's name from the list. The professor of reinforced concrete, Saliger, who was a confidante of Fillunger, reported rumors he heard in Germany that Terzaghi advanced his students to degrees only to reward them for consulting work. Worse, Terzaghi's name was now beginning to be blamed for the cost overruns of the Vienna Reichsbridge reconstruction; his flawed theory of foundation engineering, it was whispered, was behind the improper decision to build a suspension bridge in the unsuitable soil. If there was any doubt about the source of at least this last rumor, it was eclipsed by the appearance at Christmas of a new Fillunger product making these specific charges.

For the all important committee of experts, Terzaghi pinned his hopes on the participation of Schaffernak and Orley. But on December 27, a sobbing voice on the telephone informed him that Professor Orley had become very ill and died, even before the doctor arrived. This was a hard blow, only slightly comforted by the Rector's statement in the funeral service that Professor Orley had "never distorted science for personal reasons". At a memorial meeting for Professor Orley subsequently planned by the students, Fillunger sat in an empty row in a room that was otherwise crammed full. Emboldened by this apparent show of support for him, Terzaghi declared he would not lecture until Fillunger had been suspended: "Either him, or me."[18] But the Rector ruled he would have to continue lecturing. Even worse, over Karl's protests, Professor Saliger was named to the expert committee.

Terzaghi worked strenuously and exclusively on his defense and restitution. The twin committee proceedings included formal judicial hearings, conducted with courtroom conventions. Although he lacked legal training, Terzaghi found he could function effectively as his own counselor. The strategy had three parts: obtaining letters of support from around the world; drafting replies and rebuttals to the smears and testimony; and publishing a clear exposition of the great worth of soil mechanics.

Outrage among practitioners of the new profession was expectably demonstrative; from around the world arrived letters and telegrams attacking Fillunger's tract. As Hvorslev wrote, "His attempt to discredit the new science of foundations concerns of course not only you and Dr. Fröhlich but everybody who is working with it or interested in it, and how many those are, the conference at Cambridge clearly showed. He is of course in for an awful licking."

Arthur Casagrande wrote to His Magnificence (the Rector) that Fillunger would have seen for himself in Cambridge with what adulation the world now holds Terzaghi and his work and how practical it has proved to be.[19] Casagrande then began a program to obtain official letters to the Rector from the top leadership of ASCE, under the code name "Action Doggie", christened by his nickname for Ruth.[20] Austrians love nicknames. Karl called Ruth "Wackelwix" (abbreviated wwx) and she called him "Bear", which now most certainly applied.

With Fröhlich, Terzaghi now produced a comprehensive 35-page pamphlet "Soil mechanics and construction practice—a clarification".[21] They arranged for its publication as a Separate by their publisher Franz Deuticke and, on February 6, 1937, distributed it to all the 64 members of the faculty at the Technische Hochschule and some 200 other influential engineers, officials, professors, and friends throughout the world. This brochure was a patient, thorough, and unprovocative rebuttal of the negative assertions in Fillunger's tract and an uplifting, persuasive argument in favor of soil mechanics research. Soil mechanics, it reflected, arose out of urgent need almost simultaneously in four different countries, and its practical successes are unquestionable in almost all fields of construction. Since Herr Fillunger is a pure theoretician, it is not surprising that his assertions are so wide of the mark.

At first it appeared to Terzaghi that the committee of experts was moving against him. Terzaghi's suggested replacement for Orley, the Reichsbridge contractor Dr. Goldemund, was apparently coerced by Saliger to refuse the appointment. Instead of moving rapidly in evaluation of alleged harm done to Terzaghi, the committee of experts undertook a deliberate and thorough reading of his theory of consolidation. Terzaghi warned the general secretary of the Austrian Society of Architects and Engineers that he was preparing to lay the matter on their plate if the Technische Hochschule did not soon produce a report condemning Fillunger.

The analysis began to turn gradually towards Terzaghi as the experts on the Committee applied themselves diligently and succeeded in coming to grips with what Terzaghi had actually accomplished. On January 20, physics professor Flamm, an expert on the electromagnetic theory of light, delivered a brilliant analysis demonstrating that Fillunger's equation reduced exactly to Terzaghi's formulation if nonessential factors were omitted. Subsequently, Schaffernak constructed a model, using a sponge to represent saturated clay, which demonstrated neatly how the application of a sudden load immediately yields a jump in water pressure within the clay.

On January 30, Fillunger had a shouting argument with Saliger audible through the tightly shut office door, provoking the students to gather in the lobby. When Fillunger again took the stand, four days later, in place of the normal arrogance and defiance, he appeared uncertain and weak.

On February 14, Professor Schaffernak fell ill and was hospitalized with pneumonia. Terzaghi felt frightened, but needlessly so. As Terzaghi arrived at the Technische Hochschule on the morning of March 8, the press was on the phone wanting to know about the double suicide of Professor Paul Fillunger and his wife Margarete.

They had taken poison and then opened the gas in their flat. There was a farewell letter in two parts. The first, penned in a steady hand on January 30, stated that he saw his own error and regretted the slander inflicted on Professor Terzaghi. The second, from March 6, written in a distracted hand, stated his last hope for putting the matter right had vanished. He praised his brave wife for following him of her own free will.[22]

Terzaghi wrote: " Thus the carelessly prepared attack on soil mechanics and on me personally had come to a tragic end and with it also the life of a man whose true abilities would never be judged ... Just as greed in the world of business produces martyrs, so excessive need for recognition in the academic world produces traitors to science, undermines psychological equilibria, and disturbs the growth of knowledge. "

His bitterness against academia was unbounded. "The faculty holds itself out as the last and highest authority in all science. In reality it is in large part comprised of people who take possession of the arduous creations of the mind, transform them into dogma, and then close off further advance.... The types of men to whom they owe the contents of their life are at the same time their opponents. They pursue creative men as long as they live and celebrate them unctuously a century after their death. Their highest ambition is to faithfully use the rules they have learned, without considering further whether their results are right or wrong.... Many who are making pathbreaking advances must resist the iron wills of the official representatives of science."[23]

Terzaghi's assertion that Fillunger's true abilities would now never be judged was not correct. Sixty years later, de Boer, Schiffman, and Gibson,[24] carefully examining Fillunger's mathematical derivation, concluded that he had correctly formulated what is now accepted as the mechanics of porous media, thirty years ahead of his time.

Terzaghi and all the faculty were at first shaken by the news of Fillunger's death, which the Rector called "heroic". Karl had to consult a doctor about his nervous exhaustion, complaining to Fritz Schaffernak that his physical ruination was likely a part of Fillunger's grand design for his destruction. A week later he had recovered a light heart and was ready to redeem his reputation as an engineering consultant. He would set the record straight concerning the Reichsbridge project in a public lecture before the Society of Architects and Engineers.

To promote this event, he used the opportunity provided by the formal presentation of the Kollegium's conclusions, entirely favorable to Terzaghi, on April 21. At the end of this session, he took the stage to explain briefly how Fillunger's disinformation had misrepresented Terzaghi's role in the cost overrun of the Reichsbridge project, and he invited attendance at his lecture on this subject to be held April 30. The word spread widely, bringing a full, but not necessarily sympathetic, audience. The air was tense as he began.

"Gentlemen! Before I embark on my purpose I will say a few words about the reason for the lecture. I can say without exaggeration that for twenty years I have had almost no private life, since research in my own selected field claimed not only my energy but also almost all of my time. In 1929, when the Austrian Ministry for Education in collaboration with the Austrian Society of Architects and Engineers called me to a beautiful and restful working circle in Vienna, I had no foreboding that both my political convictions and my professional utterances would become the object of lively and not always beneficial interest. Before the year 1929 my political activities were restricted to occasionally reading the paper. A few years ago, without concern, I was the bearer of dangerous political ideas. The Fatherland denoted me as a Nazi, the Nazis as a Bolshevik, and the Bolsheviks as a conservative individualist. Certainly only one of the three could be right and that one is the Bolsheviks."

He then delivered a masterful technical lecture that won the day. Shortly afterwards, he took his family on a trip to the Adriatic and on returning discovered he had been elected to the Austrian Academy of Sciences.[25] Professor Karl Terzaghi was back, but not to stay.

13
Escape through External Consulting 1937–1938

Understandably, the academic world in mid-1937 was no longer Terzaghi's first interest. He fortunately managed to escape from Vienna frequently for a series of consulting assignments in Austria, Sweden, Latvia, France, Algeria, Italy, and England.

Early in September of 1937, VBB[1] brought Terzaghi to the Duna River of Latvia where the Kegums powerhouse and concrete dam were being constructed on horizontal beds of dolomitic limestone, with soft, marl interlayers. The expected quantity of seepage through the foundation, and consequent high uplift pressures on the dam, led the engineers to try to tighten the rock by grouting. When Terzaghi arrived, Sentab Company was pumping cement slurry through drillholes into the foundation rock.

By carefully observing the walls of a test shaft, Terzaghi determined the grout was not penetrating soil-filled cracks in the dolomite. He imagined that the incomplete grouting in the foundation would actually increase the velocity of water seeping in these cracks, washing out the soil fillings. By this process, in time the water-tightness of the foundation would deteriorate, allowing destabilizing pore-water pressures to build beneath the downstream portion of the foundation.

To prevent such a process, Terzaghi proposed an entirely novel approach. He had observed that sections of the foundation surface were heaving up significantly as grout was emplaced below them; the heave meant that the grout, instead of running into pre-existing rock fractures, was opening up new, horizontal cracks and filling them to make a horizontal lens of cement in the ground. He proposed to use this behavior as a construction technique, controlled by levelling surveys to monitor the pattern of heaving, in order to create a series of horizontal lenses upstream of the dam. This would slow the rate of erosion of soils out of cracks in the foundation rock by lengthening the seepage path for ground water, with the effect that the hydraulic gradient and therefore the velocity of water flow would be reduced. In other words, he was proposing to hydraulically fracture the foundation to create a series of impervious, horizontal layers of hardened grout. These would extend well upstream of the dam, 150 meters out under the reservoir. Techniques like this are now used routinely by the oil industry, but to *promote* flow, by filling the hydraulic fractures with sand, rather than to *impede* flow by filling them with cement grout.

In Italy, Karl worked on the investigations of a dam to raise an existing lake, Lago di Mezzo. The foundation geology was horribly complex as stream deposits in an alluvial fan interfingered with old lakebed clays and nearshore sands and silts. This geology set a danger that intermittent clay beds could confine a pervious aquifer (water-transmitting layer) that would bring reservoir water heads directly under the downstream part of the dam. He interpreted this potential from the results of borehole groundwater pumping tests, developing from the test data a snapshot of lateral changes in the thickness of the aquifer around the test wells by observing lateral changes in the slope of the groundwater surface. He then showed how to analyze horizontal flow rates and pressures in aquifers having variable thickness by extending Forchheimer's flownet concept.

No one could be certain of a specific geologic interpretation in such a complex subsurface, but the details of the dam's defense mechanisms might prove dangerously inadequate without this certainty. Terzaghi began to appreciate that good engineering here required an observational approach, making use of the performance of the dam as the reservoir rises for the first time. In his report to the designers, Montecatini, he prescribed the procedure that was to become his trademark in future years, a procedure that is covered by Mark Twain's personal maxim "Supposing is good, but finding out is better."[2]

"The basic assumptions for the design of a storage dam on a permeable foundation are always obtained by means of a very radical simplification of reality and we can never know in advance the nature and importance of the difference between theory and reality. For this reason, the first filling of the reservoir behind *every* storage dam on a foundation other than solid rock should be considered a large-scale experiment with a doubtful outcome. In order to be able to discover the existence of an important difference between our anticipations and reality before it is too late, it is necessary to establish at the dam site all the devices required for observing the rise of the phreatic surface[3] and the increase of the amount of seepage while the water level in the reservoir goes up. As soon as an unexpected development occurs during this process the water level in the reservoir should be kept stationary until the measures of defense have been adapted to the newly revealed conditions."[4]

Knowing that he had broken with Rodio, Francois Cementation, their archrival, reached out gingerly to get Terzaghi in their employ. They approached through their French affiliate "Les Travaux Souterrain" by means of his former assistant, Karl Langer, (who was now living in Paris running a soil mechanics laboratory for the French insurance industry). Terzaghi agreed to advise on two of their most difficult projects, the Ghrib and Beni-Bahdel dams in Algeria.

The delicate problem at Ghrib proves the aptness of his prescription for Lago di Mezzo. The rock-fill dam had been almost completed and, as the reservoir rose, a weakly flowing stream of seepage water emerged from the natural slope downstream of the dam. He was asked if the reservoir could be filled to the top. After initial study he said "No", for in its present condition it would probably fail by piping.

The sixty-meter-high Ghrib dam rests on broken shales and sandstones, with layers of uncemented fine sand, quite similar to the foundation material of Bou Hanifia. His clients had spent the equivalent of 1.5 million dollars grouting a watertight curtain, and their design assumed it functioned perfectly to prevent the passage of water under or around the dam. If this proved to be true, the agreement specified that the contractor would receive a large bonus; if the grouting functioned imperfectly, he would be assessed significant penalties.

To measure how well the grout curtain was actually performing, Terzaghi had boreholes drilled immediately upstream and downstream to observe the level to which water rose in them. If the grouting worked as the contractor insisted, there must be a difference in the water levels in these observation wells; but there was no significant difference, no drop in head across the supposed groundwater barrier. He had demonstrated just what he had warned for Bou Hanifia after his model studies.

Not only was this revelation embarrassing to his clients, but it suggested the dam would become dangerous as the water level rose in the reservoir unless the gaps could be located and plugged, or (better) the seepage caught in filtered drains. An exploratory shaft in the grouted zone revealed that the culprit was a series of fine sand layers, up to ten feet thick, which remained devoid of grout. The problem was complicated by the fact that the downstream exit for seepage water from some of these layers had been buried beneath the rock fill. Compounding the difficulty, he discovered that the sandstone holding a portion of the abutment would lose its natural cement and change in place into loose sand just on becoming wet; he predicted a large, dangerous landslide if the seepage water reached that region.

The solution was found in a variety of very extensive and difficult drain tunnels, shafts, and tiles, designed under Terzaghi's nit-picking supervision. As he later observed: "If I had designed the dam I would not even have thought of trusting the grout curtain and I would have protected the dam from the very start by means of inverted filters as I did in Bou Hanifia."[5]

Terzaghi must have been amazed when he inspected the plans for the just-completed Beni-Bahdel dam, designed by the famous Swiss engineer Stucky. The daring structure consisted of multiple, thin, inclined, reinforced-concrete cylindrical arches. They were placed in an unsymmetrical angular valley onto obliquely inclined layers of hard sandstones and softer, erodible clay-shales. Cracking had been detected in one of the concrete buttresses, and he was asked to determine the cause. Although Terzaghi was not to visit the site for another five weeks, he quickly produced a strongly worded report on the extreme hazards which this dam was now facing.

The buttress cracks, so troubling to the designer, did not worry Terzaghi as much as the very high hydraulic gradient that the dam setup across the layers of rock. He found similarity in the geological situation on the steep right abutment downstream of the dam with that of three dams that had been destroyed by piping.[6] The foundation was even more dangerous on the gentler natural slope below the left side of the dam; here the hillside was a "dip slope", meaning that the ground surface conformed exactly to the upper surface of one sandstone bed. This implied that the steep dam abutment was overloading a single inclined column of sandstone resting on shale. Jumbo Dam in Colorado failed when such a column buckled under uplift pressure.

He determined how high the water pressure would have to rise in the rock to fail the inclined column, and designed drainage works for the slope that assured it could never reach that high a value. Without this work, Beni-Bahdel dam would likely have collapsed. It was a familiar pattern: the responsible structural engineer missed the big picture.

Reflecting on these kinds of successes ten years later, Karl confided to a friend that they all had one feature in common. Soon after his arrival at a site he would observe vital details overlooked by everybody else on the job. Having recognized the elements of the problem, it was then fairly straightforward to find an adequate solution.

Many persons know soil mechanics and geology as well as he does, he asserted; but often they lack "automatic reaction to the manifestations of nature ... The average engineer does not see things as they are. He sees them as they should be according to what he has read in textbooks and heard in the classroom. He is an artisan and not an artist. Science is produced by artists and used by artisans. In primitive communities which are not yet contaminated by science, every member is an artist of a sort. By contrast, under our conditions of living, most people are union laborers of a sort and the artists are the odd characters—pathological specimens who get their chief satisfaction not out of the money they earn or the honors they receive but out of the work itself."[7]

Karl Terzaghi, July 1937.

Terzaghi with grouting contractors with whom he worked in the 1930s (left to right): Ischy, Daxelhofer, and Rodio. Photo taken in Zurich, 1949.

The problems of Algerian dams were solved by using Terzaghi's designs for filtered drainage. There was a growing demand for this technology throughout the world, and there was money to be made in their design and installation. Thus, it was expectable that sooner or later some company would offer to license his patents and to propose some kind of working agreement whereby Terzaghi could grow richer without always having to become personally involved. When he received just such an offer, however, from engineer Anton Grzywienski in Vienna, Terzaghi refused to cooperate, explaining that his filter removes only one of the many areas of uncertainty in connection with dams, and he would not take a chance in having his name destroyed by someone else's failure.[8]

He told Grzywienski that the foundation of a dam may fail without warning, taking with it the reputations of even those who had only a small part to play. Therefore, he made it a hard rule that his name could be used in a job only if all the preparatory foundation work were placed under his personal supervision. And, by the way, Karl Terzaghi didn't need any special agreements to get jobs because, as he explained, it was in the best interests of any engineer's clients to retain him wherever it is their impression that he could find a better solution than anyone else.

These conditions were well satisfied by his call to England in March of 1938. On returning to Paris from North Africa, Karl received a telegram from the contracting firm Siemens Bau Union in Berlin asking if he would help an affiliate in England solve an earthdam construction problem. On Friday morning, April 22, he phoned London and asked them for more information; a few hours later he received a visit from Sir Robert Wynne-Edwards, Job Engineer on the construction of Chingford Dam No. 2.

The affable blond, blue-eyed Wynne-Edwards solemnly spread out plans, profiles, and borehole data. After inspecting them, Terzaghi asked where the dam was located and was told it lay fourteen miles north of London Bridge. He then said: "That dam must have been designed by an enemy of the British nation because it will fail, whereupon your Parliament and Westminster Abbey may be washed into the Thames." Now the visitor smiled as he reported that it had already failed. Terzaghi asked what instructions he received from his boss. The reply: "To watch your face while you look at the profiles. If you don't show any signs of disapproval, I should take my hat and go. If you are shocked, I should put you into an airplane and bring you over."[9]

Chingford Dam was to be a five-and-a-half-kilometer long embankment varying in intended height from eleven to thirteen meters above the base. But as the embankment fill reached a height of only seven meters, a water pipe broke and the toe started to bulge; two days later cracks formed as a twenty-meter width of the dam dropped seventy centimeters and moved out four meters. Later, another section that was just approaching this height had also begun to fail. It was a classic case: the dam had reached a critical, maximum height such that its weak clay foundation was yielding. Fortunately, the failure occurred before there was any water stored, for the release that would follow reservoir breaching could flood a part of urban London, with enormous damage and death.

The English engineering response to the first failure was to flatten the slopes of the dam. They also proposed to delay further embankment construction to allow pore pressures in the foundation clay to dissipate. Terzaghi showed that the failure would occur regardless of the embankment's sideslopes because the fill was simply being piled too high for the strength of the yellow clay beneath it. It hardly mattered what inclination its sideslopes were given; the foundation would still fail. This revelation, and Terzaghi's correct instruction that they could never wait long enough for these clays to reap a meaningful pore-pressure dissipation, were a hard lesson to the British.

To add to the misery, Terzaghi discovered that the existing King George Reservoir, upstream from Chingford, which had been used as a kind of model for Chingford, was itself close to the failure point. It was a pure matter of chance, he asserted, as to whether it survived or failed—hardly a standard to be imitated.

Terzaghi was very polite with his hosts but he expressed his true feelings to Arthur Casagrande.[10] Their design was ridiculous. "Never, outside of Soviet Russia have I encountered such appalling blunders." But it gave the chance to show what soil mechanics could do "and I took full advantage of the situation." The British were cooperative and glad to be supported. He was told that the Chingford case advanced British soil mechanics by twenty years. They were even talking about hosting the next international conference. As one of Karl's friends told Ruth, the British were always late, but never too late.

To find out if the Chingford foundation weakness was confined to specific sectors of the foundation, Terzaghi offered the unusual suggestion of building the entire length of the embankment according to the original plan until every part was beginning to yield. This would determine the actual strength of every part of the long foundation, which most likely varied greatly from point to point, allowing the redesign to be tailored to the site conditions and saving a good deal of money. Unfortunately, this did not turn out to be a feasible course. Ultimately, the project was delicately reconfigured under his supervision.[11]

The center of gravity of Karl's consulting work was definitely now shifting—to the French, whose impractical flirtations with theory and overreliance on computed results he disliked intensely, and to the English, whom he had always thought to be "unpromising".[12] In truth, interaction and friendship with intelligent British engineers Binnie (whom he described as Pickwickian), Wynne-Edwards, and others was proving very agreeable; the Oxford and Cambridge clubs to which they took him harked back to the University Club in M.I.T.'s Cambridge, and the Institution of Civil Engineers, if musty and dusty, was highly dignified. He seriously considered settling here permanently.

He quickly became a regular consultant to Mowlem, Ltd., and Wynne-Edwards launched an effort to affiliate that company with Francois Cementation, with some kind of Terzaghi participation. Wynne-Edwards also stimulated Imperial College to try to appoint him to their faculty. The Building Research Station at Watford, whose soil tests for Chingford Dam had been one of its first such efforts, now proposed Terzaghi become their regular consultant on soils and foundations. It was here that Karl met and influenced young Alec Skempton, who would lead British soil mechanics in the years to come. The Research Station's director, Stradling, told Terzaghi that he had no trouble obtaining jobs for the organization but looked to him to supply what they most lacked—experience. Stradling also arranged for Karl to advise the Southern Railway in their long battle against landslide hazards along its line near Folkestone.

The landslides of the "Folkestone Warren", a reentrant three-kilometers-long and 300 meters wide on the coast between Folkestone and Dover, were older and bigger than the railway. They involved periodic large movements of giant blocks of chalk, which by some miracle had never killed anyone but had caused considerable damage. During the first world war, slides blocked the route to all train traffic for three years. Now, recent movements cracked the tunnel that made possible their relocated route, and the railroad planned a fairly extensive remediation.

Terzaghi noted with surprise that the historic movements of the slide had not produced any visible evidence of compression, such as thrust faults in the clay below the chalk, or compression ridges on the strip along the shoreline, whereas such features are usual at the toe of a large slide. He came to the opinion that the problem was driven mainly by erosion from the sea, possibly also involving dissolution of finely broken chalk debris; thus, he agreed with the railroad that improvement of the seawall would go to the heart of defense. He also proposed some regrading of dangerous steep landslide topography and adoption of good surveillance measures. The railway's problem, he told them, was like defending a long military line with too few troops; it would be better to use scouts and reserve forces for an emergency than to spread the limited forces out over the whole line and then risk a massive breach.

In December, 1940, two and a half years after his first visit, the mechanism causing the sliding suddenly dawned on him: the instability of the entire section of coast must be caused by unusually high water pressures in the pervious sandstone (the "lower greensand formation") that underlies the less-pervious stiff clay of the Gault Formation. The chalk, which lies above the Gault clay, must ride with it along the upper surface of the greensand, buoyed by the high uplift pressure. No compression features would be visible on land because they would occur out under the sea, where the surface of the greensand "daylights".

He was "so excited that it affected his dreams".[13] He asked for measurement of groundwater pressure levels in the greensand, more than twenty meters below sea level, by installing an instrument (a "piezometer") from an existing shaft. The results confirmed the hypothesis; the water pressure in the greensand was artesian, corresponding to a ground water level eight meters above sea level. The entire section of line could now be safeguarded by deep drainage works at less cost than the railroad was originally prepared to spend just to relocate the line.

He wrote to his former client, the chief engineer of the Southern Railway, this "solution of the Folkestone puzzle is so simple that I should have thought of it two years ago. It also explains the recurrence of the slides in more or less regular time intervals. These time intervals represent meteorological cycles of some sort involving the periodic advent of an abnormally high ground-water discharge from the highlands through the Greensand towards the Channel."[14]

Terzaghi had no chance to see the job to its end as the immediate sliding hazards had abated; in any event, it was not possible to conduct the expensive drainage work during wartime, the British preferring to bleed the enemy.[15] This was a classical application of Terzaghi's own theory of effective stresses, and he subsequently wrote it up as such in 1950.[16] It remains surprising that the light took so long to dawn. Perhaps it was because the engineering artist was somewhat distracted by the swift changes and giant happenings around him. In fact, when one considers the upheavals of 1938 and 1939, it is hard to imagine how he had been able to concentrate on much beyond mere survival.

On February 12, 1938, Austrian Chancellor Kurt von Schuschnigg arrived at Obersalzburg for talks initiated by Hitler. After being threatened that his country's defenses would be blown to bits if Hitler so ordered, he was presented with a draft agreement to be signed without discussion. It demanded in effect that he hand over the government and economic control of Austria within one week to the Austrian Nazis. Schuschnigg was compelled to sign and allowed but four days to obtain the approval of Austria's President, Wilhelm Miklas. To assure compliance, Germany began to flex its military muscles while Hitler addressed the world about Germany's right to protect the political and spiritual freedoms of their seven million "racial comrades" in Austria. Hitler's speech touched off Nazi rallies throughout Austria; in the main square of Graz, a mob tore down the Austrian National Flag and hoisted the swastika.

To appease Germany, Schuschnigg moved part of the way toward fulfilling the Obersalzburg agreement: he freed imprisoned Nazis, and put one of them, Seyss-Inquart, in the cabinet as Minister of Security. Rumors were flying, leading to withdrawals from banks, cancellations of business contracts, and collapse of tourism. On March 9, Schuschnigg announced a national plebiscite on whether or not to accept Hitler's demands, to be held in four days. Hitler's response was to order the invasion of Austria on March 12 in order "to restore law and order in my homeland".[17] Under intense diplomatic pressure, administered by Seyss-Inquart and his crony, functioning as marionettes in Hitler's hands, the Austrian Chancellor was coerced into canceling the plebiscite. The Chancellor now had no choice but to resign, but not before delivering a moving oration to the Austrian nation stating the extent of German coercion.

When the stubborn President Miklas now refused to appoint Seyss-Inquart or any other Nazi to succeed Schuschnigg as Chancellor, the Austrian Nazis took possession of the streets. The massive "spontaneous" demonstrations were unimpeded by the police who were completely controlled by the Nazi Security Minister. Without support from any quarter, heroic Miklas finally yielded. German troops entered Austria, followed by Hitler himself while the puppet Austrian government, on March 13, declared total "Anschluss"—the complete immersion of Austria in the German Reich.

In the wake of Schuschnigg's meeting with Hitler, a large demonstration by Nazi students took place at the Technische Hochschule. The college was relatively quiet thereafter, and on March 10 Terzaghi was able to enjoy the honor of awarding, on behalf of the faculty, an honorary doctorate to former American President Herbert Hoover. It was a calm before the tempest, as all the city functionaries, ministers, and clergy congregated in the decorated auditorium of Vienna Technical University. At the luncheon reception afterwards at the Ministry of Education, Hoover asked rhetorically of Terzaghi, his neighbor at table: "What has Hitler made of poor Germany?" Karl noted that Hoover failed to understand it was Germany that made Hitler.[18] At a dinner hosted by the American Ambassador, Karl explained to the ex-president what soil mechanics was all about and found Mr. Hoover to become almost "homesick" for his own field of mining engineering.

The next evening came the news of Schuschnigg's resignation. Ruth was elated that the hypocritical Schuschnigg system had fallen, and the Terzaghis drank Schnapps, even as German troops were crossing the border. They saw the event as the riddance of a pest, not comprehending that it was the onset of a plague.

On Saturday, March 12, the radio was reporting that Hitler would soon appear in Vienna, but he had to wait until Himmler's agents had incarcerated some 80,000 "undesirable" Viennese. On Monday morning, March

14, in the Hochschule, there was a kind of "putsch" in the Kollegium which placed Saliger in the Rector's chair. Terzaghi recorded the moment as part of Austria's sunset. In the evening, the faculty was escorted to a torchlight procession in the street.

On Tuesday, March 15, the professors were ordered by the ubiquitous brown-shirted students to march to assembly outside the New Burg. Terzaghi described the plaza as filled head to head, body to body, with some hanging from statues of Imperial Generals like grapes from a vine. Then the crowd took up a chant: "One people, one government, one leader. Who has rescued us? Adolph Hitler." When Hitler appeared from a decorated balcony, the people's jubilation was so great that several minutes passed before he could start to speak, after which the masses stood rigidly transfixed by his words.[19] In the afternoon came marching German troops again blocking off the streets of Vienna. That same day, Karl's sister Ella wrote from Graz: "Nothing but jubilation, happiness, flags, and torch parades in all the streets of Graz. My tears of joy simply won't cease."[20]

The Hochschule began to seem to Karl like a military post, with uniformed students manning assigned positions. Nazi professor Haas was appointed to serve as liaison between the party and the Hochschule, and a trivial post-doc was made leader of the faculty. The worst thing was that some students were now behaving arrogantly and impudently towards professors even to the extent of extorting money from them. Terzaghi learned from his publisher, Deuticke, that most old school books were to be burned. They could expect that the Nazis would soon attempt to purge all views except their own, since Goebbels had been burning books by Jewish, leftist and "un-German" authors since 1933 in Germany. Even before the Anschluss, Terzaghi experienced firsthand two repressions of free publishing: official refusal to allow the Vienna and Berlin publishing company Julius Springer to introduce a new Austrian journal *Wasserbau und Erdbau* because there were non-Aryans among Springer's ownership, and blocking of the second edition of *Ingenieur Geologie* because one of Terzaghi's coauthors, Redlich, was Jewish.[21]

These attacks on academic freedom opened Karl's eyes. He could no longer follow the method of survival he'd learned at M.I.T., simply to disregard what is ugly. The ugliness was everywhere. The plight of the Jews, which he had managed to disregard up to now, suddenly came into tragic comprehension. The Austrian Nazis proved quickly through organized brutality that they were even more fanatical anti-semites than the Germans. Terzaghi heard and read what was happening to them, and it sickened him. At the bank, his friend Mitzi saw the Jewish teller taken by the Gestapo to an unknown destiny. On Jewish shops appeared the graffiti "Jude," while their customers were insulted or forced to wear a label saying "this Aryan swine has shopped in a Jewish store."

Karl found his few Jewish friends and colleagues depressed and lost, and learned there was an epidemic of suicides among their community. He saw the Technische Hochshule being purged of Jewish staff. Karl agreed to advise two representatives of the Jewish students at their request, but wondered what he could possibly tell them.

Anger at the erosion of liberties gave way to fright that his freedom to travel and his wealth would be affected. He had a technical visit to North Africa coming up on March 28 and needed a French visa. To be permitted to pass German customs, it was now required to complete a form which, he discovered, had to pass through the hands of the Gestapo, requiring at least two weeks. Furthermore, the French consulate was besieged by Jews and others who wished to emigrate. As he was not a Nazi party member, he tried pulling strings with friends who were, including some who boasted low party numbers; when this got nowhere, he appealed for help from Rector Saliger, which miraculously procured the visa at the eleventh hour.

He learned from his staff mechanician, Sentall, that an ordinance likely to be enacted at the start of April would severely tax his external investments. In fact, he should consider placing all his foreign capital accounts into real estate or partnerships, preferably in Ruth's name. He immediately dispatched her to accomplish this in a quick round-trip to Boston. If necessary, they might even consider arranging a temporary divorce. Ruth packed in great haste and left on March 21, leaving baby Eric at home with Karl in the care of a live-in servant, Erna, and overall supervision of their friend Mitzi Obermayer.

Before Ruth left, they hurriedly discussed their options in Austria. Karl was not ready to give up his position, and particularly his pension. On returning from North Africa and the subsequent summons to England, Ruth's and Karl's paths finally crossed in Paris on April 27, for only one night. He had to return to resume his lectures now that the Spring break was over, but Ruth confirmed she would not accompany him to Vienna. The next morning, riding as one of only four passengers aboard the Orient Express, Karl wondered what to expect at his destination.

One of the first people in whom he confided, Fritz Schaffernak, was annoyed to learn that Ruth wanted to go home to America and that Karl, accordingly, planned to quit teaching after the end of the winter semester. Karl must have been equally put off on hearing Schaffernak's big plan to put the laboratories and staff in the service of the Nazi movement. For his first lecture after the Easter break, on May 2, Karl faced an almost empty auditorium but, by a special post-Anschluss decree, all professors were required to lecture. He entertained the half dozen (of a usual forty) students by telling them of his meeting with Hitler.

He would not stay past the end of the current semester. But where should he go? Fritz Todt had been pressuring him to join the Autobahn administration, inquiring repeatedly, both directly and through Leo Casagrande, as to exactly when Karl would move with his family to Germany. Karl responded that he would have agreed except for his overseas engineering commitments.

An idea for a compromise flashed—double residency. He would spend half of each year in Paris or London with Ruth, and the other half year with Todt's organization in Berlin. To arrange that would not be easy, for he would have to be assured the privilege to come and go across the borders of Germany without bureaucratic encumbrance. On making some inquiries, it was suggested he speak to the influential counselor Etscheit in Berlin.

So right after the week's last lecture, Karl boarded a train for Berlin and found Etscheit's refined office on the fashionable boulevard Unter den Linden. In his speech and manner, Etscheit seemed to Terzaghi to be the epitome of vanity, but he had connections and, on learning the reasons for Terzaghi's visit, said he would try to help. Karl promised to produce a letter from Todt supporting the double-residency concept, which should extract the required permission within eight weeks.

Soon after his return to Vienna, Todt queried Terzaghi's intentions yet again, through Leo Casagrande; Karl felt compelled to accept the assignment, which concerned foundations and anchors for a high bridge across the Elbe at Hamburg. Arthur Casagrande would also be joining them to start the project in early August of 1938. Terzaghi drafted a mock letter for Todt's approval and forwarded it to Etscheit.

Things were not going well in the Terzaghi home. Karl discovered that Mitzi and Erna hated each other, and the poor toddler Eric, better known as Squeezix, was caught between them. Furthermore, there were indications someone had attempted to climb in through a window during his absence. On May 21, when rumors began circulating about a German invasion of Czechoslovakia, Karl decided he would get Squeezix out of Austria, immediately. But how? His next trip to Paris was only two days away and Ruth had neglected to obtain a passport for the child.

With help from the head of his laboratory, K. Kienzl, his staff mechanician Sentall, Otto Froehlich's wife Mary, and Erna, he pulled it off. The demanding paperwork was started in several trips to the American consulate, sandwiched between classes. He placed in Sentall's hands the responsibility to receive the passport and French visa and deliver them to the railway station. Erna was to take the toddler to Mannheim where the Froehlichs lived, and Mary Froehlich would bring him to Paris. There was an anxious night for Ruth and Karl in Paris when a cryptic telegram said only that there were problems at the border. Finally, Squeezix was reunited with his parents at 6 a.m. on May 28.

The Terzaghis took two rooms in a boarding house in St. Germain-en-Laye, a suburb of Paris, and then, on June 5, leased a cozy vintage Louis

XIV house with a large, overgrown garden, that would be their temporary home. Five days later, after a round-trip to London, Terzaghi returned to Vienna on the Orient Express. On the 18th Etscheit told him: "I smoked a cigarette with an influential man." He said the double residency could be arranged on payment of one thousand Marks immediately and two thousand more when the deal was settled in about two weeks. This sum was almost half of Karl's generous honorarium from his 1935 lectures in Berlin.

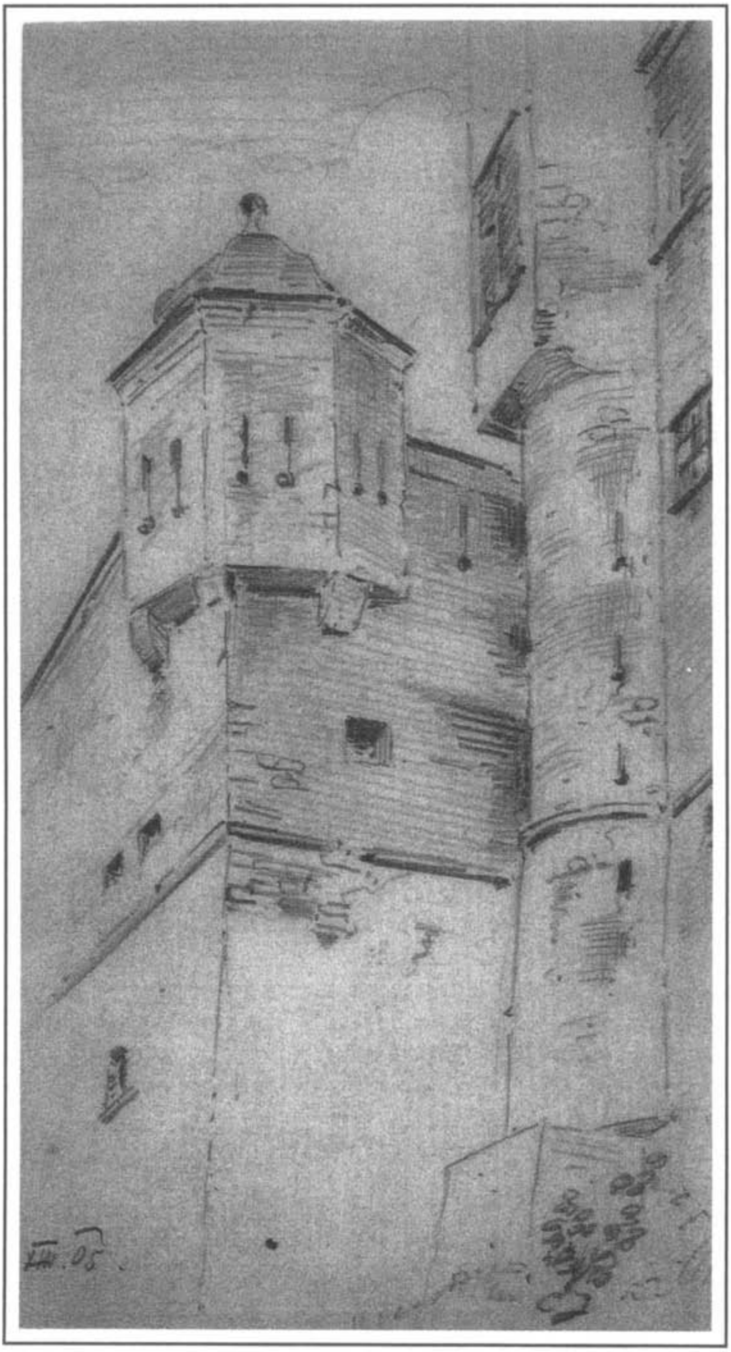
In the paper Terzaghi read of Jewish patients being abruptly discharged from hospitals. He was touched by the story of the Wolff family, whose ancestors had dwelled in the town of Eisenstadt continuously since the fifteenth century. Wolff, who founded the museum and was a renowned philanthropist, had all his assets appropriated by the Third Reich and was out begging on the streets of the town. His safety was not assured as police were prevented from combating excessive brutality against Jews.

At the Hochschule entrance, Karl saw Jewish students squatting and cleaning the pavement. Inside he learned that the teaching assistants were ready to strike. This was enough. He made a trip to Graz to say farewell to his aged mother and relatives. Karl told Ella he could not abide the unbelievably mindless Nazi regime with their brutality against the Jews, and that World War II was coming, which Germany would most likely lose. Vera, who was now in charge of a section of the league of German girls (BDM), a female version of the Hitler Youth, was annoyed with him.

Back in Vienna he gave his last lecture to a virtually empty hall, and then began the arduous work of sifting and organizing his papers and packing his belongings. On July 8, with his apartment filled with crates and boxes, he was a melancholy guest of Mitzi in the old rooms in which, more than thirteen years earlier, she played hostess during his occasional escapes from Constantinople after Olga's departure. Looking out her window, on this, his last night in Vienna, the old church tower appeared black against the moonlit clouds.

Karl's big suitcases filled with his clothes somehow caused no trouble at customs. But he sweated over the fate of the two boxes shipped to Otto Froehlich in Mannheim, which contained all his precious diaries and his consulting reports. Luckily, Arthur Casagrande, on his trip to Hamburg in August, was able to ship them on to Boston. He never succeeded, however, in withdrawing the 25,000 Marks from his bank or in shipping household furnishings.

On August 1, 1938, Karl Terzaghi wrote in his diary that Todt had refused to send the letter Etscheit needed, thereby closing out any chance of compromise. Todt made it clear that Terzaghi's service was compulsory. "To refuse meant a place in a concentration camp. Under no circumstance am I again to cross the border. At least we are all outside."[22]



1905

14
Development of the Observational Method
The War Years

Amid the deepest despair during his fight with Fillunger, Karl accepted an invitation to become a visiting professor in China; the Chinese appealed to him with their sense of humor and "gentle, human qualities."[1] He agreed to teach at the University in Peking and to organize a laboratory and a practical course for railway engineers in Shanghai.[2] This was to have started in the Fall of 1937 but, when his life at the Technische Hochshule returned to normal, Terzaghi postponed the visit until the Fall of 1938.[3] The actual extent of his commitment was never tested because in July, 1937, the Japanese invaded China.

Karl simultaneously began to explore opportunities in the United States. As the Fillunger affair drew towards a climax, Arthur Casagrande reported he believed the American situation had changed, and Karl could now expect to make a satisfactory income as a freelance consultant for the US Bureau of Reclamation and the Corps of Engineers, possibly with a base of operations in some university.[4] With Karl's blessing, he wrote to Dean Morris at Stanford, Professor Hardy Cross at Yale, President Compton of M.I.T., and his own Dean Westergaard at Harvard.

Independently, consulting engineer Willard Simpson in San Antonio, learning that Texas A&M wanted to build up soil mechanics, suggested they ought to invite Terzaghi. Karl toyed with Dean Gilchrist, who diligently followed this up, replying in April, 1938, that he probably wasn't available until the Fall of 1939, as he wanted first to finish his two-volume book on soil mechanics and foundation engineering. By sitting too long on the fence, he and Texas A&M lost this chance.[5]

As the August appointment with Todt in Hamburg neared, Karl found a real excuse for canceling. He became ill with a seriously infected wisdom tooth. His misery continued long after its extraction with postoperative fever reaching 104 °F (40 °C), severe pain, and irritation with the surgeon's fees.[6] He was also ill from the thought of spending the rest of his life behind German bars. So, he finally wrote to Professor Schaffernak to let him know he was definitely finished with teaching. He chronicled his dissatisfaction with Vienna's unfulfilled promises of support over the years, but tried to soothe the wound by closing with the now customary "*Heil Hitler*," which he had never before done.[7] He also told that his next step would be towards America. In Austria the rumor circulated that Karl had to leave because his wife was Jewish, which was not true (and which Ruth worked to disprove).

He had no specific target in visiting the U.S. except to travel around to see what might develop. Karl wrote Arthur that he planned to arrive towards the end of September, alone, hoping for a quiet place at Harvard where he could work on his book. He would return to England and France early in 1939.

It was not a trivial chore in the summer of 1938 for an Austrian resident in France to gain an American visa, even for Karl Terzaghi. There was, of course, the expectable crowding and delay at every procedural hurdle, intensified by German military maneuvers on the border of Czechoslovakia. But, worse, an American consular official, on noticing the large number of stamps in Karl's passport, must have suspected him of spying for Germany, for he demanded complete documentation of all activities on every trip out of Austria.

Karl Terzaghi finally arrived in Boston at the end of September and booked in at Harvard's faculty club. Except for an occasional lecture and a bit of cigar smoke, the students saw little of him as he slaved away on his book in the office Arthur provided. But word of his arrival soon began to attract invitations for visits and lectures, most of which Karl accumulated and organized into a major tour for the new year—to Texas A&M, the University of Texas in Austin, the University of Mexico, the A.S.C.E. in Rochester and, finally, Princeton University. But he did not defer the invitation from Dean Grinter, of the Armour Institute of Technology in Chicago, because Karl knew that construction of new subway tunnels through soft clay was about to start under the heart of Chicago. At Armour Institute, he wisely chose to speak about the dangers of tunneling in soft clay beneath cities.

Among the throng that heard Terzaghi's lecture in Chicago on December 1, 1938, was a representative of the property owners along the subway right-of-way. Within two days, Karl's friend Al Cummings of Raymond Concrete Pile Company informed him that Karl would probably be asked to serve as their consultant. But while the property owners' lawyers and archi-

Terzaghi at Harvard, Spring of 1940

tects quietly researched his credentials, the chief engineer of the Chicago Department of Subways and Traction, Ralph Burke, asked Terzaghi straightaway for a proposal. Burke wanted only a procedure to estimate the effects of tunneling on buildings along the subway lines.[8] But Terzaghi quickly elaborated an expanded program, going well beyond this limited scope, stating that soil mechanics had much to offer Chicago if the job were done correctly from the start. He proposed to be the principal consultant and that there be a laboratory, to be set up and supervised by a man of his choosing.[9]

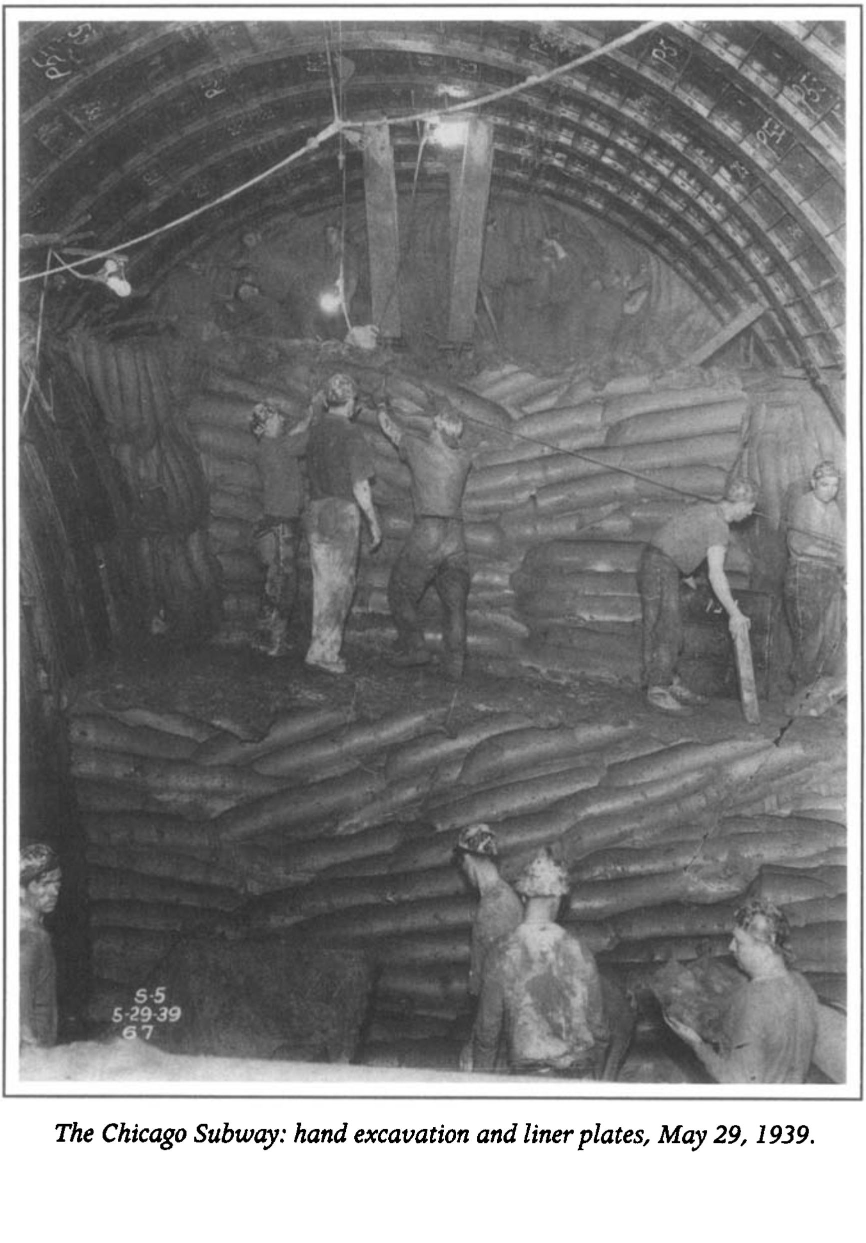
At Harvard, Terzaghi had obtained help with technical English from a young structural engineer in Arthur's group, Dr. Ralph Peck, who was accumulating knowledge in soil mechanics as a precondition to his joining the faculty of the Armour Institute. Although Arthur Casagrande thought Karl was crazy to risk losing his chance with Chicago by imposing conditions, he was quick to recommend Peck to become Karl's man on the job.

When Karl ended up with two Chicago offers, Cummings advised him to go with the city, even though his fee would be limited by the city to only $100 per day (which inspired the caption "Soil Expert Hits Pay Dirt" in the Herald and Examiner newspaper).[10] He accepted on December 29, 1938, beginning a job that propelled the young field of soils engineering.

Peck arrived on January 14, struggled to organize his staff and laboratory, and began testing the hundreds of samples already amassed by the three boring crews. Construction was well ahead of exploration. Terzaghi arrived for his first visit a week later.

Ruth, alone with Eric in France amid rumors of war, knew none of this on New Years Eve, writing to Arthur that she had received only "vague intimations—mostly in the form of postscripts" about the future plans. That their future was to center in Cambridge, Mass., was confirmed late in March, when Harvard started the process to appoint Karl as Visiting Lecturer in Soil Mechanics and Engineering Geology for three years, at a stipend of $1,000 for the first year and $2,000 afterwards. Perhaps partly in celebration, she moved down to San Raphael on the French Riviera.

In March, after a second visit to Chicago, Terzaghi visited New Orleans in connection with the ten-inch settlement of Charity Hospital, founded on piles resting on a bearing sand layer at depth. There was much commotion in the press about this building and concern for its safety. Engineers could not agree on what was happening, whether a failure of the soil beneath the piles, a squeezing out of a shallow clay layer, or consolidation settlement of a deep clay below the piles. Terzaghi proved it was consolidation settlement and showed that the differential settlements, mostly completed, agreed remarkably with those calculated by his theories. Since there was no complete engineering manual yet available on how to apply the theory of consolidation to forecast such settlements, Terzaghi wrote one to include with his final report.



The Chicago Subway: hand excavation and liner plates, May 29, 1939.

Terzaghi with Ralph Peck.

As to the building's safety, he judged that despite the large settlements it was probably no worse than most buildings founded on clay, many of which suffer higher maximum stresses in the steel skeleton than the designers imagined. However, as the building was unusual and unprecedented in several respects, he recommended reanalysis (by Hardy Cross of Yale University), offering the following statement about the limitations of judgement based on experience.

"When utilizing past experience in the design of a new structure we proceed by analogy and no conclusion by analogy can be considered valid unless all the vital factors involved in the cases subject to comparison are practically identical. Experience does not tell us anything about the nature of these factors and many engineers who are proud of their experience do not even suspect the conditions required for the validity of their mental operations. Hence our practical experience can be very misleading unless it combines with it a fairly accurate conception of the mechanics of the phenomena under consideration."[11]

In mid-April of 1939, Terzaghi returned to Europe to continue his various consulting jobs, and a new one near Glasgow—an airfield depot on clay as soft as that in the Golden Horn. He also presented a series of lectures on soil mechanics at Imperial College, and, on May 2, presented the 45th James Forrest Lecture to the Institution of Civil Engineers in London. In introducing him to the overflow audience, Binnie admitted the British had been slow to take up soil mechanics but now realized the value of Terzaghi's work. He was, in fact, only the second non-British person to receive this honor, the previous one being Marconi.

Terzaghi's lecture, entitled "Soil mechanics—a new chapter in engineering science", compared designs in civil engineering prior to the establishment of soil mechanics with contemporary designs that take advantage of the new knowledge.[12] It highlighted, among other advances, the just-obtained comparison between the observed and computed settlements of Charity Hospital. His eloquent simplicity and completeness elicited the most enthusiastic reception accorded to a speaker in the memory of the Institution of Civil Engineers.[13] Beyond mere approval, the British engineering profession was galvanized by his prediction that the day approached when Courts would decide against the designer who ignores the existence of soil mechanics.

On return from France with his family in early June, and settling into a rented home in Winchester, Massachusetts, Karl resumed his work at the Chicago Subway. The general geology is surprisingly uniform, shallow layers of recent and postglacial silt and sand passing downward through a three- to ten-foot crust of very stiff clay into clays that are softest at the top and stiffen with depth. These Chicago clays were deposited in Glacial Lake Michigan. Rock was more than 100 feet down, unreachable for subway purposes.

Tunneling in the soft Chicago clays was not new to Chicago, as the Chicago Sanitary District had constructed many large interceptor tunnels by cutting the clay in slabs by hand; they worked in an opening maintained by elevated air pressure long enough to permit the placement of steel liner plates on the exposed walls. Settlement had rarely been a problem, because the construction had largely been carried out beneath poorly developed areas. In contrast, the first subway contract had been awarded for a section under State Street, north of the Chicago River and the highly developed downtown "Loop" area. The contractor was already at work at the time of Terzaghi's first visit.

The subway structural designers were proud of their state-of-the-art analyses of many assumed loading conditions and were anxious to gain Terzaghi's praise, but Terzaghi was far more interested in the large settlements already appearing near to and above the first excavations. He believed existing theory for designing tunnels and open cuts in soft clay was simply not well enough honed by experience for use in Chicago, the only useful data being from the Boston subway. The record of subway construction in London, unfortunately, was not relevant as Chicago clay was far softer than London clay (a view he sustained in underground visits during his trip there in the Spring of '39). So right from the start he felt it important to reinforce Chief Engineer Burke's view that the initial construction was a learning opportunity; that is why he insisted on setting up a soils laboratory with Peck in charge, as well as a program of close soil sampling and testing, and a rich array of field measurements.

Burke himself was a man of no mean accomplishments. A graduate of Boston Tech (later to become M.I.T.), trained as well in the field of law, and a one-time chief engineer for a tunnel contractor, he lent his full support to Terzaghi's recommendations.

Ralph Peck was to be Terzaghi's key player, to organize and run the lab and supervise the measurements as an employee of the city while also reporting directly to him daily (a situation that Peck described as "being between two fires").[14] Karl worked out an operating tactic that focused his energy always on the most pressing needs: he would visit the job for about a week each month and follow up each visit with a memo on whatever he perceived to be most urgent. The resulting 26 Terzaghi memoranda, varying from a few pages to a complete engineering manual, proved an amazing resource for the project. These communications transformed the whole context of engineering work by forcing the city into closer connection with construction issues, where safety and cost were sensitively affected. The city had expected to leave most construction choices essentially to the contractor.

Peck found these visits to be exhilarating, making one feel he was in the midst of great discoveries. Terzaghi was charged with enthusiasm as he searched for hypotheses to explain measurements and observations. "If he dropped a suggestion, I'd break my neck to go after it," said Peck.[15] During Karl's time in Chicago, Ralph Peck's wife was neglected as the two engineers talked about new things in soil mechanics with their cronies in this or that restaurant. Karl was a catalyst.

Excavation of the North State Street liner-plate tunnels north of the river was leading to large settlements. The contractors claimed that their activities underground were quite unrelated to what occurred above, but Terzaghi knew better. He accordingly suggested that Peck and his crew try to measure the movements of the clay toward the tunnel from inside as the work progressed. Soon the crew found that, in spite of the air pressure inside and the action of the steel liner plates, the clay slowly squeezed in from the top and sides, and even from ahead of the face where the digging was going on. Moreover, they found that the settlement of the street surface multiplied by the settling area equalled, to a close approximation, the volume by which the tunnel's inner space had been reduced from the measured squeeze of clay into the tunnel.[16] Having established that reducing the "lost ground" in the tunnel would correspondingly reduce the surface settlement, the crew, with the gradually increasing cooperation of the contractors, began to learn which construction procedures caused the least movements. By developing and using these refinements, guided not by theory but field observations, the settlements of the liner-plate tunnels north of the river were reduced to about a third of those first experienced.

However, the accumulating test data from the soil lab showed clearly that the soils south of the river in the critical Loop area were alarmingly weaker than those where the first tunnels were being driven. Armed with the soils data, Burke assembled a Board of Consultants, including Terzaghi, to recommend a course of action. The Board concluded that the Loop section would have to be built by the shield method, new to the Chicago area. In this method, each tunnel is formed by jacking a circular ring, which the newspapers called a "cookie cutter", into the clay by pushing against a steel lining erected inside the rear or tail of the shield; the clay being pushed in front of the shield is cut away under the protection of the forward part of the cookie cutter. Bulkheads across the front of the shield support the clay in front as needed. In this way, the tunnel is advanced with full protection against incursion of the clay at all times.

The effects of tunneling on the buildings were complex because, as Terzaghi had described in 1928 for Detroit's Hudson Building, excavations cause buildings to move by different mechanisms.[17] If the tunnel were to drain water from clay, the clay would consolidate, causing buildings above to settle at an accelerated rate. Also, as just described, if any of the excavated surfaces of soil were allowed to move forward into the excavated space, the ground would follow, carrying the building on its back in "lost ground" settlement. Additionally, on the shield portions of the subway job, it was discovered that the forward shove of the shield could heave up and loosen the ground ahead of it, and, subsequently, after the passing of the shield, the disturbed earth would recompact or gradually drain and consolidate. To document and control potential problems it helped to know which of these mechanisms applied. Again, Terzaghi proposed thorough measurements of ground displacements on the surface and underground along the route.

The pattern and sequence of deformations were bound not to be simple because there were two parallel tubes advancing at different rates; excavation, support of the ground, lining, and grouting happened simultaneously at different places and at different rates. Furthermore, soil properties changed as the tunnel moved through new regions. All this produced an apparent disarray in the measured data and nobody could fault the engineering staff for wanting to sketch smooth curves through the scattered points on any space or time graph. Nobody, that is, except Terzaghi. He studied idealized time/displacement patterns that conformed to different stages of tunnelling and found that much of the supposed scatter had a rational explanation.[18]

Not all the subway was constructed by tunneling. At the portals and some stations, open excavations were made from the ground surface with the sides supported by sheathing of timber or steel sheet piles held in place by struts placed across the excavation as it deepened. Terzaghi had recently presented a paper before the American Society of Civil Engineers (for which he received the second of his record-breaking four Norman Medals) in which he showed that the pressure against the supports in the sands of the Berlin subway did not increase from top to bottom of the cut, as predicted by long-accepted theory, but actually decreased from about mid-depth to a very small value at the bottom. Contractors had known this for years, but until Terzaghi's explanations, classical theory had declared otherwise. When it came to soft plastic clays, however, there was doubt whether the reduction of pressure with depth could exist.

This was a matter of practical importance, because bracing in the lower part of a cut interfered greatly with the construction of the permanent structures. So Terzaghi suggested that Peck's crew measure loads in the bracing systems as well as any movements of the supports as excavation deepened. The measurements showed that the reduction of load at depth did indeed occur, and immediate savings were realized, not only in the cost of the bracing, but more importantly in freeing the working space for construction of the permanent structures.

Based on the loads and deformations Peck measured in the open cuts, Terzaghi prepared a manual on the analysis and design of struts for open cuts of the Chicago subway.[19] This was the first time anybody had documented how soft, undisturbed clays mobilized strength in a real context.[20] The success of this work led Karl to see how one could calculate the point where it would be necessary to switch from the inexpensive liner-type tunneling to the costly shield method. Obviously this happened when the soil became softer or the loads increased on approaching large building foundations or deepening of the tunnel. But this decision had never before been made on a rational basis.

The method of calculation was based on an analogy. The tunnel, argued Terzaghi, could be viewed as a kind of open cut in which the bracing was naturally supplied by horizontal pressure in the soil above. The loads are carried down to the feet of tunnel arch supports just as they are transferred down the vertical members of the strut structure in an open cut. Since he now held a rational design method for the open-cut problem using soil mechanics theory, well stocked with empirical judgements derived from the observations and measurements, he could use it to analyze the safety of a liner-plate tunnel. The unsolvable tunnel design problem in soft clay thus transformed into a solvable problem of bearing capacity at the foot of the arch supports. One was forced to use the shield method when the safety of the arch footings was too low. Terzaghi wrote to Chief Engineer Burke that he considered this the most important result to emerge from the Chicago Subway work.[21] The result came too late, of course, to be applied to the tunnels then under construction, but they were applied to achieve substantial economies when the subway was extended after World War II.

The structural design of the tunnels was based on the traditional approach in which the loads on the tunnels were considered to be unaffected by the deformations of the ground during excavation or by the deformations of the construction-stage linings. In both the liner-plate and shield-driven sections, the plans called for thick, heavily reinforced concrete linings. Terzaghi's intuition was that the deformations of the ground around the construction linings would cause a favorable and permanent redistribution of the earth pressures and greatly reduce the stresses for which the concrete linings would have to be designed. To check this idea, he got approval to build and test two experimental tunnel sections, one in tunnel constructed by the liner-plate method and one by shield. The results showed him to be correct, and the design of subsequent subway extensions profited substantially.

He fought successfully to keep these test sections from the budgetary axe, sometimes with his typical brand of humor, as in this excerpt from a letter to Burke: "In my opinion it would be a crime and a waste of the taxpayers money to liquidate these [test] sections before they have furnished all the information that can be gotten out of them. I would prefer to see some of the members of the engineering organization to be buried in concrete. The loss to the profession would be very much less severe."[22]

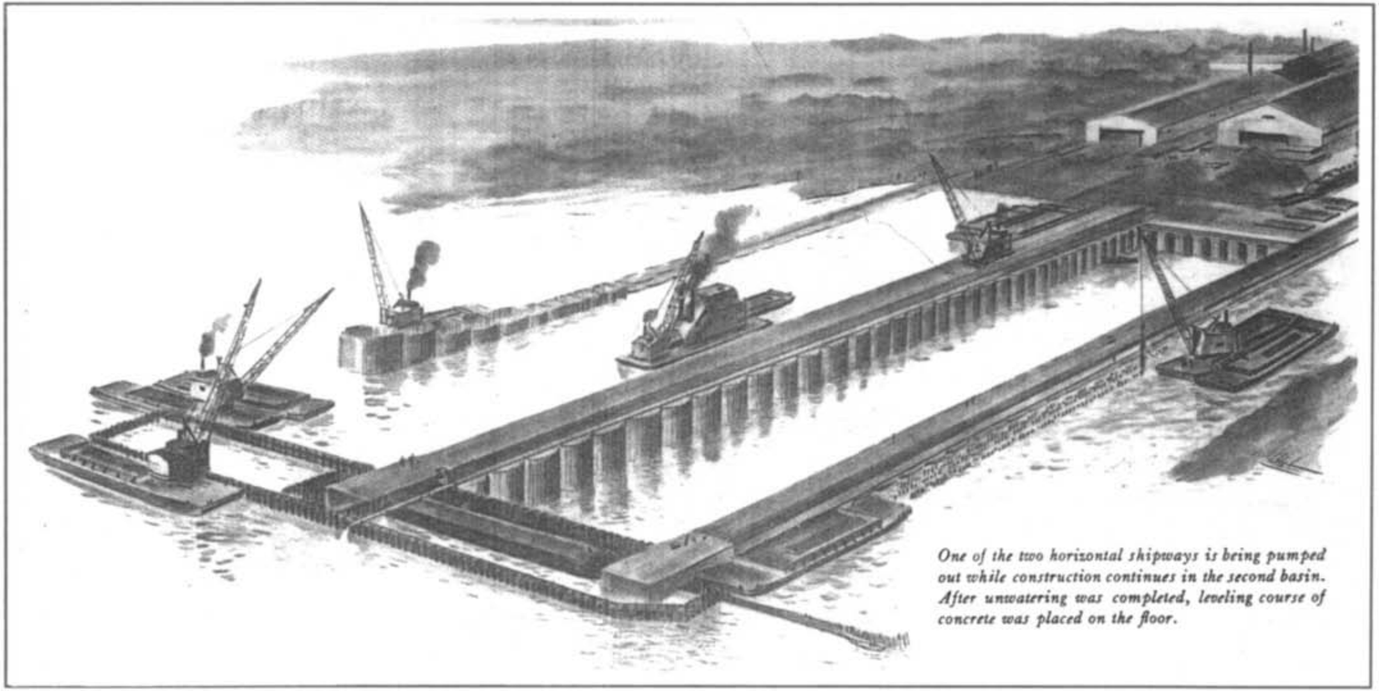
With Terzaghi's leadership, the cost per foot of the Chicago subway was less than half what it was in London, in better clay. The learning on the job that allowed 7.7 miles of "cheap and daring construction"[23] without major accidents was supported by the results of Peck and company's 25,000 soil tests, more than 700,000 level readings, detailed crack surveys in existing structures, and periodic observations in experimental sections. It was a trail-blazing case history that provided an enormous impetus to the development of applied soil mechanics. It also brought into play a resonating partnership: Terzaghi and Peck.

In June of 1941, as Terzaghi's work in Chicago was winding down, he received an inquiry from Adolph Ackerman, Director of Engineering for Dravo Corporation, who was nervous about a very moist backfill inside cellular cofferdams intended to serve as the permanent walls of shipways 10 and 11 at Newport News, Virginia. These works were being rushed into service for the construction of battleships and aircraft carriers. Terzaghi, who yearned for unusual work, was quickly drawn into an "exciting professional adventure".[24]

The principal foundation material, and backfill for the cellular cofferdams, was a "marl" consisting of firm calcareous sandy silt. It behaved like a sand in its natural state, with respect to permeability and shear strength. But, when Terzaghi remolded it in the lab at Harvard, its Atterberg limit values showed it had begun to act like a clay, an unusual behavior not previously recognized. He judged that the marl was a sand whose particles were calcareous clusters of silt and clay; disturbance would break up the clusters and give to the material the properties of a true clay.

J.S. Miller, Vice President of Dravo Corporation, which was functioning both as designer and constructor, had suggested a novel approach that would drop the cost from $10 million for the usual sloping waterways to only $3 million. The walls for the dry docks, almost a thousand feet long, would be created by driving sheetpile cells through tidewater into the marl. The cells were to be filled with sand and gravel; but the economy of using marl dredged from the shipway prevailed, the engineers assuring this material would develop adequate strength rapidly. Similarly, they assured the constructor that the organic clay soil against the base of the sheetpiles outside the walls would quickly stiffen.

But when backfill began to be placed inside the cells, it lacked stiffness and the sheetpile wall began conspicuous inward movement. To hasten the stiffening and strengthening of the marl backfill, the contractor, with Terzaghi's approval, began installing columns of sand and gravel (termed "sand piles") in twelve-inch pipes driven inside the cofferdam cells and extending down into a pervious layer in the foundation. The management complained about the delay this would cost, shouting at a meeting: "Why in hell didn't you get the doctor long ago?"[25] The sand piles greatly improved



Dravo Corporation's scheme for the Newport News Shipways.
From "Submerged Shipways," Dravo Corporation Bulletin 601(1943).

the stiffness of the cells, but as soon as the backfill reached its full height the wall began again to yield. Subsequently pile driving for the crane-rail structure provoked yet more wall deformation, now amounting to as much as seven inches.

The next step in construction would be to pump out the water within the shipway enclosure but Terzaghi warned not to dare it. He judged that dewatering would collapse the cofferdam wall. After characterizing the erratic strength of the natural marl foundation layer under the cofferdam (by means of some 5,000 water-content measurements, a great number of Atterberg limit tests and permeability tests on samples in the soils lab at Harvard), he found an economical solution to the emergency. First, remove all the highly compressible soil loading the outside of the cofferdam by digging a trench right down to the surface of the natural marl layer. (Then only the external water pressure and not external soil pressure would load the outside of the cellular cofferdam wall.) Next, he stipulated, fill the external sea-bottom trench with clean, free-draining sand and gravel, protected from inwashing of fines by an overlying filter and a layer of deposited marl. Finally, drain the sand and gravel fill to further reduce the side pressure on the wall.

When this was accomplished the dewatering could proceed, but only with very close observation of wall movements during the pumping operation. As Terzaghi insisted, a great number of instruments were readied to monitor load and deflection of points on the wall as the inside water level would descend.

The floor of the drydock had been designed as an eight-foot-thick concrete slab resting on thousands of wooden piles (about 13,000 between the two drydocks) and drained from uplift pressures by weep holes through the concrete. The floor was designed to act as a strut to prevent inward movement of the walls. A full structural floor to counter uplift pressures would have to be about twice as thick and reinforced with steel. Worried about the potential hazard of uplift pressure, Terzaghi called for installation of pressure gauges in the soil beneath the drydock shipways.

As the work progressed, America entered the war and travel restrictions were imposed on all enemy aliens without a special permit. Terzaghi applied for such a permit and was granted a Department of Justice interview on January 15; they were interested, among other things, in his relationship with Arthur Casagrande. Two days later, as he prepared to visit the jobsite for the dewatering of shipway 11, he learned that his request for a travel permit had been refused. He and Ackerman tried in vain to reverse this action, Terzaghi taking his precious countdown time to supply a long list of personal references. He wrote to Ackerman that "no one who knows me well could testify with clear conscience that I ever was in sympathy with a totalitarian system of government. Whatever rumors may exist to the contrary must issue from unreliable or from inspired sources."[26] He suspected that a German spy had planted false inferences to deny his talents to U.S. defense work as a deliberate act of sabotage.[27] As a stop-gap measure, Ralph Peck was brought down to the work site, and they all communicated by telephone.

The dewatering was scheduled for January 19. A worried and tense Terzaghi, struggling in his office to explain unusual pressure gage observations in shipway no. 10, hit on the log of a soil boring for future shipway no. 12 that showed the marl rested between elevation 30 and 35 on a bed of sand. The design assumptions had been that the marl extended to elevation 20 and was essentially impervious. The sand being horizontal, Terzaghi considered that it might well extend southward to the site of shipways 10 and 11, which would place it approximately 17 feet below the base of the concrete. Since the sand could carry high hydrostatic pressures, he raced through a computation of stability of the floor and its marl foundation under the uplift pressure of the sand horizon. His computation showed the worst possible outcome: the floor would blow up sometime after the water depth became less than ten feet. Karl's heart raced as he called Ackerman to stop the dewatering; fortunately Ackerman believed in Terzaghi and stopped the pumps—with only five feet to spare.

The next day, by Terzaghi's remote command, two auger borings were drilled under shipway 10. "They actually struck the sand whose existence I suspected at elevation 30 and 35 respectively."[28] Then four pressure gages were installed. While the results were being studied, Terzaghi sent a long memorandum to Dravo's Executive Vice President Miller explaining that there was an emergency and asking for delay in further dewatering.

The pressure gage readings presented a mystery. The phreatic surface in the sand, as indicated by a well drilled through a cell of the wall, was at elevation 94, which was truly dangerous.[29] However, the pressure gages inside the shipway floor indicated a phreatic surface of only 70, which was safe. Ralph Peck was summoned from Chicago to check on the accuracy of these gages. He found that they were in perfect working order, establishing that there was, luckily, a real zone of reduction in the uplift pressure under the floor of the shipway.

Terzaghi decided the uplift depression must be due to the escape of water through a crack formed between the inside cofferdam cells and the marl as the walls bent inward during the initial unwatering. However, this could not be counted on permanently for, in time, the marl could be expected to deteriorate, reducing the rate of flow, promoting siltation and loss of the benefit that nature had bestowed. This could happen after a period of satisfactory performance and cause the floor to burst, quite suddenly.

So on February 3, Terzaghi wrote a long memorandum to Mr. Miller. "The result of the investigation ... indicates that the shipway floor owes its present safety exclusively to the escape of water through vents whose existence nobody could possibly have suspected." He proposed to assure the safety of the floor by building on nature's design, drilling a series of sand wells all around the perimeter of the two shipways.[30] But since these could in time silt up, it would be wise not to open them for use until the pore pressure gages indicated they were needed. Terzaghi referred to this as a bleed system. It was far safer and much cheaper than adding three feet of concrete to the floor, which was management's initial proposal. On Feb. 4, in a lighthearted mood of triumph, he wrote the following paragraph to FitzHugh, the manager of Newport News Shipbuilding and Drydock.

"Without the pressure gages which I installed last fall in Shipway no. 10, nobody, including myself, would have been able to realize the impending danger. Yet you despised and neglected my dear gages.... The moral of the story is this: If the doctor says to you that you should swallow a certain pill, please shut your eyes and swallow it.... One may maintain that instructions concerning the supervision of a shipway may fall into oblivion. Here is my idea as to how this possibility could be eliminated. I noticed in front of your office building a huge monument bearing something like the following inscription: 'We build ships at a profit, if we can; at a loss, if we must; but we always build good ships.' Erect a similar monument in Shipway no 11, bearing the following inscription: 'this shipway floor is not safe unless the presure gages read less than 8 lb per sq in. We relieve an excess pressure by removing the plugs from the existing sandwells, if we can; by establishing supplementary sandwells, if we must; but we always keep the pressure below 8 lbs per sq in.'"

Thus, the drydock was able to be used with its light floor design rather than proceeding to a much more expensive structure capable of resisting the full uplift. Terzaghi considered this case to be an extension of the Chicago Subway "learn-as-you-go" method to the case of drydock construction.[31]

Later, Dravo called in Terzaghi to advise concerning deterioration of concrete in the pier of Shipway 11. On the basis of a tip from Roy Carlson at M.I.T. and a study by Ruth,[32] Karl reported that the trouble stemmed from a concentration of carbon dioxide caused by natural mixing of seawater with ground water; he proposed neutralizing this effect by displacing the aggressive waters with calcium hydroxide solution maintained in boreholes at a level to promote flow into the concrete.[33]

FitzHugh responded in that case they should fill the coreholes and themselves with scotch whiskey, which converts CO_2 water from an unpleasant into a very pleasant liquid, and if that doesn't work and the pier collapses at least they won't much care.[34] Terzaghi took up the challenge, writing that FitzHugh's proposal "strikes me as the soundest contribution which you have made to this subject up to this time." He asked FitzHugh "to bring at least some adequate samples of the essential ingredients to our next meeting in

Newport News, to be submitted to and examined and tested by the experts who participate in the conference. Experimentation should then be started without delay and you can rest assured of my wholehearted cooperation."[35]

After the January 19, 1942, adventure with the aborted dewatering of Shipway 11, Karl's first interest shifted to reclaiming his right to travel. Luck fell right in his lap on March 3 when Commander W.A. Sullivan, the Navy's supervisor of salvage operations, knocked at his office door. One week after Pearl Harbor, the opulent French oceanliner *Normandie*, had been requisitioned for use as a troop ship (to be called the U.S.S. *Lafayette*). Now it lay on its side in the mud at the French Line Pier in New York Harbor.

As the more than 1,000-foot-long liner, on which Terzaghi had once dined, was being refitted for its new role, a worker's torch had ignited some lifejackets piled in the lounge. A strong wind helped spread the fire and within a few hours the upper three decks were aflame. The N.Y. fire department could not extinguish the intense fire before the ship rolled over and capsized. It came to the bottom of its pier with an 80 degree list, resting on a rock ledge near the bow and sinking into the stiff clay at the stern.

The Navy wanted Terzaghi to help them get it free. Thus they worked to restore his mobility as a consultant, and, on May 13, Terzaghi received clearance to work and travel for sensitive projects. He was pleased about participating in this project, first in getting profiles and properties of the soil beneath the ship, then in helping to work out a safe scheme to raise the hull out of the mud.

Terzaghi's work established that the ship had shoved its way through 25 feet of soft organic clay, rotating about a point 275 feet from the bow where it contacted hard rock.[36] It was now acting as a beam spanning from the rock ledge to a defined area of contact with an underlying organic silty clay. If they attempted to float the vessel free by pumping it full of air, he warned, the clay might develop negative pore pressure and suck on the hull, and the suction force could break it apart. Predicting and controlling the deformation of the ship in time as the suction gradually declined would be a unique and exciting new application for soil mechanics.

First, he thought to calculate the rate of decline of soil suction by adapting consolidation theory. Then he hit on the idea of its direct measurement. With strain-gauge expert Roy Carlson of M.I.T., Terzaghi produced remote-reading electric pore pressure gauges, apparently the first in soil mechanics history. He proposed to emplace them in the clay below the hull to control the rate of floating the vessel. These gauges soon were in operation on two other Terzaghi jobs: the Republic Steel iron ore storage yard in Cleveland and the Necaxa Dam in Mexico.[37]

Early in 1942, as the United States sought urgently to increase production of steel, Republic Steel Company began work on a new twin blast-furnace steel mill in Cleveland; at the end of April they brought in Ralph Peck in connection with the pile foundation of its ore storage yard. He quickly solved the pile problem, but realized that the entire ore yard could fail by sliding into the river alongside. When asked for a solution by the Chief Engineer, Peck could only say: "Call Terzaghi." This was done, without any mention of Peck's conclusion. Terzaghi noted that the very heavy iron ore would be heaped to a height of over seventy feet over an area the width of a football field and about four times as long, all underlain essentially by glacial clay. He had a shock when he saw the "poor clay [that] is supposed to carry this load without any foundation."[38] Perhaps the load would have to be transferred to the rock with long piles, but that was a solution that would cost time and money not readily found.

Observing steep outcrops of sand along an escarpment on the south and west border of the site, Karl studied published literature and confirmed his conclusion that a mantle of sand had been deposited when Lake Erie stood at a level as much as 33 feet below the current level.[39] This explained why the base of the residue of these sand deposits was found 23 to 32 feet below the surface under the ore yard. The erosion that formed valleys and hills in the sand, he reasoned, must have created loadings on the clay similar to the action of ore heaps in the storage yard; to see if the clay had actually failed under these loads, he prepared a contour map for the upper surface of the clay and searched for suggestions of ancient landslides in the pattern of contours. He was encouraged that there were none.

Although the Cleveland clay resembles that of Chicago, he reasoned, the ancient preloading by burial under a layer of sand had made it stronger. Tests subsequently conducted by Ralph Peck, who by that time was working on a defense plant conveniently close to Cleveland, showed this to be correct; it had more than three times the unconfined compressive strength of the Chicago clay at the same water content. This buoyed his confidence that some sort of ore storage without a pile foundation might be feasible.

The principal difficulty, it seemed to Terzaghi, was that placement of ore piles over the clay would produce an immediate excess hydrostatic pressure exactly equal to the pressure of the ore load; furthermore, because the ore would be placed and removed often, this excess pore pressure would never be entirely relieved. The shear strength of the clay could not grow with the load, as would a sand, and it would be sufficient to sustain ore piles only up to some limiting height, which both Peck and Terzaghi guessed would be considerably less than the 72 feet Republic Steel intended. This was a critical problem because the wartime production needs of the steel mill put a premium on storing the required volumes of ore on schedule.

To monitor the growth of pore pressure with placement and removal of ore, a number of pore pressure measuring gauges were installed, using the remote-reading, Carlson electric-resistance strain gauge elements designed for the salvage of the *Normandie*. Although some of these deteriorated within several years and were replaced by simpler devices, they worked long enough to confirm that pore pressure changes almost exactly matched the pressure changes corresponding to changes in ore depth. But the situation was even more severe as the pressure gauges revealed there was an additional artesian pressure, reducing the available foundation strength even further. Terzaghi's assumptions were not pessimistic enough.

The ore was dumped by cranes between parallel walls 280 feet apart. The walls were tied together by hundreds of steel rods. If the ore load were too great, Terzaghi judged that the clay would tend to spread sideways, elongating, and ultimately breaking the tie rods. If this were true, it ought to be possible to monitor the safety of the clay foundation by simply measuring the elongations of these rods. In this way, the outward movement of the walls could be watched as each increment of ore height was added and the actual ore storage could be tailored to assure a sufficient, though minimal, degree of safety. This bold scheme could be dared because the design of the plant was such that the movement of the ore-retaining walls would not begin a sequence of successive failures leading to devastation. There was no failure. But there was some apprehension.

Terzaghi was becoming excited about this project. It was alive for him. He wrote to Peck, who was supervising the field measurements, "I consider any consulting job a waste of time unless I learn something new and important" and urged him to carry out all the measurements he had recommended.[40] The relationship between Peck and Terzaghi was a reenactment of their Chicago Tunnel experience, and they were both caught up in the drama. Buffeted between two demanding, and sometimes overlapping, consultants, Chief Engineer Larson wrote, "We appreciate any advice we can get from you or from Dr. Peck or from anyone else. We try our best to please everyone. In fact, we are trying to please so many right now that I can assure you that one or two more will make very little difference. So give us the works—both of you."[41] Shortly afterwards, the writer went on an extended medical leave.

Terzaghi's written warnings that the subsoil was inadequate took an undesirable and counterproductive turn. Instead of being charmed like Terzaghi and Peck by the opportunity to guide the work with critical observations, the overseeing War Production Board, through its engineers of the Navy's Bureau of Yards and Docks, decided on a gross modification of the design. If the subsoil was so dangerous, they protested that it must be stabilized by subsurface drainage. Both Peck and Terzaghi argued that this had little chance to work because the clay was stiff and it had been preloaded in geological history to a pressure corresponding to about 50 feet of ore; that being the case there could be little chance of drainage until the ore load had reached a height of at least 50 feet, and by that time the yard would already be approaching failure. Furthermore, driving sand pile drains through the clay would disturb it and temporarily remove a good part of the little strength it had, with great hazard.

Terzaghi was incensed that misguided or ambitious officers of the government would insist on countervening his recommendations, since it was he himself who had created the theory on which their arrogance was based. It was the Reichs Bridge case all over again, as far as he was concerned. He had responded then to ignorant government action by resigning from the job. And he threatened to do so again.

On Sept. 5, 1942, he wrote to Chief Engineer Leonard Larson of Republic Steel: "I consider any attempt to stabilize the clay beneath the ore storage by artificial means a large scale experiment the outcome of which is doubtful.... Commander Praeger thought of stabilizing the clay by means of vertical sand wells. This method is based on the theory of consolidation of which I am the author. Even the equations for computing the rate of consolidation due to a system of vertical wells were derived some eight years ago at my request by one of my assistants. I mention these facts in order to show that I have a powerful incentive to follow very closely the developments along these lines. The method has been repeatedly and successfully used on a relatively small scale for consolidating strata of very soft and young clay or mud which had very little strength in their original state. However no attempt has yet been made to consolidate a thick bed of clay with a considerable degree of rigidity. This fact governs my attitude towards the proposed stabilization.

"Although I do not deny the theoretical possiblity of consolidating the clay in Cleveland by means of vertical sand wells I would not even consider making such a large scale experiment for the first time in connection with the construction of a steel plant whose output is urgently needed by a country in a state of war.

"I am not prepared to depart from the general policy which guided me while working on the project. Neither your corporation nor the government can afford to lose any more time in haggling over engineering details and the radical modifications proposed by Commander Praeger are incompatible with the policy I pursued. Therefore I submit my recommendations with the request that you cancel my appointment as a consultant to the job unless you are able to secure authorisation to accept my recommendations without modification.

"Personally I would be pleased if my recommendations were overruled because the acceptance of Commander Praeger's plan would involve the execution of a very interesting and very instructive large scale experiment. As a matter of fact I feel very sorry that the circumstances prevent me from sponsoring the experiment myself and I would be the first one to congratulate Commander Praeger on his success."

In the face of this "ultimatum", the War Production Board backed down immediately and permitted the construction to go forward essentially as originally planned. Terzaghi had now won arguments with both Hitler and the American military establishment and, if he were the type, he could have painted both a swastika and the stars and stripes on his sleeve to keep count of his "kills".

The tie rods had been designed to reach a stress of 17,000 psi at the height of 72 feet of ore. To everyone's surprise, they had already reached twice this stress and were in a state of yield during the first ore loading season when the height of ore had reached only 22 feet. In his initial report Terzaghi estimated that failure would occur at a height of 60 feet. But he had not accounted for the artesian pressure. Furthermore, the clay had apparently begun to creep significantly at a low stress level. The ore height of 22 feet corresponded to a theoretical factor of safety of two, whereas a state of imminent failure always corresponds to a factor of safety of one. The foundation ought to have been quite safe. But the walls were moving substantially at this stress.

Extrapolating the wall deflection versus ore pressure relationship established that the walls would have failed at an average ore depth of 31 to 35 feet. Terzaghi was aware that such an accident had previously occurred at Sault Ste Marie in 1913 when during the unloading of an ore boat and a height of ore of only 40 feet, the surface of the ore suddenly subsided and the dock moved out 60 feet in a fraction of a minute; "Hence we know what to expect if we are not very careful.... The data leave no doubt that an increase of this load to a load between 2.5 and 3.0 tsf [ore height of 31 to 37 feet] would have caused a complete failure of the ore yard, the quay wall, and the ore bridge, over a length of several hundreds of feet."[42] There had been three other failures of ore yards in the Great Lakes Region—in Detroit, Buffalo, and Erie. The common feature around the shore of the Great Lakes is the presence in foundations of thick layers of glacial clay.

There was much excitement at the Ore Yard. Terzaghi wrote to Mr. Larson that the "utmost concession which I can possibly make" is to allow unloading ore up to a height of 30 feet.[43] "In engineering, no structure is considered safe unless the factor of safety is at least 1.5. By piling a load of 2.4 tsf [30 feet of ore] onto the yard we reduce the factor of safety to less than 1.1, which leaves but very little margin for the effect of an exceptional rise of the water table beneath Cleveland Heights, or of doubling the speed of ore delivery, on the stability of the base of the yard. Yet if we adhere to the customary safety requirements, we could not even load the yard as heavily as we have done during the winter of 1943 to 1944." He asked that the records be sent special delivery regularly and that he be telephoned immediately if something unusual is noticed as "I cannot afford to risk the failure of a structure with which I have been associated for several years."

By continued vigilant monitoring, the boats continued to dock and unload their ore throughout the war years and beyond without any failures, although they came quite close on at least one occasion when the ore height proved to have been badly distributed over the yard. The steel mill was never able to increase its ore storage higher than about 37.5 feet, but it was able to operate successfully without fear of failure using Terzaghi and Peck's observational method.

15

A Dizzying Pace in America The 1940s and On

After gaining a security clearance for defense work, Karl became an American citizen on March 1, 1943—calling it "the happiest day of my life"[1]—and three months later he held a U.S. passport. None of this would have materialized without a very significant effort by Adolph Ackerman, and a portfolio of impressive letters from well-placed friends, including John C. Wiley at the State Department, whom he'd befriended during the dark time in Vienna. It was full-speed now on all the facets of his rich formula for living: writing articles and books, engineering practice, lecturing and teaching, and correspondence, in about that order. He had no intention of seeking a full academic career; as a consulting engineer he was doing just exactly what he had dreamed of and took enormous satisfaction from the thought that his creations from a Bosporous cloister now moved an entire generation of engineers.

The family responsibilities fell into Ruth's department. Eric was transformed from "Squeezix" to "Skipper", and in May of 1941 he was joined by little Peggy, born while Karl was teaching in Texas. Their rented nest in the oaks and rhododendrons of Winchester convinced them to settle there permanently; so in 1941 they bought a piece of land on the edge of Mystic Lake and retained an architect. The result was a contemporary house with spacious living/dining room, parquet floors, a spiral staircase that invited surreptitious slides down the banister, and a vast picture window framing the lake and garden. Karl took intense pleasure from his children, playing, swimming, and walking—when he was there—and when the children were old enough, he made them a boat. It was a time of supreme satisfaction; the family felt fully settled and even began planning a cabin in their retreat in the Maine wilderness, where the fall colors made the Vienna Woods seem pale by comparison.

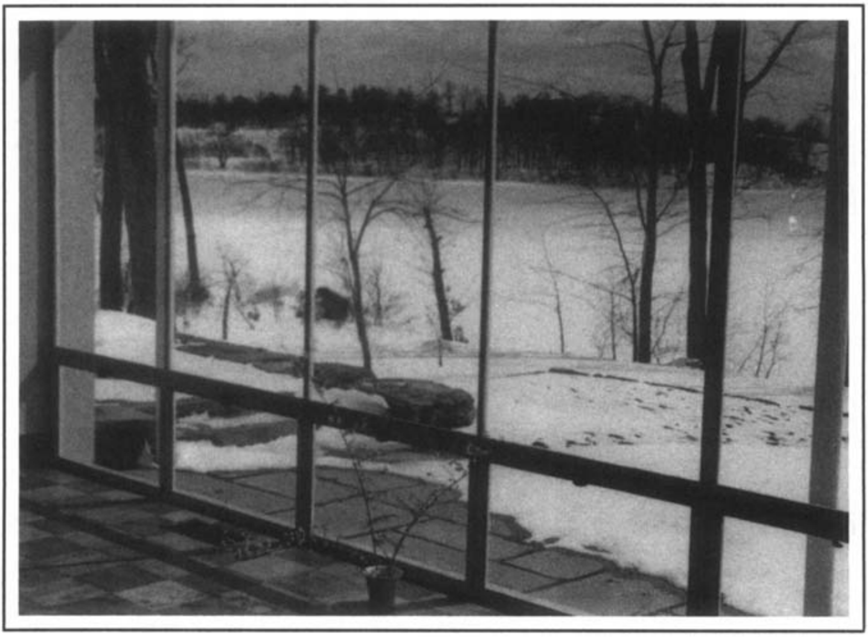
Ruth and Karl entertained and, occasionally, lodged colleagues and academic visitors. But mainly they listened to the war news and watched war movies, and like all American families, passed from fear to anticipation and final elation. There was no doubt of Karl's allegiance; America was his home now. In the war's gloomy beginning, the shocking surprise of France's rapid fall bred fear that New England might soon be invaded. He expected Russia to collapse in six weeks but thought if they somehow could miraculously resist, Germany would be doomed. He was amazed that the American boys could fight so well. As the German army collapsed he clung to the breathtaking broadcasts awaiting realization of his prediction that the German people would rebel and exterminate their psychopathic tormentors.

Karl was shocked with Roosevelt's death but decided it had come at the right time, writing that FDR "personified the hopes of the world and passed on before he was deflated."[2] The joyful news of the European war's end in May of 1945 was dampened by reflections on the human misery, mass murder, and destruction, reinforced with each of the many European letters that began to arrive. He learned that his book "Engineering Geology" had been burned and his Jewish coauthor Professor Redlich died awaiting deportation to a concentration camp. Karl called it "moral insanity".

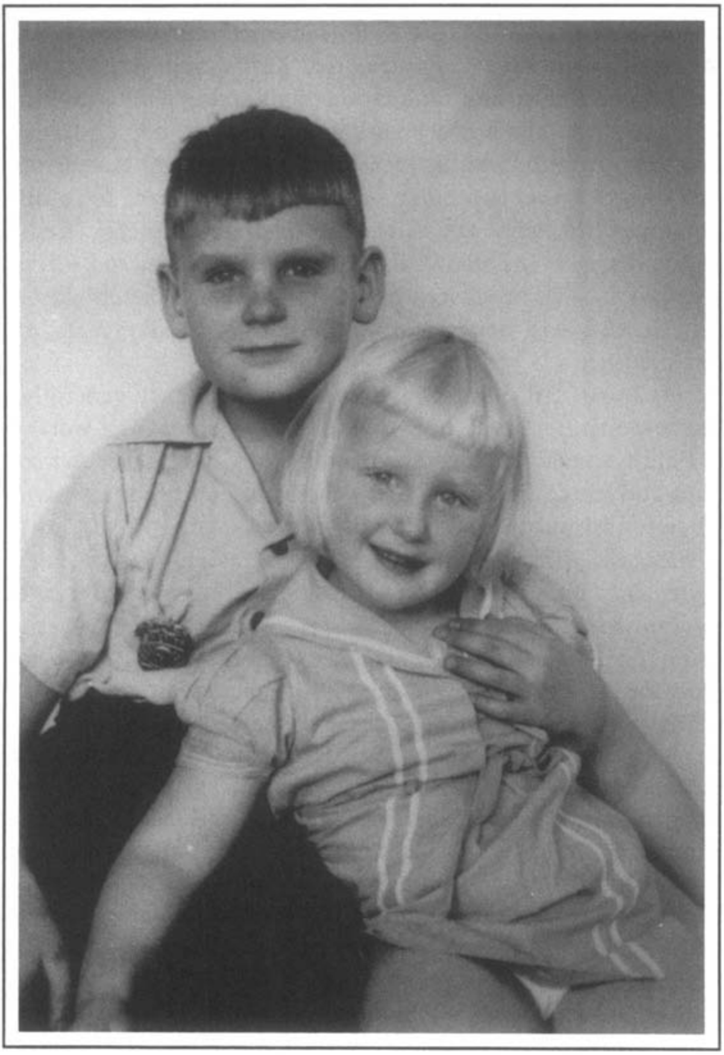
In writing to support empowering the Nazi professor Haas[3] with a position of political leadership in Austria, Karl offered the following rationale. Haas was an idealist who "regarded the party as an instrument for giving Germany and Austria the strong paternalistic central government which they believed it required. He did not foresee the domination of the party by the brutal elements in it, nor did he for a moment suspect that Nazi foreign policy would ever go beyond its expressed purpose of uniting the Germans of central Europe. His opinion of the radical anti-Semitic propaganda of the party is best indicated by his real friendship and high esteem for a gentleman of Jewish descent, Hofrat Hans Wachsman, a former Austrian States Attorney in Vienna."[4] Perhaps Karl sympathized with his old colleague and friend because he himself had been tempted by some of the same ideological traps.

Karl considered the announcement of the atom bomb to be the most fantastic event of his lifetime. "If Germany had preceded us, the dark ages may have returned."[5] He worried about the Russians, confiding to his friend von Karman that his "greatest misgivings are about those who reside within the zone of Russian occupation. The Russians are apparently the only ones among the forces of occupation who know exactly what they want and I consider them capable of acting with such speed and ruthlessness that whoever comes after them will find a firmly established one-party system and all potential sources of opposition obliterated. I have seen enough of Soviet Russia to have a fairly clear conception of the technique for achieving this end."[6]

Preparing to inspect an auger hole, February 1939.



The view over Mystic Lake from the Terzaghis' living room, Winchester, Massachusetts.



Eric ("Skipper") and Peggy Terzaghi, May 1946.

Karl's study upstairs gradually became christened with the smell and stain of cigar smoke as he slaved long hours writing reports and books.[7] Finishing volume one of soil mechanics and foundation engineering had become an obsession, and now that he had escaped Fillunger and Nazi Austria there could be no further excuses. After that would come books on applied soil mechanics, rock tunneling, and earth tunneling.

Arthur Casagrande's suggestion that Karl should write a two-volume work on soil mechanics and foundation engineering led Terzaghi to isolate theoretical concepts of soil mechanics in volume one, hoping to devote volume two to applications unhampered by mathematical clutter. His initial intent to keep the level appropriate for students was hard to fulfill, despite Al Cummings' and Ralph Peck's reading of draft chapters. The book that appeared in May, 1943, *Theoretical Soil Mechanics*, proved to be in part a reference work in which he colored in the "rough pencil sketch" of *Erdbaumechanik* with what had become, within less than twenty years, an almost complete picture.[8]

To his friend F.E. Schmitt, whose polished fluency generally heavied Karl's correspondence style, he wrote with self-deprecation worthy of G.B. Shaw: "I did not send you a complimentary copy because I don't consider it important and interesting enough. I wrote it primarily for my own sake, to get undigested fragments of theory out of my system. Yet to my surprise it is quite a success.... There is no accounting for tastes."[9] Its success was less ample with Terzaghi's friends in construction. Referring to Terzaghi's occasional employment of the uppercase Greek letter sigma for mathematical summation, FitzHugh wrote: "I remember what these denote but not having used them for more than thirty years I have concluded that life is too full of other things for me to start in with these animals again."[10]

In the preface to *Theoretical Soil Mechanics*, Terzaghi stated that this subject is incomplete without the second volume's discussion of the properties of real soils and their behavior in real applications. "Nature interferes with extensive applications of theory," he told Schmitt, and promised the "really important" second volume would follow almost immediately. His first draft of this work, *Introduction to Soil Mechanics*, had already been dispatched to the junior coauthor Ralph Peck for "editing and polishing", and was currently being used in mimeographed form as a textbook for a Navy course at the University of Illinois.

What Terzaghi meant by "editing and polishing" was itemized in the terms of cooperation with Ralph Peck. Terzaghi would supply a draft with some gaps and most of the figures. Peck would fill in the gaps and missing details, augment the examples, and perfect the English.[11] Later, he added the troublesome instruction "Don't deviate too much from my treatment."[12]

Unfortunately the writing plan did not call for Terzaghi to review Peck's work progressively. Ralph sent only the finished manuscript, on January 20, 1943, whose completion swelled him with satisfaction and accomplishment. To his chagrin Terzaghi rejected it, writing back that it was "not a ripe manuscript" but "a crude draft" occasionally sinking to the level of a mediocre examination paper. Terzaghi instructed Peck to take longer and aim for a higher standard, as Karl had done with *Theoretical Soil Mechanics* for which, he claimed, he'd spent five hours on the average perfecting each of the 900 manuscript pages.[13]

Though discouraged by this cruel shock treatment, Peck somehow found inner strength to continue, abetted by Karl's subsequent kindlier tone. The process of editing and changing dragged on and, as their discussions over the manuscript moved from English usage to critical points in the mechanics of soils, they began to appreciate that their progress was being delayed not so much by language as by frustration with the unfinished state of soil mechanics. Terzaghi explained: "For me the process of writing a book never meant more or less than sort of a mental house cleaning. It compels me to examine every little piece of my inventory. Much of it is found to be worthless and only fit for being discarded."[14] As the process of rewrite, review, and alteration dragged on year after year, it became evident that Terzaghi and Peck had become prisoners of their own observational method.

It wasn't until 1946 that the book neared completion. By then it was no longer an introduction to soil mechanics but a compendium on engineering with soils, based on precedent, wisdom, and the useful elements of the mechanics of soils: *Soil Mechanics in Engineering Practice*. This book, finally published in 1948,[15] quickly established itself as a main pillar of geotechnical education.[16]

The authors, now mutually trusting and united, ganged up on what they perceived as an increasingly theoretical and esoteric portrayal of soils in university education, as depicted in Ralph Peck's review of the book manuscript from Professor Donald Taylor of M.I.T. "Blind application of theory can directly lead to disaster" he wrote; "this is the idea which nearly ruined soil mechanics and against which the best efforts of Terzaghi and a few others have only recently been able to make headway."[17] Karl noted that Taylor, the poor fellow, was a victim of soil mechanics for which he, Karl Terzaghi, bore the responsibility.[18]

This contemporary trend in soil mechanics reignited Terzaghi's evangelical zeal to complete his book project on engineering geology. "I do hope that the practical consequences of my excursions into Engineering Geology will be less catastrophic than those of my doings in Soil Mechanics", he wrote to his friend Schmitt, adding "I blush if I think that I am partly responsible for what is being printed in this field."[19] To another he wrote, "I consider Engineering Geology an essential antidote against a too theoretical approach to practical problems involving soils."[20] But he continued to find it a "strangely elusive subject, slippery like a reptile." His book, and his lectures at Harvard must enrich the practice of engineering, setting up the geologist "not as an oracle" but as the source of working hypotheses for exploring sites and inferring the properties and conditions of different layers.

A convenient vehicle for launching this mission, at least for tunneling, walked into his office in January of 1945 in the person of R.V. Proctor, vice president and general manager of the Commercial Shearing and Stamping Company. In an effort to advance the sales of his steel supports for tunnels in rock and soil, Proctor and his structural engineer Tom White (no relative of Lazarus) were writing on the use of steel supports underground. They had experience with steel sets in some 300 tunnels over twenty years but were entirely ignorant about engineering geology. Proctor intended just to talk to Terzaghi about the problem but after two hours realized there was much more to learn. According to Karl "we both had the sensation that we lived for a long time in the same country but on opposite sides of a high wall."

The next day Terzaghi presented them with a generous proposal. He would develop and write a major section on tunnel geology and its relationship to the design of steel supports. Although various books and articles existed on tunneling, going back more than a century, there really was no systematic basis for relating the selection and use of steel supports to the different types of ground conditions. He was very pleased to work on this, especially as they agreed to pay for his research and writing as an engineering consultant.

Terzaghi considered the two men to be abominable writers, but White had a "good, instinctive grasp of mechanics" and Proctor's perceptions were remarkably clear; he was curious about things and a fine observer. "Out of the chaos seems to grow the first book giving a comprehensive picture of tunneling operations correlated with rock geology."[21] The products of this collaboration were twin books published by the company on rock and earth tunneling with steel supports.[22] Unfortunately, printing of the second work on earth tunneling, due to no fault of Terzaghi's, was long delayed, and the work appeared only posthumously.[23]

Terzaghi's system for selecting steel supports in rock tunneling that is presented in this work stands as an apt testimonial to the power of his direct and logical thinking. Instead of cramming a text full of generalities about rocks, and elaborate theory imagined to apply to them, he simply sought answers to the most basic question about rock behavior underground: what happens to the rock around a tunnel if supports are not placed, or placed imperfectly? This evoked not only rules and procedures for the designer, but as a byproduct a realistic classification scheme for tunnel ground that remained in use, even extended to nontunneling applications, half a century later. However, he never did get around to writing the rest of the book on engineering geology.

With jobs going in Chicago and Cleveland, Karl found himself often in the company of Ralph Peck during the war years, and, after 1942 when Ralph became a faculty member at the University of Illinois, Karl became a frequent visitor in Urbana. It was natural then that Terzaghi's visitor status would be regularized in some useful way by the university. In April of 1945 Department Chairman W.C. Huntington, himself interested in soil mechanics, arranged for Terzaghi's appointment as Visiting Research Professor, with a stipend of $1,500 per year and the services of two half-time research assistants (each appointed for two years to work under his direction). Terzaghi would be asked to enrich their teaching program with occasional lectures from his trove of case histories, illustrating his approach to solving problems involving soils and geology. Karl considered this appointment little more than the formalization of a twenty-year-old relationship with the institution. A jealous Arthur Casagrande saw it differently.

Arthur was by nature possessive towards Terzaghi as it was largely his doing that had brought Karl back to America. Furthermore, he really needed him at Harvard, not just as an enricher but to teach applied soil mechanics and engineering geology, for without him Arthur was almost alone.[24] When Karl's Princeton lectures in 1939 were expertly promoted by Tschebotarioff, Arthur grumbled that the Russian was taking great pains to avoid mentioning any association between Terzaghi and Harvard.[25] Terzaghi's nonrecurrent appointment at Texas didn't seem to hurt, but the arrangement at Illinois triggered an outburst that engineers are ignorant of Terzaghi's connection with Harvard.

Arthur Casagrande complained to Karl that their collaboration was languishing.[26] This was not a new plaint; in 1941 Karl wrote to Arthur that they might as well be living on different planets, not only because each was so busy but because "our mentalities are fundamentally different. Your character also pervades the field of your scientific activities. You are conservative and your opinions have a tendency to develop into convictions. My ideas are still as much in a state of flux as they have been twenty years ago and the only one permanent item in my inventory is my insatiable curiosity." He hoped they could at least communicate their observations to one another as in former days.[27]

It seems that what was developing was a kind of love triangle, the classic plot mover of romantic novels. Arthur loved Karl like a father, loved to huddle with him in dissection of issues and men, loved his German accent and knowledge of the old country, and his appreciation of fine music, art, and literature. Arthur was introverted and may have hoped Karl's easier ways with people and authority would wear off on him. Contributing to tension between them was Karl's reluctance to forget he had once been Arthur's teacher and employer. This tension sometimes approached pathetic humor, as when Karl, still technically an enemy alien, freely entertained 25 military officers attending a special course at Harvard without first obtaining authorization, something that Arthur found impossible in his own home since at this time his wife was also considered an enemy alien.[28] (Dean Westergaard told Arthur to just inform the officers not to tell her any secrets.[29]) On this occasion, Arthur laid down the law to Terzaghi. Although they were always friends, irritations resurfaced because of fundamental differences in their personalities.

Ralph Peck, on the other hand, raised in a pious midwestern family with "lemonade and table prayer"[30] was as different as could be—honest, friendly and perhaps at first a little stiff. Karl told Schmitt he could visualize Ralph "with a stiff, high collar explaining to an attentive audience that he managed an aperture in the apex of an egg, instead of simply telling them that he punched a hole into it. Yet he is the best disciple I have gotten so far because he is at least willing to listen, learn, and reconsider."[31]

There was no knowledge of any distance developing between Arthur Casagrande and Karl Terzaghi among the graduate students who came year after year to the prestigious soils engineering group at Harvard. The well-structured Harvard program was seen as a cohesive, two-professor show, even though Karl never held more than a quarter-time faculty position. His well-attended lectures at Harvard inspired not only the Harvard engineering and geology students but many from M.I.T. Thus even if his prime focus was as a consulting engineer, throughout the nineteen forties and on into the fifties the academic world still paid homage to *Professor* Terzaghi.

In 1946, Terzaghi's professorial title at Harvard was changed at his request to Professor of the Practice of Civil Engineering. This helped justify his frequent absences, sometimes for an entire semester, while Casagrande remained steadfast, carrying the entire administrative burden, while presenting clear, complete, and devoted lectures that earned him a loyal alumni.

Karl continued visiting Illinois in twice-yearly bursts of energy, when he would descend to deliver a group of three ninety-minute lectures. He was a brilliantly stimulating lecturer, revealing rich case histories to large audiences, and occasionally, using mischievous devices to convey a point.

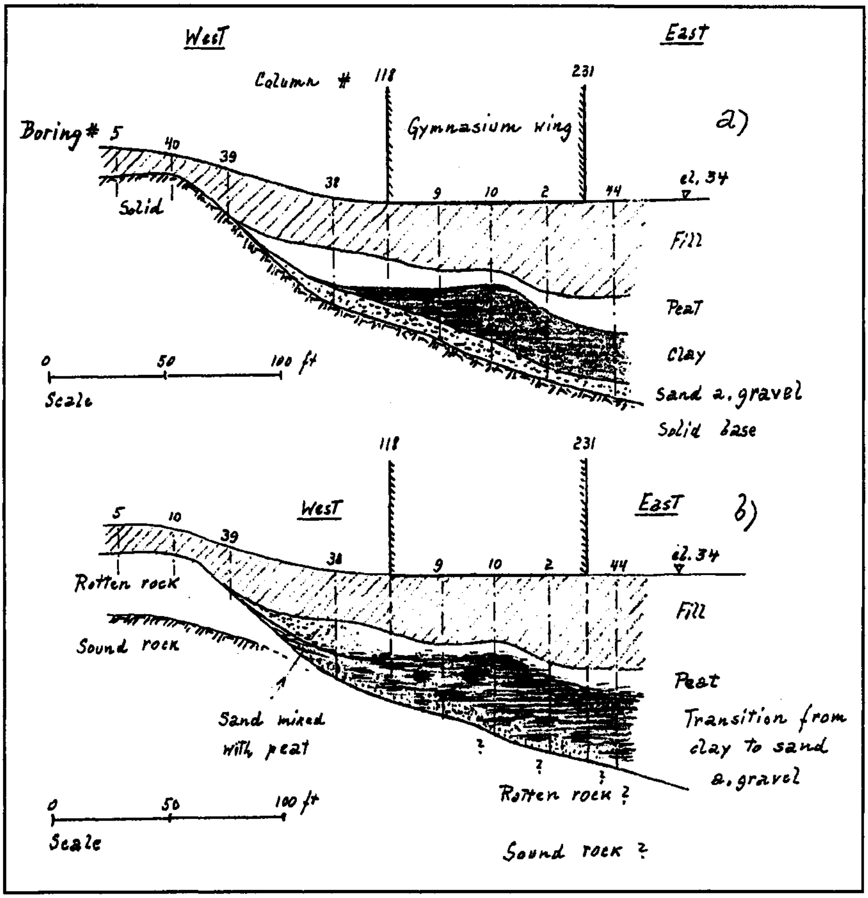
In these years, in addition to the Chicago Subway, the raising of the *Normandie*, Charity Hospital, and foundations of iron storage yards, Terzaghi had expanding work calling on his skills as geotechnical detective and designer. He helped reconstruct a failed dike in Hartford and raised a previously failed hydraulic fill dam in Mexico. He correctly predicted the ruination by sliding of a partially prepared foundation along the shore of Lake Superior. He explained the damaging settlement under a high school in New York, and surface subsidence over a salt mine in Michigan. He worked on the physics of perennially frozen ground (permafrost) for airfield foundations in Alaska and rejected the site for an airfield on clay in Sweden. He had his first connection with the clay slides of Quebec, the huge settlements of clay soils in Mexico City, and never-ending subsidence in Long Beach, California. And he took up new projects in British Columbia, France, India, Egypt, North Africa, and Brazil.

In Hartford, in July of 1941, the hollow between a new and older parallel dike was being filled with hydraulically sluiced sand to build up a highway embankment when the outer dike suddenly moved out more than sixty feet, with the fill following right behind. The hydraulic fill had been laid over a sand and silt stratum that rested directly on a deposit of "varved clay" (a laminated silt and clay laid down in an Ice Age lake). Using Corps of Engineers borehole data, Terzaghi interpreted subsurface cross-sections showing the postslide geology and deduced the development of failure in time and space. He showed that sliding initiated in the varved clay; then, after slight movement, piping began above slide-opened joints in a sewer pipe passing through the silt and sand stratum. With time a large cavity had formed, and its eventual collapse triggered the sudden large movement in the varved clay.

Most of the mass of clay was little affected by this deformation and the Corps of Engineers proposed to reconstruct the dike based on a simple stability analysis. Terzaghi showed, however, that the embankment was not as safe as the Corps of Engineers maintained because they had missed the implications of the actual failure process. As he demanded, the dike was repaired slowly by the observational method, controlled with measurements of critical pore pressures.[32]

After the Hartford dike failure, cracks began to develop throughout the Colt arms factory right behind the boundary of the slide. Terzaghi didn't think the crack pattern could be reasonably explained by proximity to a slide; he thought the culprit was more likely collapse of cavities beneath floors, probably from piping over joints in another leaky sewer during a time of high ground water. Subsequently, 48 holes drilled below damaged floors proved him absolutely correct.[33]

Terzaghi's knack of putting together a proper geological picture before drawing engineering conclusions was also demonstrated by his work in 1946 at Taft High School in the Borough of the Bronx, New York City. The new building settled badly and the City asserted Raymond Company's piles had not reached down to the specified bearing layer, a sand and gravel bed. Terzaghi observed that within a group of piles the depth at which "refusal" was obtained varied enormously, and piles of a group could often be subdivided into subsets clustering at different "refusal" depths.[34] Furthermore, plots of settlement versus time showed the characteristic shape Terzaghi had come to associate exclusively with consolidation of clay. He reasoned that there must be pockets of clay underneath some of the pile tips, even though they were mostly driven into the required bearing layer of sand and gravel.



A drawing prepared by Terzaghi to compare foundation conditions as represented by the engineer (upper section) and as actually found by the contractor according to Terzaghi's interpretation (lower section) for the foundation of Taft High School, New York. From "Memorandum on the causes of the settlement of the gymnasium wing of the William Howard Taft High School in Bronx, New York," by Karl Terzaghi (Oct. 22, 1946).

With a historical geologist's imagination, Karl reconstructed the sequence of glacial advances and retreats and sea level incursions and withdrawals that explained his corrected soil profiles. With that he demonstrated that the foundation of the settling portion of the high school lay exactly atop the shore zone of an ancient water body filling a bedrock valley. He observed how storms had carved a sea cliff around his own Mystic Lake, created 80 years before by a dam, and thus carried sands and coarser deposits out onto the near floor of the lake. The sand and gravel forming the shoreline of the much longer-lived Bronx lake would have washed similarly onto the bottom; so the zone now represented in the official soil profile as a homogeneous bed of sand and gravel with abrupt boundaries should be replaced by one of pockets and wedges of gravel and clay interspersed in a most complex manner laterally and vertically. The data from the construction of the building proved this to be the correct assertion.[35] Renowned glacial geologist Richard Foster Flint, wrote on reviewing Terzaghi's geological inference that he had read Terzaghi's report with admiration.[36]

Terzaghi testified for Raymond that the engineers had merely guessed at the geology with inadequate methods of investigation. Their errors led to inadequate design and specifications. The jury was unanimous in support of Terzaghi's side after a half-hour of deliberation.

In 1943 Karl went to Mexico with Ruth to evaluate the safety of an old dam built by the hydraulic fill method. The sixty-meter-high embankment had suffered a gross failure when construction was 90% completed in 1909, after which it had been repaired and subsequently put into uninterrupted service for power generation. The question was, could the company continue to rely on this reservoir? Deciphering why the slide had happened was partly a geologic question, for the borrow material came from quarries in two different rock types, only one of which was dense enough to displace the mud as it moved into final position in the embankment under the action of the hydraulic delivery system. When he succeeded in understanding the anatomy of this embankment, Terzaghi was able to demonstrate that the failure had emptied the dam of almost all of the soft material responsible for the slide. He concluded the dam was safe and satisfactory and proceeded to show how the owners could even increase its height by three meters, which was later accomplished.

Because of delay getting a passport and visa for Mexico, Karl chose to place a Mexican assistant on the Necaxa job until he could travel there himself. When Professor Dawson tried to nominate a student who had reportedly attended Terzaghi's lectures at Texas, Karl could not remember him and asked for more information adding: "If he is as dumb, unpractical and helpless as one of the university trained assistants I had during the last year on one of my jobs, I may come in conflict with the Mexican health authorities, because I would murder him with my bare hands and throw his corpse into the Necaxa Reservoir."[37] The "university trained assistant" mentioned in this note must have really ruffled Karl, because he continued to draw sarcasm worthy of Karl's Croatian days even a year later, writing "his education eradicated completely whatever common sense nature may have bestowed upon him. After he was fired, he was eagerly offered the position of an instructor in soil mechanics at his alma mater because now he combined profound theoretical knowledge with practical experience. Before long he will undoubtedly invade the field of 'fundamental research'."[38]

Necaxa introduced Terzaghi to Mexico, but it was foundation studies for a proposed refinery later in 1943 that showed him the Mexico City problem.[39] At the present location of this great city, Aztecs had lived on an island in a lake until it was drained and filled by the Spaniards early in the sixteenth century. A borehole below the surface now passes through more than 300 meters of "montmorillonitic" clay, a type of clay common in volcanic terrains that is capable of softening as it sucks vast amounts of water into its molecular structure. Locally under Mexico City, layers of this soil contain a volume of water more than ten times the volume of clay minerals. Horizontal layers of sand, occurring about every 100 meters of depth below the surface, allow water to drain from the soft clay, and as it does the clay consolidates and the ground subsides; but, even after the excess pore pressure under a foundation has decayed, the settlement continues at a more or less constant rate, a phenomenon known as "secondary consolidation".

The rate of settlement of Mexico City buildings jumped up with the construction of sewers at the turn of the twentieth century and accelerated further as water wells started to bleed artesian pressure from sand layers. Not only did the buildings sink, but subsidence reduced the sewer system's gradient to the extent that it could no longer work by simple gravity flow.

In many other cities, the effective load of a tall building can be reduced by excavating deep foundations, and in this way settlements can be minimized. Terzaghi pointed out to his client that this was not so easily accomplished in Mexico City because the foundations would rise as much as a meter during the excavation of the basements, with damaging differences from the walls to the center of the basement floor; then, on application of the load, they would settle by a similar amount.

Terzaghi was consulted in connection with the opera house, the Palacio de Belles Artes, which was constructed between 1900 and 1925. The building site settled eight centimeters just from pouring concrete for the foundation, and during construction the steel columns settled so much additionally that they had to be jacked up. The builders tried to stop the settlement by grouting in 1910 and 1920, without any success. The only way to stop it, Terzaghi advised, was to transfer the load of the building to a deep foundation by underpinning. He described how to plan for this in a report in 1944, warning that "any attempt to stop the settlement without making the proposed preliminary investigation would be an irresponsible gamble. Since I have witnessed many gambles of this kind I can state from personal experience that the savings associated with inadequate preliminary investigations are entirely out of proportion to the financial risks."

Six years later he returned to guide the underpinning operation. By then the problem had significantly worsened due to regional groundwater withdrawal, and the building was facing serious distortion. The regional subsidence from this cause was also causing ground cracks, which destroyed any building they happened to intersect. It was time, he argued, to organize the property owners for a regional assault on the problem.[40]

Perhaps the most extreme foundation fiasco in his Mexican experience happened to the Escuela Normal. The school's high central tower was founded on end-bearing piles at depths of thirty meters while the other parts stood on surface ("floating") foundations or shallow friction piles. Further, a tension zone passed right through the auditorium. Within two years of Escuela Normal's construction, differential settlement was so great that the structure approached collapse and had to be evacuated.[41]

Regional problems with unusual, bad-acting clays were not exclusively a Mexican affair. Brittle clay that softens suddenly to almost a liquid consistency fills the bays and estuaries of the north coasts on both sides of the Atlantic, and elsewhere. Enormous flow slides have occurred in Norway, Sweden, and Quebec, for example, as the process of clay softening suddenly transformed firm soil in place into liquid earth which then flowed out carrying away entire farms. As early as 1941, Arthur showed Karl that the Boston Blue Clay is sometimes very brittle such that with rough handling it abruptly softens to a liquid consistency. He correctly attributed this peculiarity to its initial deposition in salt water.[42]

Karl's first experience with the highly sensitive Quebec clays occurred when he reviewed the safety of a system of dikes feeding St. Lawrence River water into a power house near Beauharnois. He discovered that almost every section of the canal in which the dikes were built more than 20 feet high suffered cracking and then very sudden failure with movements of many feet. Thereafter, a wave of material (a "mudwave") would rise up above the water at the toe of the embankment and advance laterally to distances of 150 feet or more. Once started, a slide tended to spread laterally, reaching out into virgin terrain. Karl frankly did not understand this material, even though he came close to explaining it in *Erdbaumechnanik*. The origin and characteristics of extreme sensitivity in marine clays soon became a subject of research at Illinois and Harvard.[43]

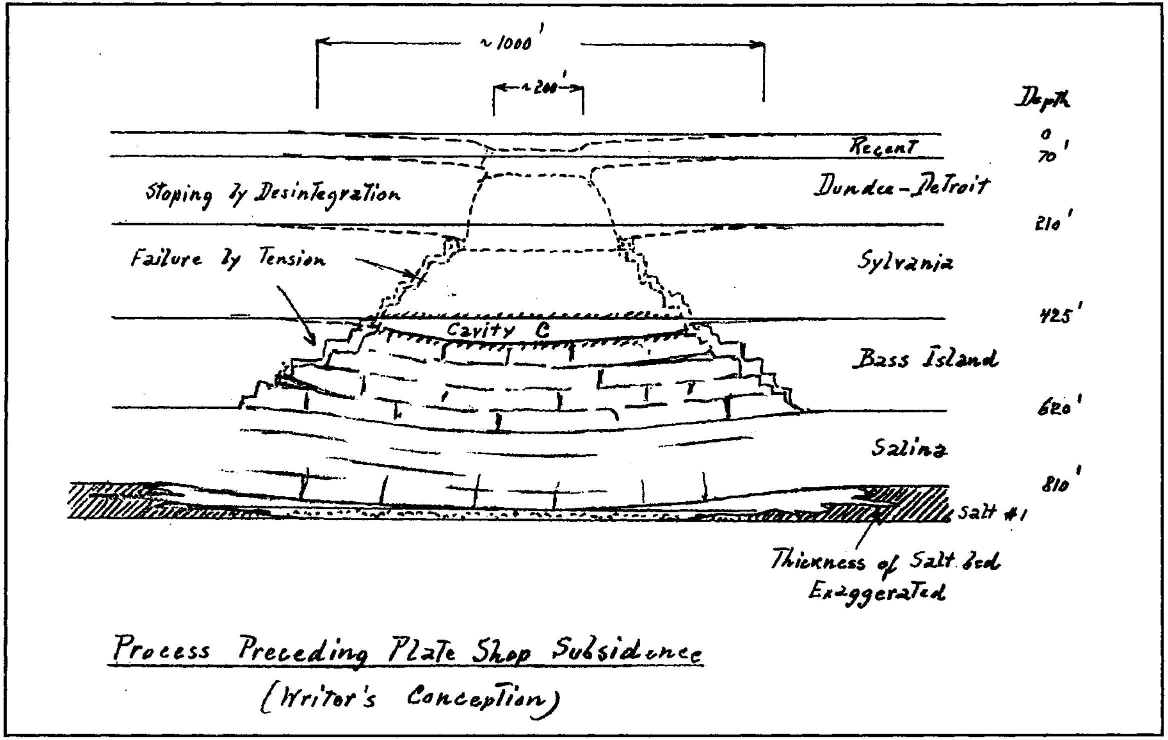
Solving problems of big settlements and surface collapse proved to be Terzaghi's affair not just in soils but in rock, as side effects of industrial operations. In the late 1940s, he came to work on both the Wyandotte brine fields in Michigan and the Wilmington oil field in California in connection with severe subsidence of the surface.

Wyandotte Chemical Corporation had been mining salt from deep rock-salt formations in Michigan since 1896, by dissolving it in place and pumping out brine. When Terzaghi arrived on the scene, in 1947, the ground had subsided as much as five feet at the surface beneath mine buildings. He disagreed with Ralph Peck that this stemmed mainly from consolidation of clay soils due to ground water pumping; the settlement was too large and, furthermore, he could demonstrate from analysis of the company's historic data that the subsidence centered over deep brine cavities up to 600 feet in width.[44] The question was, would the continuation of this subsidence lead to outright collapse at the surface, as in limestone country? From measurements of the porosities of some rock-filled cavities, he concluded that the complete closure of a cavity even 100 feet high would never reach the surface at all, but would simply create a rubble-filled cavity inside the rock. There would be no sinkholes, no collapse of the surface. But his co-consultants, Ralph Peck and Carl Bays, did not completely agree, and the management was advised in a joint report that, while not probable, sinkholes could not be precluded from forming beneath a company building.[45]

Terzaghi signed his name to this but wasn't happy to leave his client facing the portent of a sudden, violent collapse of a plant building. So he continued to ponder the question, acquiring additional data on case histories from the Solvay Company, which had experienced sinkhole formation over a good number of mines. Dissecting this information, he analyzed the geological and mechanical conditions in each case of ground collapse and classified the different mechanisms by which sinkhole catastrophes can occur. Applying this knowledge to the specifics at Wyandotte's brine works, he was able to inform the management that there was almost no danger.[46] However, in 1954, directly across the river at Windsor, Ontario, a catastrophic sinkhole did occur. It was featured on the cover of *Life* Magazine.

One of the major foundation problems of the west in recent times was accelerating subsidence over the Wilmington oil field in Long Beach, California. Soon after oil production began in the 1930s, the ground began to subside and by 1952 had reached 16 feet, with associated horizontal shortening of 4.5 inches for every 100 feet of horizontal distance.

The Wall Street Journal of Oct. 13, 1952, reported that expenditures were amounting to more than a million dollars per month to keep tidewaters from covering docks and waterfront plants, and to keep up with continuing problems. "Government and private enterprise have undertaken what is probably the greatest harbor salvage operation of all time." Millions of tons of rock were being moved every year from a quarry on Catalina Island for construction of levees and for filling in low places and another million and a half tons of fill is dredged annually from the harbor bottom. The cause, was



Terzaghi's explanation of the subsurface mechanisms responsible for large settlements of the "Plate Shop" at the Wyandotte Salt Works. From "Confidential Memorandum concerning the subsidence of Brine Fields", to Wyandotte Chemical Corporation, by Karl Terzaghi, Dec. 30, 1950.

the removal of oil, some 600 million barrels having been pumped out since 1932, as well as 200 million barrels of water and enormous quantities of natural gas.

Tidewater was beginning to encroach on city streets and industrial facilities. The Navy built 4.5 miles of concrete structures to protect its shipyard; the City of Long Beach directed an additional $30 million to continue replacing and repairing bridges, roads, piers, and buildings. Meanwhile, horizontal compression from the settlement was fracturing columns of some buildings, buckling railway tracks, and tilting bridge towers, while zones of horizontal tension were rupturing city pipes. In 1949, two hundred producing oil wells had their casings ruptured by a thirteen-inch displacement on a fault whose movement was linked with the subsidence deformation; in 1954, a further movement ruptured 68 more wells.

These problems were keenly felt by the Southern California Edison Company which owned a 43-acre steam power station on Terminal Island in Long Beach Harbor, almost exactly over the center of the subsidence trough. By 1952, horizontal compression caused by the subsidence had forced replacement of the cooling water system. The increasing magnitude of total subsidence exposed the plant to the risk of flooding so that they were compelled to construct a dike around its entire perimeter.[47]

How high a dike must be constructed would depend on how much more the ground was likely to subside. Although the Port of Long Beach issued estimates for the general welfare, their accuracy could not be relied on without the full cooperation of the oil companies, and this was not happening. In the interest of improving this situation, a conference was held at Southern California Edison's center on September 21, 1948, with representatives of oil companies, the City of Long Beach, Union Pacific, and Stanford Research Institute. The latter group invited a number of experts, including Karl Terzaghi. This led Terzaghi to prepare an informal report for Southern California Edison reviewing the possible causes for subsidence; in this report he concluded definitively that the only viable explanation for what was happening at Terminal Island was compression of the sedimentary strata caused by the reduction of fluid pressure in the oil-producing horizons.[48]

Analyzing settlement of the surface because of compression of soil was Terzaghi's invention. He reminded his client that effective stress consisted of the difference between the total load per unit area on a soil and the fluid pressure in the soil's pore spaces. Therefore, if the pore pressure were reduced by pumping while the total weight of soil remained essentially unchanged, the effective stress must increase. This increase would compress and shorten the depressured layers, and the ground would subside.

If the ground were composed of sand, the amount of settlement could be predicted by doing little more than establishing compressibility factors for the various strata and multiplying them by the increase in effective stress in each layer. If, on the other hand, the oil zone depressuring reduced the pore pressure of clay beds, there would be a lag in the resultant settlement, which could be calculated using Terzaghi's consolidation theory, now a routine and well-accepted part of soils engineering practice.

Thus, Karl Terzaghi was in his element. Or was he? The Wilmington Field produced oil not from soils but from sedimentary strata of Pliocene and Pleistocene age. While these strata might resemble soils, there was little precedent for applying consolidation theory to such materials. Furthermore, the producing horizons were not within reach of sampling tools as Terzaghi was used to prescribing for such studies as they were 2,000 to 6,000 feet below the surface. The field was cut by a number of normal faults, breaking it up into individual geological blocks, and production was occurring and had occurred at different rates over different regions within a very vast volume of rock, none of which had been sampled or tested in the way Terzaghi would normally demand. While settlement profiles had been obtained on the surface, there was little known about horizontal strains and almost nothing about the distribution of ground movement with depth. Worst of all, whatever information could be acquired about subsurface pore pressure decline in different zones was complexly presented in thousands of pages of reports, and the pores of the compressing oil reservoirs were not saturated with water but with both oil and gas.

Thus when Wallace Chadwick, vice president of Southern California Edison Co., authorized Terzaghi to make a major analysis of the problem, after reading his optimistic report of April 23, 1949, the job that lay before Terzaghi was indeed Herculean. To get underway, Karl collected and started digesting a large pile of reports, and got his client to engage a competent petroleum engineer, Charles Dodson, who would be charged with collecting, sieving, and presenting the data Terzaghi required.

Terzaghi's first big decision was whether or not the settlement was to be calculated as a simple compression, as for sands, or as a time-delayed consolidation, as for clays. There could be no doubt that the subsidence was changing with time. But this might reflect merely the spreading of the field over an enlarging region, changes in pumping rates, and changes in gas content with time rather than being caused by slowing of drainage in low-permeability clay layers, the physics Terzaghi had captured in his theory of consolidation.

Terzaghi's reading of the evidence convinced him that time-lag effects were minor and could be neglected. The oil production was from compressible sands. The intervening beds were reported to be of siltstone, derived from winds that had blown sand and silt into the ocean, and which therefore could not contain much if any clay. These siltstones were believed to be essentially incompressible.

Thus, the computation of settlement would consist of merely adding up the many individual contributions of pressure decline in different parts of the producing volumes, using the data supplied by Mr. Dodson. This was a vast project in itself, and Terzaghi's report, with appendices and drawings, is some 400 pages in length.[49] By making a fair approximation of the compressibilities of the different strata and adopting a law of stiffening with depth, he predicted that the maximum total settlement would lie between seventeen and twenty feet, assuming certain locations and rates of future oil production. In the worst case of development on the peripheries of the field, this total might go up to 23 feet, but he declared that unlikely. Thus Terzaghi advised Southern California Edison to design a dike providing adequate protection from flooding for a twenty-foot subsidence, with provisions for raising it to 23 feet if the worst would happen.

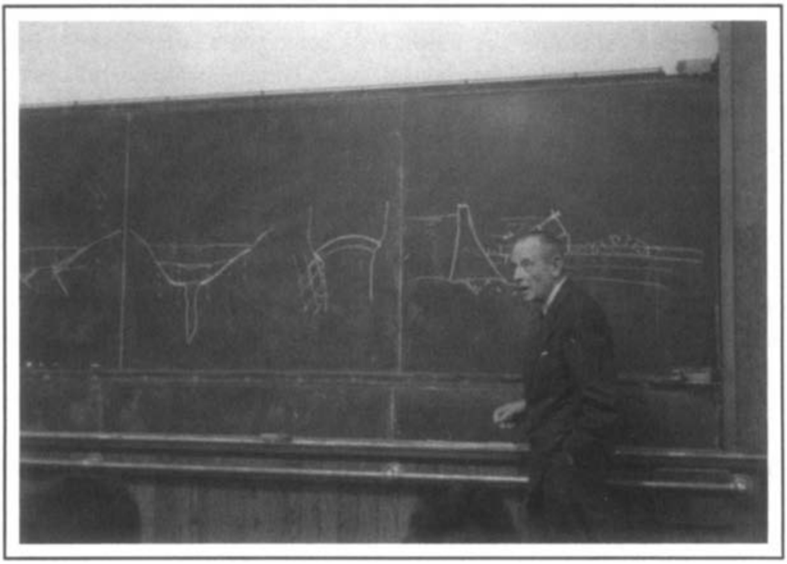
Terzaghi was not the only one making subsidence estimates. Stanford Research Institute (S.R.I.) produced a report, for the City of Long Beach, based on a complex adventure in mathematical modeling using a new theory by Terzaghi's former doctoral student, Nabor Carillo. They promised their results were better because they had used a digital computer and an exact theory—Carillo's theory of "tension centers". Since S.R.I. had enjoyed access to more information about the oil production operations than Terzaghi had been able to obtain, he believed their predicted pattern of subsidence in plan was useful, but their 24-foot total subsidence estimate he reckoned was inflated. Anyway, he thought, it was a product of mistaken mechanics from a field, applied mechanics, whose practitioners consisted mainly of "well lubricated computing machines imbibed with a superiority complex."[50]

Terzaghi's mammoth report was received in late October, 1950. By September of 1951, it was obvious that the rate of subsidence was not tapering off as Terzaghi had predicted but was reaching a new high of 0.17 feet per month. Have there been new changes in the field that would demand you modify your interpretation, he was asked? Southern California Edison was about to release a prospectus for the sale of 800,000 shares of common stock and became agitated about developing fears in the marketplace should the subsidence keep increasing. Terzaghi contributed a placating statement for their prospectus to the effect that he had predicted two years ago that the subsidence would not exceed 23 feet and he saw no reason to raise it; "however all subsidence estimates including his own are inevitably based on simplifying assumptions and as additional facts become available the estimates may require revision."[51] And so they did.

In January, 1954, Terzaghi was forced to release a new report to cope with subsidence rates consistently higher than what he had predicted.[52] He now had the advantage of surveys down the oil wells that showed the location of the seat of subsidence in the uppermost oil zones. The only way this could be explained, he proved by diligent and imaginative work, was by true consolidation effects that would produce a time delay in the subsidence. The siltstones were not incompressible as had been originally thought, and their low permeabilities inhibited drainage, both within the producing horizons and between them. The sad reality was that the real ultimate settlement would now be "considerably greater" than he had computed and, what is worse, would continue even if all pumping were to stop.

In this report of January, 1954, Terzaghi produced two projections, one somewhat optimistic, and the other entirely pessimistic. These were intended to bracket the probable settlement with time. But as the years went on it was found that the actual settlements clung to the most pessimistic curve, even exceeding its predicted ultimate value. The amount of increase was to be enormous: 23 feet in 1958, 33 feet in 1970, perhaps 38 feet in 1979. Consolidation tests and soil classification tests conducted on samples of the supposed "siltstone" by Ralph Peck some years later showed that this "rock" was in fact a typical fat clay soil, with compressibility and consolidation properties typical of such clays.[53] The geological description had been painfully misleading.

Terzaghi wrote jokingly to Dodson in April, 1952, "When I come to Los Angeles again, I will see to it that my education in the realm of oil-well practice rises to a more respectable level." In fact, he did continue to acquire savvy in this field and to introduce new methods. With Stanley Wilson's work, he brought to practice the first use of borehole slope inclinometers to measure strains associated with the oil subsidence. When the time-delay physics became recognized as a vital and unavoidable element of the subsidence process in the Wilmington field, he made the prediction that, despite its simplifying assumptions, proved to be accurate from then on. And through his diplomatic skills and contacts in high places, reaching to the president of Standard Oil, Terzaghi was able to bring about an important sharing of information about pressure-injection techniques being tried by Creole Petroleum Company in the subsiding field beneath Lake Maracaibo in Venezuela. It could be said that Terzaghi thus became one of those most instrumental in fostering the method that eventually managed to halt the subsidence—repressuring of the oil horizons by pumping water back into the pore spaces. In 1953, at the age of seventy, the Bear was still learning, not only about subsiding sediments but how to deal with his own subsiding health.



Professor Terzaghi lecturing at Harvard, 1950.

16 Harvard, India, and Brazil

In the beginning of Karl Terzaghi's consulting career, when travel by air was a heroic act, it would not have been possible to serve on so many consulting jobs without commanding one's own engineering staff. Since Terzaghi's large jobs for Newport News, Republic Steel, Long Beach and others continued over years, projects overlapped, demanding a furious travel schedule. For example, in December of 1949 Karl returned home to Winchester after an absence of six months during which he visited Brazil, Turkey, France, England, and various parts of the United States. This pace had to yield eventually. It happened in March of 1953 with a modest heart attack which landed the Bear in hospital. Twenty years earlier, on the occasion of his fiftieth birthday Karl had told his diary that it would now be "physiologically downhill"; however except for a slight arthritis, his body had coasted comfortably thereafter until, nearing 70 years of age, he complained that "an inconsequential incident",[1] meaning his heart attack, upset his schedule.[2] He rested for a while, but then jumped back in, writing, entertaining, and travelling (packing six cartons of cigarettes with his personal effects for extensive trips).

To Ruth belongs a good deal of credit for sustaining Karl's efficiency. A doctor of geology and acknowledged authority in her own right, she constrained her own professional activities in favor of complete dedication to Karl's work and welfare. She almost single-handedly raised the family and conducted the household affairs. She typed his correspondence and many reports, and functioned as his business manager, editor, and reviewer, as well as his principal chauffeur. The same Karl Terzaghi who once apparently could pilot a plane never took up driving an automobile.[3]

Karl's enormous productivity, even in the wake of his coronary, impressed most people who knew him. After being a guest in the Terzaghi's home for ten days in 1954, Professor Alec Skempton observed that from time to time Karl would take leave of his company, explaining it was necesary to work a bit, and then rejoin the party after two hours fully refreshed.

He worked highly efficiently, and required few corrections to his writing or drawings. He drew his figures by hand on a few sheets of letter paper with characteristic clarity, economy, and completeness. Said Skempton: "Winston Churchill wouldn't read a memo unless it was less than one page. Terzaghi's drawings were the same; he said that if you couldn't get it down on one letter size sheet you weren't thinking clearly."[4]

One event on the near horizon served to lighten a part of Karl's load—Harvard required retirement at age 70. The portent of losing Terzaghi agitated Arthur, and together they combed the lists of potential teachers for an assistant who could help Karl carry on a little longer, until June of 1955. Then, in an expression of devotion, Arthur successfully fought Dean McGeorge Bundy and President Conant to grant Karl the title Emeritus Professor, even though policy disallowed this for faculty positions of less than half-time. Arthur Casagrande wrote that "the next generation will recognize Terzaghi as the most eminent civil engineer of the first half of the 20th century." He noted that Karl had amassed an unprecedented number of honors and prizes and, most pertinently, has been a lion for Harvard. "The fact that he is getting paid only on a quarter-time basis" wrote Casagrande, "merely proves that Harvard has been getting something of great value at a bargain price." Thus confronted, what could the administration do but accede and grant the title.[5]

Arthur was right: Karl's physical health might be peaking, but his stature and mental abilities were on a seemingly limitless ascent. He continued to serve as President of the International Society of Soil Mechanics. He received honorary doctorates from universities and colleges in Dublin, Istanbul, Mexico, Zurich, and Lehigh (and later from Graz and Berlin). The ASCE awarded him its highly prestigious Norman Medal again and again, four times in all, and other significant prizes. They were not alone; the Boston Society of Civil Engineers decorated him four times, and additional honors were bestowed by the Franklin Institute, the Austrian Society of Architects and Engineers, and the Engineering Societies of New England. In presenting Terzaghi honorary membership in the American Society of Civil Engineers, F.E. Schmitt observed that "the effect of his far-reaching educational influence is attested by the work of his disciples in every country."[6]

This lofty perch seemed to authenticate Terzaghi as the supreme protector of soil mechanics and geotechnical engineering, a charge he managed, when asked to, with informed but abrupt pronouncements on the attempts of others the world over. Professor Terzaghi's preeminent standing also exposed him to a few criticisms by those who had been side-stepped or somehow offended, or who dared to publish prior works on subjects of his expertise.

To a prominent geologist who asked Karl's comments on his draft concerning the cooperation between geologists and engineers, he wrote, "I would hesitate to recommend its publication because the time for publishing generalities on this subject has already passed. ... An example is always more convincing than the expression of an intention."[7] In review of a new book on engineering geology, he wrote that the authors had wasted their space on irrelevant topics, "hence the perusal of the book was both unenjoyable and unprofitable. I am sorry that I was unable to discover any merits in this book."[8]

As reviewer of a publication by Bureau of Reclamation engineers, Terzaghi wrote "the only method I can think of for ameliorating the faults would be to change the author."[9] To Scripps Institute of Oceanography he pronounced that measuring water contents of deep-sea sediments without simultaneously measuring the liquid limit is "useless". Furthermore, he told them that their classification of sediments by grain size categories was an obsolete concept, "and it would be a pity if you tried to keep it alive."[10]

His sharpest tongue was reserved for a former assistant who was found to have falsified data in order to obtain a doctorate. Karl Langer had made a wonderful impression on Terzaghi as his protege in Vienna in the mid-1930s, and at his invitation subsequently organized a soil mechanics lab for the insurance companies Securitas and Veritas in France. Terzaghi wrote at this time that Langer became indispensable in France "because of his competent achievements" in organizing experiments on undisturbed sampling, improving techniques for grouting, and conducting direct measurements of clay swelling in a mine.[11] In 1939, Terzaghi considered having Langer act as his representative in Europe. Then, in late 1940, Terzaghi arranged for Langer to escape the Nazis with a position at the Armour Institute. Karl could not have known that Langer failed to arrive in Chicago because he remained in Paris to work secretly for the Nazis. After the war, Terzaghi renewed his offer of help, even proposing him as a grouting consultant for his job in India.

The revelation then of academic dishonesty from Langer was therefore understandably bad tasting to Terzaghi. Nevertheless, the strength of his action remains striking; in effect Terzaghi liquidated his former disciple, writing "I have no interest in interfering with your professional activities, because there are many other engineers who operate on the same moral plane without interference.... However I wish to forget your name as quickly as I can. Therefore I hope that you will give me no more opportunities to recall it."[12]

Another man who irked Terzaghi was Professor William Housel of the University of Michigan, one of the first to teach soil mechanics in America. However, his brand of soil mechanics excluded Terzaghi's consolidation theory. In several confrontations, Housel's dull presentations were no match for Karl's persuasive logic, and Peck's attempts to civilize Terzaghi's hostility were futile.

At Yale University, Hardy Cross, Dimitri Krynine, and Francis Baron seemed to harbor some ill feelings towards Terzaghi and Casagrande, probably in defense of perceived haughtiness. Cross and Terzaghi had somehow offended each other on the Charity Hospital job. Krynine, a frequent target of Arthur's lamentations, had dared to publish a book on soil mechanics in English before Terzaghi.[13] Krynine's textbook was not referenced in Terzaghi's later books. Baron presented a seemingly spiteful historical narrative of American soil mechanics sans Terzaghi. The pre-1914 methods, Baron wrote, "were stated in language remarkably simple, direct and understandable without needless technical terminology, symbolism, and methodology." In reply, Karl quoted the great naturalist and geologist Louis Aggasiz who said that every great scientific truth had to pass through three stages. First, it would be said to conflict with the Bible. Then people would claim it had been discovered earlier. Finally, they would protest that they had always believed it. "Soil mechanics", wrote Terzaghi," is entering the second stage."[14]

Princeton Professor Gregory Tschebotarioff believed that soils engineers never reached the third stage, but returned to the first with Terzaghi's teachings as a new Bible.[15] Having advanced Egyptian foundation engineering in the 1930s by importing Terzaghi's method and equipment from Vienna, Tschebotarioff admired Terzaghi's accomplishment. But then the two came into conflict as the Russian winced under harsh criticisms by members of Terzaghi's "clique". In turn, Tschebotarioff reported errors in a Terzaghi publication. Most seriously, Professor Tschebotarioff alleged that Terzaghi had deliberately sidetracked a paper (on submerged bulkheads) that he had submitted to ASCE; he maintained (with some justification) that Terzaghi misused his influence to delay this publication until the appearance of his own on the same subject.

Karl admonished the unlucky Russian, writing, "you are a master in the art of creating an atmosphere of disagreement by selective exaggeration.... Try to realize that all our findings, no matter how important they may be, are no more than links in a long chain and that the truth of today is almost inevitably the error of tomorrow. Everything starts with a guess and the truth is approached by increments. What you, the individual, can do is very little compared to what you owe to the community."[16]

Karl could write and speak directly because he was unwilling to get dragged into protracted arguments, his responsibilities being so constantly demanding. The free time he could muster was better spent as a cultural tourist, and, now that he was working overseas remarkable attractions opened up to him—the growing volcano Paracutin in Mexico, Mayan ruins in Yucatan, the cities of the Incas in Peru, the Taj Mahal and other treasures of India, and the archeological wonders and museums of Egypt. He and his various clients worked hard to sandwich touristic stops into his schedule. Consider this message Karl sent to an engineer arranging his consulting schedule in Kenya: "In Nairobi, I would like to visit Mr. Leakey on Saturday, January 20, provided he is in town, and I would greatly appreciate ... a trip to the game reserve in the late afternoon."[17]

The preponderance of work overseas was for dams. It was a great age for dam building the world over, for irrigation, electrification, and water supply. Whether or not one loves seeing more dams built, nothing is controversial about their challenge to the engineer and potential danger to the public. If the soil under, aside, or within a dam should pipe or slide its way to failure, all the energy stored to power a major city for a year may be consumed in one brief flash. Sometimes the most challenging part of the project is connected with the short-lived cofferdam, built to divert the stream from the work area in order to construct the main dam. Less may be known about the cofferdam's foundation conditions than for the "permanent" structure; moreover, the contractor has to gamble about what the river and the weather might do in the three or four or more years it may take to bring the main dam up. Thus, when the Indians decided to dam the Godavari River, with a floodplain almost a mile wide and flood flow four times that of the Mississippi,[18] Terzaghi was the expert they wanted.

Karl spent six difficult weeks of the Fall of 1946 in Southern India to plan the cofferdam for this monumental project, the Ramapadasagar Dam and Polavaram Reservoir. It was a time of mounting tensions between Moslems and Hindus and declining British authority. He found gross inefficiency, utter confusion, and sanitary conditions reminiscent of the worst places he'd visited in central Asia. He told his friend Fred Schmitt that the visit "sufficed to cure me from most of the illusions which I harbored concerning India since the days of my adolescence."[19]

The project, however, could only be described as fantastic. To found the concrete dam on rock it would be required to excavate through 250 feet of pervious alluvial soils below the river bottom. It was his responsibility to solve the problem of providing a cofferdam to keep this deep excavation dry. The cofferdam would have to be over a mile long and cross a section where the river rises fifty feet during flood, causing erosion ("scour") of its channel to a depth of 100 feet, or possibly even more.

At the outset, Karl was not certain he could handle it and adopted a pessimistic attitude, not restricted to the work but engulfing the whole surroundings. He wrote to Schmitt that he helped christen the new soils laboratory in a bamboo-roofed edifice in the wilderness by smashing a coconut and "leading a procession along the compression and liquid limit devices together with a native who carried an incense burner. The mosquitoes were humming and biting (no fly screens anywhere, stagnant pools galore and half of the engineers afflicted with malaria)." At the site of the dam, numerous drills were working, each with a crew of thirty and hand-dug test shafts seventeen feet or more deep "were squirming with life" as earth in shallow baskets was handed from female to female and carried away on the last one's head. The samples were mixed, and "every water content computation was a major operation."[20] The office in Madras lacked drafting tools, nobody could find plans, or even decent paper or pencils. Letters to USA don't arrive, he was told, because the stamps are stolen, telegrams arrive mutilated, the helpers forget most promises and muddle the rest, etc., etc.

But his opinion of the place turned around when he began to see how the cofferdam problem could be solved. As he turned on the fire of incessant work, Karl confided to himself that "progress in engineering calls for courage and confidence in one's judgment".[21] Now he began to love the river as "a magnificent specimen in a gorgeous setting" with monkeys on the loose and, not far away, elephants on moon-lit nights will pull up any white signs, cattle wear bells to scare away cobras, and tigers hunt in the wild. He continued to enjoy the adventure of it all, despite having to spend three days in a dismal hospital afflicted with dysentery. He especially liked the enormous attendance and wild approval he found at his several lectures for universities and engineering societies.

Terzaghi had been led to expect that the subsoil was predominately a free-draining coarse sand deposited on top of the gneissic bedrock. There would be some clay on the extreme west side of the valley (the river flows southward). Two factors controlled the layout of the cofferdam protection system: the depth to which the river could move sand during floods, termed the depth of scour, and the details of the bedrock surface.

A cofferdam would be made primarily by driving steel sheet piles. The design had to provide a sufficient depth of embedment below the surface of the alluvium that the river could not scour it out for, if it came even close, a breach of the cofferdam could result with flooding of the workings—in short, a catastrophe. The first step to determine the depth of scour was to survey the river bottom before, during, and after the passage of flood flows; however, this would not be sufficient because scour holes that formed during a flood would quickly fill up again with new sand, so a specific survey during a flood could not find every deep hole. Terzaghi proposed using an ingenious device (apparently his invention) that automatically recorded the depth of burial of weighted steel cylinders originally placed on the bed of the stream before the passage of a flood. This helped discern what the river was doing under its own course. But the river might scour even more deeply under the narrowed channel controlled by the cofferdam.

The depth of the bedrock surface was contoured by Terzaghi for the initial cofferdam layout. In the middle of the broad floodplain outcropped Mahanandi Hill surmounted by an 800-year-old temple; the current normal channel of the river was entirely to its east. Terzaghi's scheme was to excavate first on the western half of the valley, protected from the flood on the east side by a complete cofferdam enclosure extending upstream and downstream from Mahanandi Hill. The excavation would then be carried down 250 feet through the sands to reach bedrock and the concreting of the dam started. According to the plan, once the concrete had been brought up to the level of the original ground surface of the flood plain (elevation +50 feet), the cofferdam would be removed to push the river back onto the west side and a new, similar cofferdam system would be built on the east side to allow completion of the remaining portion of the dam east of Mahanandi Hill. This was a standard construction procedure for a large river, but there were few precedents for building in such a huge, hydraulically unregulated valley.

The dewatering of the excavation and maintenance of its slopes should be manageable, thought Terzaghi, because the majority of the soil was free-draining sand. To provide detailed information about the soils, well before traveling to India Terzaghi planned a dense grid of boreholes and penetration tests.[22] When he arrived at the site, the exploratory results were unfurling. Unfortunately, as he drew up inferences from the results of these investigations, it became clear that soil conditions were quite unlike what he had been led to believe. Instead of just sand, the majority of the deep west side excavation would be in a thick deposit of clay, underlain and overlain by sand. Like the treacherous London clay, it became highly plastic when remolded and offered abundant cracks through which water could penetrate and decrease its strength. The degrading clay and flowing sand strata would be unstable in any pit excavation that had not first been completely dewatered. Fortunately, the clay was a wedge that tapered to virtually nothing approaching Mahanandi Hill, and it was there that dewatering and excavation could gain a toehold.

Terzaghi proposed a test excavation in the clay to reveal the maximum safe depth to which it could be cut at different face inclinations before it would fail. He judged that for a one on four slope (one vertical to four horizontal) a conservative assumption of this critical slope height would be 100 feet, and planned his excavation scheme accordingly. But the critical height for this slope turned out to be only half that much. Moreover, in an experiment in which water was allowed to seep into the experimental pit from a concentric flooded ditch, the slope rapidly degraded and failed as the water acted on the fissured clay. This was indeed going to be a difficult job, but he still believed it could be done.

The detailed design of the cofferdam system, amounting to about four miles of dams and dikes on various soil foundations, was almost completely tailored to the depth to bedrock. The principal method of accomplishing the cofferdams would be sheetpile cells, backfilled with sand, and carried down to rock wherever possible. But since such sheetpiles could only be driven about fifty feet before the links between the individual members became defective, a 250-foot-deep excavation in such a permeable material would leave as much as 200 feet of pervious strata below it. Through these substrata an unmanageable amount of water could seep into the excavation, and the slopes would degrade by softening of clay and piping of sand.

Terzaghi's solution to this dilemma was to drive the sheet piles from the bottom of a 75-foot-deep trench, then backfill the trench with clay on the upstream side and rock fill and sand filters on the downstream side. This would require more than two million cubic yards of extra excavation, but he had the strength of his conviction and demanded it be done.

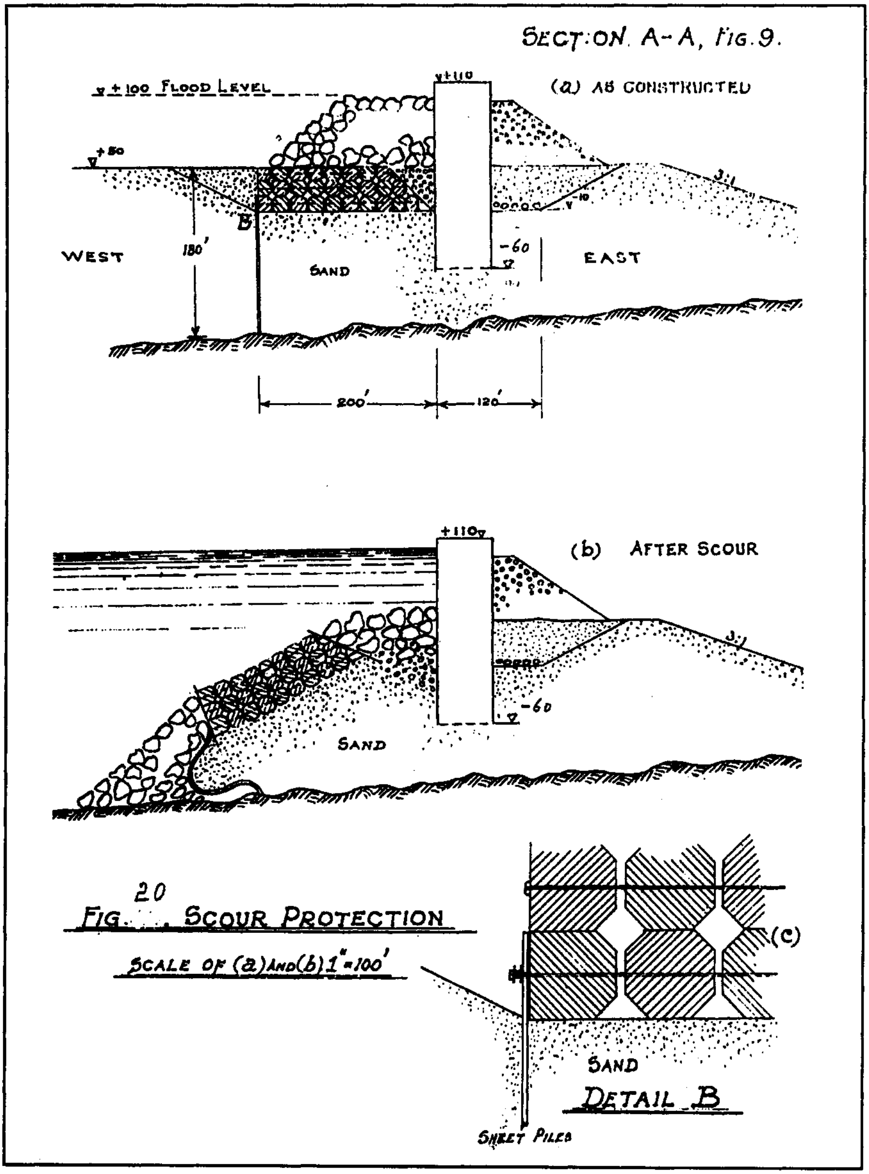
An even more serious problem was posed by the scour threat. In the section where the eastern, second-stage cofferdam ran parallel with the flow of the river, a deep bedrock scour hole had to be traversed. Terzaghi foresaw that it was likely all the sand would be scoured away from the base of the sheetpiles, causing almost certain failure.

There was no feasible way of making the sheetpiles strong enough to survive such undermining on one side. However, it would be possible to keep some of the sand against the base of the sheetpiles if the sand on the water side were armored with huge concrete blocks separated from each other by interstices of several feet and tied together with steel to create a massive chain. A doubling of the trench width was required to accomplish this. His remarkable design provided volumes of coarse rock, each piece a few cubic feet in volume, and large stones in reserve both above and aside the block chain. Upon scour, the chain of huge blocks would slide and rotate, opening up a space next to the wall, which would be automatically filled as the reserve rock rubble dropped into it. The final configuration of block chain and rubble would armor and protect the remaining sand so that scouring would proceed no deeper.

Terzaghi was in the practice of assuming the subsoil worse than it was likely to be in order to remain on the safe side no matter what. At Polavaram dam, the subsoil conditions were not as good as he had initially assumed, and with each new bit of data they grew worse. But he did not lose heart, or method to cope. Terzaghi's memorandum on the design of the cofferdam system in relation to site details, particularly bedrock topography, is the most eloquent expression of the engineer as artist.

Three months after Karl's return to the United States (after a sprint of Christmas-period lectures and visits in Egypt en route home), he was off to Brazil for his friend Adolph Ackerman. A landslide had started in a modest rock cut being made to enlarge the transformer station for the Cubatao Powerhouse. Within a few months the slide had enlarged to 600,000 cubic yards, and its headward growth began to undermine the ridge carrying seven high-pressure water lines ("penstocks") and menaced the power station; this was an extreme emergency.

Terzaghi proposed to stop the slide with drainage works, first with tunnels and drains along the sides of the moving mass and then, when it had slowed, drilled into the slide mass itself.[23] To find the surface along which the decomposed rock mass was moving he proposed a system that had worked at the Swir powerplant: a shaft driven from atop the landslide



Terzaghi's defense against scour for his cofferdam design at Polavaram Dam on the Godavari River, India. From "Report on Design of Cofferdams and on Excavation Conditions at the Site of the Proposed Ramapadasagar Dam (revised name) across the Godavari River, Polavaram, Province of Madras, India, by Karl Terzaghi; published in International Engineering Company Report to Government of Madras, July 1947 (republished in Anniv. Vol., pp. 359-393).

mass to below its greatest possible depth soon revealed the seat of sliding by offsets in its walls.[24] Similarly, trenches or tunnels were proposed to locate the slide's sides where continued movement gradually cut them off.

The slide mass was accurately mapped, and Terzaghi's drainage works brought it to a halt. Then, to increase the margin of safety, he proposed deep drainage and reinforcement works to improve the factor of safety of the penstock ridge since the effects of the slide might have cracked its decomposed rock and "experience shows that a single continuous crack may rapidly or gradually lead to a deterioration of the stability of a large mass of weathered rock." Once a slide starts, one or more of the seven penstock lines, spanning saddles on top of the ridge, would be lost. The movement of the slide alerted the engineers, and quick action not only saved the ridge but forced the company to abandon its plans for further developments on the ridge top.

After this success, Ackerman's company, Brazilian Traction, Light and Power (controlled from Toronto, Canada), retained Terzaghi for their serious problem in attempting to raise the existing Lages reservoir. There was a long and complex history of seepage, cracking, and sliding at various places around the reservoir as it had been raised in installments since its inception in 1908. Now the lake water was seeping through a low place (termed a "saddle") on the rim of the lake and generating landslides on its downstream slope, endangering the reservoir's outlet pipes. Terzaghi's intuition was that the seepage water was coming through highly fractured rock on the left side of the saddle, and he accordingly proposed a system of underground drainage galleries in the side hill to collect the water seeping into the unstable hillside.[25] This was successful in reducing the piezometric head by eight meters.[26]

This measure allowed the reservoir and its outlet works to survive its current operating water surface elevation of 423 meters but the power company's plan was to raise it further, to elevation 430, by building a dike (Lages Dike No. 4) in the saddle. Terzaghi performed an ingenious hydrologic analysis of flow and water pressure data to establish where the leaks were occurring. Then he designed a dike that would work. A rock fill would be placed on the upstream side of the saddle, in contact with a vertical filter-drain in a trench on its downstream side. This trench must extend entirely through the pervious weathered rock into sound rock below, for his analysis confirmed that, at the higher reservoir elevations, water would leak across the saddle primarily through a highly pervious zone of "hard, decomposed rock" sandwiched between impervious soils above and sound bedrock below. The water intercepted by the vertical drainage filter would be removed through a new drain-outlet tunnel.

The Canadian management found Terzaghi's proposal too expensive and counter-proposed to replace the rock fill by an impervious clay blanket upstream of the saddle. Terzaghi strongly rejected this because he found

At Vigario Dike, Brazil: Adolph Ackerman (left), Ole Strandberg (third from left), and Portland Fox (second from right). Terzaghi is between Strandberg and Fox.

Brazilian earth construction practice to be seriously lacking and had no confidence that a clay blanket, as they might construct it, would prove safe.

Terzaghi's advice was prophetic. In 1952 there was a "palace revolution," and Vice President Adolph Ackerman departed, leaving Brazilian Light and Power with reduced competence and stringent finances. The clay blanket was elected and poorly constructed just as Terzaghi warned. Worse, the drainage-filter was not extended downward into sound rock as Terzaghi had designed, and therefore it did not drain the pervious hard, decomposed underlayer of the residual mantle.

The completion of this work at Lages Dike was greatly delayed. Then when it was found to be inadequate, an attempt to cut off seepage flows by concentrated grouting proved utterly fruitless. Approaching 1960, the reservoir had still not been brought to its design elevation and the power was needed. The company swallowed its pride and pleaded for Terzaghi's help. If the reservoir were allowed to rise to 430 m. as matters stood, the stability of the entire saddle area would be doubtful and the lake might empty catastrophically through the saddle. So he worked again on the project in 1960, at the age of 77, designing a retaining wall and downstream drain. It proved to be an efficient, economical, and clever solution.

During his visits for Ackerman, Terzaghi advised on several other demanding projects in Brazil. The list includes Vigario earth dike being constructed with terrible materials, an underground power house in rock, preliminary studies for a subway for Sao Paulo, slope design for cutting through soils in a limestone quarry, and an iron ore storage yard in clay.

The iron ore storage facility (belonging to a mining company) was in sorry shape, and the apprehensive chief design engineer asked Terzaghi to review the company's plans for further development. The mining superintendent on the job distrusted the engineer's use of soil mechanics and was anxious to get the job going with inadequate, simple measures. Terzaghi considered the situation so dangerous that, in the letter of transmittal of his report, he advised the engineer to resign.[27] And he did.

The Sao Paulo subway tunnel, Terzaghi advised, would be a difficult venture through saturated fine silty sands. When a much smaller tunnel had been attempted there using compressed air, the air leaked out causing the underground problems to become desperate while the surface subsided.[28] He went no further with this job when Ackerman quietly informed Karl he was walking blindly into the midst of a public scandal caused by the questionable integrity of his associates.

Brazil was a novel territory for Terzaghi where the people and the soils were capable of unexpected behavior. Ironically, the sabotaging surprises he experienced there were imposed by political decisions from outside. A similar fate awaited him in Egypt as he undertook to chair the consulting board for design of the high Aswan Dam.

17
Cold War Politics and Expert Testimony

Egypt's life blood is the Nile. Its enormous average yearly discharge of 93 billion cubic meters (at Aswan) is enough water for the entire nation's needs, including irrigation, industrial expansion, and food. But for such a large river its flow is unusually capricious; in dry periods, like 1913–1914, the country verged on starvation, while in wet ones, like 1878–1879, floods devastated the Nile delta. Attempts to tame the Nile with dams started well back into the nineteenth century and eventually resulted in a low dam at Aswan. But by 1950 it was obvious that a much larger reservoir would be required to accommodate Egypt's growth, while neighboring Sudan was also asking for a share of the water rights.

What was needed was a reservoir so large as to hold an entire year's flow in reserve, plus an additional thirty billion cubic meters of storage to contain a great flood, and another thirty billion cubic meters to receive the vast amount of silt that would be deposited in such a reservoir. This thinking led to the creation of the Saad-El-Aali Project, whose centerpiece was the construction of the High Aswan Dam with her reservoir of 170 billion cubic meters (140 million acre feet)—five times the volume of Hoover Dam's Lake Mead.

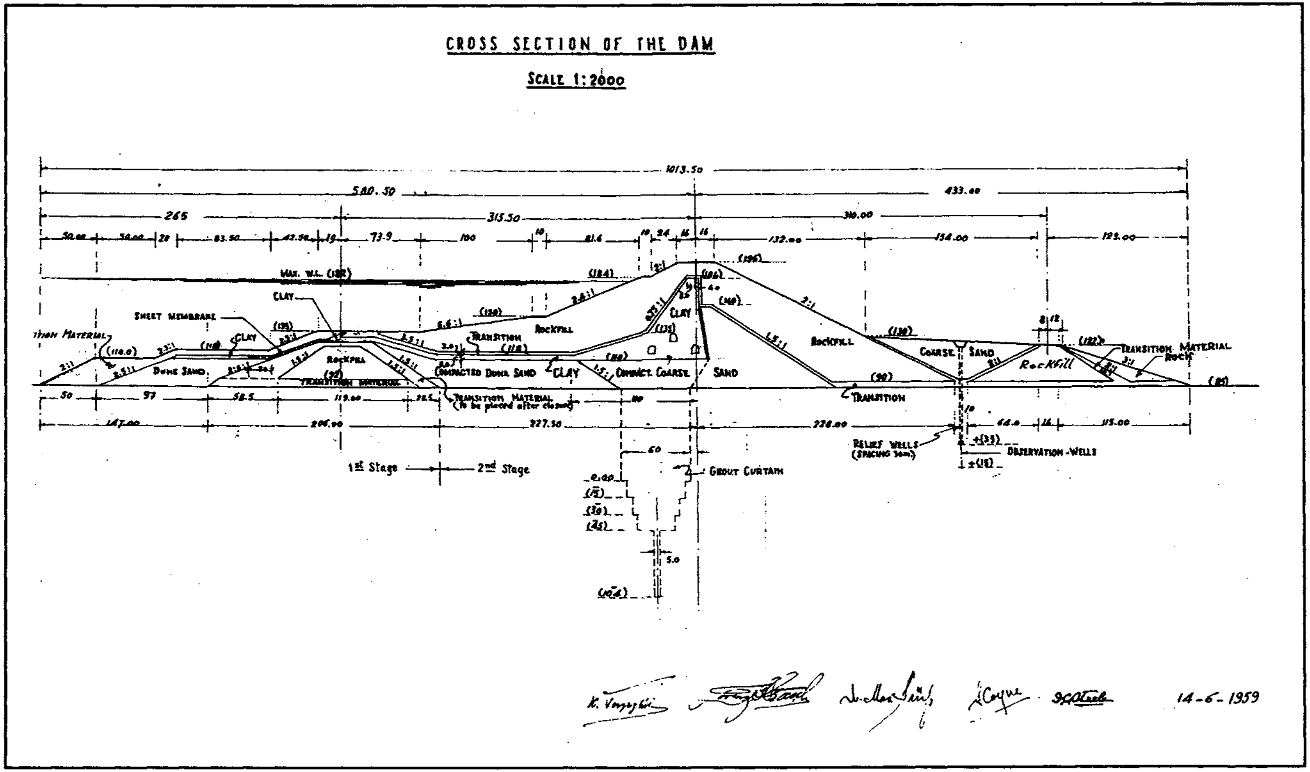
To guide the creation of a project of such vast scale would require international financing and the world's greatest engineers. Preliminary plans were invited from large design firms of Europe and a Board of Engineering Consultants was appointed to make the big engineering decisions.[1] Karl had to decline participation when first asked in 1953, because of his heart attack. When the Egyptians persisted, there was some discussion about his fee, which Terzaghi insisted must provide sufficient time for his work and be paid in advance. Finally, in July of 1954, he started his work in Cairo. At the first opportunity the other members of the Consulting Board elected Karl as their Chairman.[2]

Terzaghi quickly appreciated, and convinced his colleagues, that the most complex hurdle would be connected with dewatering the site for construction of the dam. Provision had to be made for a flow of up to 14,000 cubic meters per second past the construction site during at least one of the construction winters. Eleven thousand cubic meters per second could be diverted around the perimeter of the valley through seven tunnels, 16.5 meters (55 feet) in diameter and 2.6 km long, mined in the granite walls. Then a 40 meter (132 foot) high cofferdam would be constructed upstream and a somewhat smaller one downstream to allow construction of the main dam on the dry riverbed.

There were serious difficulties for the design of the upstream cofferdam. Half of its height had to be constructed by depositing soil material below the water of existing Aswan Lake, which varied in depth at the cofferdam site from 30 to 100 feet. A considerable flow could conceivably run over the crest of the cofferdam during the period of construction, and the embankment must have slopes such that it could resist the scour. The sediments under the dam and cofferdam site are mainly fine sands and silts extending to a depth of some 150 m (500 feet), and near the ends of the cofferdam there are pockets of boulders and layers of gravel with large voids (open-work gravel) with a very high permeability; this combination portends a very real risk of cofferdam failure by piping. "The construction of a high cofferdam on fine-grained river sediments at a site with such hydraulic characteristics is an undertaking without precedent" wrote Terzaghi.[3]

The materials available to build embankments were rock fill produced in excavating the tunnels, silt and fine sand from the river, dune sand, and clay mined from clay beds within the nearby Nubian Sandstone formation. The Board of Consultants stipulated that the bulk of the cofferdam should be constructed of the granite rock fill, constructed in horizontal layers and placed over a 23-foot-thick filter of sand above the fine-grained, valley-bottom sediments. The sand filter would continue downstream all the way to the main dam and would be capped by a low permeability blanket of compacted silt to prolong the path of seepage and reduce the danger of piping under the main dam. The main embankment would also be protected by a compacted silt core with a clay-grout curtain.

The Board of Consultants was convinced it had a prudent, safe, and constructible design for the Nile at Aswan. But a new difficulty appeared suddenly in June, 1959, one of a type that engineers are not as adept at fielding. President Nasser entered into an agreement with the Soviet Union for the Soviets to construct the first stage—the dewatering phase—of the Aswan Dam project. The Soviets had offered a loan allegedly with no strings attached, but Terzaghi suspected they would come with a rope strong enough to strangle all of Egypt.[4]



The preliminary design of Aswan Dam, signed by the consulting board, June 14, 1959.

To the West, this sudden reversal of Nasser's anti-communist stand was a surprise. Unable to obtain the handouts he wanted from the West to keep his five-year industrialization and land reclamation program on schedule and already in debt to the Russians for previous equipment loans, he accepted the Soviets' blatantly political proposition. Suddenly the Board of Consultants had a new overseer.

The Soviet engineers produced a report modifying the recommendations of the Board. They proposed to increase the quantity of rock fill in the dam by placing rock fill underneath the compacted silt blanket. Furthermore, they would eliminate the sand filter layer under the rock fill of the cofferdam. The Russians knew that internal erosion and piping are invited by placing a pervious rock fill on top of silty sediments or placing a compacted silt blanket directly on top of rock fill. But they believed they could fill the large voids of the rock fill by a novel system of washing dune sand into the rock fill after its placement, a construction technique known as "sluicing".

The Russians proposed other important modifications. They would build up the cofferdam fill by end-dumping from either side of the river, leaving a lower section for passage of the river until a sudden closure could be made by rapid filling. Terzaghi had specifically stipulated to build up the cofferdam by compacting sequential continuous layers across the entire valley. Additionally, the Russians proposed to replace most of the length of the seven diversion tunnels by open cuts, eighty meters deep into the granite.

Terzaghi was convinced this scheme was reckless and motivated mainly by the Soviets' particular deficiencies. He believed that they lacked both the equipment and the experience to organize a massive spillway tunneling project. So they would have to excavate open cuts; and since these excavations would provide excess rock fill, they elected to expand the use of rock fill in the main dam.

Terzaghi's Board unanimously rejected the proposed Soviet modifications to the design. Construction of the cofferdam from the sides toward the middle, they stipulated, would cause uncontrolled scour at the site for the main dam below the closure section and would greatly complicate the construction of the main dam. The deletion of the sand filter under the cofferdam, in favor of a layer of rock fill whose coarse voids were to be sluiced full of sand, worried and angered Terzaghi.

He wrote: "While the placement of the rock fill proceeds, sand will be sluiced into the voids of the fill. There are no practicable means to find out which portions of the rock fill remain unplugged. Therefore it will be easy for the Soviets to convince the Egyptian engineers that their procedure was, contrary to the predictions of the consultants, a perfect success. In reality, in large portions of the rock fill the voids will remain open. In spite of it, the cofferdam may serve its purpose of diverting the Nile into the diversion conduit. This would be advertised by the soviet engineers as a further proof that their procedure for filling the voids of the rock fill with sand was successful and it would increase their prospects of being trusted with the construction of the main dam (second stage)."[5]

Terzaghi continued: "The consequences of the deficiencies of the upstream cofferdam will not necessarily become noticeable until the construction of the main dam is completed and the reservoir is filled. ... If the rock fill which is deposited during the first stage of construction contains large volumes of fill material with open voids, without resting on the filter layer prescribed by the consultants, the first filling of the reservoir may be followed sooner or later by a partial or even complete failure of the dam by subsurface erosion."

When the Egyptian Director of the Sadd-El-Aali Department, Hassan Zaki, forced a reversal of his committee's initial vote to support the Board, it became clear that the Egyptians were no longer in charge. And their Russian masters were not aware of their own limitations, which could be dangerous. Terzaghi had no option but to resign.

In his letter of resignation, Karl wrote: "The upstream cofferdam may, and probably will, serve its function as a construction expedient during the first stage even in the event that all the recommendations of the Board are disregarded. However, after the dam is completed and the reservoir is filled, the service conditions of the cofferdam are entirely different from what they were during construction. As a consequence, the cofferdam may then start to deteriorate, rapidly or slowly, and at that stage it may even be impracticable to stop the process. Radical departures from the Board's well-considered recommendations concerning design and construction of the upstream cofferdam involve such a possibility. Therefore I owe it to my professional reputation to discontinue my association with both the first and the second stage of the project."[6]

At this critical time, the world was reminded of the terrible consequences of a dam failure when Board member Andre Coyne's Malpasset Dam failed in France, causing more than 400 deaths (in Frejus, very near Ruth's 1939 refuge on the French Riviera). It failed on the initial filling of the reservoir due to geological weakness in one of the rock abutments of the very thin concrete arch. Later Karl would express severe criticism of the decision to build such a structure on a geologically inadequate site. But now he comforted his distraught colleague, writing that "failures of this kind are, unfortunately, essential and inevitable links in the chain of progress in the realm of engineering, because there are no other means for detecting the limits to the validity of our concepts and procedures.... The torments which you experienced should at least be tempered by the knowledge that the sympathies of your colleagues in the engineering profession will be coupled with their gratitude for the benefits which they have derived from your bold pioneering."[7]

Waldo Bowman, editor of *Engineering News Record* asked if he might keep his copy of Karl's letter "to remind me of what one great engineer wrote to another on the occasion of the tragic failure of one of his structures."[8]

Karl resigned from the Aswan Dam job because he was not getting his way and therefore imagined the product might end up being unsafe. He would never have left merely because of controversy, for in most arguments he came out on top if winning had anything to do with logic. That was usually the way in a court of law and, accordingly, Karl flourished as an expert witness. He did his homework, wrote convincing arguments in reports rich with precedent, and presented himself in a commanding style before the judge.

In one of the litigations that followed the completion of the Chicago Subway, the opposition were so fired up in anticipation of his appearance, as the "last and star witness", that they neglected careful preparation of cross-examination of other witnesses. When the clever defense attorney realized this strategy, he simply invited Karl to stay home and rested his case. "The psychology worked beautifully. The jury returned a verdict for the city."[9]

Karl was indeed a fearsome expert witness. But his views did not always prevail, one notable case being the public tribunal that followed the partial failure of Whatshan Powerhouse, British Columbia, in August, 1953.[10] Brought to the site six weeks after the event, Terzaghi learned that the design firm H.G. Acres had been associated with the project, and he assumed that it had been the consulting firm. In fact, it had been asked only to provide advice on the engineering and economic feasibility and layout of the project at an early stage of its development when it had not yet been determined whether the penstocks would be located in tunnel or above ground. Acres' engineers did not visit the site, but based their favorable opinion on information supplied by the Power Commission. Before final design was undertaken, the Commission had decided to do the design themselves, and Acres' contract was terminated in mid-1948. The Power Commission adopted the option with a tunnel layout.

Having mistakenly inflated H.G. Acres' role in the engineering of the Whatshan Power Project, Terzaghi convinced himself that it had disserved the client by approving the Power Commission's report without conducting its own investigations or even visiting the site. He took aim at what he perceived to be an important omission in its failure to inform the Power Commission of the potentially negative effects of leakage from the tunnel and underground penstocks that fed water under pressure to the power station.

Soon after water had started flowing through the tunnel, in April of 1951, water began to seep out at the surface 600 feet south of the power house (the water flows eastward); within three months the spring had enlarged significantly and others appeared. The ground at the base of the granite cliff softened and subsided as much as fifteen feet, and some time later silty mud advanced part way to the switchyard. Twenty-eight months afterwards, on August 11, 1953, a large slide succeeded in wrecking the switchyard, and five days later while the detritus was being cleared away, a second landslide drove the remains of the transformer station out into the lake and sent a 100-ton boulder through the wall of the powerhouse. At this point, H.G. Acres was called in once more.

In reviewing this history, Terzaghi concluded that it had become obvious within a few months of the project's start up that the tunnel was leaking badly. This by itself does not spell catastrophe but, he observed, leakage water was impeded from exiting freely at the base of the valley. The reason was clear: watertight silty glacial sediments lapped against the valleyside walls of jointed granite to create a tight blanket over the pervious bedrock. The water leaking from the tunnel must therefore have built up excess pressure in the glacial sediments that uplifted this sedimentary blanket; this in turn initiated a process of incipient sliding, fissuring, and water injection in the blanket layer causing it to weaken and eventually fail.

This interpretation could have been gleaned before the design of the power complex, Terzaghi concluded, from three kinds of observations. First, the geologic picture was evident to anyone qualified who took the trouble to look. Secondly there was evidence of historic sliding (as recently as 70 years ago judging from the age of downed trees), which originated where the sedimentary blanket met the rock wall. Terzaghi assumed these older slides had been precipitated by natural seepage from unusually rapid snow melt feeding into fractures in the bedrock. Thirdly, the springs resulting from tunnel leakage, as well as natural springs in the vicinity, emerged not from the edge of the valley floor but from an elevation up to 180 feet higher, always above the top of the capping silt formation. The elevation of these springs determined the water pressure under the blanket corresponded to as much as 180 feet of water head (plus the thickness of the blanket).

Water flows very copiously out of concrete-lined pressure tunnels, proclaimed Terzaghi, if the internal water pressure succeeds in creating longitudinal cracks (cracks that are parallel to the direction of the tunnel). These are hard to see when the tunnel is empty because they will have closed up. He related his experience with a pressure tunnel tested in 1907; after it was drained and examined, the lining seemed to be intact. "However at one point, on the bottom of the tunnel, the rear portion of a frog projected from the concrete, whereas the front portion was completely flattened out and located below the concrete surface."[11] Yet the crack through which the frog had entered the concrete was barely visible. The telling of this anecdote during the tribunal was a comfort to the press, which covered the events with lively interest.

The event at Whatshan was not unique, Terzaghi observed. For example, Los Angeles Aqueduct's Sand Creek Siphon experienced a very similar history when it was filled as a test before putting the aqueduct into operation. Another case was the Mitholz slide of July 27, 1945 in the wall of Kandersteg Valley, Switzerland, where the valley side was covered by impervious glacial sediments reaching several hundred feet above the valley floor. A pressure tunnel was built 340 feet above the floor of the valley in a direction parallel to the slope and 560 feet deep into the hill. Quite suddenly one day a million cubic yards of debris ran down the valley slopes, buried some houses, and displaced the river for a length of 700 feet.

Acres wrote in their investigation after the Whatshan failure that there may not have been enough exposure of the rocks and soils during construction to warn of potential sliding. Karl rebutted this strenuously and, believing them to have been the responsible engineers, tried to pin the blame squarely on them. "One can hardly conceive of more impressive symptoms of the dangerous water pressure conditions prevailing in the ground than those which were plainly visible at the Whatshan site.... One of the principal functions of consultants consists in locating weak spots in the design and calling the client's attention to all the hazards involved in construction and operation."

He maintained that Acres, like many firms, was guilty of "excessive self-reliance," and he dared to include the following sentence in his report: "There are very few engineers who are familiar with the performance of pressure tunnels and the engineers of Acres & Co are not among them." Karl's friends Ralph Peck and Adolph Ackerman tried to argue against this line of thinking when they reviewed his report before the hearing. But Karl was obstinate and irked against what he perceived to be an engineer's failure to take responsibility. If they lacked what was necessary to see the dangers, he said, they should have brought on specialists.

Terzaghi's assertions fueled unkind publicity for the consulting company and compounded its anger, as it argued that it was not really the consulting firm on the job, but only a limited, early reviewer from a distance; in any event it *was* experienced in pressure tunnel design, perhaps more so than Terzaghi.[12] His friend Tom Leps, Chief Engineer of Southern California Edison Company, commented that "only a person in your position could afford to deal with personalities in the manner done in this report."[13]

H.G. Acres seriously considered filing a lawsuit against Terzaghi, in spite of its complete exoneration by the Royal Commissioner Clyne, who decided its role in the affair had been very limited.[14] Contrary to Terzaghi's report, the entire blame was assigned to the Chief Engineer of B.C. Power and his Commission who negligently ignored ample signals from the powerhouse operator and staff.

One of the reasons the failure at Whatshan resonated so strongly with Terzaghi was his prior personal involvement with landslides, on at least two occasions, that were set up when natural deposits blanketed the outlets of water-charged rock joints. One was the Bridge River Power House on Seton Lake, not far from Whatshan in British Columbia (discussed in Chapter 18). The other was the foundation for Marathon pulp and paper mill, Ontario, near the shore of Lake Superior.[15]

The Marathon plant was being constructed below a hill of granite that descended gradually out under the lake. The surface of the granite was buried beneath a layer of sand, a layer of clay, and an overlying layer of sand. To level the plant site a bench was cut into the natural sloping terrain and extended lakeward by a wedge-shaped fill. The foundation, designed before Terzaghi arrived on the job, was to be supported by driving 6,000 piles, 45 to 60 feet long, through the upper sand into the clay layer.

Asked for his review in 1944 when 3,000 piles had already been driven, Terzaghi requested borings to pass through the forty feet of clay into the lower sand. These showed that the water pressure in that sand was artesian, with the phreatic surface 23 feet above the level of the lake. He asked that this sand be drained before further work, but that was seen as costly. While the discussions continued, rapidly melting snow fed through joints in the granite, temporarily raising the water pressure that uplifted the clay. This set into motion 120,000 cubic yards of soil over a width of 350 feet, completely destroying the mill foundation beyond repair.

Only a week after preparing his report on the causes of the Whatshan Slide, Karl prepared the first of two reports for a dispute on Sasumua dam, under construction in the region of active Mau Mau terrorists in Kenya.[16] Designed by the British firm Howard Humphreys & Sons for the City of Nairobi, Sasumua was to be a homogeneous embankment (with a concrete core wall) built to a height of 100 feet by compacting clay acquired from the thick weathered blanket covering volcanic rocks at the site. As construction began, the French contractor found that this clay contained an exceptional amount of water which the specifications would compel him to remove at great expense before placement in the dam. To help deal with this, he hired Professor A. Caquot, an expert in the mechanics of soils, particularly from the theoretical point of view. Professor Caquot found the soil not only had a high water content but was otherwise strange; it possessed peculiarly high values of the liquid limit despite low plasticity, and an exceedingly low density when compacted (less than seventy pounds per cubic foot, which is just slightly more than the density of plain water).[17]

The quality of this embankment was to be assured during construction by controlling the water content within narrow limits, as determined by the "optimum water content" of the almost universally accepted Proctor compaction test. For a particular intensity of compaction, each soil possesses an optimum water content at which compaction gives to the soil a maximum density. The experience of earthwork showed that an embankment constructed of soil wetter than its optimum water content might acquire both a low shear strength and abnormally high excess pore water pressures. This can be dealt with by flattening the slopes, slowing the rate of construction, or drying out the soil before it is compacted. The soils in the designated borrow pit for Sasumua dam contained considerably more water than the optimum value (63% versus 50%), and Caquot advised his client that the use of this material without extensive pre-drying would be unsafe in Humphreys' dam; he called upon the owners to redesign it completely, substituting rock fill for the intended clay.

Humphreys obtained help from British soils engineer Guthlac Wilson (through his African firm Scott and Wilson) and from Professor Alec Skempton of Imperial College in London. Their work confirmed that building a dam with such material was unusual, and they also suggested a redesign, though very much less drastic than Caquot's proposal. When the contractor and owner could not reach a new working agreement, however, the City of Nairobi declared the contractor to be in default and engaged Terzaghi to advise on the safety and constructability of the original design.

After visiting the site, and reviewing the heap of data, including mineralogical studies obtained by Skempton,[18] Terzaghi produced a third opinion. He agreed with Skempton's analysis: the material was unusual because it was formed primarily of an unusual mineral, the clay halloysite, whose particles are not platelets like those of most clays but hollow tubes. In this soil, water occupies not only the usual sites *between* the particles of clay but also *within* the tubular particles; but, since this extra water lies inside the tubes, it cannot influence the forces between the particles, and is therefore inactive with respect to the behavior of the clay. Moreover, while the soil from the borrow pits was thought to be composed mainly of clay, grain size measurements yielded the result that fully half of the soil consisted of particles coarser than clay. Terzaghi agreed that it was formed of silt and sand-sized agglomerations of halloysite tubes, held in a stable array by iron-oxide cement. It was not surprising, therefore, that notwithstanding its low density, the soil's properties were excellent for an embankment and extreme design changes were not warranted. Low density in itself is not a problem, he said, for very tall buildings stand in Mexico City on soils having just half the density of the Sasumua clay.[19]

The City and Humphreys accepted Terzaghi's ideas and his various suggestions for improving the design, but the contractor stuck to Caquot's contrary opinions. Construction of the dam was completed outside the contract on a time-and-material basis under the direction of a city engineer. By the time the arbitration hearings were held, the dam was up and the reservoir was full.

Terzaghi prepared a second report in preparation for the arbitration.[20] In an initial draft, he argued that the contractor had been legitimately concerned about working with an unprecedented material, and, since the engineer had acted indecisively, the contractor was entitled to costs growing out of his delay. But he subsequently changed this opinion, probably under prodding by the city's lawyers.[21]

In any event, Karl asserted, neither the contractor nor the city's engineer was correct in assuming the case lacked precedent. In fact there were several, including a dam of similar height and design in Java (Tjipanoendjang Dam) that was built of almost identical halloysite soil; this dam had proved to be eminently stable.

In his testimony, Terzaghi argued that the low factor of safety produced by Caquot's analysis resulted from faulty assumptions and unwarranted refinements inasmuch as the dam was now functioning in an unquestionably safe manner despite the French predictions of disaster. As far as reliance on theory is concerned, "I am inclined to compare the functions of theory with those of a walking stick in rugged country. It reduces the risk of stumbling, but the walking has to be done with the legs."[22] Sasumua survived its first filling, he announced, and it is "perfectly irrelevant whether the computed factor of safety is 0.8 or two."[23]

Karl was ruthless in his attack on Professor Caquot's qualifications, writing "all of Mr. Caquot's publications in the field of soil mechanics involve only theoretical refinements of procedures which have been worked out by others, and therefore they are used by very few, if any, engineers outside of the French speaking countries. ... His attitude towards the practical aspects of this field is demonstrated by the fact that he expressed an opinion on the original design of the Sasumua Dam without having seen the site."

He himself wouldn't need to make any such stability computations, Karl said, because he saw the excellent soil properties, and took note of the Java precedent. Stability analyses are only needed to satisfy government engineers. "These government organizations have a great reluctance to carry responsibilities; they always want to be covered by something, and a factor of safety—that is something tangible. So when the general asks the captain: 'How about the safety of the dam?'—'1.51' [is the answer] and then he is happy."[24]

Terzaghi's imperious demeanor as witness fueled a strong crossexamination from the contractor's attorney, Cyril Salmon. "How would you regard a categorical statement—in a clay embankment—that a theoretical factor of safety of 1.5 should be regarded as a minimum?" Salmon asked. Karl answered, "I always explain to my students ... that the factor of safety of 1.5 is a factor of safety which you have to demonstrate in order to get permission to build, and then it is your business how you demonstrate it."

Salmon: "Did you recognize the authorship of the statement I put to you, Dr. Terzaghi? Terzaghi: "Maybe in my book on Theoretical Soil Mechanics."

Salmon: " Let me read you a passage out of your book.... I suppose that in soil mechanics, as in everything else, opinions change from time to time?" Terzaghi: "Right." Salmon: "Have they noticeably changed since last July?" Terzaghi: "No." Salmon: "On page 389 of your book [it says:] ... 'Since our knowledge of the conditions for the stability of clay embankments is still incomplete, and since in addition failure of clay embankments are by no means unusual, a theoretical factor of safety of 1.5 should be regarded as a minimum requirement.'" Terzaghi: "Yes; I put that in for state engineers." Salmon: "Well, I am looking for a footnote that says that."

As the questioning continued, the merciless examiner frequently interrupted the beginnings of Karl's embryonic lectures, deflating him to such an extent that he misspoke, and then his voice began to drop and he had to repeat answers. But while Terzaghi's execution may have withered, the strength of his logic found its mark. In the end the City of Nairobi scored a complete victory.

While Terzaghi was preparing his helpful written opinion for the City of Nairobi, he delivered a decidedly unhelpful oral opinion for the City of Honolulu, which inadvertently sabotaged his trusting colleague Ralph Peck. The opinion concerned the collapse of a half-mile-long road tunnel being mined through the Koolau Range on the island of Oahu, Hawaii. In July, 1954, shortly after advancing the tunnel face from good volcanic rock into clay and weathered rock, two cave-ins occurred eighteen days apart. Fifteen days later, while cleaning the debris, a great amount of semiliquid clay flowed into the tunnel work area killing five men, destroying the tunneling equipment, and filling up 400 feet of tunnel.

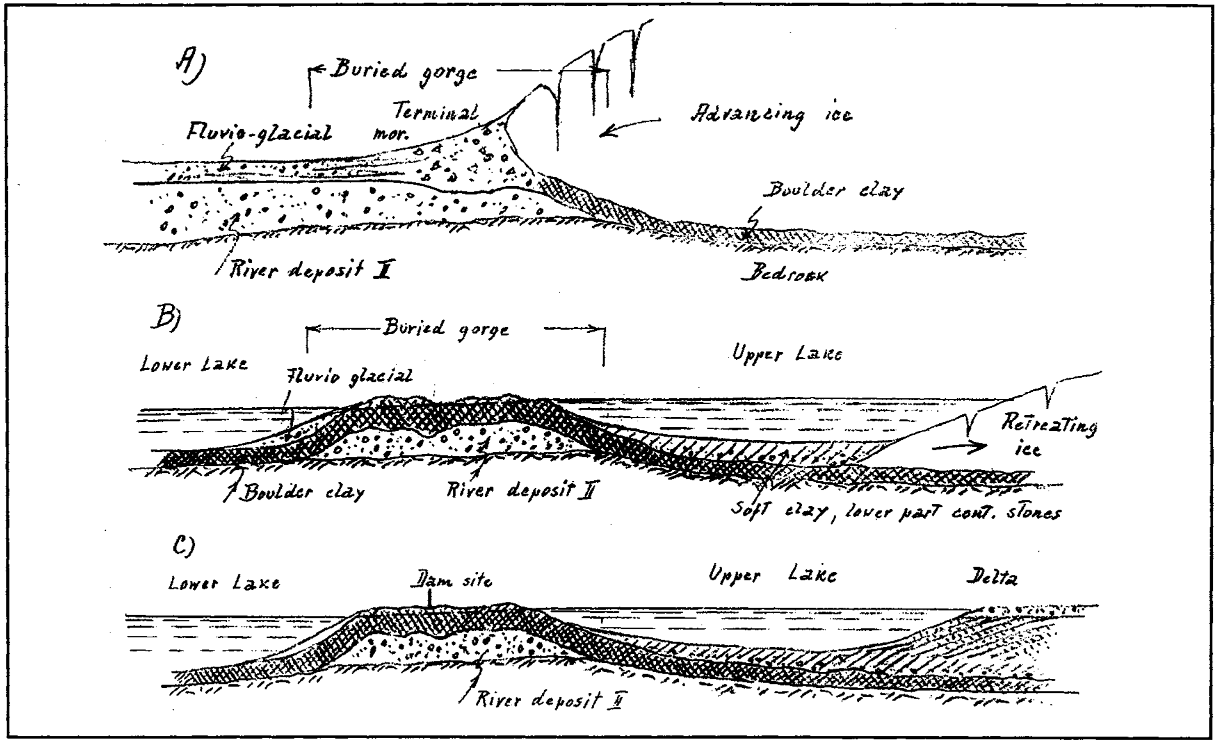
Ralph Peck, who had written a comprehensive report on how to repair the damage and restart the project with small drifts and pre-drainage, recommended that the City retain Terzaghi. On surveying the scene and reviewing the various reports, Karl was outspoken in his conclusion that the contractor was entirely to blame. On passing into soil tunneling conditions right where the geological report said he should, this incompetent contractor continued to maintain a rock tunneling technique, with the entire face open instead of driving through with multiple benches. Furthermore, he had allowed the supports to stand free of the ground they were supposed to support rather than providing a solid connection by backfilling behind them, as had been done in the Chicago subway. The City's legal department had better get to work, he advised, to throw this reckless contractor off the job so that a competent organization could be obtained to finish it, otherwise "the whole operation may terminate in financial disaster".[25]

He was also rather unfriendly to the geologist who, in his report on the geological conditions for this tunnel had written that the western section would be "a rather dirty tunnel". Terzaghi stated that such a term "leaves a wide margin for interpretation." After the failure, this same geologist produced a memorandum giving an account "from a geologist's point of view" which stated that the roof collapse and inflow of wet clay were "quite unforeseen by anyone connected with the project." Terzaghi's counter was: "If anyone connected with the project had any experience in tunneling through stiff, raveling clay he would have known that the mining technique which was used in the tunnel leads almost inevitably to the event described ... and he would have insisted that the procedure should be radically changed before it is too late."

Where Karl's report was direct, his private remarks to Peck and others were martial; not only should they fire the tunnel engineer, but all the people connected with the project right up to the City Council. After indicating the city would agree to change the contractor, the mayor surprisingly reneged, which prompted a strong letter from Ralph Peck restating the substance of Terzaghi's advice and offering to resign as consultant. Before Ralph Peck could leave, however, he was ordered to answer a $1.5 million libel suit initiated by the contractor against him.

Peck told Karl that he was suffering from Terzaghi's slander. "But," Karl responded, "I wasn't foolish enough to write it." Karl still maintained that cracking the whip and cleaning house were the right response, but he didn't have to face the consequences.[26]

Terzaghi's principal appearances as an expert witness occurred mainly when he had reached his early 70s. One might suspect that he was entering an armchair stage, content to establish truth and wisdom for projects joined only in their late stages. False!—if anything, Terzaghi courted increasing challenge as he steered his career to an adventurous climax.



Terzaghi's conception of sequential stages in the geologic history of the region of a proposed dam site at Nanaimo, Vancouver Island, B.C. From "Note concerning the geologic history of the dam sites on the Nanaimo River between Upper and Lower Lake, (B.C.)" to H.A. Simons, by Karl Terzaghi, May 27, 1948.

18
The Challenge of British Columbia

Terzaghi had established his fame solving problems of foundations. This was to continue in British Columbia for noted engineer H.A. Simons, with a series of demanding mill foundations, often involving hidden deposits of buried clays beneath the water's edge. Terzaghi knew what to look for and how to handle it, even if it involved relocating a mill site after it had been half built.

But the engineering jobs that tested Terzaghi's courage in his mature years were mainly the water and power projects in the glaciated mountains of California, and especially British Columbia. It was hydropower that had sprung Karl's engineering career and only fitting that he closed on the same note more than a half-century later. Although he now knew what had to be done to construct safe projects, it still wasn't always clear that success could be achieved. Invariably, the evildoer was the uncertainty attached to finding the boundaries and properties of geological deposits.

This was well illustrated by his experience at Vermilion dam (1949–1956) on Mono Creek in the Sierra Nevada mountain range of California. Vermilion was a kind of etude for Karl's even more demanding jobs in B.C.[1] The glacial deposits filling the canyon of Mono Creek to a depth of 200 feet were largely highly pervious sand and gravel. But the existence of an apparently continuous layer of watertight silt only thirty feet below the surface provided hope that the foundation could be sealed by connecting this impervious layer to the surface with a vertical cutoff, consisting of a backfilled trench. Although it was conventional to locate a cutoff trench for a zoned earth dam underneath its impervious core, Terzaghi recommended locating it beneath the upstream toe of the dam where it could more economically reach down to the silt layer.

But, during excavation of the cutoff trench, it was discovered that the silt was interrupted by a channel filled with sand for a 400-foot length of the eastern part of the dam axis. Eleven boreholes were put down but failed to find a lower impervious layer into which the cutoff could be extended. Thus, there would be a serious gap in the line of defense against seepage through the foundation of the dam. Fifteen additional boreholes established that a system of sand channels threatened to create a collection and delivery system to feed leakage under the dam.

Bechtel Corporation, engineers for So. Cal. Edison, recommended laying an impervious blanket over the locations of the sand channels on the reservoir bottom. Terzaghi objected, because his studies showed such a blanket would not stop this leakage; nevertheless, the blanket was provided. As the water levels rose in the reservoir, the seepage began to look ominous until the discharge miraculously tapered off.

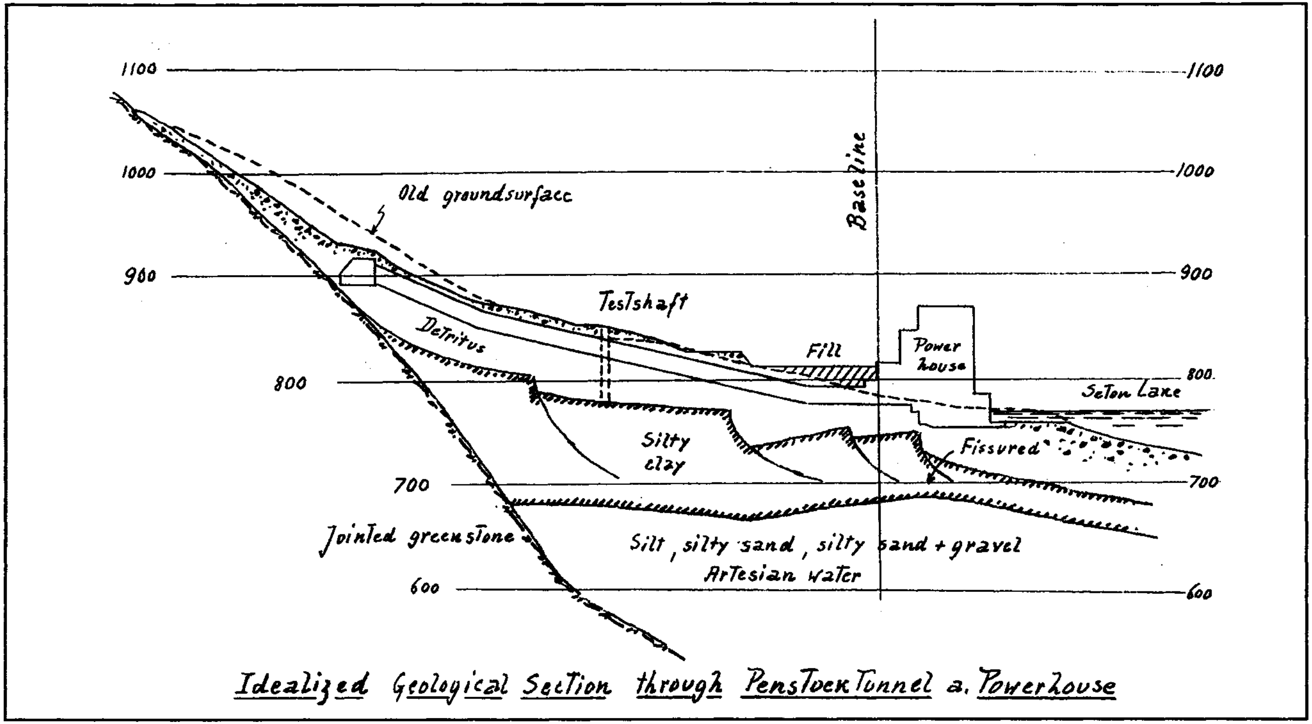
Terzaghi strained to explain this, using all the data he could muster, with the rationale that we won't understand the implications of events during further raising of the reservoir if we don't work out the physical phenomena underlying present observations. The explanation, Terzaghi demonstrated, was that the sand channels were silting up and becoming less pervious due to erosion and redeposition of material from the silty blanket placed atop them. "Hence we may have blundered, by sheer good luck, into the right solution of an essential part of our problem."[2]

At Vermilion dam, the geological surprise was disagreeable but the dam healed itself. In British Columbia, the luck was harder as Karl faced one tough job after another, several of them to construct dams at sites previously judged to be hopeless.

The accelerating tempo of challenge began at Bridge River Powerhouse on the shore of Seton Lake. Soon after its construction, the powerhouse suffered a crack in a turbine guide bracket. Subsequent observations showed that the powerhouse was simultaneously settling, tipping, and translating towards the lake, stretching and cracking the penstock tunnel that conducts water into the turbines.

The problem had been diagnosed by consulting geologist Victor Dolmage, who judged that the powerhouse site lay atop an ancient landslide. Terzaghi was sent for, but they had to wait for him to finish work in Brazil. In his first visit, late in 1950, Terzaghi observed that the north shore of Seton lake follows a high, forested terrace of interglacial or postglacial soils, except above the powerhouse area. There, in pre-history, the terrace and part of the underlying clay deposits had been eroded, he surmised, and had subsequently slid perhaps as far as 500-feet out under the lake. Karl called for a significant amount of new exploratory drilling and instrumentation to pursue this hypothesis.

It was known from previous investigations that the powerhouse was underlain by a deposit of stiff blue clay, interlaminated with silt. Furthermore, a large outcrop of sediments from atop the blue clay was found to be



Geological section showing geological conditions beneath the Bridge River Power House. From "Report on the Performance of the Powerhouse and the Penstock Tunnels on Seton Lake, B.C.", by Karl Terzaghi, August 18, 1951. Original scale 1" = 100'. Elevations are in feet. No vertical exaggeration.

dipping landward at 45°, opposite to the general lakeward dip; this could only have come about through backward rotation of a large slide block. The new investigations confirmed that the clay beneath the powerhouse was faulted and cracked and contained slick surfaces ("slickensides") that greatly lowered its shear strength.

The new, post-1950, investigations revealed that pervious, water-bearing silty sand and gravel layers could be found beneath the clay bed. The investigations succeeded in establishing that these layers held excess pore pressures corresponding to a head up to eighty feet above the lake surface. Groundwater pressures in the fractured greenstone bedrock were even higher, with heads as much as 200 feet above the lake level.[3] As at the Marathon Mill site in Ontario, the water-carrying joints in the rock charged pervious blanketing beds with water that was trapped by the overlying clay.

Karl's study of the state of equilibrium of the sediments under the edge of the lake showed that the weight of clay and overlying sediments above the pervious zone was just about the same as the uplift force from the underlying water pressure; here was a truly floating foundation. Furthermore the load of the powerhouse and associated railway fills on its landward side had brought about a critical state of average shear stress such that the safety of the entire plant was severely jeopardized.

There were two ways to correct this situation. The water pressure could be bled from the pervious beds by drilling wells into them. Alternately, a soil embankment could be constructed on the lake bottom to counterbalance the sliding tendency. The embankment solution was selected first because the gravel bed was so silty that drainage wells might not work and, more importantly, the silt would tend to plug up the water entranceways into the drains. Erosion of the silt under the high water gradients was a very real threat, as proved by great difficulties experienced in drilling exploratory boreholes; one of these deposited 160 cubic yards of silt in five weeks of wild flow where water issued from surface cracks. The construction of the counterbalancing fill succeeded in stopping the deformation of the powerhouse and penstocks and solved the problem. Subsequently, a successful bleeder well system was devised and implemented.

Another difficulty, however, lay in choosing a satisfactory site for a powerhouse extension, which was much needed by the owner, B.C. Electric Railway Company. The original design for the powerplant anticipated its future expansion. It would obviously be preferable to choose a more stable place, but drilling showed there was even higher pore pressure at the obvious alternative site. In fact, the pressure was so high at this location that the required excavation for the foundation would, in Terzaghi's estimation, "blow-up" before it had reached the necessary depth, possibly damaging or destroying the existing plant.

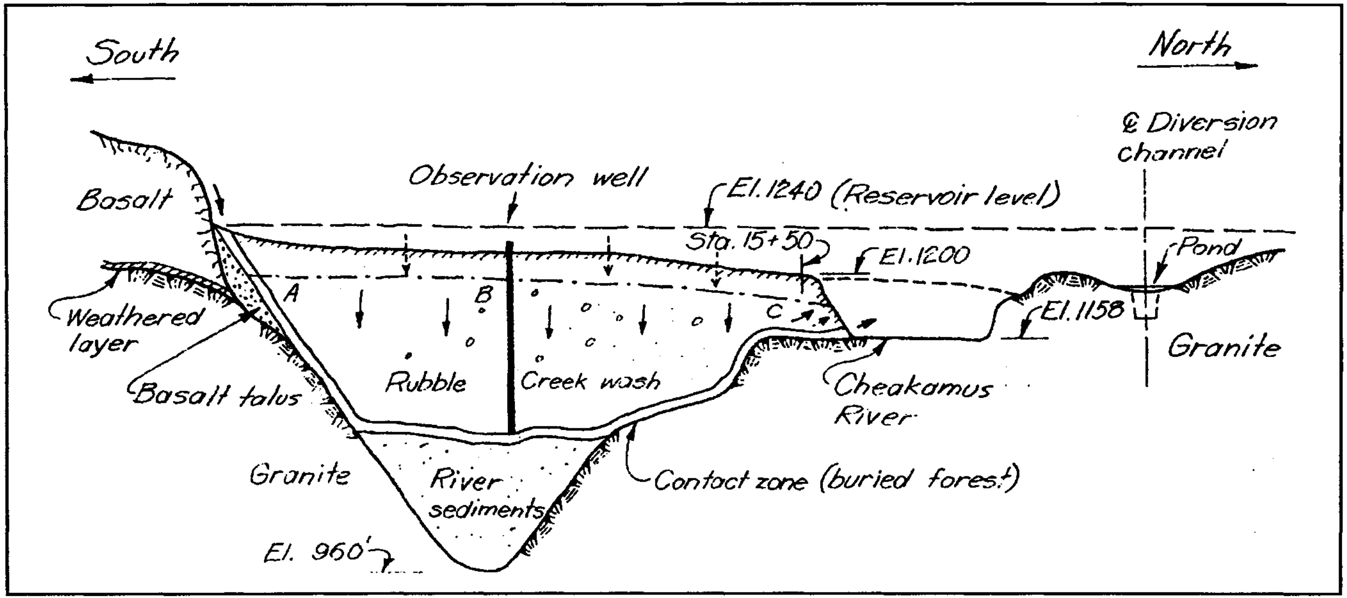
The problem of choosing an alternate powerhouse extension site proved to be a delicate matter for Terzaghi and his clients when it was discovered that the designer of the original plant, Shawinigan Engineering Co. of Montreal, had been advised by Arthur Casagrande. Casagrande had attributed the deformation of the powerhouse to recompression of the clay, following its initial expansion during excavation. He did call attention to the possible existence of deep pore pressures but did not insist on exploring this further. Arthur recognized deformed bedding in samples of laminated blue clay but attributed this to disturbance caused by driving the sampling spoon into the soil. Karl immediately identified the deformed bedding as slide-induced but, in fairness to Casagrande, Terzaghi had better samples.

Karl was gentle with Arthur, writing to his client in confidence that the subsoil conditions laid a trap that fewer than "five out of every hundred engineers would have noticed. ... If a bridge goes down, the designer is at fault, but if the site for a structure turns out to be different from what was expected, another scale must be used."[4] He thought the coincidence of building on deformed, weak deposits of an ancient landslide and at the same time having to cope with exceptionally high excess pore pressures was indeed unique, one that he had never previously experienced in his practice. Nevertheless, the owner elected to replace Shawinigan by B.C. International Engineering, Ltd., for design of the new powerhouse.

As demanding as the Seton Lake power project proved to be, its complexities were dwarfed by those of Cheakamus dam, near Garibaldi volcano, Terzaghi's next hurdle for B.C. Electric.[5] The valley floor deep below the Cheakamus River is granitic rock, but the valley had been filled with about 150 feet of volcanic rubble derived from a great andesite flow slide a century earlier. The slide entered the Cheakamus valley from the left (southeast) side and extended two and a half miles downstream. The moving slide mass buried old soil horizons and accumulated trees and branches beneath it; its zone of contact with the right bank rock wall therefore could be expected to contain open voids and be terribly pervious. There were also outcrops and foundation zones of very pervious columnar basalt and talus within and beneath the slide debris.[6]

During his first visit, in April of 1954, Terzaghi considered the following factors. The volcanic rubble was deposited as a slurry which must have initially had a consistency of a stiff concrete for in places it had flowed right around trees. This "Rubble Creek Wash", as it was called, was so soft that steel drill-casing could easily be driven for fifty feet despite the presence of stones and boulders.

Being rich in silt, the rubble was liable to piping. However, being a mix of different grain sizes without clay, it compacted to a material with the desirable, rare combination of high strength and water-tightness. It could be a satisfactory embankment material if it were possible to handle the very



Section across the buried valley at Cheakamus Dam, showing the contact zone at the base of the "rubble creek wash"; developed about 1955 and included in Terzaghi's publication, "Storage dam founded on landslide debris", Journal of the Boston Society of Civil Engineers, *Jan. 1960, vol. 47, pp. 64-94. Present scale: horizontal, 1" = 310'; vertical 1" = 155'* high water content and a significant percentage of boulders (twenty percent of the rubble's particles were more than three inches in diameter). Terzaghi advised it would be possible to build the dam of rubble wash using the observational method. This was convenient as it was the only material available in sufficient volumes to construct the dam.

The main hazard would be from the possibility of piping and leakage through the pervious contact zone at the base of the rubble layer. Since this zone continued under the entire rubble mass, it might provide short circuits for water to escape under or around the dam, particularly at its contact with the right (northwest) rock wall where the seepage path beneath the dam was short. Terzaghi repositioned and reoriented the dam axis to make it possible either to block all paths of seepage or to intercept it in drains and filters. The pervious contact zone at the right wall would be trenched and backfilled with compacted rubble wherever it lay under the reservoir within a critical distance of possible discharge points downstream of the dam.

Terzaghi made a total of sixteen visits to the site during the construction period, reporting his recommendations in reports and memoranda from 1954 to 1959 and instituting suggestions for changes at all stages. Many of these changes stemmed from the slow pace of unveiling the pervious contact zone's mysteries. Also, in order to accommodate a much larger than anticipated percentage of boulders, he had to increase the maximum allowable rock size and layer thickness (the dam was compacted in layers) and flatten the upstream embankment slope. This prompted him to write, almost defensively, "the construction of the Cheakamus dam is one of those jobs on which design and construction cannot be divorced without a risk of getting a structure which is both unsafe and uneconomical."

The problems of this project did not arise exclusively from the site geology, but also from human relationships. Terzaghi's design assured safety by intricate detailing according to the unfolding revelations of investigations and construction excavations. But safety was illusory unless construction achieved his high specifications. He protested that the contractor was inexperienced and inept, so he launched a war of memos to get a better job. He demanded an enlarged inspection staff night and day, as well as a dedicated inspection engineer devoted to finding the contractor's mistakes and overseeing their correction.

He had already requested and obtained his own personal inspector, Mark Olsen, who reported to him weekly. His prescription for Olsen's job was to "be loyal, reliable, and conscientious" and "to be able to get his information in spite of passive resistance, because B.C. Engineering[7] will consider his presence on the job, like that of myself, a confounded nuisance."[8] He asked Olsen to report in measured detail on all aspects of construction, explaining that "the one thing an engineer should be afraid of is the development of conditions on the job which he has not anticipated. The construction drawings are no more than a wish dream. I have the impression that the great majority of dam failures were due to negligent construction and not to faulty design."[9]

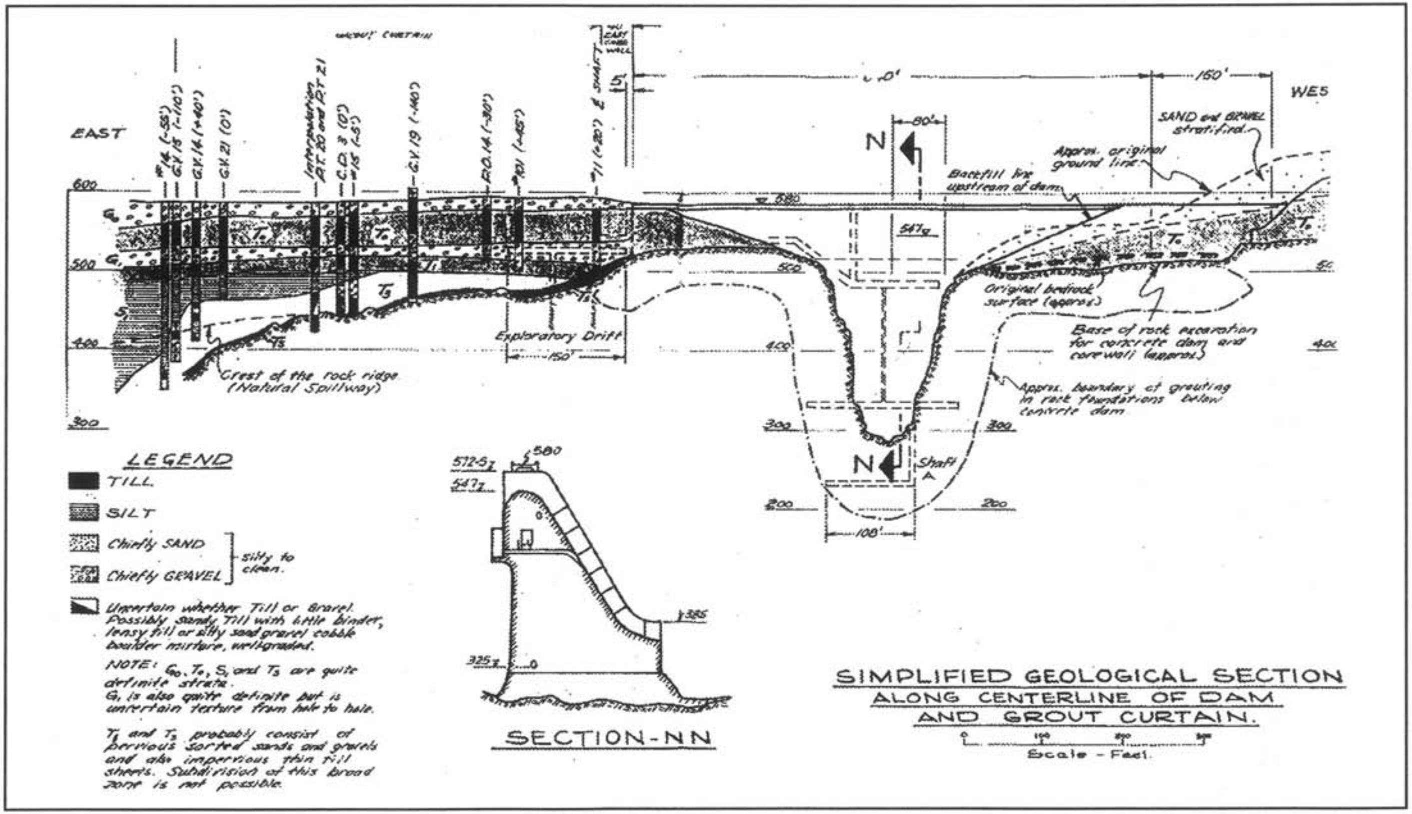
Terzaghi's initial judgment that it was possible to build a dam at this site was based partly on his confidence that the rate of leakage could be kept to below fifteen cubic feet per second. In the end, the water loss amounted to less than one cubic foot per second.[10] The decision to use the unprecedented embankment material consisting of wet, bouldery, silty rubble from the landslide turned out to be wise. The material was compacted satisfactorily with stones up to six inches, and it drained so quickly as to dry out sufficiently on the way from borrow pit to placement.[11]

It was a water supply reservoir for the city of Vancouver that challenged Terzaghi's adventurist art yet one more notch. As bulldozers began to clear the ground for the site of "Cleveland reservoir" in July of 1952, they somehow triggered a slide, which turned into a significant mudflow. Happening to be passing through Vancouver on this day to present a lecture at the University of British Columbia, Karl was asked by the Commissioner of the Greater Vancouver Water District to visit the place and advise. He reported that the slide itself was "inconsequential"; however the behavior it revealed in the materials forming the left abutment of the dam warned of similar behavior at the steep abutment slope downstream of the dam. Terzaghi advised the owners to watch the abutment very carefully as the reservoir was filled for the first time.

What Terzaghi described in his brief report was the development of a landslide resulting from piping. A volume of peat had been dug out of a 60-foot-long section of the reservoir bottom; the hollow where the peat had been removed filled quickly with clear water from below. Some days later it began to rain and hours into the storm the water became muddy, the slopes at some distance uphill started to ravel, mudflows to run, and a slide moved logs and boulders, which caused some damage.

The soil exposed in the surrounding slopes consisted of horizontal strata of glacial silt and clay as well as sands and gravels deposited in glacially fed streams. The contractor's excavations had exposed pervious sand and gravel beds through which rain water percolated; the seepage through these beds carried fine sands or silts away and excavated a subsurface channel. This robbed the base of the slope of its support and the slope started a process of failure. Terzaghi noted that Sinker Dam, Idaho, had failed approximately ten years previously after similar symptoms; a pool of clear water had suddenly turned muddy and some fifteen minutes later the dam failed. The same might be possible at Cleveland Dam, he advised.

Five years later, in 1957, at the urging of their consulting engineer Charles Ripley, Terzaghi was retained as a special consultant to the Greater Vancouver Water Board. By this time the dam had been completed and was



Geologic section along the length of Cleveland Dam and its abutments, looking downstream (south).[13]

experiencing exactly the kinds of troubles Terzaghi had foreseen. He began his work by asking Charlie Ripley to sort and assemble the overwhelming mass of data for his comprehensive review. With this he worked up "a crude but remarkably good picture of the stratigraphy"[12] and authored a monumental report.[13]

Cleveland Dam on the Capilano River is an approximately 300-foot-high concrete gravity dam filling a steep-sided canyon cut in granitic bedrock. This canyon was cut post-glacially through a narrow bedrock ridge, topped by soil, that divides nearly parallel sediment-filled ancient valleys. Downstream of the dam, the Capilano channel turns abruptly to the left; in effect, the reservoir shore, over a length of more than 1000 feet, lies on the upstream slope of the narrow ridge, formed partly of erodible, pervious sediments.

On the steep downstream slope of this ridge, where these sediments emerge charged by seepage from the reservoir, three serious risks require attention and treatment: *piping,* the natural formation and headward growth of a pipe by erosion of fine sand and silt; *leakage,* the escape of significant quantities of water from the reservoir; and *sliding,* caused by reduction of effective stress due to high water pressures under the steep slope. In this case, the sliding hazard was at least as important as the others because the outlet pipe from the dam ran along the side-hill in the middle of the downstream slope.

The potential for harmful seepage through the left side ridge was recognized and studied closely during the first filling and subsequent operation of the reservoir. The designer, International Engineering Co. of B.C., had attempted to block the seepage path through the left abutment by constructing a grout curtain over a length of 545 feet beyond the edge of the dam's concrete abutment-core-wall. Terzaghi's studies later confirmed that the grout curtain was completely ineffective. What did prove to be helpful was a blanket of compacted, watertight soils laid over the inlet area of pervious sands and gravels on the reservoir floor for a distance of 700 feet along the shore.

The solution of seepage problems was made all the more difficult by the baffling complexity of the soil materials. Over the top of the valley-fill sediments was a continuous layer of dense, glacially deposited "till", underlain by a very pervious layer of sand and gravel. Underneath this was an almost unpredictable assortment of all different kinds of sediments, produced as the glacier overrode, disturbed, and redeposited sediments in the profoundly intermixed way of a glacial terminus. Beneath all this, extending down to the bedrock, were impervious, dense older glacial and interglacial deposits.[14]

After abundant exploration and tunneling, the baffling stratigraphy yielded only some of its secrets. As a somewhat improved picture emerged, Terzaghi issued a radical remaking of his May 1959 report with a much enlarged section on the geology;[15] but big surprises lay in waiting.

In 1954, it had been decided to drive drainage tunnels from points near springs and wet spots where water obviously accumulated. One of these, Tunnel 470, was driven near the base of an eight foot thick layer of till. After excavating for a distance of 270 feet, sixty feet short of the grout curtain, tunnel supports began to fail and further mining became impossible as the tunnel face passed from sand and gravel into a silt layer. The tunnel face was blocked off and supported with a "bulkhead"; then the space between the head of the tunnel and a second bulkhead, 26 feet farther back, was filled with fine gravel. Two pipes were installed to lead water out to the portal, and the reservoir was allowed to rise.

As the reservoir came up 78 feet above the elevation of the tunnel, in June of 1955, the flow of mainly clear water gradually increased to 40 to 60 gallons per minute. Then, without any further reservoir rise, between August 8 and about September 5, 1955, the flow increased dramatically to more than 140 gallons per minute, and the water became muddy. At the same time, the flow at a spring on the slope at elevation 442, 650 feet distant, magnified by almost ten times and also became muddy. By some natural act, the tunnel had converted itself into a highly effective drain.

In studying the records of this event Terzaghi concluded that there must have been a natural rupture of the till layer above the tunnel due to seepage forces. This had created, for the first time, a hydraulic pathway between sands at about elevation 500 that connect freely with the reservoir, and the sand and gravel layer in the tunnel that had previously behaved as a separate, noncontinuous lens.

Thanks to the tunnel, and a successful drainage shaft (E2), there was now less of a problem with slope stability, but a new one of erosion. Solids were being removed with Tunnel 470 drain water at a rate of 5 cubic feet per week. How long could this go on? The immediate hazard was to the structure of the tunnel itself. But was there also the threat of failure by piping?

Continued maintenance of the drain tunnel proved costly; it was proposed to construct an additional one, with improvements in design. Accordingly the reservoir surface was lowered and 346-foot-long Tunnel 505 was driven within the dense, pervious sand and gravel that was the primary source of the seepage into Tunnel 470 from above. Tunnel 505 had an alignment roughly parallel to T470 for its first 200 feet and then curved in front of T470 a short distance above its upstream end.

The intent of T505 had been to intercept the flow into T470, in order to prevent erosion and loss of fines as the flow passed through the silt above T470. When the water level in the reservoir was allowed to rise above the level of T505, the T470 flow decreased as expected as the T505 flow picked up. The latter was essentially clear until the last seven feet of rise. But as the reservoir rose from elevation 563 to 570 (the maximum water surface), the T505 flow increased dramatically to more than 500 gallons per minute; moreover, it became very sandy, depositing as much as 70 cubic feet of sand per day at its worst.

Terzaghi agreed that "these developments were unanticipated and rather alarming." He analyzed the data with great care, pulling out hydraulic theories in attempting to distinguish between the observational signals of active piping and internal erosion (termed "scour"). The first could provoke a catastrophe. The latter would simply increase the leakage as the fine sands were winnowed out of gravel and sand mixtures. Thus he succeeded in convincing himself that piping was not going to happen, despite Ripley's real fears.

Meanwhile, the management of the water board was growing impatient with the large drainage maintenance costs of Cleveland Dam and wondering if this observational method was really a good thing. Ripley explained that Terzaghi's observational method was the only economic way to build on a such a site, where the geology was simply too complex to unravel beforehand. One could never afford to protect in advance against every conceivable contingency.

In mid-1963, erosion of sand from Tunnel 505 had settled down somewhat but was still very high. Tough Terzaghi, nearing his 80th birthday and not well, stubbornly refused to worry. It is possible, he admitted, but highly unlikely that the water is actually eroding a pipe towards the reservoir. The most likely explanation is scour, whereby the sand and gravel stratum is cleansed of some of its sand. Scour is no real problem, he thought, because if the leakage becomes an economic factor the water could be simply collected and pumped back into the reservoir.

However, to calm everybody's nerves, since the advent of real piping would precipitate a disaster, he proposed that the head of the tunnel be equipped with a very strong reinforced-concrete lining having a perforated floor; his idea was that the lining would stand until nature had reestablished an equilibrium by clogging the pipe's outlet, thereby forming a naturally deposited filter. "The cost of the installation of the reinforced concrete lining," he quipped, "reminds me of the life-insurance premiums I used to pay prior to starting my numerous long-distance airplane trips. I knew that the money was wasted unless the airplane crashed and mine never did."[16]

Karl loved to visit British Columbia, which he regarded as one of the most beautiful and challenging terrains on earth. That was fortunate because the problems he faced, like those at Cleveland Dam, claimed his best efforts almost to death's day. The last job, the construction of Mission Dam, he considered the most difficult and hazardous problem of his lifetime.[17]

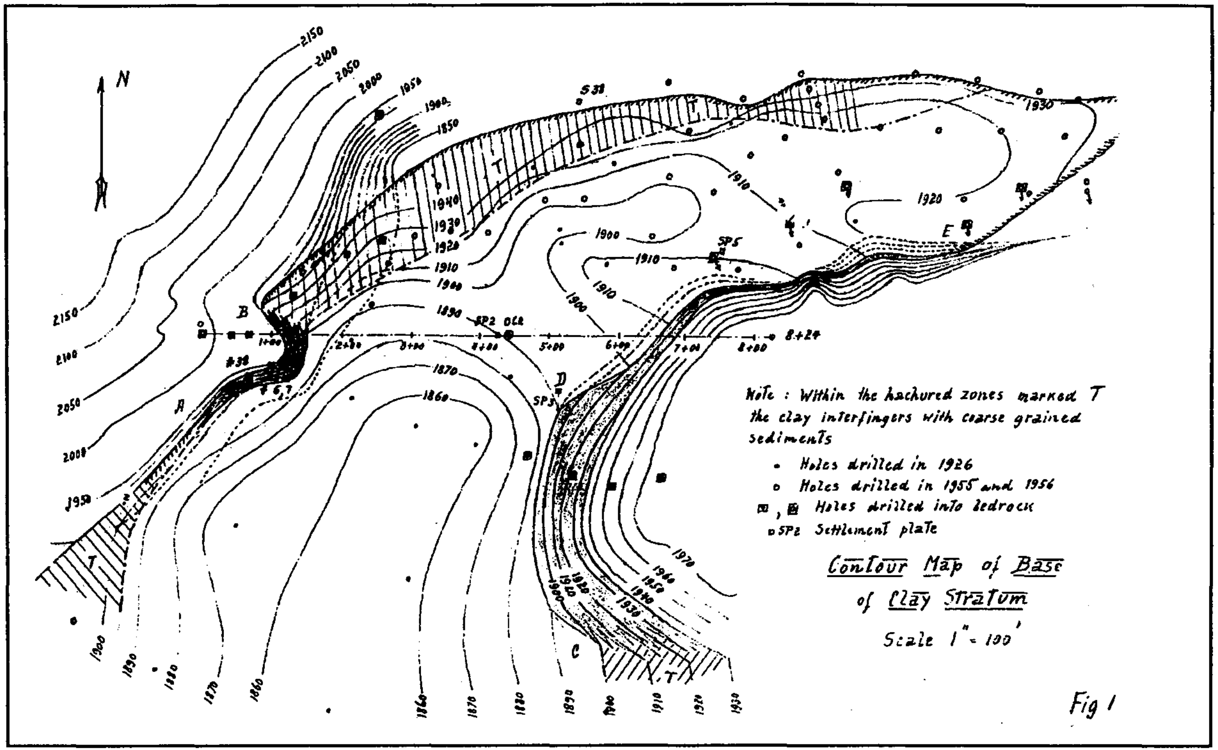
It was a B.C. Electric project. They sought to supplement the existing 60-foot-high rock-fill "Bridge River Diversion Dam" by an approximately

180-foot-high structure, to be called Mission Dam, in order to harness additional power from the Bridge River at Seton Lake. The preliminary layout had shown the need to incorporate the diversion dam within the new, higher one, and to continue to operate it throughout the construction of the higher dam. The existing dam had been designed by Shawinigan Engineering in 1945 with Professor Casagrande as consultant. It was completed in 1947. As Terzaghi started his work on Mission Dam in 1955, he decided to ask for Casagrande's participation right from the start; Arthur would work on preliminary design of the new dam while Karl devoted himself to "the broader, and very troublesome, features of the project".

"Troublesome" was the right adjective. Indeed the eight year old diversion dam had already settled up to six feet and developed sinkholes as the surface collapsed into cavities eroded in its core. If that was not enough, the dam was leaking uncontrollably through its foundation. In the face of this distressing performance of a dam 60 feet high, how could anybody dare to construct one 180 feet high? He found that a design for the new dam prepared in 1928 had fatal flaws. A second design, proposed by Huber's B.C. Engineering in 1954, brought out Terzaghi's finest sarcasm: it was a bit better, he wrote, in that the dam would survive as long as there was no water behind it.[18]

It was one of the worst damsites Karl had ever come across.[19] As usual, the problems originated with the site geology. The depth of valley sediments was great, more than 400 feet, mostly of highly pervious river deposits; but there was also an almost impervious wedge of varved clay[20] sandwiched between upper and lower pervious sediments. The clay tapered down in thickness from 70 feet beneath the crest of the existing diversion dam to just a few feet beneath the selected axis for the new dam. The designers of the diversion dam had attempted to stop subsurface flows through the upper river sediments above the clay by driving sheet-piles down into the top of the "clay layer". While this controlled the seepage immediately beneath the dam, it had no effect on leakage through the pervious deposits beneath the clay. Terzaghi estimated that unless the foundation of the new dam were sealed all the way down to rock—by means of the new art of clay-grouting, for example—leakage would be excessive, perhaps more than 100 cubic feet per second.

The clay wedge created monstrous difficulties for the foundation because it was highly compressible. Tests conducted for Shawinigan at the University of Alberta had reported the clay exhibited almost unprecedented softness which would allow the diversion dam to settle several feet. Terzaghi's later back-calculation of the actual settlements that had occurred on the diversion dam yielded a compression index value[21] for the clay of about 1.0. This was several times greater than given in the University of Alberta tests; Karl wrote that he had never encountered an undisturbed clay of that



Mission Dam: Terzaghi's working contour map of the base of the clay from which he deduced the location of the shore zone of the ancient lake. From "Preliminary report on treatment of foundation for proposed Bridge River Dam", by Karl Terzaghi, February 25, 1957.

plasticity having such a high compressibility.[22] He estimated that this great softness would allow huge foundation settlements in the new dam—up to 25 feet. The worst part was that the wedge shape of the clay formation, and its oblique orientation in the valley, would cause distortions, shears, and tensions from enormous and abrupt differences in the magnitude of settlement within the dam; these would crack the dam and the cracks would concentrate seepage flow, causing erosion of cavities which could collapse to the surface to produce sinkholes.

That these materials and conditions could cause sinkholes to form had already been well proved by the history of the existing diversion dam. For example, in April 1952, a hole was found at the crest of the dam that proved to be about 25 feet long, 10 feet wide, and 4 feet deep. By September its depth had increased to 8 feet and its volume had more than doubled.[23]

With all this, there was something else equally worrisome. The flanks of at least the left (north) slope of the canyon were covered by a thick mantle of "talus" (very coarse rock blocks). Terzaghi reasoned that these must continue at the same very steep angles all the way down to the rock floor and inter-finger with the stream deposits in the foundation. The voids of the talus could deliver enormous leakage around and under the sealing system of the dam. Moreover, if the clay layer should rest anywhere directly on talus it would erode into the large voids to produce cavities and giant sinkholes, possibly precipitating a complete loss of the dam by piping.

During construction of the diversion dam, talus had been encountered and allowed to remain because it had been judged impractical to strip it entirely free of the foundation. Some of this material had been piled up on the flanks of the diversion dam as a "random fill". The new dam would be built over this material, and it could not be removed without destroying the diversion dam, which had to remain operative during construction of the new dam. Terzaghi asked that the worst pockets of talus and rock fill under the filter layers of the new dam be mapped out during construction and filled by washing fines into the voids. First sand was spread over an exposed boulder layer and sluiced into the voids using a water jet; then the process was repeated with new sand until no additional sand entered between the boulders. Terzaghi's follow-up test pit revealed that the jet's energy waned two to three feet below the surface of the layer of boulders. "Below that depth the voids remained practically open and nothing could be done about it. What we produced was the equivalent of a film of cosmetics on the skin of a patient afflicted by smallpox." Consequently, a ten foot thick, high quality filter layer was placed on the foundation beneath the base of the dam. Its purpose was to prevent the fines of the dam from being washed into the open voids within the foundation.[24] In September and October, 1957, two sinkholes appeared at the surface of the filter before that layer had been covered with dam fill. After detailed exploration, the sinkholes were backfilled with compacted and sluiced material.

Karl had ample reason to walk away from this job, and might have done so had it not offered a supreme challenge and adventure; he had confidence in his ability. Getting the geological picture right would be a necessary prerequisite. He reasoned that controlling the hazards of the clay required intricate knowledge of the formation's shape and orientation under the project as well as the precise nature of its contacts with other sediments and talus. To unravel the geological history, he reviewed and replotted all the data from previous exploration, including about 100 borings dating back as far as 1927.[25] Once again he became an engineering geology detective in order to inform his soils engineering.

From the contours of the top and bottom of the clay formation, and its internal structure, Terzaghi produced the following narrative.[26] The clay formation was deposited in a lake at least 125 feet deep filling a trough carved by glacial action on the surface of the previous valley fill deposits. The lake had existed for about 3,000 years and the deposition of coarse-grained deposits on top of the clay layer started 7,000 years ago. Between specific points on the left and right shore the clay would have been deposited directly against rock. Up and downstream from these sections of the old lake shore, the clay must interfinger with sandy sediments in a "transition zone" with lenses and wedges of clay separated by pervious material.[27]

He noted that the soils between the clay layers in the transition zone resembled river sediments. Wave action on a talus slope couldn't achieve this, so Terzaghi concluded there must have been a fairly continuous layer of river sediments over the talus before the deposition of the clay started. With this as a working hypothesis, he found from the borings one place at which clay had been laid directly against talus, unfortunately in a particularly difficult location for the design, just downstream from the abutment of the diversion dam.[28]

The axis of the old dam spanned a narrows in the rock valley. Terzaghi observed that the upper surface of the clay upstream of this narrows undulated at about elevation 1925; since elsewhere the clay reached elevation 1960, the water depth in the lake was at least 35 feet. "The velocity of the water in a lake with such dimensions is so small that the lake basin could have been filled with coarse grained sediments only by the gradual growth of a river delta, the apex of which is located at the upper end of the lake. The clay stratum represents the bottom-most ('bottom-set') beds of the delta." This theory was supported by the finding that the upper portion of the clay layer was silty, in some cases approaching pure silt. Terzaghi deduced: "As the delta front approaches a point on the bottom of the lake, the fine-grained sediments which are deposited at that point become coarser."

Downstream from the narrows (close to and upstream of the center line of the diversion dam), the surface of the clay was irregular. Terzaghi interpreted this as evidence that, with the building forward of the delta, the clay wedge had failed under the load of sediments deposited on top of it. As the delta grew toward the narrows, its rate of sedimentation had to increase, causing excess pore pressure in the water of the clay which consequently sheared and softened. This would partly explain the very high compressibilities of the clay material and also the discovery of mixtures of silt and clay from the clay wedge with sand and gravel from the overlying river sediments. Terzaghi concluded from this picture that the precise boundaries between disturbed and undisturbed portions of the clay bed could not be found, and therefore an accurate forecast of the distribution of the settlement over the base of the proposed structure could not be made.

This understanding of the local geology underlay much of Terzaghi's subsequent approach to engineering the design and construction of this dam. The details would change from point to point, and inattentiveness during construction would invite hazards. If this dam were going to be safe, he would need authority to make adjustments here and there and, as he could not be present every day during construction, this dictated he should have at least one, preferably two, men on the job reporting directly to him. He arranged for Mark Olsen to be his number one on the site, and had the engineers hire Ralph Peck's brilliant French graduate student Yves Lacroix, who was lured by the opportunity to write a doctoral thesis about constructing a safe dam on so terrible a foundation.

The project was being built for B.C. Electric, whose responsible engineer F.A. Lazenby understood and fully appreciated Terzaghi's unique contributions, previously at the Seton Lake Powerhouse, at Cheakamus dam, and now at this daring Mission Dam. But the engineering staff preparing design drawings and administering the contract belonged to W.G. Huber's company, B.C. Engineering, at this time a subsidiary of B.C. Electric. Ignorant of the special arrangements that placed Olsen on the job as Terzaghi's inspector first on the Cheakamus Dam and now again at Mission Dam, he was impatient with Terzaghi's independence and became an adversary and obstacle. Huber played into the traditional project jealousies between design engineers and construction inspectors, until Terzaghi brought it to an abrupt end by threatening to resign if Huber did not fall into line.[29] To Lazenby, Karl then wrote, "the scope of the activities of B.C. Engineering steadily increases, but the spirit of the organization and its attitude towards expert advice remains rigidly and fanatically unaltered. Therefore it is only a question of time—and conceivably of a short time—when the discrepancy between responsibilities and performance will lead to serious consequences and I do not wish to have my good name associated with the organization which will be blamed for them."[30]

That letter upended Mr. Huber at Mission Dam, Karl commenting expansively to a friend that "I did not like his concepts of 'cooperation' and made no secret of it. As a consequence, and at an early stage of construction, he had to shift the seat of his activities to Iran or Iraq."[31] With Huber gone, Karl thought his personnel troubles were at an end as he confided to Lacroix: "I have no concern about future developments because by now everybody in the organization knows that I can bark a bit if there is no gentler way to handle a situation."[32] But he was wrong; the conflict continued with the construction management, and, before the job was finished, Terzaghi had twice more raised the specter of resignation. He was getting old, with declining health, and Mission Dam would be safe only if it was "kept out of the hands of fools".[33]

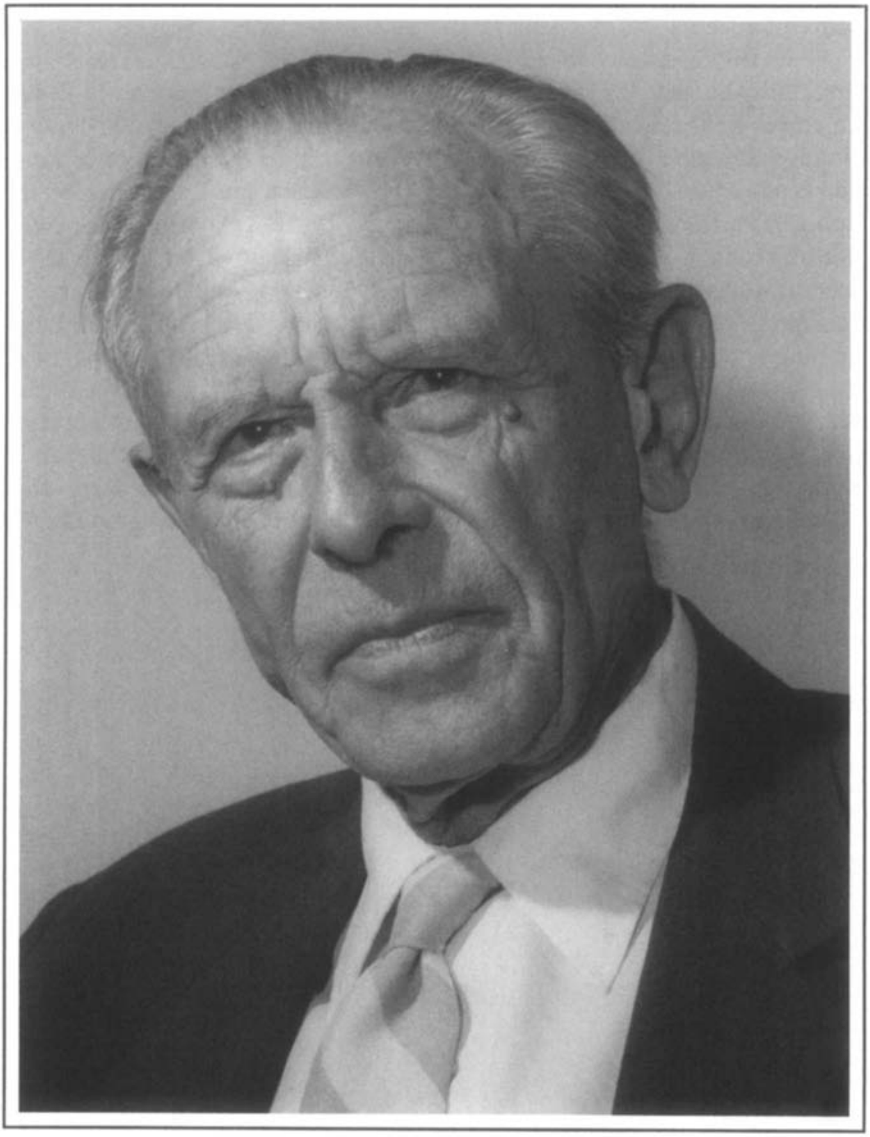
Working closely with Terzaghi, Arthur Casagrande was beginning to feel the old warmth of friendship and admiration returning. He addressed his memos "Dear Karl" and confided in him beyond the job.[34] They cooperated not only on the Mission Dam project but on the South Saskatchewan River dam (Gardiner Dam), from the 1950s to early 1963. It was Arthur who had recommended Terzaghi's participation on Gardiner dam because of the project's complexity.

Arthur was seriously troubled by the problems that had developed in the diversion dam, on which he had provided design advice to Shawinigan in the later 1940s. When Terzaghi produced a monumental report analyzing the defects and deficiencies of the diversion dam,[35] Arthur tried to evoke a placating statement from his mentor.[36] Karl had been careful to point out in his report that Arthur had wisely recommended an allowance at the crest elevation for five feet of settlement. And Karl Terzaghi continued to place confidence in Arthur, as demonstrated by nominating him to carry on as principal consultant at Mission Dam after declining health forbid Terzaghi's further visits to the site.

The philosophy that guided the daring construction to a safe end was entirely Terzaghi's. He brought in Soletanche, a firm that had carried out large grouting tests under Terzaghi's supervision at the site of Aswan Dam; they were to create a state-of-the-art grout curtain that would cut off leakage through the pervious sediments below the clay bed all the way down to the rock. (Ironically, the government sought to impose a tax on the value of the water thus saved.) He suggested pioneering use of a PVC plastic skin to prevent the clay blanket from going into tension due to a differential settlement of up to eight feet.[37]

The construction also produced one of the first North American applications of the slurry trench method to improve the sheet piles of the diversion dam.[38] Terzaghi assumed that, nevertheless, the dam would leak and sinkholes might form; but, assured that neither would prove fatal if addressed quickly, he built into the dam an elaborate instrumentation system—settlement plates, tiltmeters, water pressure gages, observation wells, and flow gages. With his nagging attention to the developing data, problems could be diagnosed and treated aggressively. Furthermore, the reservoir was drained after its first filling in 1960 to allow inspection and repair (which it proved to need).

As the reservoir moved into its critical initial operation stage, after first filling in 1960, the organization of the electric power industry in British Columbia went into a turbulent period culminating in provincialization and clouded direction. As happened at Cleveland Dam, the prospect of continuous expenditure on Mission Dam after its completion was questioned by the new Chairman of the Board for B.C. Electric, Dr. G.M. Schrum, who could not understand why the designers could not simply write down a set of specifications and forget about it thereafter. Terzaghi responded, "since Dr. Schrum is a former Dean of Physics his attitude towards Earthwork Engineering is not surprising."[39] To Lazenby, Terzaghi wrote: "The thought of the Mission Dam, whose weak spots I know so well, will haunt me until I can feel assured that full advantage will be taken of the means of observation which have been installed.... My time is obviously running short and I wish to get the Mission Dam out of my system, because I have so many other urgent tasks to perform before I proceed to 'the eternal hunting grounds'."[40]



Karl Terzaghi, June 1958.

19
The Struggle to Finish

Karl viewed his coronary of February 1953 as "a drastic reminder that life will not last forever",[1] but misinterpreted the signal as a command to step *up* the pace of accomplishment before it was too late. Only occasionally did he recharge at home or at the family retreat in Maine, aptly named "Bear's Corner". For example, in September, 1954, after a strenuous trip to B.C. and Saskatchewan, he stayed two weeks in Maine enjoying "happy times with the children and their animals" while writing a paper on engineering geology[2] before setting off again to Egypt, Austria, and England. In 1956, not atypically, he spent only three weeks at home in the period from early May to late November. But while there was no appreciable slackening of travel or commitment, he began to express himself more broadly, using speaking and writing opportunities to impart the lessons of his life to an attentive profession.

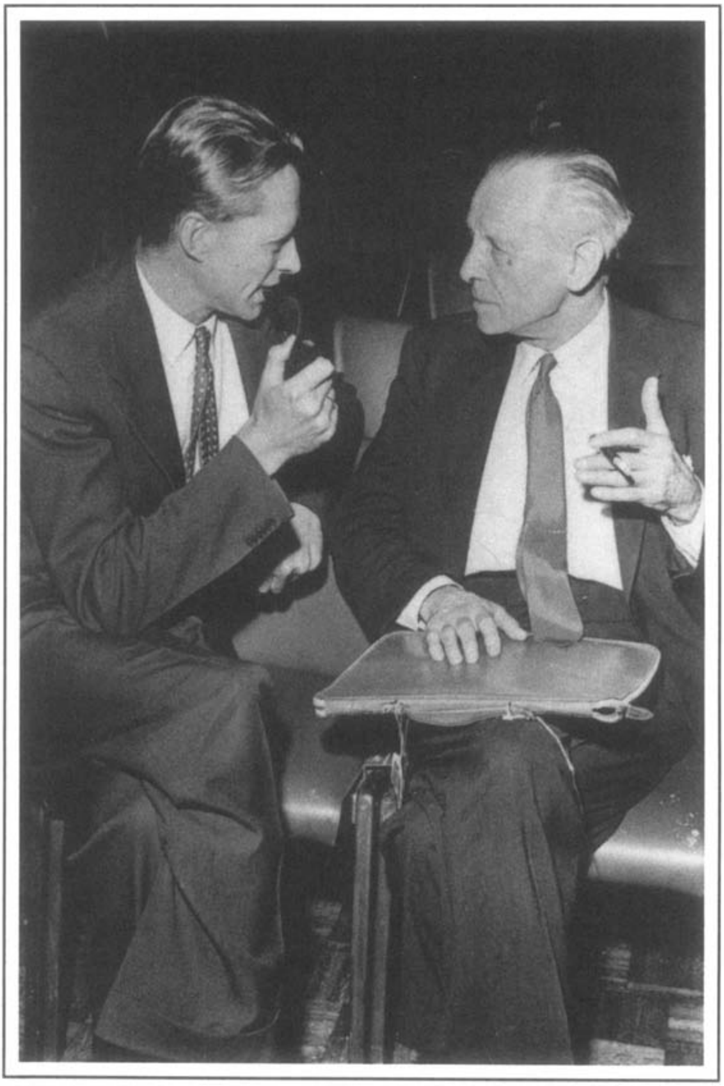
At the Fourth International Congress on Soil Mechanics in England during 1957, the occasion of his passing the President's gavel on to Professor Skempton, after 21 years, inspired an overview of soil mechanics history and his place within it. Soil mechanics, he observed, had "arrived at the borderline between science and art", explaining "I use the term 'art' to indicate mental processes leading to satisfactory results without the assistance of step-for-step logical reasoning[3] ... To acquire competence in the field of earthwork engineering one must live with the soil. One must love it and observe its performance not only in the laboratory but also in the field, to become familiar with those of its manifold properties that are not disclosed by boring records. ... Examining the array of useful knowledge which has filtered into my own system and crystallized into sound judgment, I find that it contains one ounce of geology for every pound of theory of structures and soil mechanics."[4]

In the Spring of 1957, Karl presented the introductory lecture in the engineering geology course at Harvard, being continued by Walter Ferris with help from Ruth. If you do not succeed in grasping the concepts of engineering geology, he warned, "you had better keep away from earthwork engineering." He noted that his books generally included a preface that the contents were useful only as a guide to judgement, but "unfortunately it is a widespread habit among the readers of books to skip the preface."[5] He was still troubled with this educational failure four years later, writing "I produced my theories and made my experiments for the purpose of establishing an aid in forming a correct opinion and I realized with dismay that they are still considered by the majority as a *substitute* for common sense and experience. As long as I can still crawl, think, and write I shall fight this fatal tendency."[6]

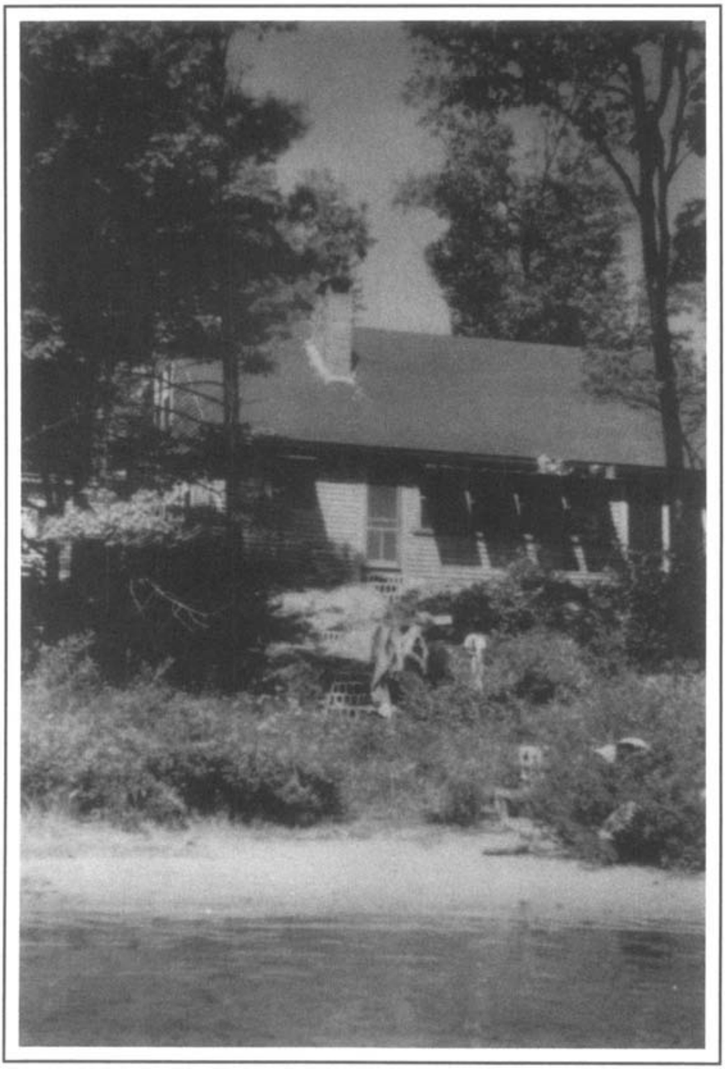
In October of 1957, the Boston Society of Civil Engineers heard a talk by Terzaghi with the unusual title "Consultants, clients, and contractors" in which he related experiences about the ethics and responsibility of earthwork.[7] He observed that his most important contributions often developed from peripheral observations on the site. His talks usually drew continuing public debate, fueled by his correspondence with friends and personal invitations to prepare written discussions in order to air additional perspectives; this popular subject launched sixteen published discussions from informed engineers, one of whom called Terzaghi a "civil engineering Sherlock Holmes".[8]

One of the most attentive of Terzaghi's followers in these years was the brilliant young director of the Norwegian Geotechnical Institute, Laurits Bjerrum. Terzaghi wrote initially to Bjerrum in 1954 after reading his manuscript on geotechnical properties of Norwegian Quick Clays,[9] a subject Terzaghi knew from his own work to be mysterious and compelling. Their convivial correspondence developed rapidly into a trusting friendship—one that brought Laurits to M.I.T. as visiting professor and repeatedly as house guest in the Terzaghi home. Thus, in September, 1957, when Arthur conceived the idea of reprinting a selection of Terzaghi's writings as an anniversary volume to honor him on his upcoming 75th birthday, Laurits Bjerrum was one of those to whom he made the proposal. The others were Alec Skempton and Ralph Peck. But Terzaghi's birthday arrived too soon for the timely realization of this gift.

Karl's perspective on October 2, 1958, from the summit attained after three-quarters of a century, afforded an almost complete overview of his own intellectual development. He could see his early experiment in wildness and sinfulness as having served a useful purpose: "It drove the inhibitions out of my system. No psychoanalyst could have done a more thorough job, and in a more painless fashion." Later when he identified what would become his work he became utterly absorbed in it, almost abandoning his personal life. "It was as if I had entered the services of a master who does not tolerate any competition.... The master turned out to be a very exacting



Karl with Laurits Bjerrum, 1958.



"Bear's Corner", near Harrison, Maine.

one, but he rewarded me generously, because in exchange for my loyalty he made me immune to three of the most disturbing mental ailments which plague humanity. These are craving for success, professional jealousy, and greed.... The peace of mind growing out of this attitude towards life is a precious asset and always gave me complete satisfaction. Therefore I shall continue serving as long as my strength lasts."[10]

The absence of the anniversary volume on this date was disappointing since Casagrande's idea had been taken up enthusiastically, yielding voluble correspondence as the group of four began to work as a *de facto* Committee with Arthur as chairman and Karl as special consultant. At first, the project seemed reasonable and tractable, but the format, content, and production of such a book simply needed more time. This was no ordinary committee; each member was an independent and eloquent statesman of soil mechanics. They were each well acquainted with Terzaghi's legacy but of somewhat different minds about what constituted the most valuable part of his enormous output.

Thus, their proceedings advanced at a turtle's pace. The words of Terzaghi were too fine to publish in a slap-dash manner, but it was hard to find a publisher willing to make the investment. Agreeing on a specific content was yet more difficult. They were all interested in showing just how Terzaghi's genius had illuminated the way but found it necessary to research precisely where, how, and when his steps of discovery fit within the fabric of engineering history. As they deliberated and rebutted, the proceedings began to resemble the debating and writing of Judaic Law by medieval rabbis.

One of the sensitive subjects concerned what Skempton might write concerning Fillunger's 1917 tests on concrete in his article on Terzaghi's discovery of the concept of effective stress. In these laboratory tests the tensile strength of concrete was found to be essentially independent of pore water pressure; Skempton considered this to be "a landmark in the development of ideas on effective stress."[11] Bjerrum agreed that Fillunger's work belongs in a historical paper on the principles of effective stress but probably oughtn't to be in a volume honoring Terzaghi. Casagrande reminded them that Fillunger had "denounced as nonsense Terzaghi's concept of pore pressures and effective stresses". The diplomat Skempton offered the following compromise: "Fillunger's tests fall very nicely into place in their historical context as being one of the series of tests made in the period around 1910–20 which implicitly show the principle of effective stress but which were not understood by their authors."[12]

All five gradually grew impatient with Casagrande's apparent inability to consummate the project. By September of 1958, Terzaghi wrote to Bjerrum[13] that "at this stage I considered it indicated to step in, because I could not yet see any signs of incipient organisation. ... To each one of the first 5 sections I wrote an introduction (about 3–6 pages) explaining T.'s[14] attitude towards its topics. Some of these introductions will be signed by Arthur and others by Peck." (Such false attributions were not included in the final volume.) He revealed that Casagrande's short draft of Karl's biography, entitled *Life and Achievements*, "read like an enclosure to an application for a job. I scrapped it and wrote it myself (40 handwritten pages). Now it seems to be juicy and lively." Bjerrum replied that he too was depressed over the slow pace and sad that the younger men were no match for Terzaghi's efficiency, adding "I wish that more people in leading positions carried around in their interior a reservoir of gall, venom and burning, fighting spirit which now and then could break through the much too nice and smooth polish."

The anniversary volume was finally published on September 29, 1960, with Ruth and Karl's suggested title *From Theory to Practice in Soil Mechanics*. It was presented to him by Arthur two weeks later before a record audience at the ASCE meeting in Boston, at which Karl also delivered a retrospective lecture entitled "Uses and abuses of soil mechanics". His talk on this occasion began as an acceptance speech for receipt of the anniversary volume in which he disguised his role in its publication, admitting only to having had a "sneak preview" of its contents.[15] In addition, announcement was made of the creation of a "Terzaghi Award" to honor achievement in soil mechanics, and he was presented with a Medal from the British *Institution of Civil Engineers*.[16]

The reviews were uniformly glowing. "Throughout the last century," said one reviewer "no civil engineer has exerted such an influence on his profession as Terzaghi, who it can indisputably be claimed, has established and developed soil mechanics as a new branch of engineering science."[17] The journal *Nature* stated that "Prof. Karl Terzaghi is one of the most interesting figures in the world of engineering science and many believe him to be the greatest civil engineer of our day. ... Few men of this stature emerge in each generation."[18] The belated review in *Geotechnique* by R. Glossup stated that "in addition to those figures in the engineering world whose names are connected with some remarkable structure, there is a small group of great engineers, often scarcely known to the layman, who have profoundly influenced the mode of thought of their contemporaries, and consequently have initiated new eras in civil engineering practice. Professor Terzaghi is one such man, and his stature is comparable to that of Navier in the early 19th century, and Euler in the 18th century."[19]

Among the grateful letters that followed the publication of *From Theory to Practice* was one from F.E. Schmitt especially commending Casagrande for his "intimate, sensitively traced story-picture of the master's development and progress."[20] This is almost laughable on two accounts. First, Terzaghi, not Casagrande, was its author. Secondly, Schmitt was the one who had successfully argued Terzaghi out of a budding plan to write his own biography. A British executive had suggested that Karl write about his life's experiences, saying, "I do not suppose that anyone will ever again have a chance to cover the wide range of problems you have covered.... Of course, if you can add the human side it would be more interesting still. In fact I think it might almost become a best seller."[21] Terzaghi told Schmitt "it could hardly be considered presumptuous if I would tell a younger generation what life and experience have taught me beyond the narrow realm of analysis and test."

Schmitt returned: "Please do not let thoughts of your approaching sixtieth anniversary discourage you: you are still young and need not yet seek consolation in settling down to writing your memoirs." There are problems in an engineering autobiography, he explained—"to choose the coverage in such a way as to awaken live interest in a sufficiently large group ... [and] how to decide between objectivity and subjectivity in the contents.... The intending author may properly ask himself whether he really wishes to paint a self-portrait." The autobiography was not to happen, even though Karl still nurtured a plan to prepare a "record of my life's experience for the benefit of those few who are born engineers";[22] some of his life's lessons were doled out piecemeal in the contemplative papers and lectures of his later years.

Almost by accident, fourteen years later, material allowing comprehensive study of Terzaghi's life and work started to flow to Bjerrum in Oslo. The occasion was Laurits' touristic visit to Karl's old offices in Vienna, in the Fall of 1957. Professor Fröhlich, in the process of vacating his offices on retiring as Terzaghi's successor at Vienna Technische Hochschule, showed Bjerrum "a large pile of dusty papers on the floor in one of the corners" of a small filing room.[23] This was the residual contents of Terzaghi's files, reports, correspondence, and memoranda stored and abandoned at the time of his flight from Vienna in 1938.

At Bjerrum's instigation, Terzaghi visited with Fröhlich nine months later, found the material "still slumbering in a quiet corner" and arranged for its removal to Bjerrum's Norwegian Geotechnical Institute (N.G.I.) in Oslo. On its receipt in October of 1958, Bjerrum's staff at N.G.I. sorted and indexed the collection, and, as Laurits began to browse his way through it, he wrote to Karl, "I have spent a good deal of time in company with the about 50 years old Terzaghi.... I am getting more and more impressed by your personality and your working capacity." Thus, a Terzaghi Library began to develop, and Bjerrum began to entertain thoughts of becoming Terzaghi's biographer.[24]

In this same year, Karl's eyesight started to weaken. This was corrected by a cataract operation on December 6, 1958. In 1959, in addition to tending his consulting jobs, he lectured in Florida, Illinois, Harvard, and M.I.T., but by the end of 1959 weakening eyesight and shortness of breath made him pause more frequently to admire the view during field visits. Then a second heart attack in January of 1960 sent him to hospital followed by a short "sentence" as "prisoner on parole"[25] and compelled him to curtail further lecturing at the University of Illinois. In explaining this to Peck, he wrote "the good old Ford which I have occupied since I was born has reached a stage at which I cannot be certain several months in advance whether it may not be in need of repair at the crucial moment.... Since the detrimental effects of wear and tear are limited to the motor and the bearings, they will have no influence on the progress of Engineering Geology."[26] Ralph responded that Karl's body was no Ford, rather a Mack truck.

The hard blow came in November of 1960, before he could finish the overdue book on Engineering Geology, which began to resemble a white whale. After a sleepless night, Karl went to the hospital for check-up and x-ray. The next day he was asked to return, whereupon the doctors discovered he had suffered an aortic aneurism. In a nine-and-a-half-hour operation on November 17, the ruptured artery was replaced by a dacron tube but, after five days and additional surgery, continuing blood clots forced the amputation of his left leg above the knee. When he returned home to find he must devote most of his waking hours in the exercise of mere existence, he sincerely believed his usefulness was over. Thus, the aging Bear set out to write an essay on the ethics of continuing a life that had reached a purposeless state.[27]

His operation was a "surgical masterpiece" he wrote but, from his perspective, merely postponed the inevitable disintegration. "The overwhelming majority of physicians stands under the compelling influence of the dogma that life as such is under any circumstances the most priceless possession of each one of his patients and that no effort should be spared to keep it going. Performance in accordance with that dogma has almost the character of idol worship and the consequences receive very little, if any, consideration."

"Once the organism has reached the state of complete deterioration," he continued, "the final departure from life is only a matter of time and the only one conceivable improvement would be to reduce the duration of that state to the inevitable minimum. Instead of doing this the physician reverts to the dogma that life as such is a priceless good which ought to be kept going until the physician's scientific resources are exhausted. There is no scientific nor humanitarian argument which could be raised in support of this dogma. Therefore like the dogmas responsible for the propaganda against birth control it must have its roots in deeply buried substrata which were deposited long before rational thinking became an essential ingredient of the human mentality."

Terzaghi must have been moved by a friend's rebuttal that the philosophical inspiration of the essay was "counter proof to your theories ...

clearly showing the enormous importance of agonies and sufferings in the development of the human race.... These unavoidable elements of our lives have creative forces to which the human race owe as much of value as to physical fitness and generally acclaimed vigor and virility."[28]

Terzaghi's espousal of "mercy killing", in any event was too early both for society and for himself. Not only did he fail to find a publisher for this thoughtful, pessimistic paper, but his condition and spirit began to improve as he learned to get around with two canes, then just one, and ultimately with an artificial limb. His spirit even survived a second cataract operation in July, which drew from Yves Lacroix the observation that "the parallelism of the lines of your handwritten letter of July 23 and the pertinent questions that you raised with respect to my dissertation would have left your eyesight difficulties unsuspected."

Karl no longer dared long-distance travel but he could meet with engineers—including whole boards of consultants—in his home, and he could certainly think and write. Knowing he had little time left, Karl concentrated his work on a list of priority subjects: to guide Mission Dam to a safe resolution and write both its final report and a case history for publication, and to bring out some of his most important ideas on engineering geology of soils and rocks in a series of publications.

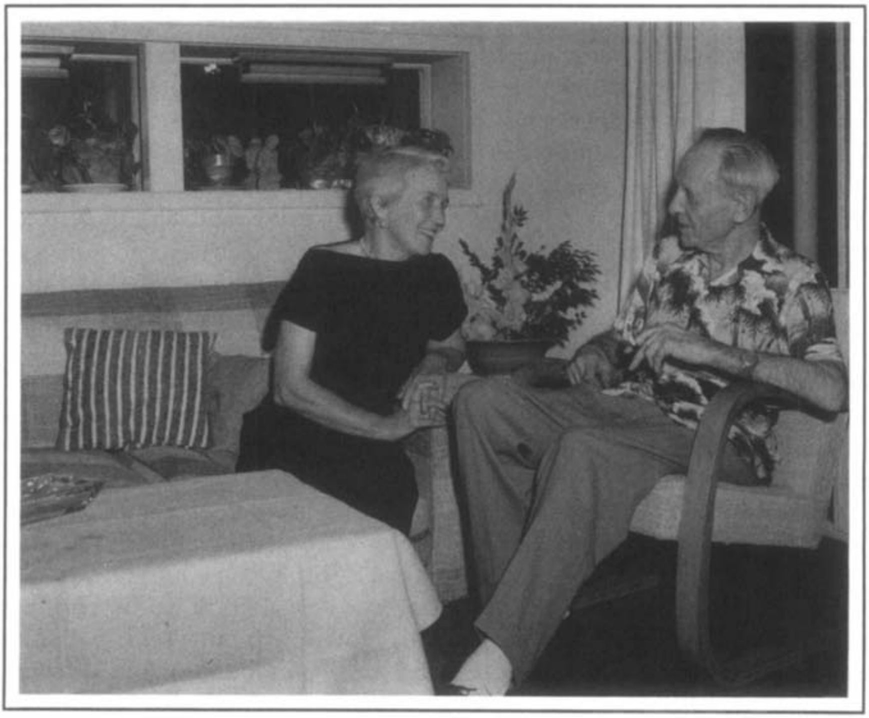
He also read earnestly in the new field of "rock mechanics" to discover its achievements. While Terzaghi's great fame was deservedly attached to the development of engineering with soils, his zeal sprang as much from hard rock which he knew as hiker, climber, and geologist. Not infrequently his consulting involved "rock engineering" questions, while his portion of Proctor and White's book on rock tunneling was arguably the finest contribution anybody had yet published in this domain. Therefore, he could hardly fail to be curious when a new field and a new international society sprang up in the field of rock mechanics in the late 1950s. To his friend Dunn of International Engineering, Terzaghi wrote, "I am now engaged in squeezing the last drops out of the orange and my attention is concentrated on a new specter on the horizon called rock mechanics."

He was dismayed by his discoveries. "The deeper I penetrate into the field of rock mechanics," he confided to Bjerrum, "the more this field interests—and frightens!—me."[29] The subject is shot through with "theoretical nonsense". The French, who "still believe that one can get at the rocks with a slide rule—if one works hard enough",[30] were trying to use rock mechanics to design tunnel supports. Obviously one could not acquire the necessary data in advance as the performance of rock depends principally on the properties at its weakest points, which one can't see until the tunnel has already been driven.[31] As he read through a book entitled *Rock Mechanics,* his initial enthusiasm changed to finding it "queer", then "abominable in every respect", and finally "one of the most superficial, disorganized and misleading books I have seen for a long time."[32] After wading through numerous publications on measurements of stress inside rock masses, he found very few conclusions of interest to the civil engineer.[33]

Rock mechanics had some real accomplishments, he noted, but many more unfounded wishdreams and "blind optimism".[34] Too much about rock behavior depends on geological details that can not be known with confidence. It was the same story as in soils engineering but even more to the point, because there were few civil engineering design problems in rock that lent themselves to a theoretical approach; furthermore, investigations in rock are more costly. Computations based primarily on assumptions that can't be checked just divert the designer's attention away from recognizing and trying to plug real gaps in knowledge. Thus, when Harold Harding asked if he might be permitted to quote Karl's remark that "mathematicians should be kept in cages and fed problems through the bars," Karl replied that, since the time he first conceived this, "he has discerned that some members of the soil mechanics field and more recently the rock mechanics fraternity deserve the same treatment."[35]

A soils engineering friend of long years standing inadvertently brought Terzaghi's negativism on himself by inviting Karl's review on draft recommendations for rock mechanics investigations at the site of a very high concrete, gravity-arch dam. Terzaghi, who never gave opinions without thorough preparation, over a period of some four months reviewed not only the report but much of the pertinent engineering literature; he then sent a 28-page, highly critical review that amazed its recipients, as well as a bill for fifteen days of services. In response to a defensive rebuttal, Terzaghi wrote that the reactions to his criticisms "resemble a discussion of faith by an agnostic and a Catholic. I started out as a Catholic but turned into an agnostic under the demoralizing influence of too many contacts with reality."

Now Terzaghi's friend had a problem. What should he do with Terzaghi's statement that the recommended program would be "worthless and to a degree worse than worthless"? The report had already been sent to the client. He confessed that he had requested Terzaghi's review comments not as a professional assignment but as a personal favor and in trade for sharing with him the information his company had compiled on rock mechanics, as well as for the many hours he had spent digging out material for Karl over fifteen years. The friend wrote, "I must say that I was completely taken by surprise by the scope of your review memorandum which was almost as detailed as our report," while confessing that he had no funds with which to pay the fee. Terzaghi said, never mind the fee but for heaven's sake "[your company] should stick to those fields in which at least one of the senior members of the firm is an outstanding expert. Otherwise they are at the mercy of junior engineers, and by signing reports, the quality of which they cannot judge, they may jeopardize their good reputation."



Karl and Ruth at home in Winchester on Karl's 75th birthday.

As his time began to run out, Terzaghi decided to publish articles on rock mechanics in hopes of "dampening the wave of enthusiasm by pointing out what we do not or cannot know in this field, as I did before in the field of soil mechanics."[36] This effort yielded significant contributions on stress measurements in rock[37] and problems with rock slopes,[38] as well as another describing how rock weaknesses ("sheet joints" in granite) had affected design and construction of Mammoth Pool dam.[39]

Early in 1962, Arthur Casagrande asked Karl's help on a sensitive problem. Already somewhat jealous of Otto Fröhlich for his award of an honorary doctorate by the Technische Hochschule in Munich, as well as "the Golden Engineering Award" by the Technische Hochschule in Graz, Arthur became absolutely incensed when he read the preposterous statement in the *Austrian Engineering Journal* that these honors had been bestowed on the "co-founder of soil mechanics".[40] Arthur noted sarcastically to Karl, "I am deeply depressed by the fact that I have to start from scratch studying soil mechanics. All the years I have wasted!" He asked Terzaghi's intervention and, as was always his characteristic, Karl undertook a careful investigation.

Karl concluded that this was indeed "an appalling injustice" and dispatched letters to four influential German academicians asking them to write to the Austrian journal in order to set the record right.[41] Arthur Casagrande was the foremost of his early disciples, he explained, helping to build techniques of soil testing and to discover the physical properties of soils fully ten years before Fröhlich began to contribute skillful but merely theoretical variations.[42]

In the meantime, Casagrande decided to ask help from Hugh Golder in Canada, a man with diplomatic skill whose "unique sense of humor" could impart to a letter to *Geotechnique* "just the right touch of sting."[43] Golder offered to ghostwrite a letter for Casagrande's signature, to be entitled "Claims to Fatherhood". It began: "Whilst browsing through some technical journals recently I came across a reference to a 'joint founder with Terzaghi of Soil Mechanics'. This leads me to meditate on the interesting fact that an allegation of paternity which may be regarded as an embarrassing accusation at one stage can become an eagerly sought honor if a child distinguishes itself in later life. For the sake of future historians of the subject, and as there will assuredly arise many kings who knew not David, can we not agree that there is no ambiguity of paternity in this case, although the identity of the mother remains in doubt unless this be fecund mother earth." After identifying the key publications of Terzaghi that established the "conception" and "birth" of soil mechanics, Golder concluded with the pun on the name "Fröhlich" that "one man alone was responsible for this achievement, and no one could be *happy* who claimed to share it with him."[44]

Towards the end of 1962, it was hard for the Bear to be happy; although Karl could now get around and could again work in his upstairs office and smoking-den, he suffered increasing backaches and occasional fainting. He disliked his salt-free diet but liked the routine of choosing his work topic without ambitious preconceived scheduling.

Nevertheless, he continued to produce reports, memoranda, articles, discussions, closures, correspondence, and notes. Karl continued to serve on the Board of Consultants for design of Gardiner Dam on the South Saskatchewan River with unstable valley sides and foundation. He kept up with the worries and responsibilities at Cleveland and Mission Dams, and for the latter he worked hard with Yves Lacroix's data on preparation of a report to predict the future performance of the dam.[45] When Yves asked how much time he ought to spend on writing his own final report, Karl returned this advice: "Spend on it as much time as necessary to inform the reader with as few words as practicable about all the significant findings and about the essential features of the construction operations which have been performed."[46]

He also tried to complete a revision of *Soil Mechanics in Engineering Practice* with Ralph Peck, having turned over to Professor Richart at Michigan the task of revising *Theoretical Soil Mechanics*. During 1962, Karl felt touched by the award of an honorary doctorate from his alma mater, the Technische Hochschule in Graz, and conferral of "The Moles' Award" by that fraternal organization of heavy constructors from whom he professed to "have learned so much".

Despite all this productivity, as Karl started his eightieth year, in October of 1962, he hoped it would be his last, writing "life ceases to be a source of satisfaction: eyesight fading quite rapidly, daily meals absorbed with utter reluctance, left leg amputated, right foot full of sores, unable to move about freely, short of breath, heart kept going by pills, and memory getting unreliable. Yet what a blessing to approach the end without being haunted by religious superstitions, knowing that the end *is* the end."[47]

In this mood, as 1962 closed Karl decided it was time to write parting letters to his friends.[48] It was a moving greeting with the information that, since he could hardly read or write, life for him was no longer worth living and he hoped soon to die. He'd reached the end of his journey and wanted to say thank you and goodbye. The letters were particularized for each recipient; to Bruno Sander, for example, whom Terzaghi had known for fifty years, he wrote that "the hours and days they'd spent together were the happiest of his life.... Farewell dear comrade and soulmate." This outpouring of feeling inevitably returned a series of emotional responses that brought climax and release to Karl's feelings. But it was much too early. He was treating his life's end like the first filling of a reservoir, a target that had to be well prepared in good time so that all was safely in readiness for the extreme test.

With this same determination, Karl had written down his last wishes to Ruth six months earlier. His ashes were to be interred in South Waterford, Maine, near Bear's Corner, with the simple memorial message: "Karl Terzaghi, a civil engineer. He has lived without compromising, served his chosen profession to the best of his abilities and died without having anything to regret." Selected contents of his library should go to Bjerrum for the Terzaghi Library in Oslo. "There is nothing to feel sad about," he wrote, "because the end is an essential and inevitable part of the existence of our species." Now, in the morbid spirit following his 80th birthday, Karl entered a personal epitaph at the top of his work diary for 1963: "1883–1963—25 years of groping in the dark and 55 years of strenuous efforts. One veil torn down, but many others concealed behind."

Just as his essay on mercy killing was written too early, so was his epitaph, for Terzaghi struggled on, giving his best judgment and keen analysis of engineering issues for almost another year, but with difficulty. In June of 1963, Yves Lacroix, busy with Karl finalizing their paper on Mission Dam, wrote to Bjerrum that Karl suffered from acute arthritis and had to be rubbed with codeine and wear foam-rubber pads, one of which he termed 'underpinning', and another which helped prop up his elbow to write with his faithful Waterman fountain-pen. He sits and works in the dining room armchair stationed on a small rug and when it is time to be moved from the work table to the dining table or bedroom, Ruth gets him there by pulling the rug and its cargo, which he calls "The Orient Express"; the small steps in elevation between rooms are referred to as "navigation locks". He was working about four hours a day and could no longer see well enough to use a slide rule, "but Dr. Terzaghi's eyesight was good enough to discover that the sketches that I brought him were wrong and inconsistent." Ruth was his ever-constant nurse, secretary, and companion.

Karl's eightieth birthday in October of 1963 brought a wide outpouring of friendship and appreciation by mail, telegraph, and word. Bjerrum's was typical, saying that Karl's work will be our inspiration for generations and that "it exemplifies the critical judgment and scientific humility so necessary in our field."[49] Among the many acknowledgements Karl sent out in the next few days was one to E.P. Hamilton of John Wiley & Sons declaring that he no longer could hope to finish his book on engineering geology "because this subject is, for the time being, too much in a state of flux and my time is running out."[50] The "flux" was possibly the stern wake of Moby Dick.

Karl Terzaghi's struggle ended on the twenty-fifth of October, 1963. "And so this great man has left us," wrote Arthur. "Soil mechanics has lost its father and I feel as if I have lost my own father for a second time."[51]

Five years earlier Karl had delivered a prepared speech which included the following honest and sincere expression of his pragmatic philosophy of life.[52] "I must confess that the value of my achievements is of no more concern to me than the market value of an apple is of any concern to the tree on which it has grown. Our achievements are—or should be—the result of a natural process of sprouting, growing and maturing in accordance with a predestined pattern. The meaning of the pattern, and the function of our existence in the resplendent and awesome world into which we were born are far beyond the microscopic range of our comprehension. The best we can do is to live and act in tune with our pattern and without wasting our time trying to answer unanswerable questions. The answers would not even serve any practical purpose because, as Dr. Faust has discovered at the end of his turbulent career, "Der Mensch in seinem dunklen Drange ist sich des rechten Weges wohl bewusst." [Man in his dark yearnings is fully conscious of the right path.][53] If you discern your pattern before it is too late and remain faithful to it you shall approach the end of your journey with a deep sense of fulfillment, regardless of whether you were born to be a master or servant, mother or mistress. Otherwise you may depart before you have ever found out what the word 'living' means."

He certainly lived.

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Epilogue

The draft paper on Mission Dam prepared jointly with Yves Lacroix met repeated rounds of criticism from Ruth and Arthur, appearing finally in *Geotechnique* March, 1964. This was a Terzaghi memorial issue containing also a biography by Arthur Casagrande and a friendly remembrance by R. Glossup, as well as Karl's remarkable essay "About Life and Living" and the coda of his bibliography.

On reading the article on Mission Dam, Dean Geoffrey Meyerhof of the Nova Scotia Technical College was so impressed that he proposed to the British Columbia Hydro and Power Authority that Mission Dam be renamed *Terzaghi Dam*. This was quickly sealed and presented formally at the special session in memory of Terzaghi that opened the Sixth International Conference on Soil Mechanics and Foundation Engineering, in Montreal (September, 1965). Terzaghi Dam stands now serene before its majestic lake, adorned by a simple plaque that stamped Karl Terzaghi's name on a piece of the place he loved. Nothing could have pleased him more.

Notes

List of Abbreviations

Anniv. Vol. = *From Theory to Practice in Soil Mechanics: Selections from the writings of Karl Terzaghi.* Laurits Bjerrum, Arthur Casagrande, Alec Skempton, and Ralph Peck, editors (John Wiley & Sons) (1960)

Terz. Mem. Lect. (1973) = *Proceedings of the Terzaghi Memorial Lectures at the International Seminar on Soil Mechanics and Foundation Engineering,* August 14–16, 1973 (Bogazici University, Bebek, Istanbul, Turkey). S.S. Tezcan and A.S. Yalcin, editors

Mein Lebensweg = Unpublished autobiographical essay entitled *Mein Lebensweg und meine Ziele (My life and my goals)*

ENR = *Engineering News Record* (McGraw Hill)

ASCE = American Society of Civil Engineers

M.I.T. and MIT = Massachussetts Institute of Technology

I.C.E. = Institution of Civil Engineers (London)

tsf = tons per square foot

psi = pounds per square inch

Prologue

1. The two quotations in these introductory paragraphs were found among Terzaghi's papers. He had used them as handouts in his course on engineering geology (according to Walter Ferris). They were quoted by Laurits Bjerrum in his article "Some notes on Terzaghi's method of working" in the Anniv. Vol. (See List of Abbreviations.)

Chapter 1

1. According to the Kaiser's document conferring title, he was born in 1806, but the registry of births states 1805.

2. Part of the Austrian Habsburg Empire until 1860 and now a region of Italy.
3. The tradition of bestowing titles upon military officers with more than 30 years continuous service was instituted by Empress Maria Theresa in 1757.
4. The German rank was *Oberstleutnant.*
5. From Terzaghi's correspondence with Prof A. Myslevic, July 17 and 31, 1962.
6. Related by Ruth Terzaghi in "Reminiscences of Karl Terzaghi", *Terz. Mem. Lect.* (1973), pp. 156–171.
7. From *Mein Lebensweg.*
8. In Austria at this time, three academic paths were available for children departing from Volksschule at the age of 10: the high academic path, with readings from original classic literature in Latin and Greek, called *Humanistisches Gymnasium*; the middle academic path, with Latin but no Greek, called *Realgymnasium*; and the practical path, termed *Realschule,* preferred for children by families pushing their sons toward the military or engineering professions.
9. Related by Ruth Terzaghi in "Reminiscences of Karl Terzaghi" in *Terz. Mem. Lect.* (1973).
10. Diary entry for September 18, 1901.
11. *Mein Lebensweg,* p. 3.
12. From diary entry of September 18, 1901.
13. From diary entry of September 18, 1901.
14. From a lecture to the Freshmen class at Harvard, 1941.
15. From diary entry for Sept 18, 1901.
16. From lecture at M.I.T. entitled "Engineering Education", 1927.
17. From Terzaghi's letter to his son Eric (Skipper), March 5, 1956.
18. From letter to his son Eric, March 5, 1956.
19. In the novel *Angle of Repose.*
20. Guenter Cerwinka, "Filia hospitalis—Studenten, Hochschule und 'Kulturkampf' im literarischen Werk Ferdinand Wittenbauers (1857–1922)" [Students, university and the war of cultures in the literary works of Ferdinand Wittenbauer] Schriftenreihe des Steirischen Studentenhistoriker-Vereines, Folge 21, 1993 (Graz).
21. He was a member of the Allemannia "Corporation".
22. From "Engineering Education", a lecture presented at M.I.T., 1927.
23. Manuscript not yet discovered.
24. Letter to his son Eric, March 5, 1956.
25. *Mein Lebensweg,* p. 4.
26. *Anleitung zu Geologischen Aufnahmen* [*Manual for Geological Surveying* (*Outlines of Field Geology*)] by Ferdinand Geikie, translated into German by Karl Terzaghi (Franz Deuticke, 1906).
27. From Terzaghi's "Vorwort des Uebersetzers" [Translater's Foreword] to his translation *Anleitung zu Geologischen Aufnahmen* of Geikie's *Manual of Field Geology.*

28. "Geologie der Umgebung von Flamberg im Sausal [Geology of the Flamberg Region, Sausal" *Mitteilungen der Naturwissenschaftlicher Verein für Steiermark*, pp. 131–146.

29. Letter to son Eric, March 5, 1956.

30. *Mein Lebensweg*, p. 5.

Chapter 2

1. "My toughest foundation job", by Karl Von Terzaghi, *New England Construction* July, 1936, p. 16.

2. *Mein Lebensweg*, p. 5.

3. *Mein Lebensweg*, p. 7.

4. "Silo der Gipswerke in Egeres, Siebenbürgen" *Beton und Eisen* vol. 7, no. 3, pp. 57–59; "Bau der ersten österreichischen Glanzstoff-Fabrik in St. Pölten" [Construction of the first Austrian rayon factory in St. Poelten] *Beton und Eisen*, vol. 7, no. 4, pp. 98–100; and "Bestimmung des Druckes auf die Wand eines Silotrichters" [Determination of the pressure in the wall of a silo funnel]. Zuschriften and die Schriftleitung" *Beton und Eisen* vol. 7 no. 13, pp. 326,327 and vol. 7 no. 14, p. 350. (All in 1908).

5. April 17, 1909.

6. Letter to Professor Wittenbauer, August 7, 1910.

7. Letter to Prof. Wittenbauer, April 17, 1909.

8. Letter to Prof Wittenbauer, December 8, 1909.

9. Letter to Prof Wittenbauer of August 10, 1910.

10. "Bemerkung zur Tektonik der Umgebung von Buccari" [Remarks on the tectonics of the Buccari Region] *Geologische Mitteilungen-Zeitschrift* der *Ungarischen geologischen Gesellschaft* vol. 41, pp. 684–695. He wrote to Wittenbauer, Aug 7, 1910, that by the third day Dr. Vogl and he battled over the entire route, and he was thus invited to publish the debate immediately.

11. Letter to Wittenbauer, December 8, 1909.

12. "Beitrag zur Hydrographie und Morphologie des kroatischen Karstes" [Contribution to the hydrology and morphology of the Croatian Karst] *Mitteilungen der Königlichen ungarischen geologischen Reichsanstalt*, vol.20, no.6, pp. 230–321; later reworked and published as "Landforms and subsurface drainage in the Gacka Region in Yugoslavia", *Annals of Geomorphology* vol. 2, no. 1/2 (1958), [reprinted in the Anniv. Vol., pp. 81–105].

13. *Mein Lebensweg*, pp. 8,9. Professor Penck. Jr. acknowledged Terzaghi in his "Tectonic fundamentals of Western Asia-Minor"; Lehmann did so in a paper on karstic phenomena in the Alps.

14. The quotations in this paragraph are all from the letter to Prof. Wittenbauer, August 7, 1910, from Kitzbühel.

15. The quotations in this paragraph are from Terzaghi's letter to Prof. Wittenbauer, August 7, 1911.

16. From letter to Prof. Wittenbauer, August 7, 1911.
17. *Mein Lebensweg*, p. 11.
18. Letter to Wittenbauer, August 7, 1911.
19. Letter to Wittenbauer, November 30, 1911.
20. Diary entry, November 6, 1911.
21. From Terzaghi's diary for 1912.
22. The doctoral thesis was entitled "Berechnung der kreisrunder Behälterböden" [Calculation of the foundations of circular tanks].
23. *Berechnung von Behältern nach neueren analytischen und graphischen Methoden*, published by Julius Springer, 1913.
24. The method of functional variations in Lagrangian coordinates using Ritz's procedures.
25. Letter to Wittenbauer of August 8, 1912.
26. *Zeitschrift des österreichischen Ingenieur- und Architektenvereins*, (1913) no 32, p. 509.
27. Olga was the younger sister of Ella's husband, Fritz Byloff.

Chapter 3

1. From Karl's letter to his grandfather, March 10, 1912.
2. From Karl's letter to his grandfather, February 19, 1912.
3. Letter to Grandfather, February 19, 1912.
4. Terzaghi liked to pun and play with words.
5. Vienna Tagesblätter in the *Feuilleton* section. The piece is entitled: "Across the big pond".
6. From Karl's letter to his grandfather, March 10, 1912.
7. From Karl's letter to his grandfather, March 10, 1912.
8. Karl's letter to grandfather, March 10, 1912.
9. Letter to Karl's grandfather, May 13, 1912.
10. From Karl's letter to his grandfather, March 26, 1912.
11. *Mein Lebensweg*, p. 12.
12. From Karl's letter to his grandfather, March 26, 1912.
13. Karl's letter to his grandfather, March 29, 1912.
14. Karl's letter to his mother, March 28, 1912.
15. Karl's letter to his grandfather, April 5, 1912, written from New York.
16. This report has not been found.
17. Diary, April 29, 1912.
18. The Titanic manuscript was lost or delayed in the mail. To Terzaghi's frustration, Prof. Pöschl's proofs for Terzaghi's editing were also lost in the mail (possibly a victim of the Titanic).
19. Diary entry for August 16, 1912.

20. "Das Hochwasser des Mississippi" [A Flood on the Mississippi]: in the *Feuilleton* section of Vienna's daily newspaper *Die Tagespost*, June 12, 1912.

21. From "Das Hochwasser des Mississippi".

22. "Auch ein Kriegsschauplatz" [One more theater of war] in the Feuilleton section of *Die Tagespost*, June 1, 1912.

23. He wrote to his grandfather, June 26, 1912, that this was paid for from the $100 received from the Hungarian Geological Survey for his article on karst.

24. Karl's letter to his grandfather, June 26, 1912.

25. Letter to Wittenbauer, August 8, 1912.

26. Letter to Wittenbauer, August 8, 1912.

27. From Karl's letter to his grandfather, June 26, 1912.

28. From Karl's letter to his grandfather, August 10, 1912.

29. Letter of September 17, 1912.

Chapter 4

1. Diary entry, August 16, 1912.

2. Karl's letter to Wittenbauer, December 24, 1912.

3. Letter to Wittenbauer, December 24, 1912.

4. *Mein Lebensweg*, p.17.

5. Diary entry for January 24, 1913.

6. From an unpublished essay by Karl Terzaghi, 1913, entitled "Vagabunden."

7. The entries are as follows: "Die Industrialisierung der Freude" [The industrialization of pleasure], "Die neue Demokratie" [The new democracy], "Wahltag" [Election Day], "Ein Totenfeuer" [A roundup]; "Vagabunden" [Vagabonds]; "An der Bai von San Francisco" [At San Francisco Bay]; "Ein Veteran" [A veteran]; "Sittliche Entrüstung" [moral indignation]; "Am Lake Kachess" [At Lake Kachess]; "A chance for everybody"; "Dissonanzen" [Dissonance]; "Auch eine Sylvesternacht" [Yet another New Year's Eve]; "Einst und Jetzt" [Then and Now]; "Widersprüche" [Contradictions]; "Fortschritt" [Progress]; "Sarah Bernhardt im Variété" [Sarah Bernhardt in Variety]; "Wer ist der Autor" [Who is the Author]; "Durch den Westen Nevadas" [Across Western Nevada]; and "Propaganda".

8. Letter to Wittenbauer, December 24, 1912.

9. From "Einst und Jetzt".

10. From "Sarah Bernhardt".

11. From "Sonntagsgedanken" [Sunday Thoughts].

12. "Dynamit—a word concerning a New York catastrophe" published in the *Feuilleton* section of Vienna's *Tagespost*, date undetermined.

13. Letter to Wittenbauer, March 6, 1913.

14. The work was being performed on the property of Lewis Hydraulic Company, adjacent to the gas company.

15. Letter to Wittenbauer, November 5, 1913.
16. Diary entry from January 8, 1913.
17. Letter to Wittenbauer, January 8, 1915.
18. Diary entry of August 14, 1914.
19. From "About Life & Living" written in 1923 and published posthumously in *Geotechnique*, vol. 14, no. 1, March 1964, pp. 51–56.
20. Diary entry of August 21, 1927.
21. Diary article for September 21, 1915.
22. From data presented by Paul Fussel (1975) in *The Great War and Modern Memory*.
23. Diary entry, November 1, 1915.

Chapter 5

1. Described in letter to Ralph Peck, September 8, 1959.
2. The scientific work was guided by a list of distinguished professors attached as advisers to the Aspern Facility; this list included Proll from Hanover, Von Mises from Stassby, von Karmann from Aachen, Grimmwald from Prague, and Kann from Vienna.
3. Ruth Terzaghi in "Reminiscences of Karl Terzaghi" in *Terz. Mem. Lect.* (1973) pp. 156–171.
4. From letter to Andre Coyne, December 14, 1959. The circumstances of this letter are discussed in Chapter 17.
5. Diary entry of September 14, 1925.
6. Letter to son Eric, March, 1956.
7. From diary for January, 1912; the inheritance he and Ella were told in 1912 they could expect was 150,000 Crowns.
8. From Terzaghi's "Near East Recollections", 1925.
9. Lynn Scipio "My thirty years in Turkey" (Richard R. Smith Publisher, Inc., Rindge, NH, 1955).
10. From Terzaghi's unpublished essay, "Near East Recollections", delivered to the Twentieth Century Club, Boston, October 22, 1925.
11. From Karl's letter to his son Eric, March, 1956.
12. From diary entry for September 9, 1916.
13. From Terzaghi's article "L'École Imperiale d'Ingenieurs" [The Royal School of Engineering].
14. Letter to Prof. Wittenbauer, December 17, 1916.
15. From letter to Wittenbauer, December 17, 1916.
16. Diary entry for March 7, 1917.
17. Karl v. Terzaghi (1917) "Zur türkisch-asiatischen Bewässerungsfrage" [Concerning Turkish-Asiatic Irrigation Questions] Precise date and publication medium uncertain. A copy was found in the Terzaghi Library at NGI.

18. *Mein Lebensweg.*

19. From Terzaghi's Presidential Address at the First International Conference on Soil Mechanics and Foundation Engineering, Cambridge, Mass, June 1936, reflecting on his literature review of 1918. This article was reprinted in the Anniv. Vol., pp. 62–67.

20. "Die Unzulänglichkeit veröffentlichter Baubeschreibungen" [The inadequacy of published articles on construction] *Zeitschrift des Österr. Ingenieur- und Architektenvereins* (1917) Heft 21.

21. From Terzaghi's paper "Old earth pressure theories and new test results" *ENR,* vol. 85, no. 14, pp. 108–113 (1920).

22. K. Skibinsky theorized the behavior of a collection of ideal spheres in "Das Gleichgewicht des Rolligen Materials" [The equilibrium of rolling materials] *Österreich. Wochenschr. f. öff. Baudienst* (1916 and 1917). J. Boussinesq had also started such work in 1917. Experiments along the line of Terzaghi's were conducted by G.H. Darwin in 1883: "On the horizontal thrust of a mass of sand" *Exc. Min. Proc. Inst. Civ. Eng.* vol. LXXI.

23. "Die Erddruckerscheinungen in örtlich beanspruchten Schüttungen und die Entstehung von Tragkörpern" [Earth pressure phenomena in locally stressed rubble and the development of reaction zones], *Österreichische Wochenschrift für öffentlichen Baudienst* no. 17–19, pp. 194–199, 206–210, 218–223.

24. "Old earth-pressure theories and new test results" *ENR* (1920) vol. 85, no. 14, pp. 632–637 (republished in the Anniv. Vol.).

25. "New facts about surface friction" *Physical Review* vol. 16, no. 1, pp. 54–61 (1920). Republished in the Anniv. Vol. pp. 165–172.

26. Unfortunately, his name was translated as "Charles", providing some confusion for later librarians.

27. *ENR,* vol. 85, no. 14, September 30, 1920, p. 631.

28. *Mein Lebensweg* pp. 20, 21, 26, and 27. On this same topic Terzaghi argued that his exeriments on earth pressure with a ten-centimeter-high wall were better than those of Jacob Feld in Cincinnati in a testing bin six feet high at the front and twelve feet at the back. Terzaghi wrote to Feld "I was not interested in the quantities but in the principles and in this case the size of the box makes no difference" (in letter to Feld, November 23, 1920). Subsequently he wrote "You followed the strictly empirical method, while my efforts are directed towards mechanical interpretation of the facts, no matter whether they were observed on a large scale or on a small one (letter to Feld, August 5, 1923).

29. At Kleinoscheg.

30. In letter to Wittenbauer, January 23, 1918.

31. Letter to Prof. Wittenbauer, July 9, 1918.

32. Cetin Soydemir, "Terzaghi's period in Turkey" in *Terz. Mem. Lect.* (1973).

33. Terzaghi letter to H. Peynircioglu as reported in his paper "Terzaghi in Istanbul and his Studies on Golden Horn Clays", in *Terz. Mem. Lect.* (1973).

34. Letter to Prof. Wittenbauer, December 17, 1916.

35. Diary entry of August 1, 1918.

36. Information from: L. Scipio *My thirty years in Turkey; Mein Lebensweg*, p. 21.; and diary entries, summer 1918.

37. "Völkische Kultur oder rassenfremde Zivilisation" [National culture or racially foreign civilization] in letter to Wittenbauer, May 20, 1918. Terzaghi's friend Mitzi Obermayer referred to safeguarding his copy of "Geschlecht und Kultur" (Race and Culture) in her letter of December 29, 1923.

38. Terzaghi's letter to Wittenbauer, July 9, 1918.

39. Dr. Müller-Heinz, later to become the Minister of Justice for the German government.

40. In letter to Wittenbauer, August 23, 1918.

41. The record of Terzaghi's writings is amazingly complete, with various drafts and emendations preserved alongside the published originals, as well as all kinds of memos, lists, notes, receipts, and so forth. The conspicuous absence of this manuscript, or any reference to it, even in his autobiographical essay *Mein Lebensweg und meine Ziele* suggests it may have been destroyed. Terzaghi had sent a carbon copy to Wittenbauer in 1918 with his dedication.

Chapter 6

1. From *My Thirty Years in Turkey* by Lynn Scipio.

2. From *My Thirty Years in Turkey* by Lynn Scipio.

3. From Terzaghi's diary.

4. Diary entry for February 2, 1919.

5. Diary February 2, 1919.

6. W.P. Bligh (1910). "Dams, barrages and weirs on porous foundations" *Engineering News*, p. 708.

7. The "head" is the height difference between the water reservoir's level upstream of the dam and the surface of the water at the toe of the dam.

8. The "permeability" to water is the property controlling the discharge rate of water through a soil, per unit of area, and per unit gradient. (It is now more generally termed "conductivity".)

9. Diary entry from March 17, 1919.

10. This case history was mentioned in Terzaghi's "Advisory Report on the construction of a dam for the Svarthalsforsens Powerhouse on the Ingdals River", for the Stockholm Electricity Works, June 19, 1937.

11. Laurits Bjerrum and Unni Oiseth (1971) Terzaghi Library Memoir Number 1 (1971) "The Terzaghi Library", p. 7. (This is the only number of the intended series that was ever published.) Bjerrum's anecdote continued: "Terzaghi emphasized several times their importance to the Terzaghi Library. However, he never showed them to any one and even Mrs. Terzaghi had never seen them until they were found after Terzaghi's death, at the bottom of a shoebox filled with notebooks."

12. Letter to Prof. Wittenbauer, February 15, 1920.

13. These results were published in "New facts about surface-friction" *The Physical Review,* N.S., vol. XVI, no. 1, July 1920, pp. 54–61 (reprinted in the Anniv. vol. pp. 165–172).

14. Diary, May 18, 1919.

15. Diary entry for March 21, 1920. According to "Darcy's Law", the permeability is a constant, regardless of the gradient driving the flow. What Terzaghi was observing were nonlinear phenomena caused by changes in soil structure accompanying changes in the hydraulic gradient.

16. Letter to Wittenbauer, February 15, 1920.

17. As he described in the February 15, 1920, letter to Wittenbauer, he planned to send the series of articles to *ENR* in March, 1920. They would consist of "1) Contradictions between old earth pressure theories and fact; 2) Elasticity and viscosity of sand; 3) New methods of calculating sand pressures against wall props; 4) Principal types of sliding friction between macrosocopic grains at rest and their physical significance; 5) Sliding friction between microscopic particles, the effect of mode of shearing, and the types of internal friction; 6) elasticity and viscosity of clays; 7) The physical causes of the properties of clay; and 8) The relationships between the strength properties of sand, clay, and concrete.

18. Letter from F.E. Schmitt to A.J. Ackerman, October 15, 1941.

19. From "Consultants, clients, and contractors" *Journal of the Boston Society of Civil Engineers* vol. 45 (1958), no. 1, pp. 1–15.

20. From letter he wrote on Nov 3, 1959, to Director Le Paige of Sofina in Brussels.

21. Diary entry of October 4, 1920.

22. K. Terzaghi (1921) "Die physikalischen Grundlagen des technisch-geologischen Gutachtens" [The physical bases for engineering geology opinions], *Zeitschrift des Österreichschen Ingenieur und Architekten Vereines,* vol. 36/37, pp. 237–241.

23. Terzaghi letter to the editor of *ENR,* June 2, 1921.

24. A. Atterberg (1913) "Die Plastizität und Bindigkeit liefernden Bestandteile der Tone" [The plasticity and cohesion-furnishing components of clays], *Internat. Mitteilungen für Bodenkunde.* Atterberg determined water content values at which clay passes from a liquid to a plastic condition, which he called the Liquid Limit (LL) and from a plastic to a semi-solid condition, which he called the Plastic Limit (PL). Terzaghi was reporting values of LL and PL in his papers.

25. Diary entry for March 15, 1922.

26. A.W. Skempton (1960) "Terzaghi's discovery of effective stress" in the Anniv. Vol., pp. 42–53. These experiments are first described in Terzaghi's article: "Principles of soil mechanics: VII—Friction in sand and in clay", *ENR,* vol. 95, no.26, December 24, 1925, pp. 1026–1029.

27. Ingersoll and Zobel (1913). "Mathematical theory of heat conduction" (Ginn & Co., N.Y.).

Chapter 7

1. From Terzaghi's lecture "Near East Recollections" to the Twentieth Century Club, Boston, October 22, 1925.

2. From *The Observer*, recorded in Terzaghi's diary of March 24, 1919.

3. Much of this information was drawn from Lynn Scipio's book *My Thirty Years in Turkey*.

4. Diary entry of November 7, 1922.

5. From Terzaghi's lecture "Near East Recollections" to the Twentieth Century Club, Boston, October 22, 1925.

6. Diary entry of August 3, 1919.

7. Diary entry of November 5, 1923.

8. From Terzaghi's lecture "Near East Recollections" to the Twentieth Century Club, Boston, October 22, 1925.

9. From "Near East", a lecture by Karl Terzaghi to the M.I.T. Women's Association, January 16, 1926.

10. Diary entry of April 20, 1921.

11. Diary entry of November 12, 1924.

12. Letter to F.E.Schmitt, August 29, 1945, written as criticism of President Gates' autobiography "Not to me only".

13. From a letter written to Robert College Professor Wiley on November, 1924.

14. Published in *Geotechnique*, vol. 14, no. 1, March 1964, pp. 51–56.

15. Terzaghi may have met Wegener in Austria, as the geographer was a personal friend of Terzaghi's brother-in-law, Fritz Byloff.

16. Herbert H. Einstein (1991) "Observation, quantification, and judgement: Terzaghi and engineering geology" *Journal of Geotechnical Engineering*, vol. 117, no. 11, November, pp. 1772–1777.

17. Finally published in Geotechnique, vol. 14, no. 1, March 1964, pp. 51–56 in the special Memorial Issue issue that contained Terzaghi's obituary and his last technical paper, "The Mission Dam". There was disagreement as to the inclusion of this article. Bjerrum suggested it because he loved it, but Prof. Skempton was strongly opposed as it was not "vintage Terzaghi".

18. The title of his paper, published in the proceedings of this congress is "Die Theorie der hydrodynamischen Spannungserscheinungen und ihr erdbautechnisches Anwendungsgebiet" [The theory of hydrodynamic stress phenomena and its application to engineering in soils], pp. 288–294.

19. Diary entry for April 26, 1924.

20. Allen Hazen (1869–1930) was an expert on sanitary engineering and, in particular on filtration of public water supply (on which topic he had authored two books).

21. *Mein Lebensweg*, p. 25.

22. Letter from Terzaghi to Otto Fröhlich, described in his diary entry of April 29, 1920.

23. The introduction, translated by Arthur Casagrande, was published in the Anniv. Vol., pp. 29–61.

24. Published in *Verhandlungen der Geologischen Bundesanstalt* 1925, no. 2, pp. 67, 68.

25. In *Zeitschrift des österreichischen Ingenieur- und Architektenvereins* vol. 3/4.

26. Reviewed by George Paaswell in *ENR* vol. 94. no.12, March 19, 1925.

27. Diary entry for April 7, 1925.

28. In *Schweizerische Wasserwirtschaft* (1925) vol. 10, p. 249.

29. From Gustav Ryba in *Der Kohleninteressent* (1925), no. 20, p. 160.

30. John Ripley Freeman (1855–1932) a graduate of M.I.T. in 1876, was an accomplished and justifiably renowned engineer who helped Boston, New York, San Francisco, Baltimore, Los Angeles, and other cities to obtain satisfactory water supplies. In 1922, he served as President of the American Society of Civil Engineers.

31. From T. William Lambe, "Terzaghi and soil mechanics at M.I.T., in *Terz. Mem. Lect.* (1973) pp. 24–48.

32. Diary entry of July 1, 1925.

33. Letter of June 30, 1925 from Spofford to Terzaghi. Terzaghi subsequently learned that the amont of the stipend was $2,000 plus $500 for travel to and from Europe. When he did not in fact return to Turkey, he was asked to refund $250.

Chapter 8

1. Diary entry of August 4, 1925.

2. George Paaswell, among other distinctions, had brought out a book entitled *Retaining walls, their design and construction* in 1920. Lazarus White, President of Spencer, White and Prentis, published a well-appreciated book *Modern underpinning: development, method, and typical examples*, in 1917 (only four years after a previous book on the history and construction of the Catskill water supply system of the City of New York).

3. Diary entry of August 29, 1925.

4. *Mein Lebensweg*, p.28.

5. Diary entry of August 31, 1925.

6. Charles Terzaghi (1926) *Principles of Soil Mechanics, a summary of experimental studies of clay and sand* (McGraw Hill, N.Y.). The chapters cover cohesion, compressive strength, and permeability of clay, consolidation and settlement of clay, physical differences between sand and clay, elastic behavior, friction, and future developments.

7. *ENR*, vol. 95, no. 19, November 25, 1925, p. 740.

8. *ENR*, vol. 95, no. 25, December 31, 1925, p. 1056.

9. Moran (1864–1936) was senior member of Moran, Proctor and Freeman. He specialized in the foundations of bridges, with important structures over the

Delaware, the Hudson, and other rivers to his credit and, late in life, the San Francisco–Oakland Bay Bridge.

10. Letter to Editor of *ENR*, vol. 95, no. 24, p. 969.

11. *ENR*, vol. 95, no. 25, pp. 1006–1007, 1925.

12. Letter to Editor of *ENR*, vol. 95, no. 24, November 26, 1925.

13. Letter from Terzaghi to F.E. Schmitt, October 18, 1943.

14. About twelve years Terzaghi's senior, Spofford was not only chairman of civil engineering at MIT but principal of the Boston firm Faye, Spofford and Thorndyke. Among his publications were two important books: *Theory of Structures* (1911) and *Theory of Continuous Bridges and Arches* (1937).

15. Discussed in Chapter 7.

16. Diary August 1, 1927.

17. Diary, March 10, 1926.

18. Samuel W. Stratton, born 1861, was a mechanical engineer of distinction who served on the faculty of the University of Illinois and simultaneously as Director of the National Bureau of Standards from 1901–1923, before his tenure as President of M.I.T. (1923–1930).

19. The Clemens Herschel Prize; the paper was "Modern conceptions concerning foundation engineering", printed in the *Journal of the Boston Society of Civil Engineers*, vol. 12, no. 10, pp. 397–439.

20. The mechanics of adsorption and of the swelling of gels in *National Symposium on Colloid Chemistry*.

21. ASCE *Proceedings*, (1927) vol. 53, pp. 2263–2294; ASCE *Transactions* (1929) vol. 93. 270–405.

22. Karl must have been fascinated with this engineer of wide experience, who had developed a water supply for Zacatecas, Mexico, and land "reclamation" in New Orleans, and who included in his resume that his hobby was "tinkering".

23. Letter to Arthur Shaw, January 21, 1928.

24. Diary entry of March 2, 1926.

25. Diary entry of March 5, 1926.

26. The advisory committee also included bridge engineer Ralph Modjeski, sanitary engineer Allen Hazen, foundation engineer Charles Gow, and building engineer Morris Knowles. Modjeski (1861–1940) was an Austrian Pole educated in France, noted for his design and construction of bridges, largely through his firm Modjeski and Masters. Morris Knowles (1969–1932), chief of the Pittsburg firm bearing his name, was an expert in design of water works.

27. *Erdbaumechanik* was never translated into English, but quickly into Russian.

28. According to Professor John Christian, this conversation was related by Arthur Casagrande to Steven Poulos.

29. Letters from Terzaghi to Arthur Casagrande, August 4 and 12, 1926.

30. From a conversation with Arthur's widow, Erna Casagrande, September 25, 1995.

31. Diary entry of October 4, 1929.

32. *Mein Lebensweg,* p. 31; and discussion by C.H. Eiffert "Application to hydraulic-fill dams" to a paper by G. Gilboy in *Transactions of ASCE for 1929,* Proc. Structural Division, December 1929, pp. 2556–2560.

33. Interview with Doctor Alberto Ortenblad published in a Brazilian volume commemorating the Terzaghi Centennial, entitled *Karl Terzaghi, Aspects of his life and work* (in Portuguese) by the Associacao Brasileira de Mecanica dos Solos (Brazilian Society of Soil Mechanics) (1983). Ortenblad's thesis concerned auto-consolidation of accumulating sediments.

34. Charles Terzaghi, (1929) "Soil studies for the Granville Dam at Westfield, Mass." *Journal of the New England Water Works Association,* vol. XLIII, no. 2, pp. 191–223.

35. The failure of Langewald dam in 1922, resulting in the Willimansett Flood, was reported in *Engineering News Record,* vol. 89, p. 121.

36. Based on Terzaghi's report on the underground conditions existing at the dam site of the proposed Chicopee Dam, Chicopee, Mass., August 12, 1926, to Messrs. Morris Knowles, Inc., Consulting Engineers, Pittsburgh.

37. Based on Terzaghi's report on the underground conditions existing within the boundaries of the South Meadows Tract, Hartford, Connecticut, November 28, 1928, to Fay, Spofford and Thorndike, Consulting Engineers, Boston.

38. Oxbow Dam on the Muskegon River, reports of June 12 and 18, 1928, for the Consumers' Power Company, Jackson, Mich.

39. W.O. Crosby, July, 1913, "Report on the new site of the Massachussetts Institute of Technology".

40. Based on Terzaghi's report on the investigation of the underground conditions at the site of the proposed buildings of the Massachusetts Institute of Technology, October 13, 1926.

41. Terzaghi's report on the settlements caused by the construction of the foundations of the new J.L. Hudson Building in Detroit Michigan, August 4, 1928, for Spencer, White and Prentis, New York.

42. From diary entry of June 25, 1928.

43. The dam that was eventually built, 1933–34, was named Madden Dam (according to J. David Rogers).

44. Unfortunately Terzaghi's report of April 2, 1929, seems to have been lost (according to his own letter to Simons of February 24, 1941).

45. This information is contained in an appendix to Terzaghi's "Advisory Report on the construction of a dam for the Svarthalsforsens Powerhouse on the Ingdals River, for the Stockholm Electricity Works", June 19, 1937.

46. Diary, May 29, 1929.

47. Diary, October 31, 1926.

48. Diary, June 8, 1926.

49. Diary, November 7, 1926.

50. "Technische Hochschule" is now being translated, not only in Vienna but generally, as "Technical University".

51. Diary, March 5, 1928.

52. Harald M. Westergaard, a Dane who completed his PhD at the University of Illinois, served on the Univ. of Illinois faculty in applied mechanics and theory of structures from 1916 to 1936, thereafter becoming Dean of Engineering at Harvard.

53. Diary April 29, 1928.

54. Diary, January 1, 1929.

Chapter 9

1. "Effect of minor geologic details on the safety of dams" Published as AIME Tech. Pub. 215 (1929) and republished in the Anniv. Vol. ; rewritten in German in *Die Wasserwirtschaft* (1930), vol. 10.

2. From Terzaghi's unpublished essay "Return to Germany", from 1929.

3. From Terzaghi's unpublished essay "A trip to Soviet Russia" (1929).

4. Reference to "The Lower Depths" of Maxim Gorki.

5. From Terzaghi's lecture "The Russian Experiment" presented to the Texas Section of the Society of Professional Engineers, in Austin, March 20, 1941.

6. Letter of T. to Lazarus White, December 10, 1929.

7. Brandl, H. (1993) "History of the institute for foundation engineering and soil mechanics at the Vienna Technical University" in *Mitteilungen für Grundbau, Bodenmechanik und Felsbau,* Heft 2, pp. 43–70.

8. From Karl's letter to Ruth January 26, 1930.

9. April 1, 1930.

10. The street on which the Terzaghi's lived in Vienna changed its name regularly, driven by the winds of Austrian politics. Prof. Heinz Brandl advised that current maps show the street as Roosevelt Platz; from 1934–38 it was Dollfuss Platz; from 1919 to 1934 Platz der Freiheit; and before that Maximilian Platz.

11. Letter from Terzaghi to Arthur Casagrande, January 7, 1930; reproduced in "Karl Terzaghi—his life and achievements" in Anniv. Vol., p. 15.

12. Letter from Terzaghi to Lazarus White, December 29, 1930.

13. Letter from Arthur Casagrande to Terzaghi, February 29, 1932.

14. Letter from Terzaghi to E.F. Kelley, Director of Research of the Bureau of Public Roads, November 14, 1932.

15. Letter from Arthur Casagrande to Terzaghi, February 26, 1930; a second on this theme, September 25, 1930.

16. Terzaghi's letter to Gilboy was written November 6, 1930, while Gilboy's reply was written on December 1, 1930.

17. Letter from Arthur Casagrande to Terzaghi, May 22, 1933. In anger, Arthur asserted he'd had enough "Jewish unscrupulousness" and would prevent White from lecturing again at Harvard. However, he did again invite Lazarus White to

lecture, when Karl visited Harvard in 1936; at that time Karl noted that Arthur couldn't stand White.

18. Leo Casagrande went on to develop a new method of stimulating drainage of water from fine-grained soils using electric potential gradients and the phenomenon of "electro-osmosis".

19. Letter of Arthur Casagrande to Terzaghi, October 4, 1931.

20. Letter from Terzaghi to Arthur Casagrande, November 5, 1932.

21. Letter from Terzaghi to Arthur Casagrande, March 25, 1933.

22. On the subject of Leo Casagrande's research—electro-osmosis.

23. Letter from Terzaghi to Buisson, December 8, 1937.

24. Deutsche Forschungsgesellschaft für Bodenmechanik [German Research Institute for Soil Mechanics]. The members included German government ministers, highway and railway officials, industrialists, and professors from the major universities.

25. On a return trip in September, 1931, he also studied and disapproved the site of a 182-meter-high arch dam site on limestone in Sulak Canyon, Daghestan, as well as investigating a smaller concrete gravity dam site on fractured basalt in Armenia.

26. His experiments demonstrated that the "effective size" of the sand had to be greater than 0.05 millimeters in order that the process successfully halt the flow.

27. From Terzaghi's letter to J.S. Miller, February 10, 1944. Terzaghi discovered that while the gel does not lubricate, it does serve to open the cracks and admit the cement by preventing water from bleeding away into fine cracks ahead of the cement.

28. Letter from Terzaghi to J.S. Miller of Dravo Corporation, February 10, 1944.

29. "Sondages, Etanchements, Consolidations, Procedes Rodio", with offices in Oran and Paris.

30. Letter of June 15, 1934 from G. Ischy to G. Rodio.

31. Advisory report on the foundation of house number 38 Johann Strauss-gasse, Vienna, August 2, 1931.

32. Prof. Brandl of the Technical Univ. of Vienna, translates *Reichsbrücke* as "Empire bridge". Terzaghi worked to reconstruct this bridge and the result was the Second Empire Bridge. That was damaged by bombing in the war and eventually collapsed on the first of August, 1976. The present bridge is the third Empire Bridge.

Chapter 10

1. Letter from Terzaghi to Rendulic, December 22, 1934.
2. Letter from Terzaghi to Arthur Casagrande, February 11, 1935.

3. "Large Retaining-Wall Tests—a series of five papers reporting fundamental results" in *ENR*: "I. Pressure of dry sand" (February 1, 1934) pp. 136–140; "II. Pressure of saturated sand" (February 22, 1934) pp. 259–262; "III. Action of water pressure on fine-grained soils" (March 8, 1934) pp. 316–318; "IV. Effect of capillary forces in partly saturated fill" (March 29, 1934) pp.403–406; and "V. Pressure of glacial till" (April 19, 1934) pp. 503–509; with corrections on p. 747 and a closure in p. 55, July 12, 1934. To this set can be added Terzaghi's *ENR* papers "Record earth-pressure testing machine" (Sept 29, 1932), pp. 365–369, and "Retaining-wall design for Fifteen-Mile Falls Dam" (May 17, 1934), pp. 632–636.

4. Erddruck auf halbstarre Stützmauern.

5. The manuscript "Earth Pressure and Earth Resistance—An elementary introduction in soil mechanics" was *reviewed* by Arthur Casagrande and Philip Rutledge, the latter then a graduate student and research assistant at Harvard. They thought the work was excellent but would be hard-going for students. Terzaghi had hoped Casagrande would actually do final editing for him. The material of this manuscript was no doubt incorporated in large measure in "Theoretical Soil Mechanics". (See the later note concerning Terzaghi's letter to Hamilton of May 14, 1935.)

6. *Ingenieurgeologie* [Engineering Geology] by K.A. Redlich, R. Kampe, and Karl Terzaghi, (Springer, Vienna) (708 pages). Terzaghi's portion comprised chapters on soils and soil investigations, tunnels, landslides and subsidence, bearing capacity, dams and reservoirs, foundations on peaty soils, and highway subgrades, including frost action.

7. From a review of *Ingenieurgeologie* in Wasserwirtschaft (1929) no. 23, p. 419.

8. Letter from Terzaghi to E.P. Hamilton of John Wiley & Sons, March 24, 1934.

9. Letter from Terzaghi to Arthur Casagrande, November 5, 1932.

10. In Terzaghi's letter to Arthur Casagrande, March 10, 1934.

11. Letter from Arthur Casagrande to Terzaghi, June 23, 1934.

12. From Terzaghi to E.P. Hamilton, November 14, 1934.

13. Terzaghi letter to Arthur Casagrande, January 24, 1931.

14. Letter from Arthur Casagrande to Terzaghi, October 29, 1934. Karl took this advice to heart and on May 14, 1935, he wrote to E.P. Hamilton of John Wiley & Sons: "Working on the book on foundation engineering I came to realize that soil mechanics and soil physics need more space so it will be necessary to divide the project into two books. Hence I am now working on a book with the title 'Earth Pressure and Earth Resistance. An Elementary introduction into soil mechanics' to be about 700 typed pages and 250 illustrations... This is intended to introduce the reader into soil mechanics and will be followed up by Foundation Engineering." But on October 27, 1935, he wrote to P. Laupmann in Leningrad: "I am writing a book on earth pressure and stability problems on the basis of physical properties in which I try to answer all the problems you have posed. ... I have been working on this book for one and a half years and hoped to finish it this month but I underestimated the amount of work and the required time. On the chapter on shear strength, approximately 200 handwrit-

ten pages, I have worked four months, ten hours a day. I have already thrown three drafts into the waste basket ... I am half way satisfied with the fourth."

15. Letter from Terzaghi to E.P. Hamilton, November 14, 1934.
16. Diary entry for October 20, 1931.
17. Diary entry of October 24, 1931.
18. Letter from Terzaghi to Lazarus White, October 19, 1931.
19. Letter from Terzaghi to Giovanni Rodio, October 14, 1931.
20. John R. Freeman passed away on April 9, 1932.
21. From letter to Lazarus White, January 4, 1932.
22. Diary entry for March 29, 1934.
23. Letter from Arthur Casagrande to Ruth Terzaghi, October 14, 1934. Arthur was irritated because, instead of a fee for his summer's work in Germany, he had arranged for the Germans to send a contribution of $1,200 to Harvard to support research in soil mechanics. But Harvard refused to accept any donation from Hitler's Germany.
24. Letter from Ruth Terzaghi to Arthur Casagrande, April 23, 1934.
25. Letter from Arthur Casagrande to Karl Terzaghi, December 26, 1934.
26. *Mein Lebensweg*, p. 56.
27. Letter from Terzaghi to Lazarus White, February 11, 1935.
28. Letter from Terzaghi to P. Laupmann, October 27, 1935.

Chapter 11

1. The name—Märzfeld—was a play on words [unwittingly both in German and in English]: March refers both to the god of war and the month of Hitler's reestablishment of the military draft.
2. Diary entry for October 31, 1935. Details of the project stated by Terzaghi in his diary were combined with data given by Albert Speer "Inside the Third Reich" (1970), Phoenix paperback edition, pp. 113–115.
3. Zweckverband Reichsparteitag-Nürnberg.
4. From Terzaghi's comments on the preliminary report of Vattenbyggnadsbyran, August 11, 1936, concerning the Mingechaur Water Power and Irrigation Scheme in Transcaucasia. Terzaghi visited the site in September, 1935.
5. Rain water can become an acid by dissolving carbon dioxide. A certain amount is normally acquired in passing through the atmosphere and the upper layers of soil containing plant life. A strong acid can be produced when water comes in contact with a strong concentration of carbon dioxide, as found in the pores of the Keuper sandstone at Nuremberg.
6. This narrative was derived mainly from Terzaghi's diary of November 3, 1935, (including all the quotations) and partly from *Mein Lebensweg*, pp. 58, 59. Prof. Brandl of the Technical University of Vienna believes, from personal discussions with former students, that Terzaghi had met Hitler more than once and had even

had a private lunch with him. There is no confirmable evidence of this. The diary account does not report that Terzaghi spoke about his preferred scheme for the foundation, but the autobiography account implies that to be true.

7. Information from Albert Speer, *Inside the Third Reich,* p. 175.

8. From Albert Speer's *Inside the Third Reich,* pp. 270–280. Speer suspected Goering; but at any rate Goering was too late in arriving at Hitler's office after the crash for Hitler had already signed the order establishing Speer as Todt's successor.

9. Diary entry for December 1, 1935.

10. The quotation is from *Mein Lebensweg,* p. 61.

11. Gordon A. Craig, *The Germans* (Putnam, 1982, reprinted by Meridian, 1991) pp. 7, 8.

12. The speaker was Julius Streicher, the Nazi Minister of Culture.

13. Diary entry of December 4, 1935. Walter Rathenau, the brilliant Jewish foreign minister of Germany, who had stated "We must find ways to bring ourselves together again with the world." was murdered on June 24, 1922, by right-wing antisemites. See Gordon A. Craig, *The Germans* (Putnam, 1982, reprinted by Meridian, 1991) pp. 141–143.

14. Diary entry of January 8, 1936.

15. On May 20, 1936, after completing an addendum to his report, he distilled his arguments about the pressure in crossbracing in a lecture to the Boston Society of Civil Engineers entitled: "A fundamental fallacy in earth pressure computations", which was published by the society.

16. From Terzaghi's letter to Arthur Casagrande, July 15, 1935. (The names have been changed to protect the innocent.)

17. From conversation with Arthur's widow, Erna Casagrande, September 25, 1995.

18. Diary entry concerning October 21, 1936.

Chapter 12

1. *Theorie der Setzung von Tonschichten; eine Einführung in die analytische Tonmechanik* [The theory of the settlement of clay beds; an introduction to analytical clay mechanics] (F. Deuticke, Leipzig) (1936).

2. For discussion of Fillunger's derivation see R. deBoer, R.L. Schiffman, and R.E. Gibson (1996) "The origins of the theory of consolidation: the Terzaghi–Fillunger dispute." *Geotechnique* vol. 46, no. 2, pp. 175–186.

3. Diary entry for March 13, 1936.

4. Technologische Gewerbemuseum.

5. Data from *Neues Wiener Abendblatt,* no. 67, March 8, 1937.

6. Submergence of a dry specimen reduces its unit weight by an amount equal to the unit weight of water multiplied by the quantity $(1 - n)$ where n is the porosity of the specimen. This answer is different because it encompasses not

only the buoyant effect but the weight of water in the pores of the submerged soil.

7. According to Terzaghi and Rendulic's publication "die wirksame Flächenporosität des Betons" [The effective surface porosity of concrete], *Zeitschrift des österr. Ingenieur- und Architektenvereins*, Heft 1–2, Jan. 12 1934, Fillunger's expression gave the buoyant force of concrete equal to ($n' - n$) multipled by γ where n' is the porosity of the stone aggregate, n is the porosity of the sand-cement mortar, and γ is the unit weight of water. The terms n' and n are defined otherwise, according to De Boer and Didwania's reading of Fillunger's 1913 paper "Der Auftrieb in Talsperren" [Uplift in Dams] *Österreichische Wochenschrift für den öffentlichen Baudienst*, Heft 19, pp. 532–570; n' is stated to represent the volume porosity and n to represent the surface porosity of the concrete. See R. De Boer and A.K. Didwania, "The effect of uplift in liquid-saturated porous solids—Karl Terzaghi's contributions and recent findings." *Geotechnique*, vol. 47, no. 2 (1997), pp. 289–298.

8. Diary entry for December 10, 1932. Terzaghi later reported his meeting with Fillunger having taken place on December 14 in "Niederschrift über die am 23 Dezember 1936 durchgeführte Einvernahme des Zeugen o.ö. Professor Dr. Karl Terzaghi", which was the text of a supplement to his testimony before the faculty hearing.

9. That the concrete specimens obeyed the effective stress law "almost" perfectly was shown later to be an artifact of experimental inaccuracy; the "almost" could be dropped. Another way to show that concrete behaves like an ideal porous medium is to demonstrate that the uplift force of a pressure in the pore-water of concrete equals the product of the water pressure and the *whole* of the area across the concrete, not just a *proportion* of the whole area; in Terzaghi's language, in the ideal porous material the "effective surface porosity" is unity. Terzaghi and Rendulic's experimental results were presented in this mode. But on October 18, 1935, he reported in a letter to engineer B. Hellstrom at VBB in Sweden that he had "prepared an as yet unpublished presentation in which the need to define an effective surface porosity has been dropped." This, as explained by an example, was nothing more than analyzing the degree to which a triaxial compression specimen with known external confining pressure and known internal pore pressure obeys the effective stress principle. "The practical effect of this is the same as the results of my investigations on the effective surface porosity."

10. From an unpublished (and not widely circulated) addendum to *Mein Lebensweg und meine Ziele* entitled "Kontroverse mit Professor Fillunger und ihr tragischer Ausgang" [The controversy with Professor Fillunger and its tragic outcome], Winter 1936/37, page 1.

11. deBoer, Schiffman, and Gibson, in the work previously cited, described Fillunger's defensive resistance to O. Hoffman's suggestion to take the worst uplift case for design, which he presented in "Zur Frage des Auftriebes in Talsperren" [On the question of uplift in dams], *Die Wasserwirtschaft*, Heft 1/2, pp. 5–10 (1929).

12. In Addendum to *Mein Lebensweg* : Kontroverse mit Professor Fillunger.

13. According to testimony given to the faculty committee investigating their dispute, as reported by deBoer, Schiffman, and Gibson (see second note of this chapter), Fillunger had initiated this meeting, which took place in a cafe and in which Fillunger "brusquely ordered Terzaghi not to submit his paper."

14. Diary entry of February 16, 1934.

15. *Mein Lebensweg*, p. 54.

16. Letter from Terzaghi to F.E. Schmitt, July 28, 1944.

17. Letter from Terzaghi to Harold Harding, Dec. 8, 1952.

18. Diary for January 11, 1937.

19. Letter from Arthur Casagrande to the Rector of the Technische Hochschule in Vienna, January 25, 1937.

20. From her maiden name, Doggett.

21. "Erdbaumechanik und Baupraxis, Eine Klarstellung" [Soil mechanics and engineering practice, a clarification] K.v. Terzaghi and O.K. Fröhlich (Franz Deuticke) (1937), 35 pages.

22. From Terzaghi's letter to Professor Schaffernak, March 9, 1937 and newspaper clippings of March 8 in *Neues Wiener Abendblatt,* and *Das Echo,* and March 9 in *Wiener Neueste Nachrichten.*

23. In Addendum to *Mein Lebensweg*: Kontroverse mit Professor Fillunger und ihr tragischer Ausgang, Winter 1936/37.

24. R. deBoer, R.L. Schiffman, and R.E. Gibson (1996) "The origins of the theory of consolidation: the Terzaghi–Fillunger dispute" *Geotechnique* vol. 46, no. 2, pp. 175–186.

25. Previously Terzaghi had been admitted as a Corresponding Member, a status that Fillunger asserted showed that he was second-rate.

Chapter 13

1. "VBB" is the Swedish consulting firm Vattenbygnaddsbyran.

2. *Mark Twain in Eruption*, edited by Bernard DeVoto (Harper & Brothers, (1940) p. 324.

3. The "phreatic surface" is the surface to which water entering a hypothetical open tube at different points in the subsurface would rise in that tube. Different regions of a dam foundation can possess different phreatic surfaces.

4. From Terzaghi's "Preliminary report on the proposed earth dam across the river Adige at the South end of the Lago di Mezzo, Italy" August 8, 1939. The completion of Terzaghi's participation in this project was interrupted by the war.

5. Confidential letter from Terzaghi to J.S. Miller of Dravo Corp., February 10, 1944.

6. Woodward and Fergus Falls dams in the USA and Dolgarrog Dam in Australia.

7. In an enclosure to a confidential letter Terzaghi wrote to F.E. Schmitt, December 26, 1947, for his use in preparing introductory remarks on Terzaghi's award of Honorary Membership in ASCE.

8. However, when Arthur Casagrande asked if he could use Karl's filter method with the Terzaghi name attached in Corps of Engineers Projects (letter of April 29, 1938), Terzaghi agreed without conditions (letter of May 14, 1938).

9. Terzaghi described these events in his diary for April 22, 1938, and in the mansucript that he provided for Arthur Casagrande's draft of "Karl Terzaghi—His Life and Achievements" in the Anniv. vol. The presentations differ in details.

10. Terzaghi's letter to Arthur Casagrande of June 8, 1938.

11. In letter to Adolph Ackerman, February 4, 1942, Terzaghi wrote about Chingford: "I was able to demonstrate to the satisfaction of everybody concerned that the entire structure was on the verge of failure and I saved the dam by redesigning it completely."

12. Terzaghi's letter to Arthur Casagrande, June 8, 1938.

13. Letter from Terzaghi to G. Ellison, December 7, 1940.

14. Terzaghi's letter to G. Ellison, February 15, 1941.

15. Terzaghi wrote to Ellison on December 8, 1943: "After all these experiences, I no longer doubt that the recurrence of the slides in the Folkestone Warren could be prevented forever by bleeding the Greensand. For the time being it is quite obviously more important to bleed the common enemy."

16. "Mechanism of Landslides" in *The Berkey Volume*, Geological Society of America, pp. 83–127 (1950) [reprinted in the Anniv. Vol., pp. 202–245.

17. Reported by William Shirer in *The Rise and Fall of the Third Reich* (Simon and Schuster, 1960), p. 336.

18. Diary entry for March 3, 1938.

19. Terzaghi's diary entry for March 15, 1938.

20. Letter to Karl from Ella Byloff, March 15, 1938.

21. The draft for the second edition was almost in final form; portions are to be found in the Terzaghi Library.

22. Diary entry for August 1, 1938.

Chapter 14

1. From Tezaghi's letter to Dr. C.F. Gates, May 25, 1945.

2. The invitation came jointly from the Chien Tang River Bridge Engineering Office (Letter from T.E. Mao of February 7, 1937) and the University of Peking (personally delivered in Vienna in January, 1937, by Prof. Fang-Yin Tsai, structural engineer, who was then a visitor at the Univ. of Berlin in Charlottenburg).

3. On June 7, 1937, he wrote to Chatley, Chief Engineer of Whangpoo Conservancy District, Shanghai, that he intended to spend a year in China from

Autumn of 1938 (and accepted honorary membership in the Foundation Reseach Committee of the Chinese Engineering Society.)

4. Letter from Arthur Casagrande to Terzaghi, March 19, 1937.

5. Terzaghi's letter to Dean Gilchrist of April 28, 1938. Correspondence between Gilchrist and Terzaghi went on almost monthly from February 16, 1938 into 1939.

6. This illness prompted Terzaghi to petition the Ministry of Education for an unpaid recuperative leave, consisting of the Fall semester of 1938, at the end of which he would be officially released from his chair at the Hochschule. This got him nowhere.

7. Karl wrote to Prof. Schaffernak on August 23, 1938. Schaffernak was so angered and hurt by this letter that it took him until May 29, 1939, to reply.

8. Letter from Ralph Burke to Terzaghi, December 5, 1938.

9. Letter of December 12 from Terzaghi to Ralph Burke.

10. January 20, 1939. Terzaghi had asked for $150 per day; the city council had to approve even the smaller amount. In contrast, Peck was earning $300 a month and laborers earned thirty cents an hour.

11. From Terzaghi's "Preliminary Report on the Settlement of the Charity Hospital Building in New Orleans, Louisiana." April 9, 1939.

12. Published in the *Journal of the Institution of Civil Engineers* (1939) vol. 12, no. 7, pp. 106–142 (reprinted 1969 by I.C.E. in the volume *A century of soil mechanics*, pp. 151–187).

13. According to the reports of "old timers", as Terzaghi wrote to Arthur Casagrande, May 18, 1939.

14. Letter from Ralph Peck to Terzaghi, July 22, 1939.

15. Personal communication from Ralph Peck.

16. More precisely, the integral of the surface settlement over the area in which it occurred produced a volume approximately equal to the volume by which the tunnel space was reduced through squeeze.

17. See chapter 8, p. 108.

18. The displacements at a fixed point in the earth as different arrangements of tunnel openings passed by yielded model curves resembling the plots geophysicists use to interpret the change in the value of some measured quantity as an instrument is flown, or wheeled, or floated by.

19. Memorandum concerning the results of the pressure measurements in open cuts on the subway of Chicago, by Karl Terzaghi, to Mr. Burke, March 26, 1941. This memo was written over a six-week period in Austin, Texas. Terzaghi billed for only one week's work. The results reflect close collaboration with Ralph Peck.

20. From Terzaghi's letter to Arthur Casagrande, April 7, 1941.

21. Terzaghi's letter of March 26, 1941.

22. From a letter to Ralph Burke, April 4, 1941, the former chief engineer of the Chicago subway job.

23. From the introduction to Terzaghi's "Final Report on the Construction of Shipways no 10 and 11 for the Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia", August 24, 1942 (approximate date).

24. In Terzaghi's letter to Dean Westergaard at Harvard, February 5, 1942.

25. Letter of April 9, 1947, from Adolf Ackerman transmitting notes from his personal diary.

26. From Terzaghi's letter to Adolph Ackerman, February 4, 1942.

27. In letters from Terzaghi to A.J. Ackerman, December 10, 1941, and January 18, 1942.

28. Letter from Terzaghi to J.S. Miller, February 3, 1942.

29. The meaning of the term *phreatic surface* is explained in note 3, Chapter 13.

30. Terzaghi specified the sandwells should go all the way through the marl and the underlying silty sand to elevation 0. But, through an unfortunate choice of words, which he later attributed to being under a severe state of stress, the interpretation was to end them just five or six feet below the top of the sand at elev 28. Terzaghi was crushed when he learned this, much later. It was his mistake in communication. Ackerman comforted him by assuring him they were still able to serve the intended purpose.

31. This term was used in Terzaghi's "Final Report on the Construction of Shipways no 10 and 11 for the Newport News Shipbuilding and Dry Dock Company in Newport News, Virginia", August 24, 1942 (approximate date).

32. Reported in two papers by Ruth D. Tezaghi: "Concrete deterioration in a shipway" *Proceedings of the American Concrete Institute,* vol. 44, no. 40 (1948), pp. 977–1005; and "Concrete deterioration due to carbonic acid" *Journal of the Boston Society of Civil Engineers* (1949), p. 136 (awarded the Clement Herschel Prize in 1950).

33. Terzaghi recommended this formally on May 29, 1946, in "Final report on the North Gate Pier of Shipway no. 11 in Newport News, Virginia".

34. Letter from FitzHugh to Terzaghi, February 11, 1944.

35. Letter from Terzaghi to FitzHugh, February 21, 1944.

36. Terzaghi's "Report concerning the soil conditions at the site of S.S. *Lafayette* at pier no 88 in New York, N.Y." April 15, 1942.

37. Terzaghi enlisted the aid of MIT instructor John Lowe in the development of the pore pressure gauge on these jobs. The Navy reported that soil suction did not develop in the eventual salvage operation.

38. Letter to Ralph Peck, April 29, 1942.

39. H.P. Cushin, F. Leverett, and F.R. van Horn, "Geology and Mineral Resources of the Cleveland District" *U.S. Geol. Survey Bull.* 118 (1931).

40. Terzaghi's letter to Ralph Peck, July 6, 1942.

41. Letter from Leonard Larson to Terzaghi, Dec. 14, 1943.

42. Letter to L.T. Tanney, Chief Field Engineer, Republic Steel, May 6, 1944.

43. May 11, 1944.

Chapter 15

1. From interview of Ralph Fadum, April 5, 1996. Professor Fadum served as Karl's driver and witness on this occasion.

2. Diary entry for April 12, 1944.

3. Karl Terzaghi's close friend over many years; probably the one he referred to as "Rabbit" (from *Hase*—German for rabbit).

4. Letter from Karl Terzaghi to Headquarters, First Service Command, Security and Intelligence Division, Boston, June 17, 1945.

5. Diary entry for August 1, 1945.

6. Letter from Terzaghi to Theodore von Karman, August 3, 1945.

7. Arthur Casagrande related that initially the ventilation system spread the smoke through the new house too thickly for the family while Karl complained the smoke was too thin in his office; this was corrected by cutting the study out of the ventilation loop. (In "His space vehicle is the planet earth", *Saturday Review*, September 2, 1961, pp. 42, 43.)

8. Letter from Terzaghi to Bruno Sander, October 28, 1941.

9. Letter to F.E. Schmitt, October 4, 1943.

10. Mayo FitzHugh of Newport News Shipbuilding to Terzaghi, May 12, 1943.

11. Letter from Terzaghi to Peck, February 18, 1942.

12. In letter from Terzaghi to Peck, April 4, 1942.

13. From Terzaghi's letter in mid-February, 1943, as related in Ralph Peck's article "Soil Mechanics in Engineering Practice: The story of a manuscript" in *Terz. Mem. Lect.* (1973), pp. 51–79.

14. Terzaghi's letter in reply to Peck's of February 25, 1942, as reprinted in Ralph Peck's article "Soil Mechanics in Engineering Practice: The story of a manuscript" in *Terz. Mem. Lect.* (1973), pp .51–79.

15. The publisher was John Wiley & Sons, Inc.

16. Fourteen years later, Terzaghi observed that the larger number of readers were practicing engineers. "College teachers seem to shy away from it," he wrote to his friend Glossop on December 17, 1962, "and the reasons are obvious. They do not like to advertise how little we really know."A third edition, with additional coauthor Professor Mesri, was published in 1997.

17. Letter from Ralph Peck to E. P. Hamilton, President of John Wiley & Sons, publishers, July 31, 1944.

18. Diary entry of August 10, 1944. Despite Terzaghi and Peck's criticisms, Taylor's book *Fundamentals of Soil Mechanics*, also published by Wiley in 1948, proved to be one of the mainstays of the profession, a publishing and engineering success.

19. Letter to F.E. Schmitt, October 18, 1943.

20. From letter to Mr. T.E. Mao, China Bridge Co., June 26, 1945.

21. Diary entries for April 23 and 24, 1944.

22. *Rock Tunneling With Steel Supports* by Robert V. Proctor and Thomas L. White, with an "Introduction to Tunnel Geology" by Karl Terzaghi, Commercial Shearing and Stamping Company (1946); and *Earth Tunneling With Steel Supports*, by the same authors (with a note that sections covering geological investigations and ground loadings were prepared by Karl Terzaghi).

23. It seems somewhat scandalous that Terzaghi's name was not indicated as coauthor to each of these important books.

24. During the war, Arthur Casagrande brought in Stanley Wilson to teach his airfield course. Mr. Wilson remained at Harvard as a junior faculty member in the postwar period. According to Ralph Peck, both Arthur and Karl relied on him heavily, especially for development of field instruments. Karl inspired Stan to develop the highly successful inclinometer known as *The Slope Indicator*, which was an improvement on a device developed by Tshebotarioff to measure the inclination of sheet piles.

25. Letter from Arthur Casagrande to Terzaghi, March 9, 1939.

26. Diary entry from June 24, 1946.

27. Letter from Arthur Casagrande to Terzaghi, April 7, 1941.

28. During the war, about a hundred airfield batallions were created, and one geotechnical officer was assigned to each. To train these officers Arthur Casagrande ran seven-week programs at Harvard, which contributed significantly to the war effort. (Information from Professor Ralph Fadum, interviewed April 5, 1996.) Some have found it ironic that Arthur Casagrande was engaged in the establishment of airfields from which bombers might attack Germany's Norwegian submarine pens that had been fortified by Leo Casagrande.

29. In letter from Arthur Casagrande to Terzaghi, July 22, 1942.

30. Terzaghi's note in his diary entry of June 14 after spending an evening with Ralph's parents in their home in Denver.

31. Letter from Terzaghi to F.E. Schmitt, August 13, 1946.

32. Terzaghi's "Report to the Flood Commission of the City of Hartford concerning the reconstruction and completion of flood protection works between Morgan Street and Station 95+73 in Hartford, Conn.", November 17, 1941.

33. "Report concerning Settlement of the ground surface beneath concrete floors in the factory buildings of Colt's Patent Fire Arms Manufacturing Company, Hartford, Conn.", by Karl Terzaghi and W.F. Uhl, May 12, 1944.

34. The depth at which the pile cannot be driven further.

35. From Terzaghi's "Memorandum on the causes of the settlement of the gymnasium wing of the William Howard Taft High School in Bronx, New York," Oct. 22, 1946.

36. Letter from Richard Foster Flint to Terzaghi, January 31, 1946.

37. From Terzaghi's letter to Professor Raymond Dawson, October 2, 1942. The job in which he struggled with an inadequate assistant was Dravo's Newport News shipway.

38. From Terzaghi's letter to F.E. Schmitt, October 18, 1943.

39. Recommendations concerning the Foundation Studies for the Proposed Oil Refinery in Atzcapotzalco, Mexico, by Karl Terzaghi, Nov. 16, 1943.

40. Terzaghi wrote two reports on this structure: (1) "Memorandum Concening the Data on the Settlement of the Palacio de Bellas Artes", April 17, 1944; and (2) "Memorandum concerning the underpinning of the Palacio de Bellas Artes", Sept. 12, 1950.

41. Terzaghi wrote a "Memorandum concerning the present condition of the Escuela Normal", Sept. 13, 1950.

42. In letter from Arthur Casagrande to Karl Terzaghi, February 19, 1941. Following Terzaghi's idea expressed in *Erdbaumechanik*, Casagrande discussed the formation of loose "honeycomb structure" of silt and clay sediments deposited in sea water in his 1932 paper "The structure of clay and its importance in foundation engineering," *Journal of the Boston Society of Civil Engineers.*

43. It was not until about 1953 that Ivan Rosenquist, at the Norwegian Geotechnical Institute, demonstrated that the phenomenon stemmed from a structural collapse of clay plates, which changed rapidly from an initial edge-to-face arrangement into a denser parallel arrangement (like the collapse of a house of cards). The initial unstable arrangement of clay platelets was fostered by deposition in seawater, as Casagrande had surmised, and the structure became metastable if the clay's porewater were replaced by fresh water. I. Rosenquist, "Considerations on the sensitivity of Norwegian quick clays" *Geotechnique* (1953) vol. 3, pp. 195–200.

44. In Terzaghi's "Report on subsidence at North Works, Wyandotte Chemical Corporation, Wyandotte, Michigan, March 23, 1947.

45. Report on the subsidence situation at the North and South Works in May, 1950, by Karl Terzaghi, R.B. Peck, and Carl A. Bays, June 10, 1950.

46. "Confidential Memorandum concerning the subsidence of Brine Fields", by Karl Terzaghi, Winchester, Mass, Dec. 30, 1950.

47. Information from the company's "prospectus for sale of 800,000 shares of common stock," April 15, 1952.

48. Informal Report on the Subsidence of the Wilmington Oil field west of Long Beach, Cal. by Karl Terzaghi, Winchester, Mass., April 23, 1949.

49. Report on Effects of the Terminal Island Subsidence on Long Beach Steam Station of Southern Cal. Edison Co, by Karl Terzaghi, August 30, 1950. CONFIDENTIAL.

50. From Terzaghi's letter to Wallace Chadwick, April 11, 1952, which transmitted a report with an appendix entitled: "Comments on the report 'a mathematical analysis of the subsidence in the Long Beach-San Pedro Area' by D.C. McCann and C.H. Wilts, dated November 1951."

51. In Southern California's Prospectus dated March 19, 1952.

52. Memorandum concerning the subsidence of power stations no. 1 to 3 on Terminal Island, to W.L. Chadwick from K. Terzaghi, Winchester, Mass., January 12, 1954.

53. Reported in letter from Ralph Peck to Chief Harbor Engineer of Long Beach, Mr. Shoemaker, December 12, 1958.

Chapter 16

1. Terzaghi's letter of March 13, 1953 to Professor W.S. Hanna.
2. In Terzaghi's letter to Prof. Hanna in Cairo, March 13, 1953.
3. During the war years, Karl was also driven between his home and the campus by Arthur Casagrande's assistant Ralph Fadum, who served as a faculty member at Harvard from 1937 to 1943. Professor Fadum remembered fondly that Karl was often so preoccupied with thought that he would have been an utterly unsafe driver. Fadum quipped that you almost had to hold his hand in crossing a busy street. (From an interview with Professor Fadum, April 5, 1996.)
4. Notes on interview of Professor Alec Skempton, December 15, 1993.
5. Letter from Arthur Casagrande to Dean Haertlein at Harvard, November 6, 1953.
6. Remarks on introducing Karl Terzaghi for Honorary membership in the American Society of Civil Engineers at the Annual Meeting of the Society, New York, January 21, 1948.
7. Letter to Clifford Kaye, January 3, 1949.
8. Letter to Andrew Neilly, Jr. of John Wiley & Sons, April 26, 1955.
9. Letter of February 28, 1950 to Gail Hathaway, Chairman of USCOLD.
10. Letter to F.P. Shepard, May 21, 1953. Shepard protested that the method reveals something geologists want to know, namely ancient sedimentary environments.
11. In *Mein Lebensweg,* supplement, p. 9.
12. Letter to Karl Langer, March 21, 1951.
13. D.P. Krynine, *Soil Mechanics,* McGraw Hill, N.Y. (1941).
14. Francis Baron's article is entitled "The Study of Earth: An American Tradition", *Civil Engineering,* vol. 11, no. 8, August, 1941, pp. 473–476. Terzaghi's reply is in the October issue, vol. 11, no. 10, p. 614.
15. Gregory Tschebotarioff, "Half a century of soil mechanics—some thoughts for the future in the light of the past." *Engineering Issues—Journal of Professional Activities* ASCE, vol. 102, no. EI3, July, 1976, pp. 321–337.
16. Letter from Terzaghi to Gregory Tschebotarioff, August 25, 1951.
17. From letter to Hugh Dixon, of the engineering company Humphreys, December 13, 1955.
18. The fifty-year flood was estimated as two million cubic feet per second.
19. Letter to F.E. Schmitt, December 16, 1946.
20. Diary entry for November 9, 1946.
21. Diary entry of November 19, 1946.

22. In a dynamic penetration test, a cone or a steel pipe is driven into the ground and the number of blows to advance a unit distance is recorded. By means of such tests the most important quality of sands, the relative density, would be determined directly, and bore holes would be needed only sparsely for calibration purposes. The *relative density* of a soil is defined by the relative position of its void ratio in the window from maximum (most loose) to minimum (most dense) conceivable values. With his preliminary report, Terzaghi provided an appendix explaining the various methods for conducting penetration tests. Although new to many engineers, penetrometers had a record of 25 years use in Sweden, Holland, and elsewhere, and Terzaghi himself had invented and used a waterjet penetrometer (called a "water-pressure sonde") in 1929 for study of soils along the New York subway.

23. Excerpts from his consulting reports on this landslide were reprinted in the Anniv. Vol., pp. 409–415. For that publication, the location and name of the slide were redacted.

24. This is the essential idea of Stanley Wilson's borehole inclinometers, mentioned in connection with the Long Beach case history.

25. "Left" and "right" refer to these directions when looking in the direction of flow.

26. The "piezometric head" is the height of the phreatic surface above an arbitrary reference level.

27. Report on the results of an examination of the proposed project for the ore storage area and conveyor tunnels at the mines of Cia. Vale do Rio Doce S.A., Itabira, Brazil, by Karl Terzaghi, April 30, 1947.

28. Terzaghi's short report is entitled "Answers to the questions contained in Mr. Alfredo Figlionini's letter of December 9th, 1947, concerning the Sao Paulo Subway", Dec 11, 1947.

Chapter 17

1. The preliminary designs were prepared by Hochtief and Dortmund Union, and the final design was initially awarded to Sir Alexander Gibb & Partners from UK.

2. The other members were I.C. Steele, Max Pruess, Lorenz Straub, and Andre Coyne. Later, J. Barry Cooke joined the board and became its secretary.

3. Memorandum of June, 1959, entitled "Transcript of Interview. Subject: The Aswan High Dam Board of Consultants Meeting, Cairo, June 1959".

4. In letter from Terzaghi to Laurits Bjerrum, January 22, 1960.

5. Memo of June 1959 previously cited. Terzaghi's disrespect for the sluicing method is understandable, but it is interesting to note that he recommended this method in 1957 for filling the large open voids in a random fill that had unfortunately been allowed in portions of the foundation of Bridge River Diversion Dam; if unfilled, he thought, these would lead to sinkholes in the new Mission Dam, which would incorporate the older dam. (Discussed in his letter of March

16, 1957 to W.G. Huber and his Mission Dam report of February 25, 1957.) The method of sluicing was experimented with but did not work as the larger stones in the filter material arched over the large pores and prevented the fines from entering. (Mission Dam is discussed in Chapter 18.)

6. Letter to Hassan Zaki, November 21, 1959.

7. Letter to Andre Coyne, December 14, 1959.

8. Letter to Terzaghi from Waldo Bowman, January 6, 1960.

9. In letter of May 22, 1945 from counsel Melaniphey to Terzaghi in the Great Northern Theater and Hotel Bldg. case.

10. For his testimony, Terzaghi prepared a comprehensive document entitled "Report concerning the Causes of the Whatshan Slides," Nov. 16, 1953.

11. Engineer J. Barry Cooke told Terzaghi he had seen compressed fish and pieces of wood in such longitudinal cracks.

12. Terzaghi was quite troubled by the difficult position he was in with respect to Acres. He had served once as their consultant and was friendly with one or more of their engineers. But, he maintained "the conclusions were forced on me by the facts. I had no choice" (letter to counsellor Charles Tysoe, Nov 12, 1953). However he did apologize to Acres' president, Andrews, (letter of December 12, 1953) explaining that the offending sentence had been included when he was irritated to learn they had not visited the site; he had intended to expunge it from the report.

13. Letter from Tom Leps to Terzaghi, March 3, 1954.

14. Charles Ripley wrote to Terzaghi, November 24, 1960, that Terzaghi seemed to have "taken considerable care to be considerate of H.G. Acres' position in outlining what [he] felt to be the cause of the difficulty. It is unfortunate that they took such offence at your report. They were obviously unable to read or examine your report objectively due to their involvement in the accident."

15. "Report on the foundation conditions at the site of the sulphate pulp mill, Marathon Paper Mills of Canada Ltd.," December 28, 1944.

16. "Report on the design of Sasumua Dam" Nov 24, 1953.

17. In terms of Arthur Casagrande's classification system for soils embracing a plot of the plasticity index against the liquid limit, the Sasumua clay plotted well below the usual line (Casagrande's "A line").

18. Performed by R.H.S. Robertson.

19. Professor Leonardo Zeevaert explained (in interview of February 19, 1998) that chemical bonding between the particles in the Mexico City clay can increase its strength to workable values despite its low density.

20. "Report on the Controversies between the City of Nairobi and the Sasumua Dam Contractors", March 9, 1956. In 1958, Terzaghi published "Design and performance of the Sasumua dam" *Proceedings of the Institution of Civil Engineers*, vol. 9, pp. 369–394 and vol. 11, pp. 360–363.

21. But Terzaghi also stated emphatically his view that the contractor was motivated mainly by having selected too low a unit price when he found he would have to dry the material to achieve optimum water content and had no experi-

ence in drying out a material. He showed incompetence in demanding to be told how to do this in a letter to the engineer.

22. From Terzaghi's replacement pages for sections of the report, "Comments on the Topics Assigned to K. Terzaghi in 'Preliminary Advice on Evidence' April 13, 1956".

23. Letter from Terzaghi to Hugh Dixon of Humphreys, December 12, 1955. Note that the "factor of safety" is defined such that a value of one means the dam is at the point of failure, while any value greater than one implies the existence of a margin of safety.

24. From "Transcript of testimony given by Karl Terzaghi before Arbitration hearing, Nov. 26, 1956: Equator Roads and Civil Engineering Limited, Claimants with Cyril Salmon and E.J. Rimmer and F.E. J. Allemes, attorneys for the Claimants; and The City Council of Nairobi, Respondents, represented by Leonard Caplan, J.S. Daniel, and C.F. Schermbrucker."

25. From Terzaghi's "Report on the Reconstruction of the Caved-In Section of the Wilson Tunnel", January 15, 1955.

26. Personal communication from Ralph Peck. Apparently Peck was actually on the runway when a judicial order forced him to deboard (without baggage).

Chapter 18

1. Terzaghi's work is presented in ten reports/memoranda from Nov. 12, 1949 to Jan. 8, 1956. He summarized this work in the prize-winning paper "Design and performance of Vermilion dam, California", coauthored with T.M. Leps, published in *Proceedings A.S.C.E.* vol. 84, no. SM3 (1958). He also wrote about another very interesting Southern California Edison Project in "Dam foundation on sheeted granite", published in *Geotechnique*, vol. 12, no. 3, pp. 199–208 (1962).

2. From Terzaghi's "Memo concerning time lags in leakage from Vermilion Reservoir" to R.W. Spencer, manager of Southern Cal. Edison's Engineering Department, January 8, 1956. The process Terzaghi described as a natural occurrence resembles the sluicing operation Terzaghi denied could be achieved by the Russians at Aswan Dam.

3. In letter from Terzaghi to F.A. Lazenby, February 15, 1952.

4. From Terzaghi's letter to T. Ingledow, V.P. and Chief Engineer of B.C. Electric Railway Co. Ltd, August 18, 1951.

5. The case history of Cheakamus Dam was described in Terzaghi's publication "Storage dam founded on landslide debris" *Journal of the Boston Society of Civil Engineers*, vol. 47, pp. 64–94 (1960). His first consulting report on the job ["Report on the proposed storage dam south of Lower Stillwater Lake on the Cheakamus River, B.C.", April 12, 1954] was reprinted in the Anniv. Vol., pp. 395–408.

6. Columnar basalt is volcanic flow rock cracked into columns by tension during cooling, as at the famous Devil's Postpile Monument in California.

7. The design engineers for Cheakamus Dam. B.C. Engineering was formed by a union of B.C. International Engineering, headed by W.G. Huber and B.C. Electric Railway, Ltd. After the merger, the new company had no further direct connection with International Engineering or its parent Morrison Knudsen. B.C. Electric Railway became simply B.C. Electric.

8. From Terzaghi's letter to F.A. Lazenby, July 22, 1955.

9. From Terzaghi's letter to Mark Olson, January 6, 1956.

10. From Terzaghi's publication "Storage dam founded on landslide debris", *Journal of the Boston Society of Civil Engineers*, vol. 47, (1960) pp. 64–94.

11. Still, questions may be asked about this job. First it was an adventure that might have turned out differently, perhaps unsafely so, had Terzaghi's constant and thorough attention not been focused on every minute detail over a period of years. Secondly, some ask why Terzaghi had not considered the frightening possibility that the landslide, which had given birth to the Rubble Valley Wash, might recur. The "barrier" at the base of Lower Garibaldi Lake, from which the giant flow slide had emerged, continues to provide an extreme geologic hazard, and one that the construction of Cheakamus Dam may have worsened by placing a reservoir in its runout path.

12. From an interview with Mr. Charles Ripley, August 9, 1993.

13. "Report on stability conditions at East Abutment of Cleveland Dam, Greater Vancouver Water District, British Columbia", May 30, 1959, with three appendices.

14. Terzaghi worked out the geological picture with the help of engineering geologist, and by now his good friend, Dr. Victor Dolmage.

15. Report on stability conditions at East Abutment of Cleveland Dam, Greater Vancouver Water District, British Columbia, June 30, 1961, with three appendices. This is an updating of the May 1959 report, the words the same except for inserted passages.

16. Memorandum to Charles Ripley, January 25, 1963.

17. Letter from Terzaghi to H.W. Smith, June 4, 1958.

18. From letter to Charles P. Dunn, September 29, 1961.

19. Stated in Terzaghi's "Report on design and construction operations, proposed Bridge River Dam, B.C.", May 14, 1956.

20. Varved clay is a finely layered clay deposit alternating between more and less silty layers; it originates from deposition in a lake whose surface freezes annually.

21. The field compression index was equal to about 1.0.

22. In Terzaghi's report of February 25, 1957, he wrote: "The writer never encountered an undisturbed clay resembling the Bridge River clay for which C_c had a value as high as unity."

23. Another factor causing the development of sinkholes in the original diversion dam was poor construction practice, related to imperfect filling of boreholes in the vicinity of the core.

24. From Terzaghi's letter to Tom Leps, February 10, 1958. It was largely this lack of success with sluicing fines into the voids of coarser material that set Terzaghi so adamantly against the proposal of the Russians at Aswan Dam.

25. Report of February 25, 1957.

26. Presented in Terzaghi's "Preliminary report on treatment of foundation for proposed Bridge River Dam," February 25, 1957.

27. This was entirely analagous to the situation at Taft High School in the Bronx, N.Y. (discussed in Chapter 15), where in 1945 he showed the damaging differential settlement arose from consolidation of exactly this type and origin of transition zone between clay and coarse-grained sediments.

28. Later, several other such places were found in the same general region.

29. Letter from Terzaghi to W.G. Huber, May 27, 1957.

30. Letter from Terzaghi to F.A. Lazenby, June 6, 1957.

31. Letter to Charles P. Dunn, September 29, 1961.

32. Letter from Terzaghi to Yves Lacroix, February 18, 1958.

33. In Letter from F.A. Lazenby to Terzaghi, November 7, 1960.

34. Until at least 1952, Arthur typically addressed his letters "Dear Professor Terzaghi", whereas Terzaghi generally wrote "Dear Arthur".

35. "Report concerning construction and performance of Bridge River Diversion Dam, February 14, 1958.

36. In his letter to Karl, March 12, 1958, Arthur posed the following hypothetical question: "Let us assume that the explorations for the Mission Dam had been carried out without the knowledge we derived from the Diversion Dam, what is the probability that a satisfactory design could have been evolved if one had followed what you would consider a thorough job by an experienced soils engineer?" Unfortunately the answering letter, if there was one, has not been found.

37. PVC-KF367, according to Charles Ripley.

38. In this method, bentonite-clay is mixed with water into a slurry and poured into a continuous trench; the density of the slurry supports the walls of the trench while operations are conducted in the trench bottom.

39. Letter from Terzaghi to Yves Lacroix, February 7, 1962.

40. Letter from Terzaghi to F.A. Lazenby, February 7, 1962.

Chapter 19

1. Year's end entry for 1953 in Terzaghi's work diary.

2. "The influence of geological factors on the engineering properties of sediments", *Economic Geology, Fiftieth Anniversary Volume*, pp. 557–618 (1955).

3. In effect, soils engineering had returned to its roots, but on a higher level. Professor T.L. Brekke tells of a student who, after hearing a particularly complicated lecture on physics thanked the professor as follows: "Before I heard you speak I was confused on this subject. Now I am still confused, but on a higher level."

4. Professor Alec Skempton considers that Terzaghi's great contribution was to replace the ninteenth-century tendency to "write science" by the combination of science with practice. This was Terzaghi's supreme message. (In an interview, December 15, 1993.)

5. Included in "Soil Mechanics in Action" *Civil Engineering*, February, 1959.

6. From a letter to C.P. Dunn, September 8, 1961.

7. Published in the *Journal of the Boston Society of Civil Engineers*, vol. 45, (1958) no. 1, pp. 1–15 and no. 3, pp. 275–277. This paper was reprinted in the Anniv. Vol.

8. Discussion by H.J.B. Harding, Consulting Engineer, London, in *Journal of the Boston Society of Civil Engineers*, July, 1958, pp. 263–266. Engineer J. Barry Cooke of the Pacific Gas & Electric Company was influenced by Terzaghi's discussion of the merits of individual consulting in deciding to leave PG&E to become one himself (in letter from Cooke, October 2, 1961).

9. Bjerrum's article was "Geotechnical properties of Norwegian marine clays", *Geotechnique* vol. 4, (1954) pp. 49–69.

10. Written in Terzaghi's work diary for 1958.

11. In letter from Skempton to Terzaghi, March 4, 1959. Fillunger's tests were on "unjacketed" specimens, implying that the external and internal water pressures were equivalent.

12. Letter of May 22, 1959 from Alec Skempton to Terzaghi; in an earlier attempt Skempton had written "not *fully* understood" but Casagrande suggested deleting "fully".

13. In Terzaghi's letter to Bjerrum, September 30, 1958. This was one of the few letters in the mass of correspondence on the writing of the Anniversary Volume that was sent without also sending copies to the whole committee.

14. T's means Terzaghi's. Karl often identified people in his letters by only the first letter of their last name, providing a riddle for the researcher.

15. This talk was published under the title "Past and future of applied soil mechanics" in *Journal of the Boston Society of Civil Engineers*, April, 1961, pp. 110–139, with discussions by Ralph Peck, James Stratton, and W.J. Turnbull as well as Closure by Terzaghi.

16. The James Alfred Ewing Medal.

17. Review of "From Theory to Practice in Soil Mechanics" in *Civil Engineering and Public Works Review*, vol. 56 (1961) no. 659 (Author's initials D.L.B.)

18. Kevin Nash, "K. Terzaghi: Founder of the Science of Soil Mechanics." A review of "From Theory to Practice in Soil Mechanics" *Nature*, vol. 161, July 15, 1961, p. 210.

19. R. Glossup, "Review of 'From Theory to Practice in Soil Mechanics'" in *Geotechnique* vol. 13 (1963), pp. 91–92.

20. November 1, 1960.

21. Quoted by Terzaghi in his letter to F.E. Schmitt, October 14, 1943.

22. Written in Terzaghi's year's end summary for 1955 in his work diary.

23. *Proceedings of the Sixth Conference on Soil Mechanics and Foundation Engineering* (Montreal), vol. 3, pp. 78–79; remarks by Bjerrum in the opening session in honor of Karl Terzaghi.

24. This plan was cut short by Laurits Bjerrum's untimely death in 1973.

25. In letter to F.E. Richart Jr., February 2, 1960.

26. Letter to Ralph Peck, March 4, 1960.

27. "A layman's opinion concerning the physicians attitude towards life", unpublished.

28. Letter from lawyer Wilhelm Henrichsen, March 8, 1961.

29. Letter to Laurits Bjerrum, January 31, 1962.

30. From letter to Charles Dunn, September 29, 1961.

31. From letter to Skempton, January 11, 1961, and letter to R.W. Spencer, July 31, 1961.

32. From letters to Laurits Bjerrum, January 12, 1962, and January 31, 1962. The book is "La mécanique des roches" by J.A. Talobre.

33. In Terzaghi's letter to Bjerrum of September 13, 1961, he said the work of Nils Hast was like an oasis in a desert, but on September 20, 1961, he reported to Bjerrum after studying Hast's work that there is only one case record "from which conclusions of interest for the civil engineer can be derived."

34. From year's end statement in work diary for 1961.

35. Letter to Harold Harding, December 16, 1961.

36. Letter to T.M. Leps, February 2, 1962.

37. "Measurement of stresses in rock" *Geotechnique,* vol. 12, (1962), no. 2, pp. 105–124.

38. "Stability of steep slopes on hard unweathered rock" *Geotechnique,* vol. 12, (1962), no. 4, pp. 251–270.

39. "Dam foundation on sheeted granite" *Geotechnique,* vol. 12, no. 3, (1962). Terzaghi had advised the owner, Southern California Edison Company, on this job.

40. *Österr. Ingen. Zeitschrift*, January, 1962

41. Professors Leussink, Lohmeyer, Peterman, and Siedeck.

42. Arthur Casagrande was justified in feeling hurt. His record of achievement in soil mechanics was among the most brilliant of any in soil mechanics, not only in the early days but throughout his long career, until his death in 1981. As Terzaghi's assistant in the late twenties he greatly advanced laboratory testing and description of soil index properties: grain size distribution, permeability, and Atterberg Limits. He was a pioneer in explaining the structure of clay soils and the need to work with minimally disturbed samples. He significantly improved the consolidation test and showed how to find the preconsolidation pressure of a clay. He pioneered the concept of a critical void ratio in sands. He advanced the art of making seepage estimates with Forchheimer's flownets. And he made significant contributions to measuring the shear strength of laboratory specimens of soils. These and other keystones in the history of soil mechanics

were deftly promoted through his outstanding teaching and extensive consulting activities.

43. Letter from Arthur Casagrande to H.Q. Golder, March 9, 1962.

44. Letter from Hugh Golder to Arthur Casagrande, March 20, 1962. *Fröhlich* can be translated as "happy". Arthur did not accept the responsibility of signing such a letter and let it drop.

45. Forecast of the performance of the Mission Dam. B.C., by Karl Terzaghi, February 26, 1963.

46. Letter to Yves Lacroix, July 6, 1962.

47. Entry in work diary for October 2, 1962.

48. His list included Arthur Shaw's widow, the Vienna mechanician Sentall (from the time of the Anschluss), Bruno Sander, Harold Reiterer (an artist who had painted Karl at work in the 1930s), G. Ischy, Wynne-Edwards, Victor Dolmage, R.W. Spencer, and artist Hilde Uray (who sculpted his bust for the Terzaghi Library).

49. Telegram from Laurits Bjerrum, October 2, 1963.

50. Letter to E.P. Hamilton, October 6, 1963.

51. The first quote was written to Ralph Peck on October 25, 1963, and the second to Laurits Bjerrum, November 25, 1963. According to Leo Casagrande's widow, Carla Maria Casagrande, Arthur's father, August Casagrande, died by suicide following a period of depression brought on by his internment and escape from a Siberian prisoner of war camp after the first world war. He had walked from Siberia back to Austria.

52. Presented to the guests at his 75th birthday celebration, October 2, 1958.

53. From Goethe's *Faust*. Terzaghi had made much of this sentence in the instructive letter he wrote to his son Eric two years earlier (March 5, 1956).

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