Risk of collapse features from near surface cavities in old mining cities

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Abstract: Before the industrial revolution in the 19th century, mining concentrated on near surface coal and ore deposits. This caused the growth of old industrialized centres in many European countries. In places the exploitation of ornamental stone or the construction of large cavities for ice, beer or wine production was also undertaken. In recent development, rehabilitation or re-use of abandoned mining or industrial sites has caused difficulties. Collapse features, unknown underground openings, risks of ground subsidence or the effusion of methane are obstacles for investment in these areas.

Based on the abandoned coal mines north of Aachen, Germany, the search for and detection of previously unknown shafts, old galleries and mined coal seams are presented. Furthermore, the subsequent remediation measures are dealt with, for example the construction of reinforced concrete slabs on top of the bedrock, placing and compaction of the fills or at other sites design and execution of extensive grouting work. The analysis of the industrial history, the interpretation of old maps including their transformation into the actual coordinate system of modern maps has proven to be a successful tool. Special GIS-based maps show the local hazards considering the geological situation, mining operations in the past, overlying sediments and other information. A method for estimating the maximum size of possible collapse features is currently being researched.

Résumé: Avant la révolution industrielle dans le 19. siècle l'industrie minière se concentrait aux mines près de la surface, de manière qu'aux nombreux pays européens des centres industriels s'étendraient, où se trouvent aussi l'exploitation locale des matériaux de construction ou la création des grands caves comme dépôt de glace, bière ou vin. Des trous sous-sol inconnus, le péril d'affaisement ou du méthane échappant empèchent l'investissement pour la réhabilitation ou la reprise des mines abandonnées et des sites industriels.

La région houillière d'Aix-la-Chapelle serve à l'exemple pour la recherche des puits inconnus et des mines près de la surface. Le procédé de la consolidation est décrit, p.e. la construction des plateaus du béton au fond, la mis en place et la compaction du remplissage, la planification et la réalisation de la cimentation. Une méthode prometteuse est l'analyse de l'histoire industrielle, l'interprétation des vieilles cartes topographiques contenante leur transformation à une système de coordonnées actuelle. Des cartes spéciales fondant sur GIS démontrent des zones de péril en considération de la situation géologique, l'exploitation minière passée, la couverture sedimentaire et des autres informations.

Keywords: abandoned mines, cavities, friction angle, geographic information systems, grouting, risk assessment

INTRODUCTION INTO EUROPEAN MINING HISTORY

In pre-historic and historic ages until the 19th century, mining activities could be carried out only in shallow depths, in general above the ground water level. After exploitation, many shafts and galleries were not re-filled, at least not according to modern standards and technologies.

Consequently, ancient mining cities are undermined by a lot of known or unknown underground cavities of unknown stability. In parts, these cavities are still present, partly they have collapsed or might collapse in the future. This means a major geological hazard.

In the past, many ancient mining areas, with the related geohazards, were excluded from any construction measures due to local knowledge. In other cities housing areas and later industrial sites were constructed above active or abandoned mine workings. Paris is a typical example with it's widely spread underground excavation of gypsum and limestone. In Germany, Oppenheim at the Rhine River, several other cities and a lot of villages are undermined by kilometres of galleries for the deposition of beer, wine and ice, taken from frozen rivers during the winter season. In the Harz and Erzgebirge Mountains shafts and galleries from ore mining are widely spread.

But the most important mining legacies in Europe result from hard coal mining in a long belt from Great Britain and northern France via Belgium and Germany up to southern Poland and the Ukraine in the east. The Aachen hard coal mining district is described in the following chapters as a typical example for recent problems resulting from mining legacies.

HAZARDS RESULTING FROM FORMER MINING ACTIVITIES IN THE AACHEN HARD COAL MINING DISTRICT

The Aachen hard coal mining district is one of the oldest mining areas within Europe. Mining activity is proven to date back as far as the 12th century. Mapped information about the mining legacies before the 19th century is almost nonexistent. The former mining activity resulted in various hazards for buildings and people.

Abandoned shafts often only have a partial or unstable filling or in some cases even no filling at all. This can lead to sudden collapse features at banking level. Moreover, mine gas (methane) can be emitted into the atmosphere through shafts. This is especially dangerous if such gas can accumulate underneath, or even within, buildings and ignite at some moment. The number of such potentially dangerous shafts within the Aachen hard coal mining district currently is estimated with more than 800 within an area of only about 19 km².

Collapse features also occur above outcrops of mined coal seams. Underground mining spaces, which are stable in the first instance, can become unstable with time due to numerous processes, e.g. decay of supports, progressive failure, creep, weathering, hydraulic changes and stress redistribution.

Dewatering galleries usually have rather small dimensions of up to about 1.4 m x 2.0 m and often are partially filled with sludge. A cover of 10 m Carboniferous rock is deemed to be sufficient to keep the roof of the void stable. This is the case for almost all galleries within the Aachen hard coal mining district and are therefore neglected as hazard sources in this paper.

Another post mining hazard is induced by the end of mine water drainage. Mine water is rich in dissolved salts and minerals and can pollute the groundwater, rivers, lakes and the soil, if it rises and is allowed to enter these media. Beyond this, mine water recovery can lead to differential heave along tectonic faults and damage buildings significantly.

HAZARD ZONE DESIGN

For different hazard sources, different approaches to the design of hazard zones are currently applied. The hazard zone design methods related to coal seam outcrops on the one hand and shafts on the other hand are depicted in the following sections.

Coal seam outcrops

Due to the intensive folding of the Carboniferous rock, the hard coal seams within the Aachen mining district crop out at the top of the Carboniferous. If these coal seams were mined at shallow depths, the roof can collapse at some point in time and the cavity can then migrate upwards resulting in a collapse feature at banking level.

In the last 5 years, in the Aachen hard coal mining district intensive theoretical work has been done to distinguish different hazard classes as shown in Table 1. These depend on the dip angle of the coal seam and its workability, i.e. thickness of the coal seam and the evidence of mining activity from historical documents. The coal seam inclination is considered, since cavities in steep coal seams tend to last for a longer time than such in plane coal seams because the vertical underground stresses generally are larger than the horizontal components. Hence, the probability of cavities still being present and potentially hazardous is higher in coal seams with a steep inclination.

Table 1. Hazard class assessment above coal seam outcrops

Hazard class	**Criteria**
Hazard class 1	High probability of collapse features / subsidence (evident mining activity and coal seam dipping > 36°)
Hazard class 2	Medium probability of collapse features / subsidence (Main coal seam dipping > 36° without mining evidence, Main coal seam dipping ≤ 36° with mining evidence)
Hazard class 3	Low probability of collapse features / subsidence (Coal seam dipping > 36° without mining evidence, Main coal seam dipping ≤ 36° with uncertain mining evidence)
-	Remediated area / Area with proven stability

If hazard class 1 or 2 are assigned, on-site investigations are needed before building can be permitted. In zones with hazard class 3, further intensive investigations are necessary for sensitive buildings of the geotechnical category 3 according to the Eurocode 7 (power plants, chemical facilities, etc.).

The width of the hazard zone perpendicular to the coal seam outcrop comprises the endangered area at the top of the Carboniferous and twice the thickness of the overburden assuming an angle of break of 45° within the overburden (see Figure 1). The size of the hazard zone along the coal seam outcrop depends on mining activity and geological constraints, e.g. faults. The width of the endangered area at the top of the Carboniferous is estimated based on an empirical alignment chart by Hollmann & Nürenberg (1972).

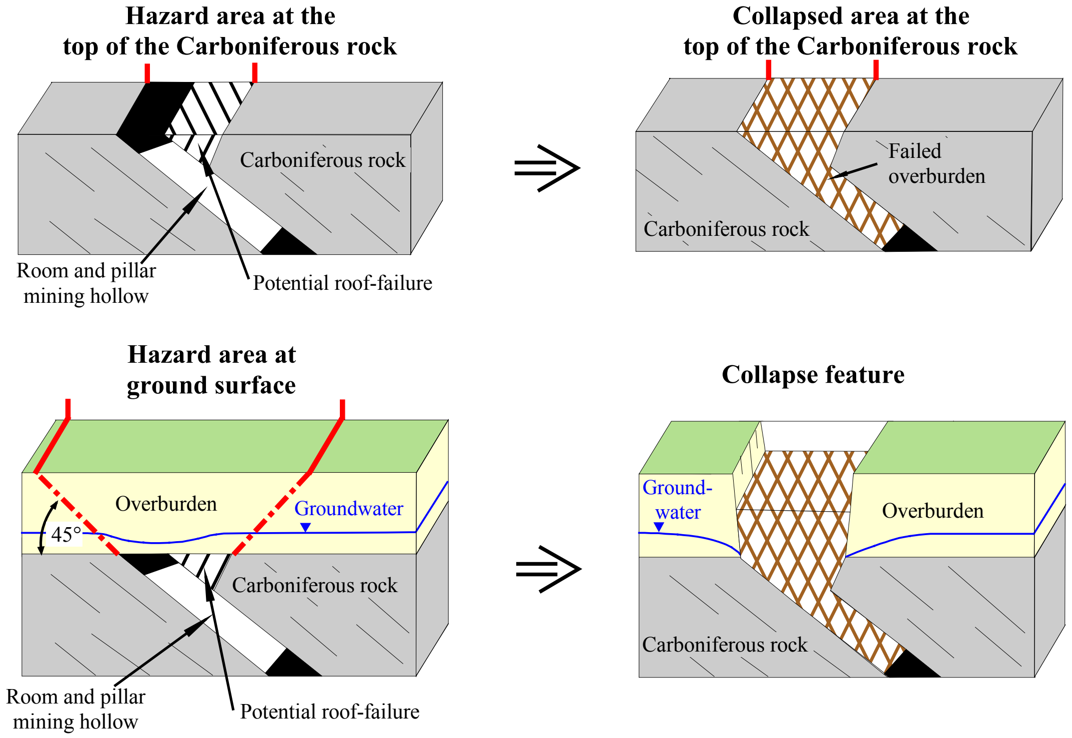

Figure 1. Hazard of collapse features above coal seam outcrops

Shafts

Shafts pose two kinds of hazards to the ground surface; collapse features and methane gas emissions. For both kinds of hazard, different hazard zones are assigned.

Collapse features

Shaft hazard zones for collapse features are designed assuming an angle of break of 45° within the overburden as shown in Figure 2. The diameter of the hazard zone for collapse features comprises the shaft diameter, twice the thickness of the overburden, twice the thickness of the shaft support and twice a safety distance of 1.5 m for possible disaggregation of the rock surrounding the shaft.

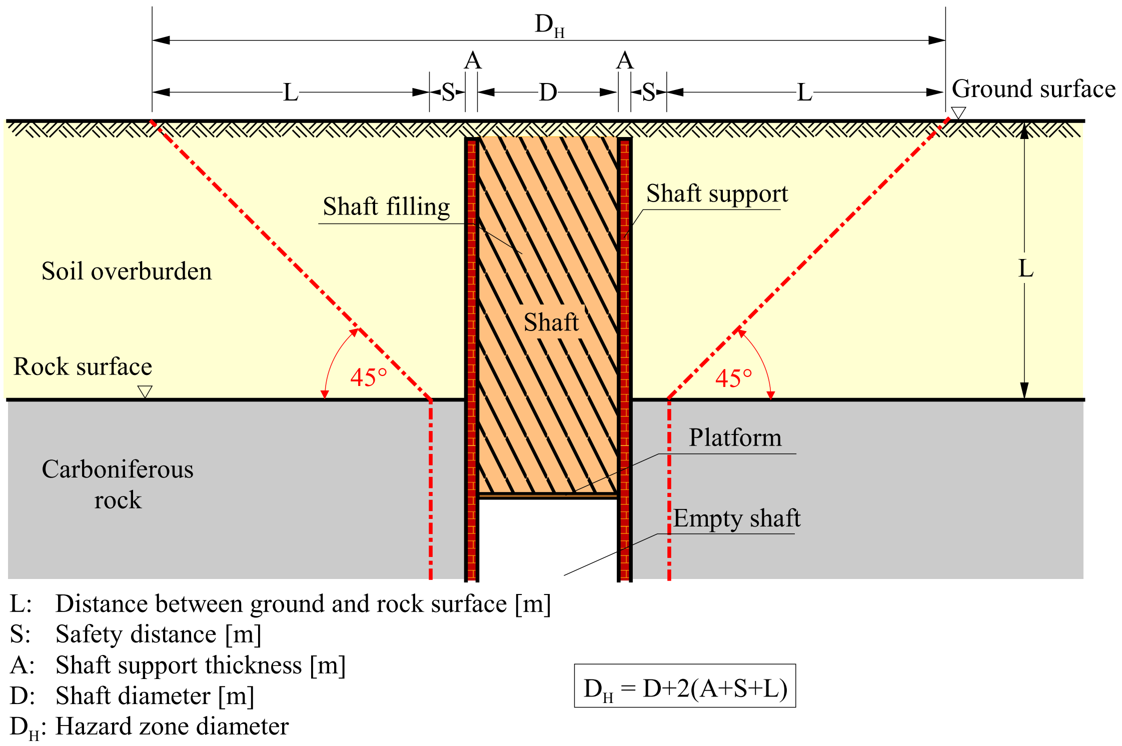

Figure 2. Shaft hazard zone design

Gas emission

Around shafts, a gas hazard zone for potential methane gas emission with a diameter of 40 m is assigned. Within this hazard zone, buildings must be protected against gas for example by granular fill venting media and gas proof membranes. Water pipes, in which gas could accumulate, also have to be sealed against methane.

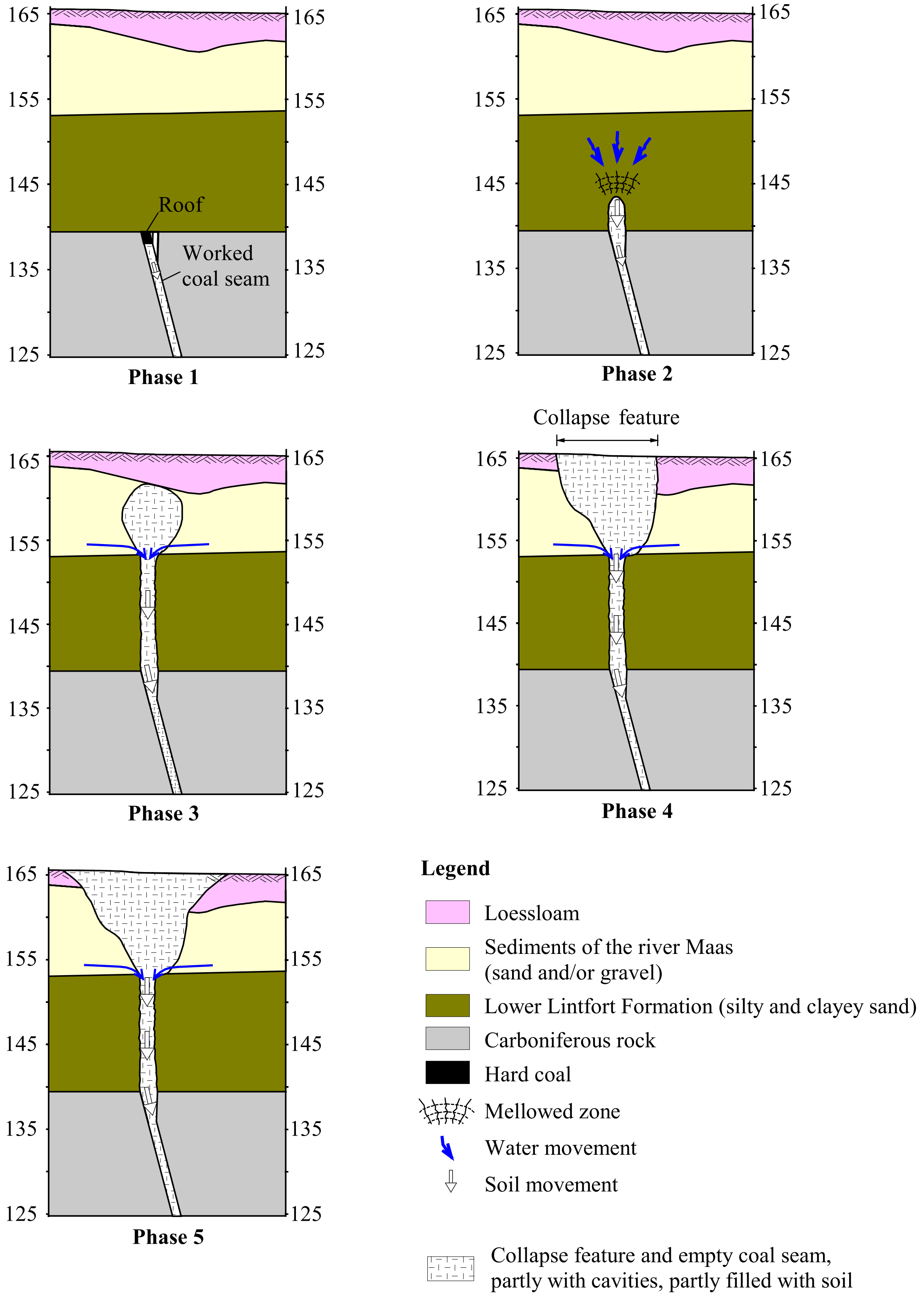

Figure 3. Multiple phase model

PROPOSAL FOR THE FUTURE DESIGN OF HAZARD ZONE WIDTHS

The hazard zone design methods currently used for the Aachen hard coal mining district assume an angle of break of 45° within the soil overburden above coal seam outcrops and around mining shafts. This approach does not take into account any soil mechanical properties of the different soil strata of the overburden. In order to minimize the width of hazard zones, a new approach to the design of hazard zones based on a geotechnical model of the processes within the overburden is actually under development for the Aachen hard coal mining district (Heitfeld et al. 2005). One of the authors (Mainz) is planning the publication of a PhD thesis on this subject for 2006.

Within the study, borings and penetration tests on collapse features above coal seam outcrops were analysed and extensive laboratory works were performed in order to determine the mechanical properties of the different types of soil strata of the overburden. The field investigations revealed that the collapse process can be partitioned into single process phases with different collapse geometries depending on the soil properties (s. Figure 3). In phase 1, the roof pillar of an empty coal seam collapses. The resulting opening at the top of the Carboniferous induces an erosion pipe migrating upwards through the cohesive Lower Lintfort Formation in phase 2. As soon as this erosion pipe reaches the gravels and sands of the sediments of the river Maas, the cavity starts widening whilst continuing to advance towards the ground surface (phase 3). At some point in time, the soil arch above the cavity becomes too thin and hence unstable. Phase 4 is reached when this soil arch collapses and a collapse feature occurs at ground level. Typically the soil arch collapses along vertical shear planes. The collapse feature then enters phase 5, forming slopes according to the angle of friction of the soil, if no remediation is implemented. Nowadays an immediate filling of the collapse feature can be assumed for the Aachen hard coal mining district, preventing the collapse from entering phase 5.

The fact that within the Lower Lintfort Formation no growth of the cavity towards the sides was observed and the cavity develops as a vertical pipe, can be explained by the cohesion of this layer. This cohesion prevents the Mohr-Coulomb failure criterion from being fulfilled (Heitfeld *et al.* 2005). The upward migration of the cavity is a pure vertical erosion process. When the cavity reaches the gravel and sand of the sediments of the river Maas, the soil properties change and the cohesion drops. Now the Mohr-Coulomb failure criterion is fulfilled (Figure 4) and the soil shears with an angle of break of $\beta = 45° + \varphi'/2$ resulting in a funnel shaped part of the collapse feature. The fact that collapse features are spatial objects, hereby has no influence on the inclination of the shear planes (Matsouka & Nakai 1983).

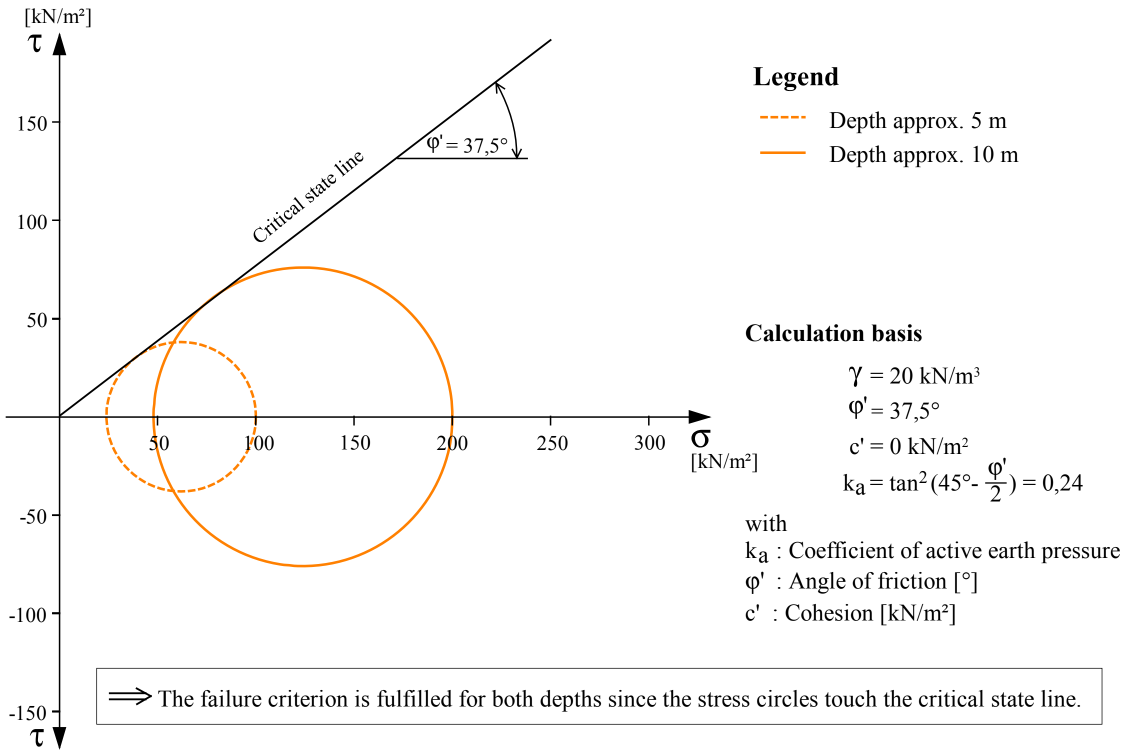

Figure 4. Mohr-Coulomb failure criterion for the Sediments of the river Maas

These observations allow for the formulation of a model for the future design of hazard areas above coal seam outcrops within the Aachen hard coal mining district (see Figure 5). In this model, it is assumed on the safe side that the funnel shaped part of the collapse feature can propagate until the Loessloam is reached, before the vertical shear plane forms. Before using this model in practice, safety factors should be agreed with the particular responsible mining authorities.

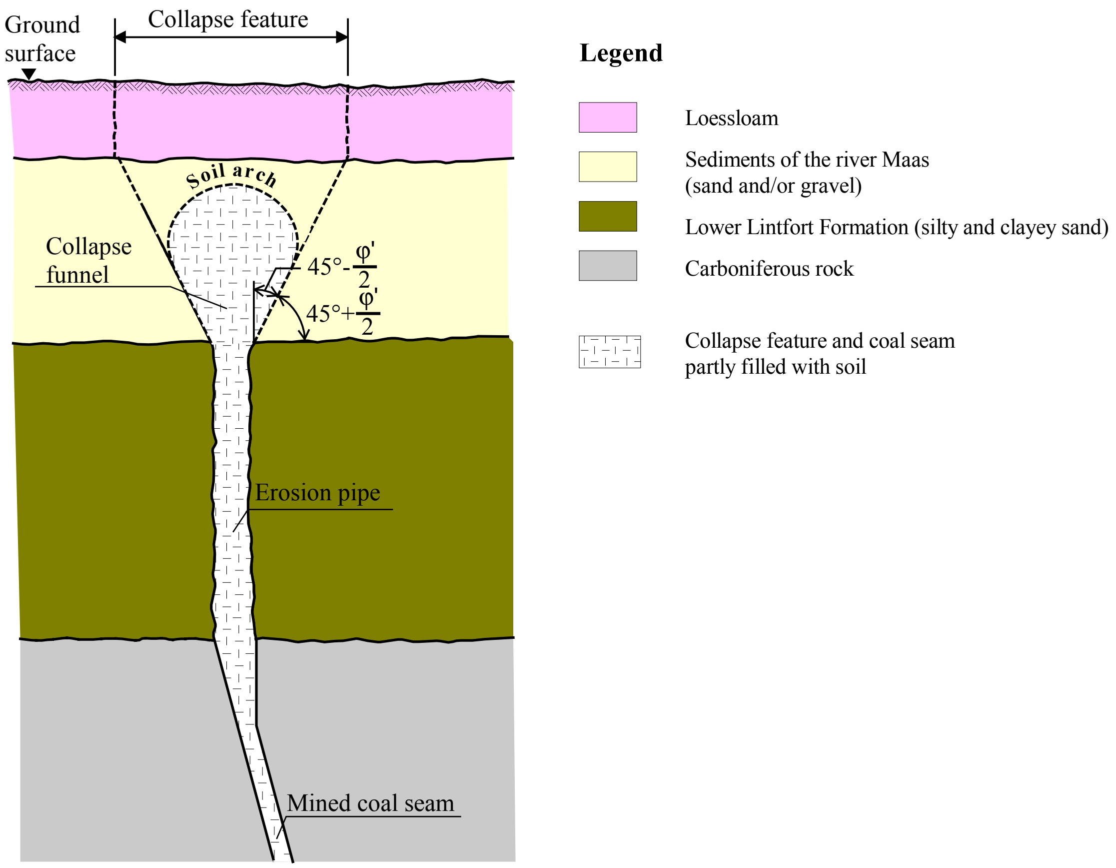

Figure 5. Collapse feature model

Theoretically, this model also should apply to shafts. If for example a shaft is filled partially above a platform, a collapse feature could develop in two ways. If the shaft timbering does not decay and the platform and filling fails into the deeper parts of the shaft, at ground surface a collapse feature occurs with the inner diameter of the shaft support.

If on the other side, the shaft timbering decays whilst the shaft filling keeps its position due to friction forces, a collapse feature could develop similarly to the process described above by continuous upward migration of a cavity (see Figure 6).

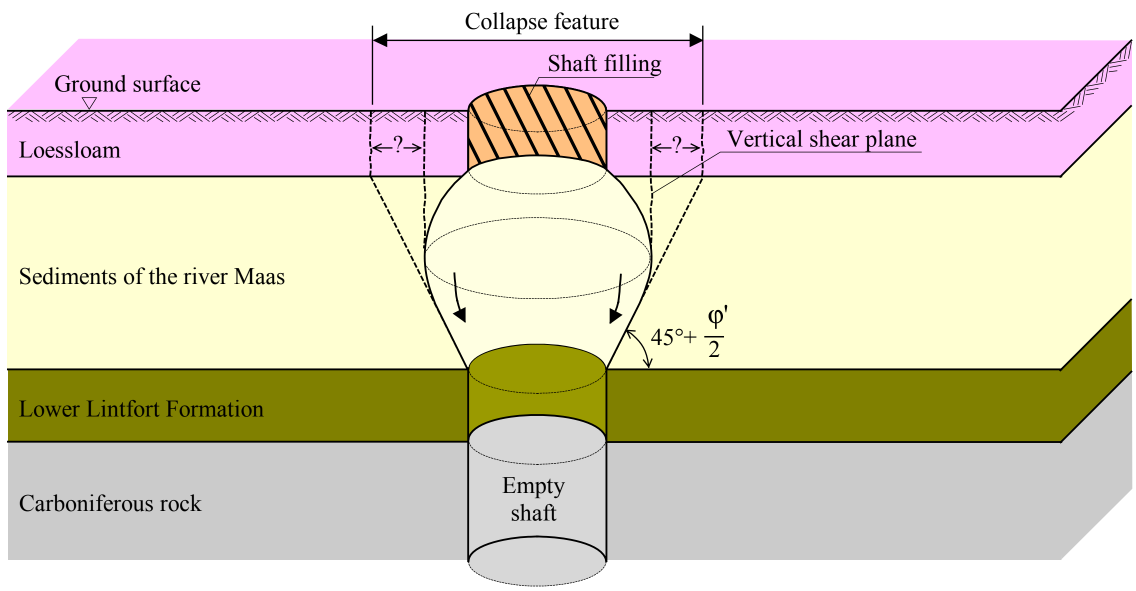

Figure 6. Collapse feature above a shaft

HAZARD SOURCE DETECTION METHODS

Desk Study

The identification of possible hazard sources from ancient hard coal mining activities within the Aachen mining district has been developed methodically during the last years by a working group of engineering geologists, civil engineers and mining engineers. The concept is based upon a connection of modern computer technologies and classical methods of geology and engineering geology.

When investigating post mining legacies, the first problem is that the old maps and profiles sometimes are heavily damaged and beyond this are not based on the coordinate system which is commonly used today. In recent years, it was decided by the working group to scan such old mining plans with an A0 colour scanner in order to prevent further loss of information.

In a second step, the mapped information is projected upon the actual topography using modern software (WGEO® Georeferencing & Geoimaging). At the same time, rectification and recovery of the inner geometry of a map can also be performed if necessary. Depending on the quality of the originals and the local conditions, a location accuracy of about ± 10 to 15 m can be achieved using this method. Further editing of the georeferenced maps takes place using a GIS-System. Figure 7 shows a detail of a georeferenced historical map with some highlighted mining legacies.

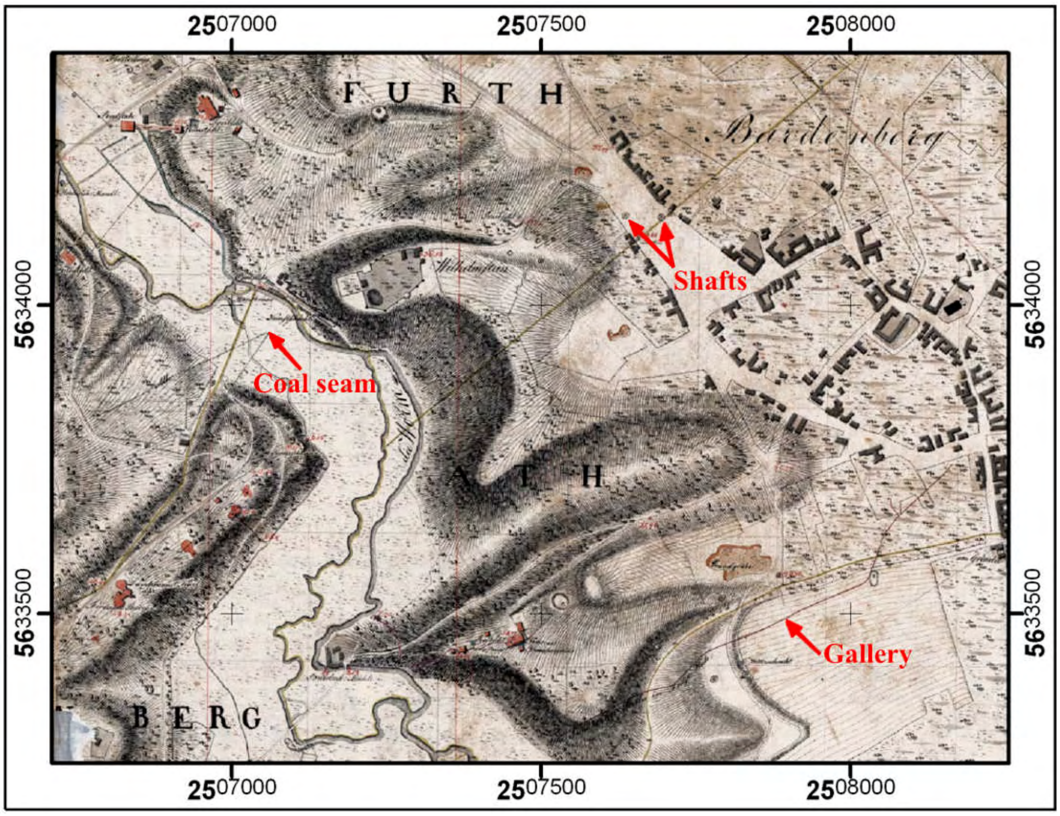

Figure 7. Georeferenced historical map with some highlighted mining legacies

Parallel to this, systematic methods of registration and analysis of historical maps, two different databases with data related to currently 800 old shafts and about 8,000 mining documents were also established. In the database 'Mining shafts' each datasheet contains all available information about a single shaft, ranging from basic topographic data (coordinates, banking level, etc.) up to more specific information like history, function, timbering or former remediation works. The second database 'Mining documents' comprises all available information about old mining documents that are preserved in the archives. The data sheets contain for example specifications about author, year, kind of map, mapped area.

Recently an important tool has been implemented in both data bases to find and list up all mining shafts as well as all mining documents for a defined area. This search function is based on coordinates and the official maps. The two databases together render a first possibility to get a general view on the mining legacies, that have to be expected in a certain area. For the next years, the set up of a Geo-Information-System "Mining Legacies" for the Aachen hard coal mining district is planned. This GIS-Project is intended to be used by the local authorities to get a basis of evaluation for further land planning.

The registration and analysis of the historical documents in most cases allow for a first spatial demarcation of areas in which shafts and galleries have to be expected. Whilst infrastructural mine components, such as shafts and galleries, are usually depicted in old maps, the shallow working areas are usually not documented. Because of these circumstances it is crucial for a systematic investigation to work out a clear geological tectonic model based on an analysis of all available documents. In this context, it is most important because the Carboniferous rocks are folded intensively within the Aachen hard coal mining district and there are numerous tectonic faults. A projection of all known mine workings, of the mineable coal seams as well as the axes of synclines and anticlines onto the ground surface (respectively the top of the Carboniferous if overburden is present) is the basis of the demarcation of hazard zones as well as for the choice of the location of borings.

Field Investigation

Two objectives of the field investigations performed in the last years within the Aachen hard coal mining district can be distinguished. On the one hand, mining legacies had to be detected and assessed with regard to planned buildings and to be stabilized if necessary. Such investigations and rehabilitation schemes usually were financed by the building owner. On the other hand, some shafts and shallow mine working were investigated as part of a public hazard assessment programme. Field investigations are an important chance to review the theoretical hazard potentials and allow for a continuing adjustment of the assessment criteria of hazard classes.

For the localization and investigation of shafts as well as for shallow mine workings, core drillings are proven to be essential. The old shafts and also the shallow mine workings often are filled with a mixture of sand, gravel, silt, stones, mine waste and rock debris which have got a weak consistency, representing a loose packing density. Trials to find such zones with rotary borings and other destructive drilling methods in most cases had insufficient results. Geophysical methods on trial areas were likewise insufficiently successful. One reason for these deficient results is that the Carboniferous bedrock in many areas is covered by up to 25 m of soil which has a significant influence on geophysical methods. Moreover, the filling material of the shafts is often composed of a mixture of the local overburden, so that no clear differences in the geophysical properties are present.

Commonly, the search for old mining shafts within the Aachen hard coal mining district is performed using inclined core drillings. These borings aim at on the proposed shaft filling from a safety distance. The theoretical aiming point is chosen in such a way, that the entrance of the boring into the shaft lies within the Carboniferous rock. This may mean that up to 25 m overburden have to be penetrated first, but it also means a much higher safety for men and equipment during the drilling works. Investigation borings on shallow mine workings are performed in a similar way as inclined core borings into shafts. Figure 8 shows an inclined corehole for detecting a shaft in the direct vicinity of residential buildings.

After a shaft has been investigated sufficiently in terms of its location and dimensions, a vertical investigation boring is drilled through the shaft filling. For safety reasons this vertical boring is executed from a steel platform in order to minimize loads and vibrations from the boring works on the shaft filling.

Figure 8. Inclined boring on a shaft with adjacent residential housing

Examples of the experiences made with such vertical borings into old shafts during the last years are:

- The shaft was filled with soil down to a wooden platform. Below the platform the shaft stood empty.
- Within the shaft filling cavities and very loosely compacted material were encountered.
- The shaft filling became unstable due to the boring works and at banking level settlement occurred.
- Wooden constructions which had collapsed into the shaft and some filling materials (e.g. boulders, ropes, iron parts) resulted in major technical difficulties during the boring works.

REMEDIATION METHODS BASED ON TWO CASE STUDIES

Two significantly different case studies are discussed below. In case study 1, a commercial area was planned on agricultural land at the border of a city. Intensive investigations and rehabilitation measures of coal seams underneath a thick overburden were necessary before the start of the building construction works. In case study 2, a collapse feature had occurred on an old shaft surrounded by only a thin overburden. Remediation of the hazard source had to be implemented.

Case study 1: Investigation and stabilization of worked coal seams underneath a thick overburden as a preventive measure before start of building construction

The city of Herzogenrath, north of Aachen, has been influenced by hard coal mining activity for centuries. Here the coal seams crop out at the ground surface within deep valleys, whilst in other areas the Carboniferous rock is still covered by about 25 m thickness of overburden.

With cessation of the deep mining activity and the ongoing structural change, a previous agricultural area of 110,000 m² with mining legacies was planned to become a new technology park. The analysis of the historical maps and the elaboration of a geological-tectonic model identified 10 old shafts and 13 coal seams on site, cropping out at the top of the Carboniferous, underneath a soil cover of 25 m. For these coal seams according to the mining documents it had to be assumed that shallow mining took place up to the top of the Carboniferous rock.

In some parts, there were collapse features depicted in the historical maps indicating the possibility of mining cavities migrating through the overburden up to the ground surface. The methods for assigning hazard classes to coal seams as described above were not yet completed at the time of these investigations. Instead, the essential results of the field investigations described below were used to assess the theoretical hazards. Within the scope of the investigation of the shallow coal seams, in about 1 year 224 core borings were drilled with in total approximately 9,500 m of boring. The objectives of the borings were to determine the possible worked coal seams in a depth of about 15 m underneath the top of the Carboniferous rock. Hence, the depth of the investigation borings was about 40 m. 5 of 13 coal seams cropping out at the top of the Carboniferous extensive shallow mining workings were detected. The main results of the borings can be summarised as follows:

- About 32 % of the borings had eye-catching results indicating shallow mining.
- In 58 % of these borings, completely disaggregated rock was found at the depth where the worked coal seams were expected. Here, the worked coal seams obviously had mostly filled up with failing roof rock and compaction processes.
- Only in one of the 72 eye-catching borings a cavity with a horizontal length of about 0.8 m was found.
- In 42 % of the eye-catching borings, soil from the overburden was found within the mined coal seam, indicating an upwards migration of the cavity through the overburden.

The mine workings investigated by the borings were stabilized by cement grouting. The injections were generally performed in an A-, B- and C-series with decreasing distance between the borings. Usually, the distance between the borings in the critical coal seam parts was about 10 m. In cases where the ground took up very high grout injection volumes, the spacing was reduced to < 5 m. Figure 9 shows the underground cement injection capacity of the three injection series on the coal seam ‘Großathwerk’ as an example. Thus it appears that the overall cement injection quantity (solid contents) at the beginning of the injection (A-series) was 8.6 t/boring. In the B-series, the overall cement injection quantity dropped down to 5.2 t/boring and in the C-series the underground only took up 2.9 t/boring on the average. Table 2 shows the main injection results for all 5 mined coal seams on site.

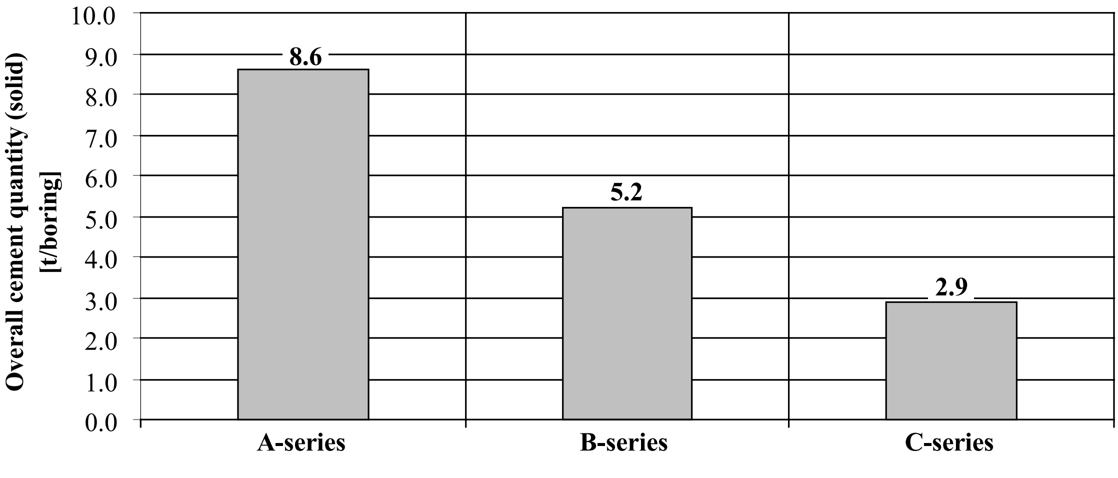

Figure 9. Cement injection quantities of the injection series on the coal seam ‘Großathwerk’

Table 2. Injection results

Coal seam	No. of injection borings	Cement Quantity (solid) [t]	Overall cement quantity (solid) [t/boring]
Schmalemau	7	70.6	10.1
Rauschenwerk	16	47.4	3.0
Großathwerk	47	357.8	7.6
Furth	52	332.1	6.4
Croat	17	318.6	1.6 (18.7*)
Total	139	1,126.5	8.1

* tectonic faults crossed by drillings

Table 2 shows that a total amount of about 1,100 t (solid contents) was injected in order to stabilize the shallow mine workings. The main coal seams ‘Furth’ and ‘Großathwerk’ and also the relatively thick ‘Croat’ seam took up the highest quantities with about 300 to 350 t each.

Case study 2: Stabilization of two shafts after a collapse feature in a thin overburden

A collapse feature occurred in 2003 on a parking and turning area of a factory. A truck broke into the collapse feature with its front axle. The collapse feature had a diameter of about 2.4 m and a depth of about 1 m (see Figure 10.). The analysis of the available mining documents indicated that the collapse feature most likely occurred above an old hard coal mining shaft. In this part of the Aachen hard coal mining district, the Carboniferous is only covered by a relatively thin overburden (< 5 m).

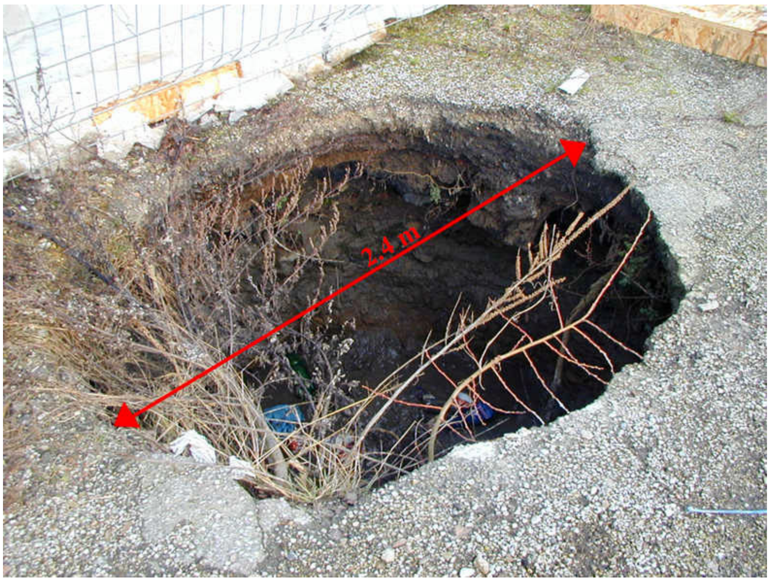

Figure 10. Collapse feature above an old mining shaft

Subsequent boring works were carried out to investigate the causes of the collapse feature. The dimensions of the assumed shaft and possible destabilized zones surrounding the collapse feature clearly identified that not only had a collapse feature occurred above an old extraction shaft, but there was also another old shaft within a distance of only 6.5 m. Moreover, the ground surface settled when the inclined core borings were drilled into the shaft. The pros and cons of different stabilization methods were evaluated. Finally, it was decided to excavate both shafts down to the stable and firm Carboniferous rock and to construct reinforced concrete slabs upon the rock surface. This was undertaken by excavating two pits with an inner diameter of 5 m and 5.5 m, with shotcrete walls. In both excavation pits, the top of the Carboniferous was reached at a depth of 5 to 6 m. The contours of both old mining shafts were clearly visible in both pits although no shaft timbering or masonry was observed. Figure 11 shows the old shaft with rectangular dimensions of 1.8 m x 2.5 m found underneath the collapse feature.

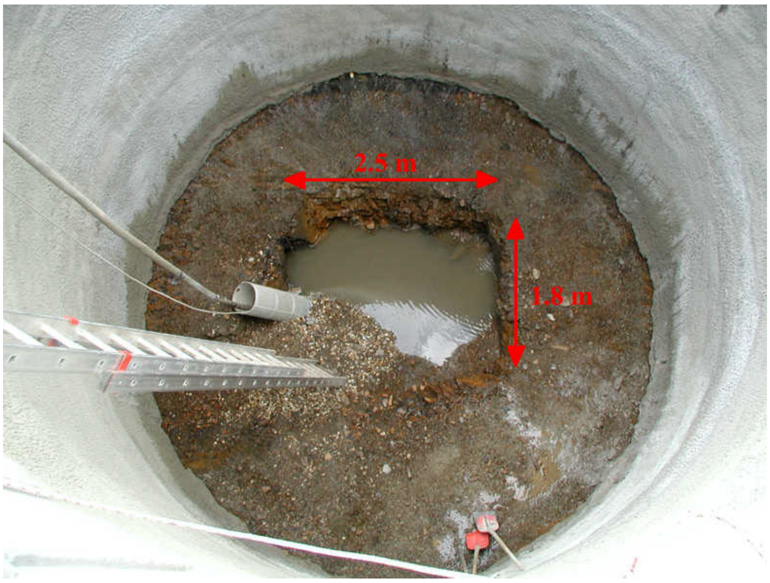

Figure 11. Floor of the excavation pit in a depth of 5.9 m with the outline of the old extraction shaft

The second shaft, which was not mentioned in the historical documents, was significantly smaller with dimensions of about 1.3 m x 1.6 m. During the excavation works, when the filling of the larger shaft was dug out, it appeared that the filling material of the shaft was silt and sand of a weak consistency and hence had little bearing capacity. It can be assumed that a cavity had existed underneath the bituminous pavement for longer and the weight of the moving truck induced the collapse feature.

Both shafts were stabilised with reinforced concrete slabs as shown in Figure 12. In each slab a refill opening was installed with a control shaft going up to the ground surface. The control shafts were then filled with gravel. In a monitoring programme the filling of the control shaft and the filling of the old shaft is controlled with regard to settlements. If necessary, gravel can be refilled.

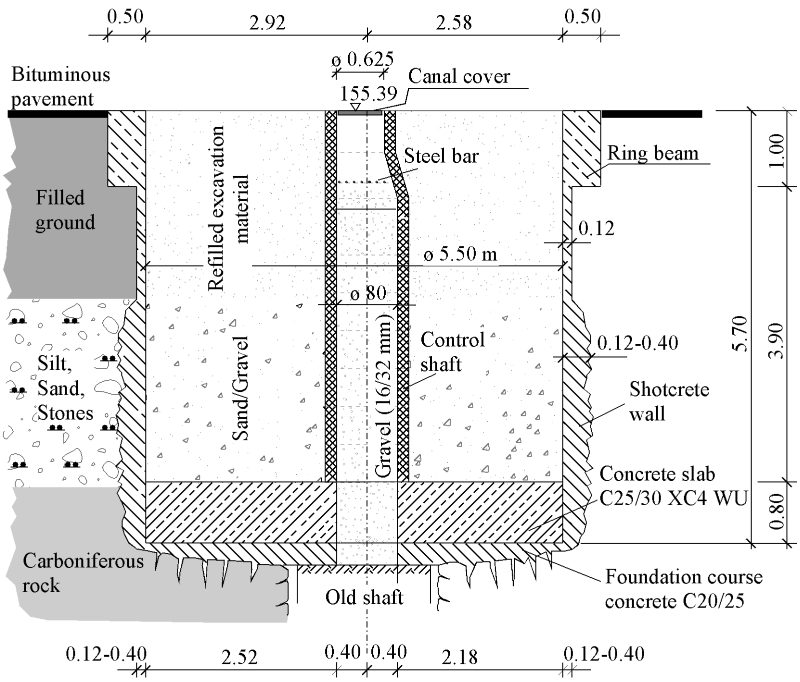

Figure 12. Profile of the excavation pit with old shaft and reinforced concrete slab

OUTLOOK

In the future, the remaining mining companies in most parts of Europe will concentrate exploitation areas of very high capacities and consequently other mine fields will be closed. On the other hand, increasing underground structures in urban areas requires adequate management of the hazards resulting from mining legacies and subsequently the development of hazard zoning systems and a risk assessment acceptable by the public. Metro lines, alignments for water supply, sewerage, energy supply and telecommunication, as well as deep foundations or the exploitation of geothermal energy, demand a more detailed knowledge of underground cavities. Therefore, a Europe-wide database and an information system integrating all recent technical experiences and results, as well as the regulations offered by the Authorities, is recommended. A new international ISRM working group on mining closure may be a first helpful step to strengthen the exchange of international experiences about mining legacies. Models respecting the local geological conditions and their mechanical properties as proposed above may become an appropriate tool to manage this widely spread problem in urban areas.

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