Soil & Sediment Contamination, 17:323–345, 2008

ISSN: 1532-0383 print / 1549-7887 online
DOI: 10.1080/15320380802143922

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Enhancing the Safety of Tailings Management Facilities

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Unsafe tailings management facilities (TMFs) have caused serious accidents in Europe (e.g., Baia Mare, Romania, in 2000, Aznalcóllar, Spain, in 1998, and Stava, Italy, in 1985), threatening human health/life and the environment. While advanced design, construction and management procedures are available, their implementation requires greater emphasis. An integrated research project funded by the European Union was carried out between 2002 and 2005 with the overall goal of improving the safety of TMFs (Sustainable Improvement in Safety of Tailings Facilities–TAILSAFE, http://www.tailsafe.com/). The objective of TAILSAFE was to develop and apply methods of parameter evaluation and measurement for the assessment and improvement of the safety state of tailings facilities, with particular attention to the stability of tailings dams and slurries, the special risks inherent when such materials include toxic or hazardous wastes, and authorization and management procedures for tailings facilities. Aspects of tailings facilities design, water management and slurry transport, non-destructive and minimally intrusive testing methods, monitoring and the application of sensors, intervention and remediation options were considered in TAILSAFE. A risk reduction framework (the TAILSAFE Parameter Framework) was established to contribute to the avoidance of catastrophic accidents and hazards from tailings facilities. Tailings from the mining and primary processing of metals, minerals and coal were included within the scope of TAILSAFE. The project focused on the avoidance of hazards by developing procedures and methods for investigating and improving the stability of tailings dams and tailings bodies.

Keywords mining, extractive industry, tailings, tailings management facility, tailings pond, non-destructive testing, site investigation, neutron logging, parameter framework

Introduction

Tailings are fine-grained wastes of the mining industry, output as slurries, due to mixing with water (or solutions containing different chemicals) during mineral processing. Tailings

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management facilities (TMFs) consist of tailings ponds or lagoons, tailings dams and tailings transport systems (usually pipelines). Though separate units, the mineral processing mills have great influence on the operation and safety of tailings facilities. Deposits of these residues in ponds, usually confined by man-made dams, can present a serious threat, especially where there is improper handling and management.

An integrated research project funded by the European Union was carried out between 2002 and 2005 with the overall goal of improving the safety of TMFs (Sustainable Improvement in Safety of Tailings Facilities–TAILSAFE, http://www.tailsafe.com/). The objective of TAILSAFE was to develop and apply methods of parameter evaluation and measurement for the assessment and improvement of the safety state of tailings facilities, with particular attention to the stability of tailings dams and slurries and the special risks inherent when such materials include toxic or hazardous wastes. Aspects of tailings facilities design (Schönhardt et al., 2007), water management and slurry transport (Böhm et al., 2007; Debreczeni and Meggyes, 2007), non-destructive and minimally intrusive testing methods (Niederleithinger et al., 2007), monitoring and the application of sensors, intervention and remediation options (Mylona et al., 2007) and authorization and management procedures (Kreft-Burman et al., 2007) were considered in TAILSAFE. A risk reduction framework (the TAILSAFE Parameter Framework) was established to contribute to the avoidance of catastrophic accidents and hazards from tailings facilities (Engels et al., 2007). Tailings from the mining and primary processing of metals, minerals and coal were included within the scope of TAILSAFE. The project focused on the avoidance of hazards by developing procedures and methods for investigating and improving the stability of tailings dams and tailings bodies (Roehl et al., 2007; Meggyes et al., 2008).

The project's case study sites were tailings facilities in Germany, Northern Hungary, Southern Hungary, Romania, and the UK.

From among the numerous approaches of enhancing safety of tailing facilities as undertaken in the TAILSAFE project, this paper will deal with site investigations with special emphasis on neutron probing, non-destructive geophysical testing methods, authorization and management procedures, developing the parameter framework, and safety considerations.

1. Test Site Investigation in Hungary

1.1. Site Characterization

Four test sites have been investigated within the TAILSAFE project, mainly for potential use of non-destructive methods to determine the parameters related to the stabilization of the tailings facility. Two test sites have been selected in Hungary: uranium mill tailings ponds near the city of Pécs, Southern Hungary, and a tailings pond from zinc/lead ore flotation process near Gyöngyösoroszi, Northern Hungary.

1.1.1. Uranium mill tailings site (Site N1). Hungary was a uranium producing country until 1997, when uranium mining and processing activity was terminated on grounds of economy. About 20.3 million tons of mill tailings were accumulated during the uranium processing activity and they were placed in two tailings ponds with a total area of 156 hectare. The soil beneath the ponds had been treated with lime to decrease hydraulic conductivity. Nevertheless, the soil still exhibits a water conductivity of $\sim 10^{-8}$ m/s, which has led to the seepage of large volumes of process water from the tailings ponds into the subsoil. Therefore remediation of the tailings ponds is focused on two main tasks: long-term stabilization of the tailings bodies and groundwater remediation around the tailings ponds.

1.1.2. Lead–zinc ore flotation tailings site (Site N2). In Northern Hungary, near the village of Gyöngyösoroszi, a zinc-lead ore flotation plant was operated until 1986, when mining and processing was stopped. During the mill's operation 2.94 million tons of flotation tailings were accumulated in three tailings ponds. The tailings ponds were abandoned in 1986; their area is 22 hectare.

1.2. Tailings Characterization

Within the TAILSAFE project different non-destructive methods (NDM) have been tested to clarify the range of their potential application for tailings characterization (s. Section 2). As a part of the program, drilling core samples were collected from the tailings by drilling on different places of the tailings piles. The collected samples were analyzed partly to give background for the interpretation of the results of NDMs, partly to receive additional information regarding the stability of the tailings body and the extent of their contamination with hazardous elements. Based on an earlier publication (Hoffman, 1998), neutron logging was tested for determination of volumetric water contents of the tailings both in the uranium mill tailings and the flotation tailings.

1.2.1. Water content of uranium mill tailings. One of the most important parameters determining stability of tailings bodies is their water content. The change in the water content can be considered as an indicator of the consolidation process. Though water content can be estimated based on earlier water balance data, the current state of the tailings can only be characterized by current real data. Therefore drilling has been undertaken on tailings pond N1 to take core samples from the tailings and from the soil under the tailings pond. The total depth of the borehole was 35 m. Samples were analyzed for water content and other components (see below). The drilling was carried out in the transition zone of the tailings pond loaded with relocated material (approx. 3–4 m) from another part of the tailings pile. Location of the drilling (ZQ) and the calibration hole for the neutron probe are shown in Figure 1.

Figure 2 shows the water content of tailings samples as a function of depth. It can be seen that the water content of the mill tailings is more than twice the water content in the soil under the tailings. This indicates that the consolidation process of the tailings is still going on though the pond has been non-operational for ten years.

1.2.2. Water content of flotation tailings. The water content of the flotation tailings was determined by drillings carried out at six locations on the ponds and analyzing of the collected samples (Figure 3), and was found to be significantly lower than that of the uranium mill tailings (Figure 4). The difference can be explained by the different character of the two tailings bodies (mill tailings were chemically treated and contain gypsum and hydroxides, while flotation tailings just consist of particles of ground ore).

The average water content is approx. 35% and is almost independent of the depth of the tailings. The low value for D-1 borehole samples (D-1, D-2... denote the drillings) at a depth of approx. 10 m is explained by an embedded waste rock pocket.

1.2.3. Neutron logging of boreholes. Settlement gauges usually monitor the consolidation process. This method is perfect if general information is needed concerning the overall

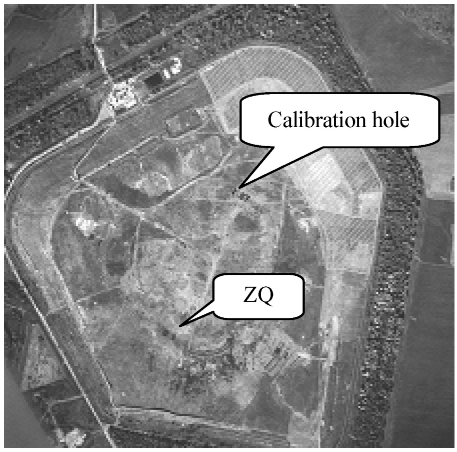

Figure 1. Tailings pond N1 with the location of the drilling ZQ and calibration hole.

consolidation of the tailings but it does not provide information about water distribution over the whole cross-section of the deposit. Both for practical and theoretical reasons it is desirable to have information on the water distribution in the tailings body and its change over time. This can be achieved only if the water content is measured directly at appropriate depth intervals. Neutron logging is one of the methods, which can be used in fixed measuring holes in the tailings material. In the framework of the TAILSAFE project, neutron logging of tailings was tested. Some measuring holes were constructed (Ø = 31 mm tubes were pushed into the tailings).

The experimental neutron probe was calibrated for slimes containing 20–40–60–100% of water. The function of counts per second of the probe vs. volumetric water content of the material at the same depth was determined. Practically the sensitivity of the probe (Am-Be neutron source, 1.2 GBq activity) was 5.5–7 cps per % (% by volume) of water depending on the adjustment of the instrument. It was found that the relation between the cps reading (counts per second) and the volumetric water content is practically linear over a broad range of water content, thus the calibration curve for water content in the tailings can be determined easily by logging the borehole.

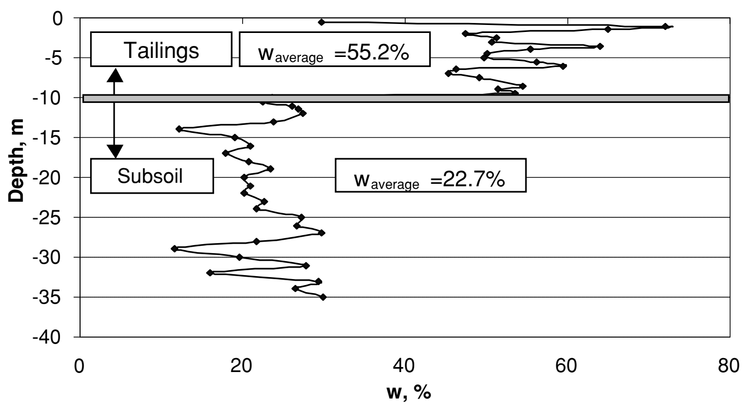

Figure 2. Water content (w, %) of the tailings and the soil underneath.

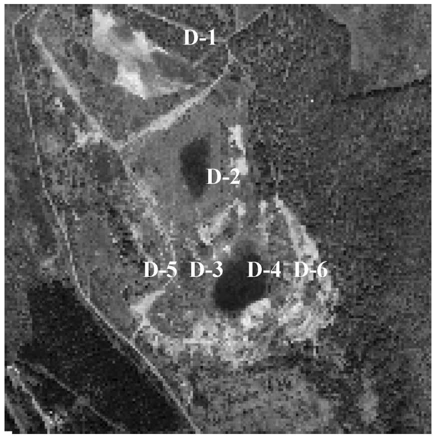

Figure 3. Test site with flotation tailings; drilling locations.

The reliability of the method was demonstrated on both sites. On the uranium mill tailings site a special calibration borehole was built by pushing a tube (closed at bottom) into the tailings. In the immediate vicinity of the borehole, samples were taken at different depths of tailings to determine the real water content in the laboratory (drying samples at 105°C).

Water contents of the tailings samples and measured using the neutron probe in the calibration borehole are presented in Figure 5. The data obtained using the two methods are very similar, and the conclusion can be drawn that the counts from the neutron probe are a real indicator of the water content of the tailings. Therefore neutron logging can be used for water content determination, and presumably for monitoring of the consolidation process.

Neutron logging was also undertaken in the flotation tailings. Pushing a steel tube into the tailings, a measuring hole with a depth of 12 m was constructed and neutron logging was carried out. Tailings samples were also taken from the tailings near the hole. The water contents of core samples as determined in the laboratory and water content calculated from the neutron logging data are presented in Figure 6. The results are in good agreement with each other, thus the conclusion is that neutron logging provides reliable results for the volumetric water content of flotation tailings.

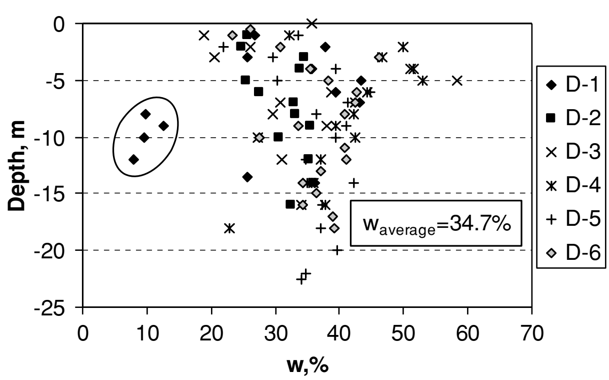

Figure 4. Water content of flotation tailings (Gyöngyösoroszi, Northern Hungary).

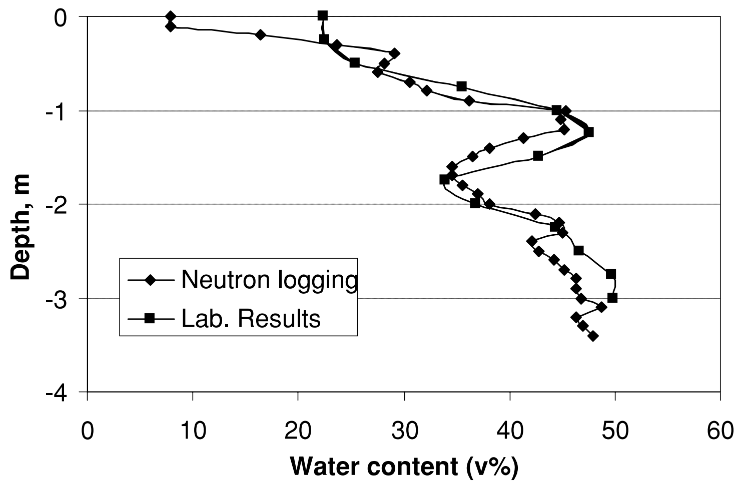

Figure 5. Comparison of water content of tailings measured by neutron logging and oven drying (105°).

1.3. Contamination of Subsoil and Groundwater

Tailings are often a source of contamination. Migration of solutes can contaminate both soil and groundwater. The migration rate of different compounds, e.g. nuclides, depends on many factors. Although theoretical calculation is possible, direct measurements providing more reliable information on contamination are preferred in practice.

1.3.1. Contamination situation of uranium mill tailings. At site N1 (uranium mill tailings, Southern Hungary), the tailings pond has no or only poor lining, and a large amount of process water has seeped into the soil beneath the tailings. The seepage is detected in monitoring wells installed around the tailings ponds. The depth of contaminant penetration

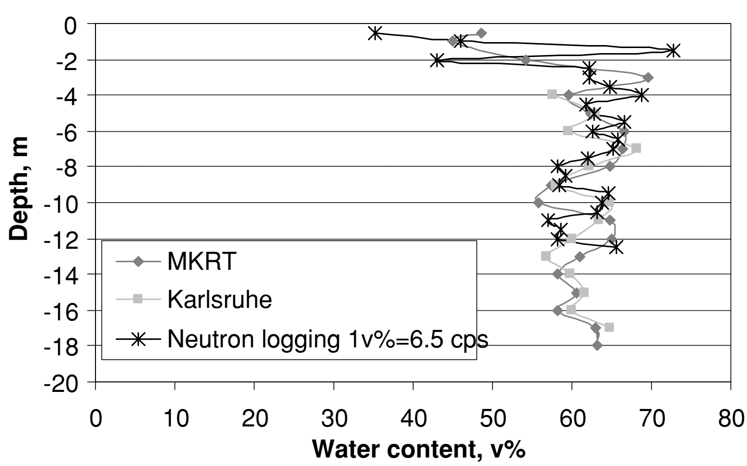

Figure 6. Water content measured in two different laboratories (MKRT: Mecsek Öko Rt and Karlsruhe University; oven drying at 105°) and calculated from neutron logging.

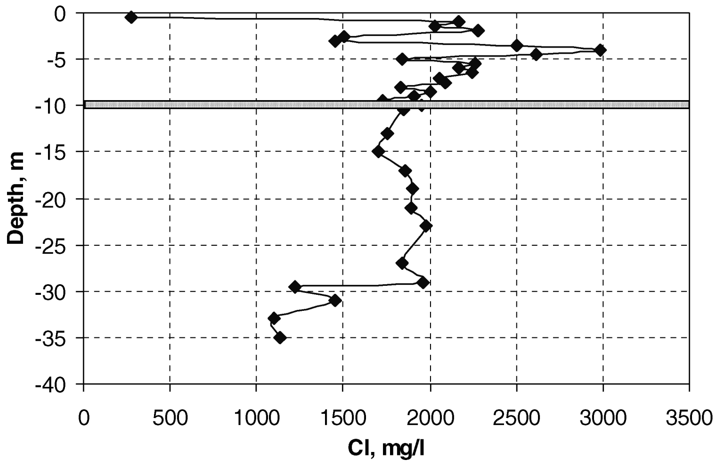

Figure 7. Chloride concentration in uranium mill tailings and in the subsoil.

in the soil beneath the ponds was determined within the current project for some selected components.

For this purpose, samples collected for the determination of water content (as mentioned above) were additionally analyzed for different constituents both in the solid and pore water. In this paper only the chloride content of the pore water is presented. These data were obtained analyzing water extracts from samples (diluting the portion of sample with distilled water). Taking into account the dilution factor, pore water concentrations of chloride and selected nuclides in tailings and soil beneath the tailings were obtained. The data are presented in Figures 7 and 8. The thickness of tailings is approx. 10 m, the original soil can be found below 10 m.

The chloride concentration in the tailings varies between 1.5–2.5 g/l, decreasing with depth (this is due to the change in chloride consumption during the milling process). It is also obvious that chloride ions (and some other ions not listed here) are migrating into the subsoil, where their concentration is practically constant to a depth of 10 m (20 m from the

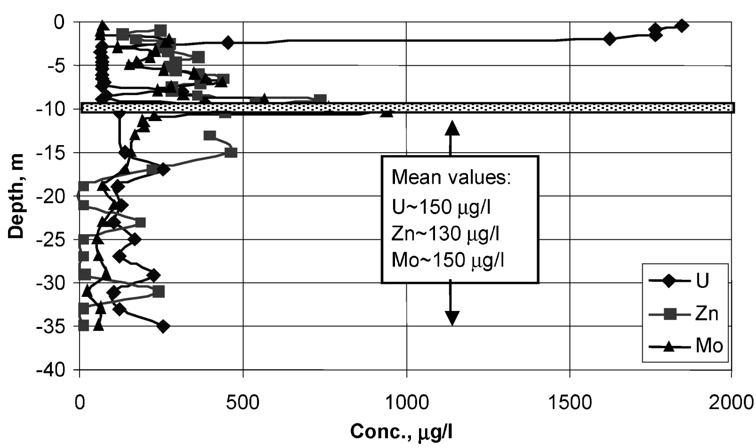

Figure 8. Contamination of pore water with U, Zn, and Mo.

Table 1
Contamination of subsoil under flotation tailings

Samples	Selected heavy metals, g/t							Zn/Cd
	As	Cd	Cu	Hg	Mn	Pb	Zn	
Average from core samples of 6 drillings	272	16	389	2	1, 189	990	2, 340	150
Basement, subsoil	47	1.6	39.6	0.6	576	81	235	156
Background	17	1–3.5	10	<1	44	34	10	

tailings surface). Therefore the groundwater restoration system has first of all to be capable for treating the shallow groundwater.

In Figure 8 the contamination caused by U, Zn and Mo (the most relevant nuclides for the site) are presented. Both the tailings water and subsoil pore water are contaminated only slightly with these elements (100–200 μg/l). Especially the relatively low uranium contamination is remarkable. But the pore water of the upper meters of tailings exhibits an elevated uranium concentration of up to 1800 μg/l.

1.3.2. Contamination of subsoil on flotation tailings pile. Samples collected from six drillings at the flotation tailings site in Northern Hungary (N2) for determination of water content have also been analyzed for different components. Data for some heavy metals in tailings samples, the subsoil, and the accepted background value for the soil in the location are summarized in Table 1. Contamination of the subsoil is detected first of all for zinc and manganese. It is obvious that this contamination is due to the downward migration of these elements. At the same time the data prove that heavy metals released in the oxidation process are bound to the soil particles.

2. Investigation and Monitoring

For the assessment of the stability of tailings dams detailed understanding of geometry, structure, material parameters and their spatial variability is necessary. The history of the facility is also important.

In most cases the available data are insufficient. So at the starting point of an assessment procedure a desk study should be performed, checking all material available from the owner, authorities and geological survey. Based on this an investigation strategy will be developed, including sampling, standard mineralogical and chemical analysis and non-destructive geophysical surface and borehole methods. The results have to be assessed and interpreted to provide valuable information for the geotechnical engineer. For stability calculations not only the standard methods, but also advanced techniques, taking into account variability and uncertainty, should be applied. The outcome of all investigation, measurement and calculation influences remediation measures and monitoring schemes to protect health and the environment against future accidents.

The TAILSAFE project provides a fair amount of useful information and research results on these topics:

- a guide for sampling and analysis;
- new stability calculation algorithms;

- a set of non-destructive/geophysical methods, both standard and advanced, with possibilities and limitations;
- a list of available monitoring methods.

Only some examples can be presented here. A flowchart was designed to guide those in charge for the investigations through the different steps of strategy design, measurement and assessment (Figure 9).

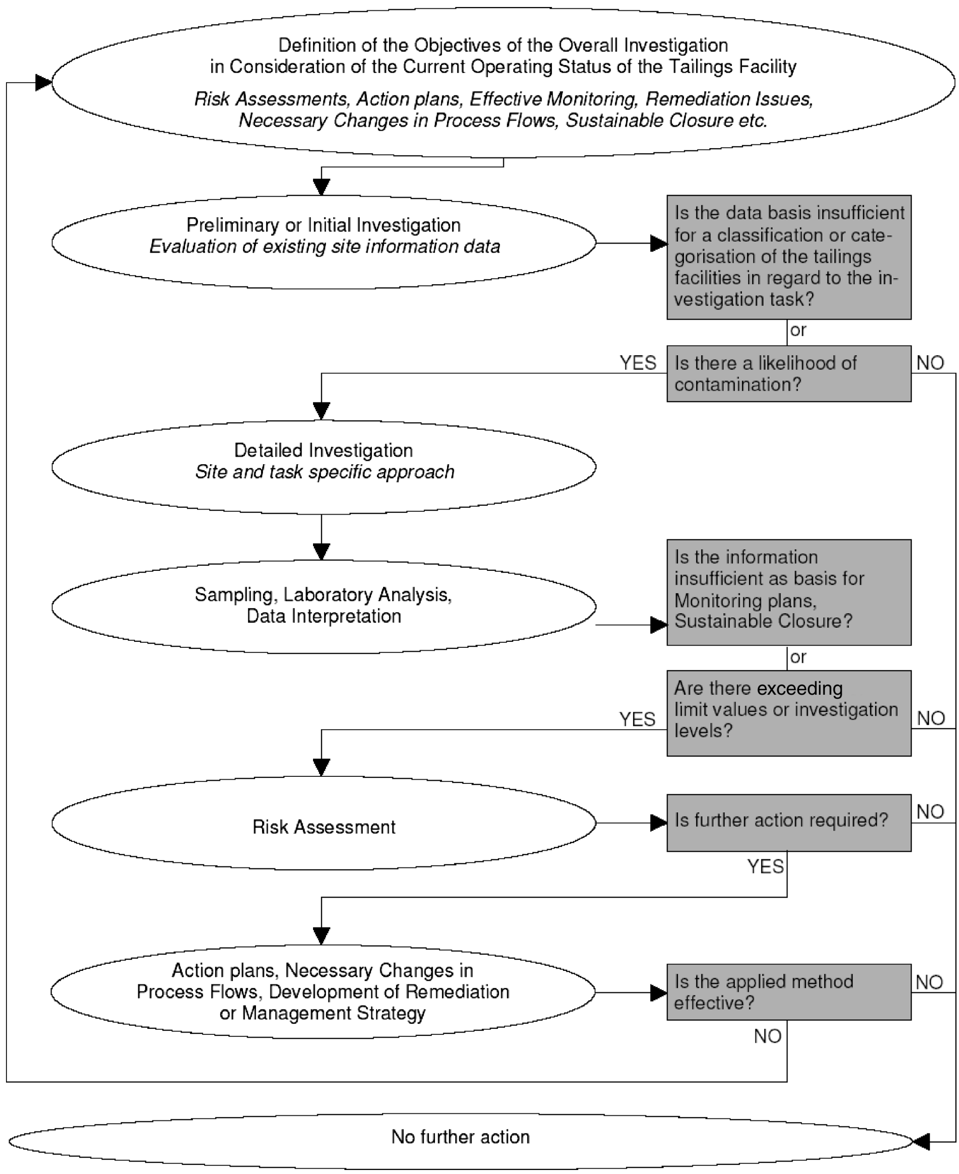

Figure 9. Flow chart describing role of site investigation in general assessment.

A set of new stability calculation methods dealing with parameter variability, uncertainty and interpolation between data points was developed. Main target was to improve the reliability of the techniques.

Another focus of the project was the evaluation and optimization of geophysical methods. Conventional investigation techniques (mainly sampling and analysis) deliver only information on single points. Due to the high variability inherent to tailings dams this may be misleading. Thus geophysical methods, acquiring information on larger areas, sections or volumes may be of high value. The main disadvantages are limited resolution, penetration depth and the need for "translation" of the physical parameters (e.g. electrical resistivity or seismic velocity) to the parameters needed by the geotechnical engineer. Two advanced methods are described below.

Geoelectrical methods measure the distribution of electrical resistivity in the subsoil from the surface. The resistivity depends on material, water content, ion content in the pore water and other parameters. So the method can provide valuable information on the phreatic surface or contamination, but the interpretation is often ambiguous. The SIP method (Spectral Induced Polarization) measures additional parameters such as chargeability of "phase," which are helpful in distinguishing e.g. material changes from changes in water content (Figure 10).

The SASW (Spectral Analysis of Seismic Waves) method utilizes the behavior of the so-called Rayleigh waves: the depth of penetration is related to their frequency, the elastic properties to their speed. Impulses generated by sledgehammers are recorded by geophone arrays. Sophisticated data processing and modelling is used to provide one- or two-dimensional depth profiles of shear wave velocity, which can be converted into elastic moduli. The method was successfully tested on the plateau of tailings facilities (Figure 11). The vertical shear wave profile calculated from the data identifies the base of the tailings within 5% of the depth known from boreholes. The velocities can be used for a qualitative assessment of elastic moduli. The application of this method on dam crests or slopes still provides further challenge.

3. Towards a New European Legislation

Tailings dams are usually operated by mining companies and remain under supervision of state mining authorities. However, tailings dams safety is often not the priority of mining

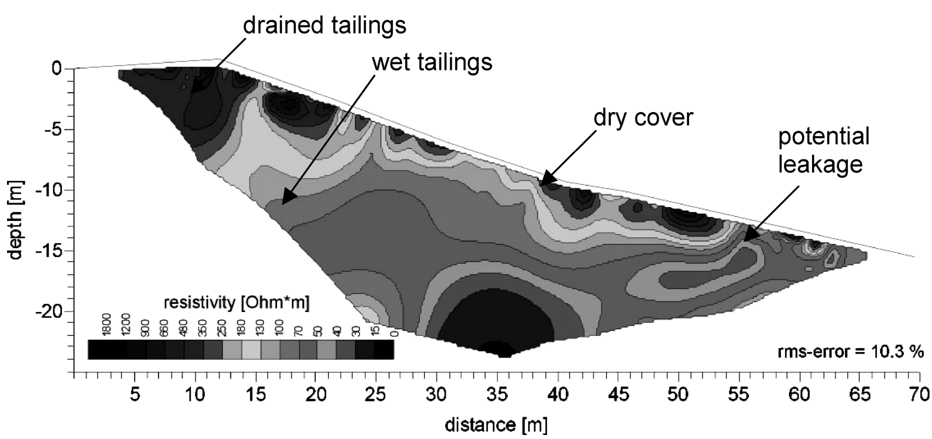

Figure 10. SIP cross-section through a dam of the Romanian TAILSAFE test site.

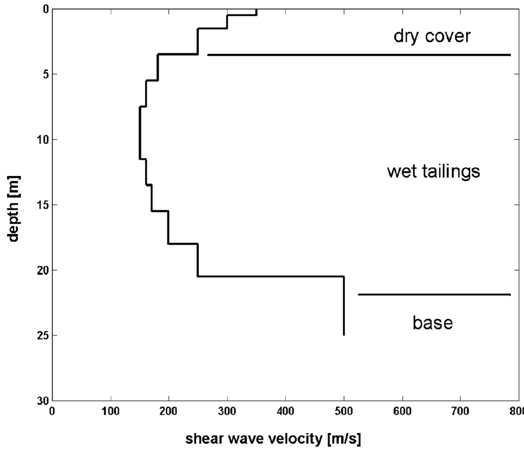

Figure 11. SASW measurements and results on the German TAILSAFE test site. Left: Equipment set-up, Right: Vertical profile of shear wave velocities.

safety legislation, if it is considered at all. In many cases it remains outside the scope of dam safety regulations in force for water retention dams.

Legislation applicable to tailings management facilities varies in the different EU member states and it usually includes environmental protection legislation, waste legislation, water legislation, and construction laws. The examples chosen show a wide European scope and progressive legislation. For instance, in Poland tailings dams are subject to the following laws: the Construction Law & Polish Norms (regulates design and construction), the Water Law Act (licence to operate), the Act on Environmental Protection (EIA and monitoring), and the Act on Waste (payments for discharge of water).

The Geological and Mining Law does not apply to tailings facilities. Tailings dams are classified in the same way as water retention dams and constitute four classes. All above-surface/raised tailings dams, whose impoundment area is larger than 10 ha, are subject to the Act of 9 Nov 2000 on Access to Information on the Environment and its Protection and on Environmental Impact Assessment (EIA). According to this law, granting a decision whether to permit a proposed project that may have significant impact on the environment requires an environmental impact assessment procedure to be carried out. The EIA needs to be performed also when a tailings dam is modernized or extended. The local EIA commissions include: a Marshall of a Voivodship (the main administrative district in Poland), representatives of science and non-governmental organizations concerned with environmental protection.

In Ireland tailings management facilities are regulated by the following laws: Environmental Protection Agency Acts (Part IV- IPPC Licensing), Waste Management Acts 1996–2003, Water Pollution Acts 1977–1990, Minerals Development Acts 1940–1999, and Irish Planning and Development Act 2000.

No specific legislation concerning tailings dams exists, but Ireland has adopted the UK legal system. The UK's Reservoirs Act 1977 works as an operational law, although it is not legally binding. ICOLD recommendations concerning safety of tailings dams have had an impact on the practice in Ireland as well as Canadian and Australian guidelines. All instructions and issues connected with safety of TMFs are included in the operational permit of a mine.

The authorization process for mining activities includes, *inter alia,* the Integrated Pollution Control Licence (IPC). Since 1994 this licence has been required to be obtained from the Irish Environmental Protection Agency (EPA) for most large industrial activities in order to commence or continue operation. The requirements of the IPC licence correspond to the requirements of the 1996 European Union Integrated Pollution Prevention and Control Directive (Council Directive 96/61/EC of 24 September 1996). The integrated permit replaced previous national legal requirements to obtain multiple authorizations for air, water and waste emissions. Derham (1999) points out that the Irish IPC legislation is stricter than the current European Union one as it brings both mining and processing of minerals into the IPC licensing net. One of the documents central to the licence decision process undertaken by the Local Government and EPA officials is the Environmental Impact Statement. The requisite scope and content of the EIS is laid out in the 1985 EU Directive (85/337/EEC) and in Guidelines on the Information to be contained in Environmental Impact Statements published by the Irish EPA (Derham, 1999).

At the level of the European Union there was until recently a lack of specific legislation concerning waste from mining operations. Tailings management facilities were, *inter alia,* subject to the Waste Framework Directive 75/442/EEC of 15 July 1975 (amended by Directive 91/156/EEC of 18 March 1991) and the Directive Concerning Landfill of Waste (1999/31/EC of 26 April 1999), which outlines surveillance programs for water, leachates and gases and requires that the results of monitoring must be shared with authorities. This directive also applied to waste "resulting from prospecting, extraction, treatment and storage of mineral resources," except if they are non-hazardous and inert (Article 3.2). Certain mining wastes are covered by the list of hazardous wastes (European Waste Catalogue, decision 2001/118/EC, an amendment of the earlier Directives 2000/532/EC and 94/3/EC). Because the Landfill Directive is meant to deal with general and common aspects of landfill management, some of its provisions are not compatible with best management practice or do not deal with management issues specific to the extractive sector, such as stability of dams of tailings ponds. Some of its provisions, such as a ban on the disposal of liquid waste into landfill, a general ban on the co-disposal of non-hazardous with hazardous waste or with inert waste, and finally a requirement to install a barrier and a liner to be put under a landfill site in order to prevent groundwater pollution, are impracticable in the case of extractive industries waste (Commission of the European Communities, 2003), mainly due to the specific production processes. This situation required the creation of an appropriate legal framework that would exempt waste from the extractive industries from the scope of the Landfill Directive and establish tailor-made rules (see below).

Tailings management is currently also a subject of Discharges into Water Directive 76/464/CEE with other directives on discharge of dangerous substances, e.g. Groundwater Protection Directive 80/68, Water Framework Directive 2000/60/EC and the Environment Impact Assessment (EIA) Directive (85/337/EEC) (amended by Directives 97/11/EC and 92/104/EEC). The latter one is an integral part of the laws on mining operations for most of the EU countries.

The relatively recent mining-related accidents, Baia Mare/Romania in 2000 and Aznalcóllar/Spain in 1998, and the pollution they caused have attracted the attention of the public to the environmental and safety hazards of mining activities. The European Commission's responded to these accidents by a Communication on the "Safe operation of mining activities: a follow-up to recent mining accidents." The Communication sets out three key elements envisaged to improve the safety of mining operations: a revision of the Seveso II Directive (96/82/EC of 9 December 1996) on the control of major accident hazards involving dangerous substances to include in its scope tailings ponds and dams used in connection with mineral processing of ores; a Best Available Technique (BAT) Reference Document on tailings and waste-rock management to reduce everyday pollution and to prevent or mitigate accidents in the mining sector; and a proposal for a Mining Directive.

The Commission launched the proposal of the new directive "on the management of waste from the extractive industries" on 2 June 2003. The aim of the proposal is "to set minimum requirements in order to improve the way in which waste from extractive industries is managed by specifically addressing environmental and human health risks that may arise from the treatment and disposal phases of such waste. By encouraging waste recovery in particular, the Proposal aims to contribute to the conservation of resources in serving to reduce pressure on the exploitation of virgin natural materials. The promotion of recovery could also reduce overall environmental impact by lessening the need to open new mines" (Commission of the European Communities, 2003).

The new Mine Waste Directive (2006/21/EC) was adopted on 15 March 2006, which applies to waste resulting from the mineral industry and from quarries. Such wastes are no longer covered by Directive 1999/31/EC on the landfill of waste. The directive contains, *inter alia,* a range of conditions to be included in the operating permits, a range of general obligations concerning waste management, the obligation to characterize waste before disposal or treatment stages, measures to ensure the safety of waste management facilities, a requirement to create closure plans for waste management facilities, an obligation to ensure an appropriate level of financial security.

It is believed that a common set of rules at EU level will establish a level playing field in terms of minimum administrative control and supervision in the extractive industrial sector. The Mine Waste Directive was published in the Official Journal on 11 April 2006 and entered into force on 1 May 2006. The Member States must implement, and operators must comply with, the Mine Waste Directive by 1 May 2012, while financial guarantees are to be in place by 1 May 2014.

The member countries will face a problem of implementation and consequently of enforcement of this act. The tasks of national administrations will include the creation and maintaining regulatory, inspection and enforcement systems capable of meeting the new Directive's obligations. Most of the costs will be related to employing additional technical and administrative staff. New obligations will also be faced by mining entrepreneurs. These costs may be divided into three groups: one-off costs arising from the adjustment to the new requirements and operating conditions for the operating and planned mining waste management facilities; additional costs arising from the operation of the mining waste management facilities; and additional annual costs when the exploitation of mineral resources ceases or the mining waste management facilities are closed (Commission of the European Communities, 2003).

4. The TAILSAFE Resource

4.1. The Resource Concept

The TAILSAFE Resource is a risk management tool to assist all those concerned with improving the safety of tailings facilities. Its purpose is to help users systematically assemble, reconcile and share data and experiences relating to the improvement of safety of tailings facilities.

Risk management is ultimately a matter of controlling critical parameters. The Resource, like TAILSAFE, focuses not only upon what the critical risk factors are in preventing tailings spills and contamination. It also addresses the management practices and protocols for properly detecting, measuring, monitoring, and evaluating those risk factors, plus the regulatory requirements, preventive measures and intervention actions which enable their control.

4.2. Information Sources for the TAILSAFE Resource

The Resource is based on established industry and regulatory guidelines, supplemented by international expertise and industry inputs, plus specific research by the TAILSAFE partners. The framework was developed and refined throughout the TAILSAFE project, for which it provided a means of defining and tracking common parameters across all workpackages. During this development process, the aim has been to gradually transform an initial parameter framework from a descriptive treatment of parameters and procedures critical to the safety of tailings facilities, into a risk reduction tool incorporating scenarios of practical help in the hands-on management of their design, construction, operation and rehabilitation. The TAILSAFE Resource can be further refined and updated on an ongoing basis through user feedback.

4.3. Underlying Elements of the TAILSAFE Resource

The development of the Resource has been approached on two levels. The basic concept and underpinning rely on the definition of

- procedures relating to the design, building, running and closure of tailings facilities;
- safety-critical parameters in the undertaking of those procedures and the organization of those parameters and procedures into hierarchical structures, in order to relate them in a well-defined, manageable and memorable way. Tied in closely with this is a library of cross-sections, diagrams and images to help the user identify and assess likely scenarios and related parameters.

4.4. Working Front-end for the TAILSAFE Resource

The navigational and diagnostic web-based interface of the Resource embodies good/bad practice checks in question-answer form. It also employs a hierarchical structure, and has been set up to address the same critical parameters and reflect a similar design-build-run-close procedural sequence, so that it may eventually be used in conjunction with the underlying specialist languages.

This "front-end" manifestation of the Resource additionally allows users to approach from regulator, designer, operator or management roles and perspectives. It is seen as addressing the practical needs of stakeholders, by offering ready access to well-structured and well-illustrated guidance materials, with links to more specialized sources of information elsewhere. In this guise, the Resource is primarily an educational, motivational and support tool, which can eventually be adopted in packages and programs for the training and certification of tailings professionals.

4.5. Development of Working Front-End

This involved two parallel and inter-related processes:

- Development of the layout, look and feel of the user interface, and its implementation in computer database and webpage terms;
- Development of the hierarchical structures for tailings facility parameters and management procedures, comprising:

  a. Key topics from each of the regulator, designer, operator and management perspectives, drawn up in consultation with expert industry advisers;
  b. Content to cover each topic, relying initially on governmental, industry and TailSafe sources, to be gradually supplemented with case study material and user feedback;
  c. Diagnostic trees, enabling the user to access the content efficiently in a context-dependent interaction, and incorporating links to external sources.

There has been continual modification of this framework as it is fleshed out. The diagnostics tool is very complicated; for example, a single decision tree of six levels can have about 75 web pages. Slotting in questions as the database is built required a considerable amount of work to page structures and linking.

4.6. Preview of Front-End "Look and Feel"

The layout is a vital factor in determining the usability of such a tool. Below are screenshots of how the web interface looks (Figures 12 and 13). On the left-hand side is the navigation frame. On the right-hand side is the topic information window. The screenshots sample sequences in a user's selections from the diagnostic trees, and show the type of information and guidance for that result.

4.7. Navigation Options in the TAILSAFE Resource

The Front-End navigation frame of the Resource presents various ways of accessing information, and these depend partly upon earlier user choices (if any):

- At the starter screen (or home page) there will be the ability to select a particular approach or discipline in terms of:*regulator/designer/operator/management* (the distinctions between these being further elaborated via a help button facility or a brief overview of each discipline on the home page). This helps focus on the responsibilities of each particular user, and to filter out a great deal of guidance more appropriate to the other roles and perspectives.
- Once within the chosen discipline, the user will be guided through the relevant diagnostic trees topic-by-topic, the route depending upon previous answers. For example, in the Fig. 12 screenshot an operator user has the choice of *day-to-day*, *management* or *reporting* activities, and within them he/she can select parameters of interest, such as *water management*.
- At any stage, filter and search buttons can instead be used to target information more directly. The *filter* system will rely upon diagrammatic representations of aspects of tailings facilities (and is at a relatively early stage of development). The *search* facility allows the user to enter a word-based search, and also serves to help access more specialist definitions and terminology.

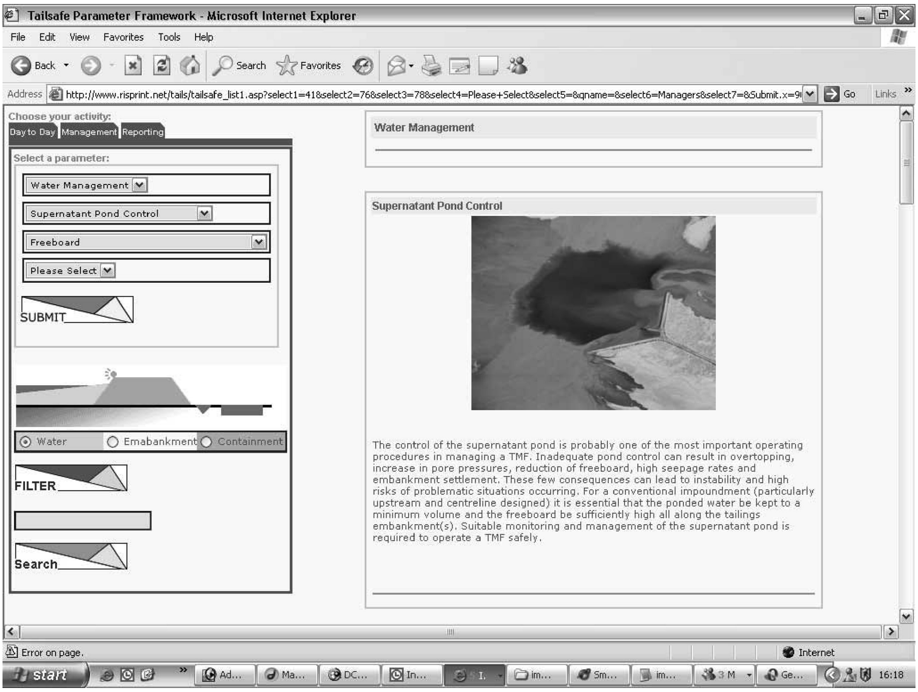

Figure 12. The user has selected '*water management*' parameters from the diagram which filter the results shown in the dropdown boxes above.

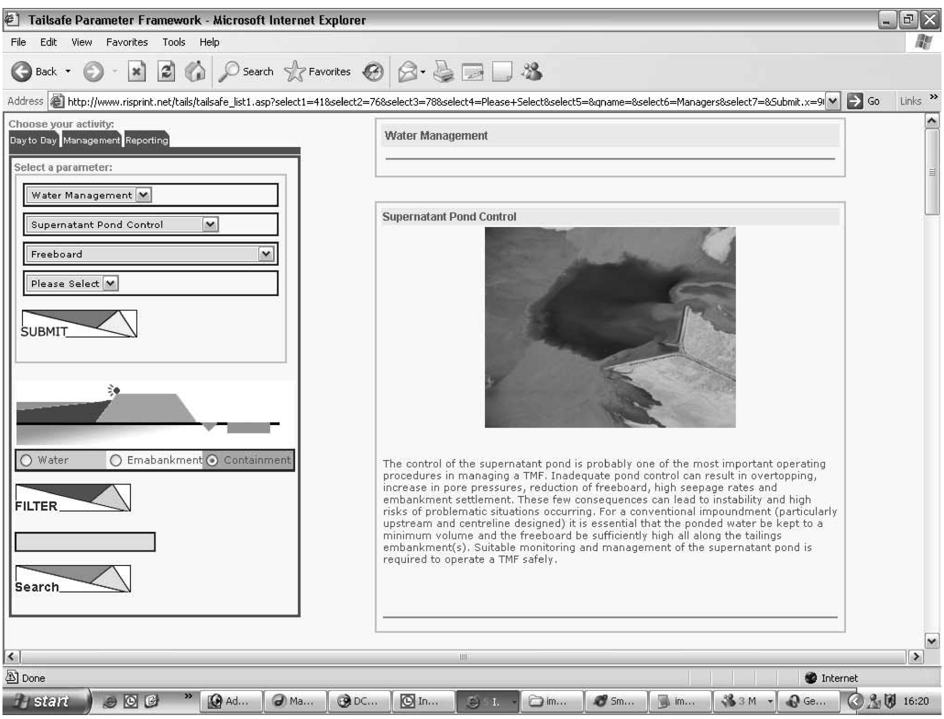

Figure 13. Here the user has selected '*containment*' to filter out the dropdown boxes accordingly.

- The final output of a searched parameter or procedure is intended to be a constructive answer, with external links to load up diagnostic packages, actual case studies, illustrative photos and diagrams, options for remedial measures, etc.

4.8. Example[s] of Topic List[s]

To give a flavour of the levels of detail reached in the Resource these are the topic hierarchies under the Designer and Operator disciplines regarding water management of a tailings facility:

Designers	Operators
Water balance requirements	• Water management
TMF water management	• Supernatant pond control
Freeboard design limits	• **Diagnostics tool**
Storm design	• Freeboard
Storm event considerations	• Water balance management considerations
Decant system(s)	
Decant towers	• Decant tower
Decant barges	• Procedures for adding and removing collars
Emergency spillways	• Procedures for raising the tower
Reclaim ponds	• Shutdown (decommissioning a tower)
Evaporation/treatment and/or polishing ponds	• Problems with decant towers
Seepage control	• Decant Barge
Embankment barriers	• Procedures for moving a barge
Grout curtains	• Standby pumps and generators
Cut-off trenches	• Reclaim pond(s) control (including dosing)
Slurry walls	• Diagnostics tool
Return system	• Emergency shutoff valves from a decant tower(s) or barge
Collection ditch	• Cleaning
Collection well	• Emergency overflow ponds
Liners	• Seepage monitoring and control
Tailings slimes	• Diagnostics tool
Clay liners	• Monitoring bores
Synthetic liners	• Seepage collection wells
Weaknesses with membrane liners	• Production bores
	• Internal toe drains
	• Seepage interception trenches

This table is a good example of how the operator's roles and responsibilities differ considerably to the designer's. An operator has to manage the tailings facility as set out in the operator's manual, which would have been drawn up by the designer to meet performance specifications and requirements. To assess this, the designer needs to look at a wide range of scenarios and parameters, to identify options and practices that will best ensure a reliable, low risk and safe tailings facility over its life cycle. From this table, it is clear that segregating content can remove a great deal of irrelevant information between the different disciplines responsible for aspects in the management of a tailings facility.

The diagnostic routines for the operator in effect become a training tool (as mentioned previously) to identify problems by going through a series of questions and answers, directed at finding an appropriate mitigation or contingency measure. The reason for such a systematic approach is that day to day operations (as conducted by the operators) can dramatically swing the balance between well and poorly managed tailings facilities, over what can be very short periods of time. It is essential that operators are trained to identify, assess and be confident in their decisions on how to deal with problematic situations, both quickly and effectively. The Resource gives them an accessible resource covering a wide range of situations and solutions that no single operator can have experienced directly at a typical stage in a typical career.

4.9. Implementation

The working front-end relies upon ASP (Active Server Page) technology that obtains information from an online Microsoft Access database. The reason for this choice is primarily to take advantage of the Internet, which is now commonly found in offices all over the world. This also allows for direct links to content in html pages, plus easy input of data in Word and other common formats. The underlying technical languages have been developed as a modular series of Microsoft Access spreadsheets, through which a more expert user will be able to browse or cycle in checking out a particular problem situation or problem-solving procedure.

4.10. Limitations

Although the Resource is intended to be comprehensive in many respects, in others its scope is strictly limited, at least at present. In particular:

- While brief comment may be offered on the costs and viability of tailings management options, where considered helpful, no systematic attempt is being made to incorporate cost and viability parameters into the framework under the present TAILSAFE project. The Resource must thus be used not to determine actions, but only to inform them alongside such other vital factors.
- The initial focus of the Resource is upon measures to prevent failure occurring, rather than clean-up measures following a tailings spill. Thus the downstream effects of catastrophic failure are largely treated as externalities beyond the scope of the current risk management framework.

4.11. Risk Reduction via the TAILSAFE Resource

Basically, then, the Resource is a tool to help identify critical parameters and parameter values in the design, construction, operation and closure of a tailings facility. It incorporates diagnostic routines, which lead the user to typical prevention, solution, or mitigation measures and strategies to reduce the risk of tailings facility failure. It can only offer and advise on options, and must be complemented by all the appropriate team expertise and checks and balances. It is mainly directed at tailings facility managers and operators, for training on possible scenarios that have been experienced in the tailings industry, as well as undertaking the various roles and responsibilities that essentially govern the performance of the facility. But regulators and designers should also find the tool most useful for identifying weaknesses, alternative approaches, or areas of their tailings control, inspection and management programmes that may be lacking in detail and understanding.

5. General Remarks on Safety Considerations

In the different parts of their lifecycle, tailings facilities meet the goal of sustainability at an adequate level of confidence when they have no adverse effects on humans or the environment. To fulfil this rather trivial demand, a more sophisticated analysis on safety, reliability and risk is necessary, which takes into account the specific conditions of tailings facilities, i.e. time dependence of the produced residues, change in quality, inadequate construction control and prolonged growth of the impoundment over decades, storage of more or less toxic residues and their presence in the environment over geological periods.

The individual technical processes and parameters, which can cause adverse effects, are well known. However, safety seems to be an issue that deals with knowledge of parameters and interactions as well as a question of proper design, management and monitoring of the site. In any case, we need a powerful tool to assess and manage the different data as a basis of decisions. Summing up, there are two major components relevant for safety considerations: impacts on the site and the response effects.

Impacts can be gravity of the tailings, different forces of water and wind, accelerations due to earthquakes or the content of contaminants within the impoundment. Effects are the interactive response of the parameters and of the environment due to several impacts. With a view on risk and reliability we can characterize two different groups of effects: reduction of structural safety and environmental damage. However, we have to define for both of them what failure means, how adverse the result should be to be called a failure. In engineering terms this means to define limiting state conditions.

If the effect results in the decrease or loss of structural stability of the impoundment or the surface, we are forced to take adequate measures to achieve strengthening. For the assessment of this we need several geometrical data. Investigation and monitoring should deliver soil mechanical parameters of the dam and the transition zone on the one hand and an idea of the future maximum potential impacts on the other.

In all issues of environmental hazard we can use the well-established source-pathway-target framework used in contaminated land risk assessment. But there is an evident difference to common contaminated sites: the amount of contaminants within the impoundment and the resulting duration of possible threats. Besides, often there is no specific legislation to demand remediation measures for mining waste and tailings facilities.

With a view to enhancing the level of safety the final key question might be: "What is the major risk, originating from all this impacts and parameters?" There is no clear answer to this important question. The most sensitive parameters and the most critical impacts, their frequency and the severity of an adverse event will change from site to site depending on the type of tailings, the periodical change in dam construction technique, the pore water pressure distribution within the transition zone, the capacity of the subgrade to transport or adsorb contaminants, the surrounding geological conditions and the distance of downstream residential area and infrastructure. In most cases such an analysis will provide the result that risk will be in relation with an effect of water. Therefore water management and monitoring as well as establishing threshold values of pore water pressure and seepage level is one of the most important tasks. If we want to identify the relevance of risk-related parameters or the vulnerable points of a facility, we are forced to analyse complex processes and scenarios and we must estimate the likelihood of interactive influence of impacts and effects. The steps needed to enhance the safety level of any specific site are similar:

(i) HAZARD IDENTIFICATION. This means data collection, identification of site conditions, physical parameters of the impoundment and the tailings, topography, geology and hydrology. The question in this first step is: *What are the fundamentals of a potential problem?*
(ii) HAZARD ASSESSMENT. The aim of this step is to set up event trees or fault trees for imaginable scenarios. This includes compound processes with different impacts and interactions. The question in this step is: *How big might the problem grow?*
(iii) RISK ESTIMATION is the quantitative analysis of all those scenarios, combining the branches of the event trees with estimated probabilities and sum it up to the likelihood of a certain scenario. The question therefore is: *What will be the effect of a certain scenario and how strong will it be?*
(iv) RISK EVALUATION. In this final step all knowledge about the probable adverse effects is summarized and, taking into account the socio-economical and legal aspects, the risk and reliability assessment is reduced to the simple question: *What might happen and does it matter?*

These steps will provide an adequate and objective database for better decisions on design, processing, remediation, mitigation of hazards and after-use of tailings facilities and thus a powerful tool to enhance safety level of any tailings facility during the different cycles of life.

6. Design Considerations for New Tailings Management Facilities

The decrease in annual failure frequencies of tailings facilities starting from the 1970s is a logical consequence of the increase and spreading of knowledge and advances in design procedures and management. Therefore major relevant aspects that will influence the safety and reliability of future tailings disposal facilities are site selection, conception of storage, quality and procedure of design, management and qualification as well as experience of personnel for operation.

The choice of a site and a storage conception basically depends on both the properties and the environmental impact of the residues as well as the topographic, hydraulic and geological conditions. The engineering properties are divided into specific characteristics of strength, drainage conditions and the ability to spread or retain contaminated material. Groundwater protection and stability of the subsoil, the retaining dam and the tailings are the main boundary conditions for planning a tailings-settling basin. The starting point therefore is the usually high risk potential of such a dump because of its stored contaminated material.

Objective of a site investigation is to obtain the most complete and accurate estimate possible for the location, the extent and the engineering character of the soil and the rock, underlying the basin and the impoundment, with regard to the limits of time, money and practicality. Kind and extent of the site investigation depends among others on factors such as morphology and infrastructure of the site, type and behavior of the tailings, geological and hydrological situation of the site, and on the expected safety category of the facility.

Even during the stage of conceptualization of a new site and integrated with the preliminary site selection the future tailings deposition facility should be classified into a safety category defining the potential of possible hazard. An update or reclassification should be made during the development of design and during further milestones of life cycle. Some guidelines and manuals such as ICOLD-CIGB (1989) and South African Bureau of Standards (1998) give suggestions or schemes for classification and there is an assent that the reasonable likely adverse impact to human beings and to nature should be the main criterion to classify a proposed project in one of the categories low, middle or high hazard. The minimum standard of investigation and planning procedures should be correlated with these safety classes.

The design procedure for a proposed tailings disposal facility is an ongoing systematic process that takes into account all the relevant factors and criteria to provide an acceptable and known level of reliability for the mine residue deposit. As an overall aim a proper design should optimize functionality, environmental impact and cost over the entire period from site selection through operation towards closure and aftercare. For any phase of the life cycle of a project good design results should be available in reports, specific studies, working and as-built drawings as well as operating manuals and monitoring requirements. Background studies concern safety classification, risk estimation, environmental impact assessment, characterization of the chemical, physical and structural behavior of the residues, geological, geotechnical and hydrological assessment of the site, water management, monitoring and auditing.

There should be at least three levels of study and design. At the stage of conceptualization one has to deal with site selection, technical variability of the produced residues, order-of-magnitude cost estimation and preliminary studies concerning potential risks, safety classification and possible environmental impacts. Subsequently, the financial variability of the project has to be established in a second stage. Furthermore final engineering decisions and assessment of full environmental impact are required. In the final stage of design, detailed engineering and construction drawings and specifications have to be prepared for all basic elements such as infrastructure, impoundment, pond, dam, discharge pipeline, recycling system, spillway, seepage collection, drainage systems, instrumentation and monitoring, taking into account the entire life cycle of the facility. Within the legal and environmental framework the objectives of design in all these stages have a strong bearing on construction, commissioning, management of operation and, finally, on decommissioning and closure. Therefore the quality of design is a fundamental criterion for the sustainability of the tailings disposal facility. Sustainability is satisfied if the intended purpose is fulfilled as expected under all external environmental influences that are reasonably likely to occur.

Design should be undertaken by suitably qualified personnel. Another important factor influencing the success of the process is an adequate continuity of communication of the personnel involved in investigation, design, construction and commissioning. In any case, depending on the classification of safety of the facility and the complexity of the task, design and construction should be supervised and reviewed by the judgement of independent experts.

7. Outlook

Though public awareness, our understanding of basic processes and parameters, design and construction practices and legislation have been substantially improved during the last few decades, more than 1000 people were killed by accidents due to failures in tailings management facilities during the last 60 years. This fact indicates that increasing the safety of tailings management facilities is still a major challenge, though a decreasing tendency in major hazards and tailings-related accidents is very promising. The TAILSAFE project briefly introduced here supported this objective by further developing non-destructive testing methods and addressing aspects of tailings facilities design, water management and slurry transport, remediation options and authorization and management procedures. A risk reduction framework benefiting from a broad knowledge about parameters—the TAILSAFE Resource—will help avoid catastrophic accidents caused by tailings facilities. Safety and design considerations including hazard identification and assessment, risk estimation and evaluation contribute to putting tailings management engineering onto a more scientific footing both in Europe and worldwide.

Acknowledgement

This research was supported by the European Commission within the Thematic Programme "Energy, Environment and Sustainable Development" of the 5th Framework Programme for Research and Technological Development (project name: Sustainable Improvement in Safety of Tailings Facilities - TAILSAFE; contract no: EVG1-CT-2002-00066).

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