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## **Current practice in tailings ponds risk assessment**

*Key words: tailings ponds, stability, risk assessment*

### **Abstract**

*Current practice for risk assessment posed by surface tailings/waste storage facilities is presented. This involves current legislation and regulations applied in EU countries and over the world and the basics concerned with tailings impoundments design as well. It was proved that a current activity at the existing tailings impoundment structures is presently confined rather to field measurements, monitoring and surveillance understood as a basic source for a "real time risk assessment".*

### **1. Introduction**

The first documented attempt of geo-environmental risk analysis considered the petrochemical plant on Canvey Island at Thames, in London area (HMSO, 1978). In 80-ties, this kind of risk analysis was performed already for different industrial branches such as chemical, petrochemical plants, automotive manufacturing, railway, water supply etc. Presently, also forestry, public service, mining and local communities exhibit increasing awareness of the rationale within the procedures of Risk Assessment and Risk Management. Therefore one may observe the increasing demand for risk level information, on measures applied for its mitigation and on the legal responsibilities. In the same time the industry and the government agencies encounter financial and labour limitations in initiatives which may satisfy involved communities. Since risk perception level depends, among others, on quality of the knowledge about the actual risk level, the principles of reliable methods of risk assessment as well as dissemination them within communities technological/engineering issues and socio-psychological aspects, also referring to surface tailings ponds' construction and further exploitation are particularly important.

Larger and larger volume of industrial waste dumped into tailings ponds or storage yards as well as relatively low level of acceptance of local societies towards their enlargement or further exploitation, indicate the necessity for developing safety assessment procedures bonding multifaceted aspects of identification of hazards and their superimposing as well as determining effective and socially allowable and expected technical and organizational means of these hazards mitigation and prevention. Communities in industrial

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and post-industrial regions are often exposed to several hazardous processes developing within dam's and filling's structure of tailings ponds, resulting in possible earth dam instabilities following soil liquefaction due to e.g. strong mining-related seismic event associated with heavy rains. Hence, the adoption of a combined multi-risk-oriented analysis, in which investigations focus on the inter-correlation between events and their possible conjunction, is absolutely necessary.

The problem of risk created by tailings ponds, landfills and waste stockpiles is known widely for many years, particularly as an issue of earth dam's stability and a number of bulletins prepared by International Committee of Large Dams (ICOLD) were devoted to this subject. Pond embankments failure in Aurul S.A. Mine in Baia Mare (Romania) caused launching a large European research project TAILS SAFE (2004) completed in 2004 by an international consortium. However, this valuable work does not indicate recommended computational procedures which may help in real risk values estimation, especially for a case of statistically non-homogeneous natural and man-made environment subjected to various randomly defined external natural inter-correlated influences such as floods, rainfalls, earthquakes, tectonic movement of surface geological deposits (rocks and soil). These effects in conjunction with possible mining-related static and dynamic influences are extremely complex and therefore their analytical (numerical) solutions are unavailable in literature. The second from shortcomings of the above mentioned research project is lack of reference to risk management problems, which should be quantitatively and qualitatively confronted with allowable/tolerable/ultimate level of risk.

Taking into account the above mentioned problems one may conclude that there is a large room for new analytical tools which could permit integrating most of hazards posed by extractive waste storage facilities under the one general risk paradigm adequate also for different industrial branches/activity. Therefore in 2008 the large collaborative project "Integrated European Industrial Risk Reduction System – IRIS" has been commenced within the 7th Framework Programme (FP7-NMP-2007-Large-1) of EU. In this project Work Package 4 is devoted to mining industry, particularly to risk assessment and management addressed to tailings ponds and other waste storage facilities. The project will fill a presently existing gap in the engineering good practices transfer to communities, stakeholders and decision makers and furthermore, it will serve as a model for dissemination of the elaborated solutions. They will permit exploring new research domains concerning development of new methods and analytical tools for quantitative risk assessment as well as this knowledge promoting amongst practitioners. This will create a space for long-term cohabitation with hazards related to industrial tailings storage structures, providing support for practitioners to produce a comprehensive risk management and prevention policy. The new approach will utilize the data taken from at least three large sites from different European countries.

Unlike the previous works, the IRIS project offers integrating two basic paths of ponds safety estimation, each of them of extreme internal complexity:

- the path embracing analytical methods and measurement techniques addressed to a general problem of risk estimation in a case of possible structural instability due to natural and man-made hazards, and
- the path grouping analytical methods and measurement techniques useful for environmental risk assessment, for a case of soil/water possible pollution in accordance with the European regulations.

Each of the mentioned groups will utilize its own characteristic analytical and measurement methods as well as the specific methods of concluding. The final integration of the paths will take place as the appropriate procedures permitting the total risk assessing. Selected parts of his approach, concerning in particular a structural instability potential, will be outlined in the next parts of the paper.

## **2. Causes of tailing ponds failures in general view**

Due to unique conditions concerning geology, mineralogical properties of extracted ore, topography of surface as well as due to different technological mining systems and procedures, different mines produce unique tailings materials which are stored in surface storage structures of different technical and safety characteristics. All these objects are constructed according to laws and codes applicable to tailings storage facilities, nevertheless many failures of tailings dams occurred in European countries each year. Among the main reasons of such events occurrences we may indicate:

- insufficient knowledge of material characteristics,
- improper calculation models and theories describing the physical behavior of structures,
- operational departure from the prior accepted design criteria,
- lack of appropriate structure monitoring including the water level measurements,
- insufficient understanding of connections between the instability manifestation and the causes.

Therefore one may conclude that tailings dams safety should be explicit included within the well organized legislation system permitting mining companies to operate in possibly safest and effective manner.

At the advent of mining, tailings were disposed in the closest location, even put directly into flowing water or the existing drainage systems. Sedimentation in downstream watercourses however brought concerns about water use and therefore tailings began to be stored behind earthen dams, which were often constructed of tailings and other wastes.

More recently, concerns have been raised about the stability and environmental performance of tailings dams and impoundments. Stability concerns are raised in part by the use of tailings material in tailings

dams/embankments; to mitigate these concerns, such embankments often rely on a certain amount of controlled seepage to enhance stability, which in turn affects environmental performance.

Inactive tailings impoundments also are receiving more attention due to the long-term effects of windblown dispersal, ground water contamination, and acid drainage. In many cases, the costs of remediation can be considerable, significantly exceeding the costs of original design and operation of the tailings impoundment.

Impoundment of slurry tailings is the most common method of disposal (Fig. 1) and are the main focus of this report. Impoundments are favored because, among other things, they are "economically attractive and relatively easy to operate" [6].



Fig. 1. Spigotting outlets in *Żelazny Most* tailings pond (KGHM Polska Miedź S.A., Poland)

Tailings impoundments can be and are designed to perform a number of functions, including treatment functions. These include [6]:

- removal of suspended solids by sedimentation,
- precipitation of heavy metals as hydroxides,
- permanent containment of settled tailings,
- equalization of wastewater quality,
- stabilization of some oxidizable constituents (e.g., thiosalts, cyanides, flotation reagents),
- storage and stabilization of process recycle water,
- incidental flow balancing of storm water flows.

There are, however, a number of disadvantages to tailings impoundments requiring attention in design, including [6]:

- difficulty in achieving good flow distribution,
- difficulty in segregating drainage from uncontaminated areas,

- difficulty in reclamation, particularly with acid-generating tailings, because of the large surface area and materials characteristics,
- inconsistent treatment performance due to seasonal variations in bio-oxidation efficiency,
- costly and difficult collection and treatment of seepage through impoundment structures,
- potentially serious wind dispersion of fine materials unless the surface is stabilized by revegetation, chemical binders, or rock cover.

Tailings dams share several features with water retention dams but also have considerable differences. One main difference is that they are usually raised in stages during the life of the associated mine. In the past their construction was usually under the control of mining personnel who might not have been experts in dam construction. In this report an overview of the issues concerning legislation, management and surveillance procedures for the tailings dam is presented. The procedures concerning water storage dams are presented first as many of these procedures are also applicable to tailings dams. A few examples of the European countries presented in this chapter might not necessarily reflect the best practice in the world but they still give a hint of a practical point of view on the subject [11].

### **3. Current EU legislation and regulations on tailings facilities safety**

#### **3.1. Legislation on waste or tailings**

The Waste Framework Directive 75/442/EEC of 15 July 1975 (amended by Directive 91/156/EEC of 18 March 1991) lays down general provisions and principles for the handling of waste. The Directive states that Member States must take necessary measures to ensure that "the wastes are covered or disposed of in such a manner that they have no impact on human health or cause any environmental damage". This Directive applies to "...waste resulting from prospecting, extraction, treatment and storage of mineral resources" in the absence of specific Community legislation on mining waste (issue clarified by the Commission in its Communication on "Safe operation of mining activities: a follow-up to recent mining accidents") [11].

The Directive concerning Landfill of Waste (1999/31/EC of 26 April 1999) outlined generally surveillance programmes for water, leachates and gases. This directive also applies 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 were 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 was 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, like for instance, stability of dams in tailings ponds. In Annex I (General Requirements for All Classes of Landfills) it required maintaining the following *stability condition*: “The emplacement of waste on the site shall take place in such a way to ensure stability of the mass of waste and associated structures, particularly in respect of avoidance of slippages. Where an artificial barrier is established it must be ascertained that the geological substratum, considering the morphology of the landfill, is sufficiently stable to prevent settlement that may cause damage to the barrier”.

The Council Decision 2003/33/EC of 19 December 2002 on establishing criteria and procedures for the acceptance of waste at landfills (Acc. to Annex II to Directive 1999/31/EC) included also Appendix A on safety assessment for acceptance of waste in underground storage. This “risk assessment” analysis must include the following components:

- geological assessment
- geomechanical assessment
- hydrogeological assessment
- geochemical assessment
- biosphere impact assessment
- assessment of the operational phase
- long-term assessment
- assessment of the impact of all the surface facilities at the site.

Moreover, the Decision presented more clearly the overview of land filling options provided by the Landfill Directive (see Fig. 2 and Table 1).

In April 2006 entered into force the Directive 2006/21/EC of 15 March 2006 on the management of waste from extractive industries and amending Directive 2004/35/EC. This Directive provides for measures, procedures and guidance to prevent or reduce as far as possible any adverse effects on the environment, in particular water, air, soil, fauna and flora and landscape, and any resultant risks to human health, brought about as a result of the management of waste from the extractive industries. This Directive requires for each waste landfill the waste management plan (WMP) to be prepared with the following aims:

- to prevent or reduce waste production and its harmfulness
- to encourage the recovery of extractive waste by means of recycling, reusing or reclaiming such waste
- to ensure short and long-term safe disposal of the extractive waste, in particular by considering, during the design phase, management during the operation and after closure of a waste facility and by choosing a design which **ensures the long-term geotechnical stability of any dams** or heaps rising above the pre-existing ground surface.

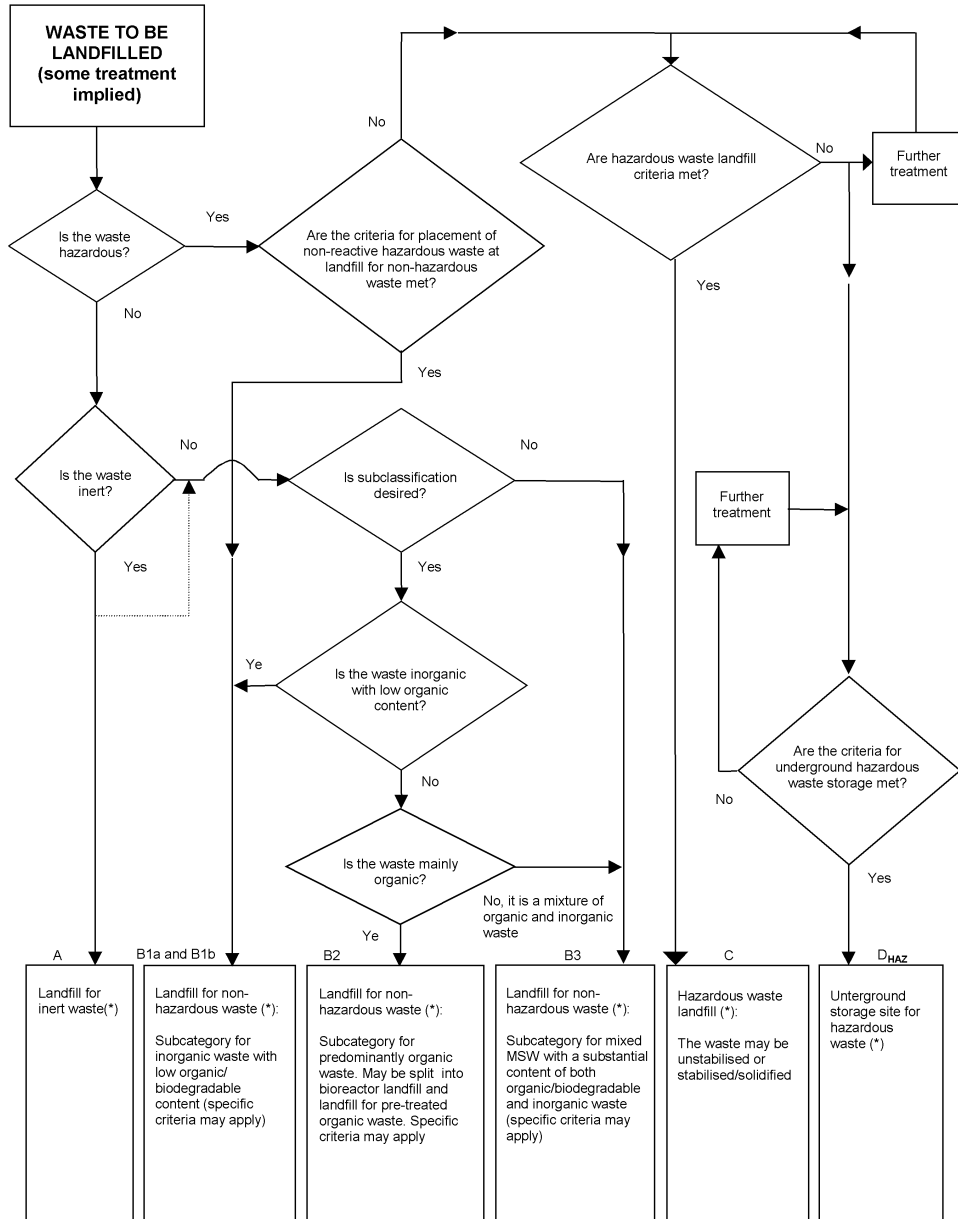
Table 1

Overview of landfill classes and examples of subcategories  
(Council Decision 2003/33/EC)

Landfill class	Major subcategories (underground storage facilities, monofills and landfills for solidified, monolithic (*) waste possible for all landfill classes)	ID	Acceptance criteria
Landfill for inert waste	Landfill accepting inert waste	A	Criteria for leaching and for content of organic components are set at EU level (section 2.1.2). Criteria for content of inorganic components may be set at Member State level.
Landfill for non-hazardous waste	Landfill for inorganic non-hazardous waste with a low content of organic/biodegradable matter, where the wastes do not meet the criteria set out in section 2.2.2, for those inorganic non-hazardous wastes that may be landfilled together with stable, non-reactive hazardous waste	B1a	Criteria for leaching and total content are not set at EU level
	Landfill for inorganic non-hazardous waste with a low content of organic/biodegradable matter	B1b	Criteria for leaching and content of organics (TOC) and other properties are set at EU level, common for granular non-hazardous waste and for stable, non-reactive hazardous waste (section 2.2). Additional stability criteria for the latter are to be set at Member State level. Criteria for monolithic waste must be set at Member State level
	Landfill for organic non-hazardous waste	B2	Criteria for leaching and total content are not set at EU level
	Landfill for mixed non-hazardous waste with substantial contents of both organic/biodegradable waste and inorganic waste.	B3	Criteria for leaching and total content are not set at EU level
Landfill for hazardous waste	Surface landfill for hazardous waste	C	Criteria for leaching for granular hazardous waste and total content of certain components have been laid down at EU level (section 2.4). Criteria for monolithic waste must be set at Member State level Additional criteria on content of contaminants can be set at MS level
	Underground storage site	D <sub>HAZ</sub>	Special requirements at EU level are listed in Annex A

(\*) Monolithic waste subcategories are only relevant for B1, C and D<sub>HAZ</sub>, and possibly A.

Acc. to this Directive, each operator shall, before the start of operations, draw up a major-accident prevention policy for the management of extractive waste and put into effect a **safety management system** implementing it. As part of that policy, the operator shall appoint a safety manager responsible for the implementation and periodic supervision of the major-accident prevention policy. The major – accident prevention policy should consider, among others, identification and evaluation of major hazards i.e. adoption and implementation of procedures for systematically identifying major hazards arising from normal and abnormal operations and assessment of their **likelihood and severity**.



(\*) In principle, underground storage is also possible for inert and non-hazardous waste.

Fig. 2. Diagram showing the landfilling options provided by the Landfill Directive (1999/31/EC)

The competent authority shall draw up an external emergency plan specifying the measures to be taken off-site in the event of an accident. As part of the application for a permit the operator shall provide the competent authority with the information necessary to enable the latter to draw up that plan. No waste facility shall be allowed to operate without a permit granted



by the competent authority and including all the mentioned above information. Moreover, the competent authority shall satisfy itself that, in constructing a new waste facility or modifying an existing waste facility, the operator ensures that the waste facility is suitably constructed, managed and maintained to ensure its **physical stability** and to prevent pollution or contamination of soil, air, surface water or groundwater in the short and long-term perspectives as well as to minimize as far as possible damage to landscape.

The Directive 2006/21/EC is a base for the Polish Extractive Waste Act of 10 July 2008.

### 3.2. Legislation on water

In the EU, the management of water is based on an integrated management system depending mainly on quality standards and limit values for emissions. Directives also concerned with tailings sites are, for example:

- Discharges into Water, Directive 76/464/CEE with other Directives on discharges of dangerous substances
- Groundwater Protection Directive 80/68
- Water Framework Directive 2000/60/EC supplemented by Directive 2006/118/EC on the protection of groundwater against pollution and deterioration.

The aim of the Water Framework Directive is to provide a general framework for the protection of all waters. Although not explicitly mentioned, point sources of water pollution such as, for instance, acid drainage generated by tailings ponds will have to be covered by the characterization of pressures and impacts in a river basin. The requirements of the Water Framework Directive apply also to the pollution originating from abandoned facilities of the extractive industries [11]. The Directive 2006/118/EC basically covers criteria for the assessment of good groundwater chemical status and criteria for the identification and reversal of significant and sustained upward trends and for the definition of starting points for trend reversals.

### 3.3. Legislation on environmental issues

The Environment Impact Assessment (EIA) Directive (85/337/EEC) (amended by Directives 97/11/EC and 92/104/EEC) is an integral part of the laws on mining operations for most of the EU countries. The primary objective of the EIA is to ensure that projects which are expected to have significant effects on the environment are subject to an assessment of their likely impacts. In particular, quarries, open-cast and underground mining and drillings are included in the scope of this Directive.

EIA is a process for anticipating the effects on the environment by an activity. An Environmental Impact Statement (EIS) is the document produced as a result of that process providing information which the

competent authority uses in determining whether consent should be granted or not.

The Directive 2004/35/CE on environmental liability with regard to the prevention and remedying of environmental damage included the influences of all landfills and waste storages.

### **3.4. Legislation and regulations on tailings facilities safety in different countries**

Legislation and regulations applicable to tailings dams differ considerably amongst the countries.

The International Commission on Large Dams – ICOLD (1989) provides various recommendations on how tailings dam statutory legislation could be arranged. These contain provisions for commissions, registers, permit procedures for design, construction, operations and maintenance, supervision, authorities, inspections and rehabilitation.

In Australia the legislation concerning mining includes the Mining Act and the Mines Safety and Inspection Act. In some cases, additional Acts (Aboriginal Heritage Act, Conservation 10 and Land Management Act, Land Administration Act, Local Government Act, Soil and Land Conservation Act, Wildlife Conservations Act, Native Title Act) are also adapted. All TSF in Western Australia are categorized as a Category 1, 2 or 3 facility. The TSF categorization is based on its “hazard rating”, coupled with the maximum embankment height. All TSF over 15 m in height are considered to be Category 1 facilities, i.e. those requiring the most stringent attention [11].

ANCOLD published its “Guidelines on Risk Assessment” in 2003. It contains very usable information on methods for estimating the probability of failure for embankment dams (see tab. 2).

Regulation of mining in the USA is the responsibility of the individual states. Jurisdictional processes vary from state to state with a focus on outcomes rather than operating procedures. For example in the state of Nevada, the Bureau of Mining Regulation and Reclamation (in cooperation with other state, federal and local agencies) regulates mining activities under regulations adopted in 1989.

Table 2

Extract of recommended methods for estimating the probability of failure for embankment dams [1]

Load Condition	Failure Mode	Recommended Methods	
		Preliminary and Portfolio Assessments	Detailed Assessment
Normal operating	Embankment instability and loss of freeboard	Historic performance plus judgement	Historic performance plus judgement, probabilistic analysis if sufficient data is available
	Internal erosion and piping in the embankment, foundation, and embankment to foundation	Historic performance with detailed failure paths; or event trees for all critical failure paths	Event trees for all failure paths
	Spillway wall instability	Analysis plus judgement	Analysis plus judgement
Flood	Embankment overtopping	Flood level AP usually estimated without modelling prior water level. Historic performance plus judgement to assess depth of overtopping giving failure	Flood level AP modelled with prior reservoir water level. Historic performance plus judgement to assess depth of overtopping vs probability of failure
	Embankment instability and loss of freeboard	Covered in normal operating load calculation	Historic performance plus judgement; probabilistic analysis if sufficient data available
	Internal erosion and piping in the embankment, foundation and embankment to foundation	Covered in normal operating load calculation if using historic performance; or event trees for all critical failure paths	Event trees for all failure paths
	Spillway and spillway energy dissipator scour and overtopping of spillway chute walls	Analysis, results of modelling if available, and judgement	Analysis, results of modelling if available, and judgement
Earthquake	Embankment instability and loss of freeboard for dams not subject to liquefaction	Earthquake AP of peak ground acceleration. Simplified deformation analysis, or judgement. Reservoir assumed at full supply level	Earthquake AP of peak ground acceleration. Simplified deformation analysis, unless critical, where advanced numerical modelling may be used. Prior reservoir level modelled
	For dams subject to liquefaction	Earthquake AP of peak ground acceleration, single design magnitude. Simplified liquefaction analysis	Earthquake AP of peak ground acceleration, with magnitude contributions. Detailed liquefaction analysis. Prior reservoir level modelled
	Internal erosion and piping in the embankment, foundation and embankment to foundation	Earthquake AP of peak ground acceleration, with detailed failure paths and judgement. Reservoir assumed at full supply level	Earthquake AP of peak ground acceleration, with event trees for all failure paths. Prior reservoir level modelled.
	Spillway wall instability	Earthquake spectral analysis, pseudo static analysis plus judgement	Earthquake spectral analysis, pseudo static analysis plus judgement
Reservoir Rim Instability	Overtopping of dam by flood induced by landslide in the reservoir	Judgement based on topography, geomorphological mapping and historic landsliding	Landslide hazard assessed by air photo interpretation, inspection, and geomorphological mapping, and history and mechanics of sliding. Wave heights calculation from volume and velocity of slide.

With the passage of the National Dam Safety Program Act of 1996, Public Law 104-303, ICODS and its Subcommittees were reorganized to reflect the objectives and requirements of Public Law 104-303. In 1998, the newly convened Guidelines Development Subcommittee completed work on the update of the following guidelines:

- Federal Guidelines for Dam Safety: Emergency Action Planning for Dam Owners, FEMA 64, October 1998, reprinted April 2004
- Federal Guidelines for Dam Safety: Selecting and Accommodating Inflow Design Floods for Dams, FEMA 94, October 1998, reprinted April 2004
- Federal Guidelines for Dam Safety: Hazard Potential Classification Systems for Dams, FEMA 333, October 1998, reprinted April 2004.

With the amendment of the Act into the National Dam Safety and Security Act of 2002, Public Law 107-310, former ICODS Subcommittees were reorganized under the National Dam Safety Review Board (NDSRB). In 2004, two task groups finalized the ongoing work of the previous Subcommittee on the update of the following guidelines:

- Federal Guidelines for Dam Safety: Glossary of Terms, FEMA 148, printed April 2004
- Federal Guidelines for Dam Safety: Earthquake Analyses and Design of Dams, FEMA 65, printed May 2005.

Particularly FEMA 65 provides very important regulations concerned with safety of embankment dams subjected to seismic action.

The Canadian Dam Association (CDA) has strong links with various US organizations, and will be significantly influenced by the major Canadian dam owners, such as BC Hydro. CDA has published the Canadian dam Safety Guidelines in 1999, which retain traditional analysis of safety factors as the method of assessing dam safety.

Mining in South Africa is regulated by the Water Act, 1998, the Minerals Act, 1991 and the Mine Health and Safety Act, 1996. The Department of Minerals and Energy (DME) is responsible for implementing the provisions of the Acts. Government Mining Regulations had come into force in 1976 and they required a minimum freeboard of 0.5 m to be maintained at all situations for a tailings dam, in order to store rainfall occurring once in a hundred year without any fear of overtopping [11].

Still in the EU countries there are valid specific legislation concerning waste from mining operations, although it is currently adopting to the above mentioned EU law. At the moment, the members States have their own mining and environmental legislation which covers the mining branch and is applicable to the tailings management facilities.

In Romania specific regulations on tailing ponds were covered by the law and special orders are issued by the Ministry of Water and Environment Protection and the Ministry of Industry and Resources. Also In Hungary a specific regulation on tailing ponds existed.

Tailings dams in Finland are included in the scope of the Mining Act and Mining Decree. It is required in the Mining Law that suitable and applicable parts of the dam safety guidelines should be taken into account and the safety requirements stated in the Mining Law correspond to those of the Dam Safety Act. Other laws applying to tailings storage facilities are: the Environmental Protection Act (86/2000) and the Waste Act (1072/1993).

In the UK tailings dams are regulated by the Reservoir Act 1975. It applies to tailings dams which still contain water and are capable of holding more than 25,000 m<sup>3</sup> of water above natural ground level. Spoil heaps and lagoons of liquid wastes at mines and quarries are subject to the Mines and Quarries (Tips) Act 1969 and the related 1971 regulations, which lay down detailed requirements concerning their stability and safety. However, no tailings dams guidelines or codes of practice exist. Other laws applicable to tailings management facilities are the Health & Safety at Work Act 1974, the Mines & Quarries (Tips) Act 1969, the Mines & Quarries (Tips) Regulations 1971, the Environment Act 1995 and the Record of refuse deposited on active classified tips, Regulation 14 'A'.

In Poland tailings dams are the outside the scope of the Geological and Mining Law Act. They are regulated mainly by the Construction Law and the Polish Norms (design and construction). Regulations concerned with tailings dams in Poland one may find in:

- The Construction Law & Polish Norms (design, construction)
- The Water Law Act (license to operate)
- The Act on Environmental Protection (EIA, monitoring)
- The Act on Waste (payments for discharge of water)
- The Order of the Ministry of Environment of 24 March 2003 on location, construction, exploitation and closure of any waste storages.

Tailings dams are classified in the same way as water retention dams and constitute four classes. All over surface raised tailings dams which impoundment size is more 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. According to this law, granting a decision whether to permit a proposed project which 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 EIA should contain, inter alia:

- a concise description of the project (nature, size, location, type of technology, etc) and the conditions for site use at the stages of construction, operation and closure
- the determination of the impact of the project on the environment, including the case of an emergency hazard to the environment
- a description of measures to prevent and reduce the impact on the environment

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- a comparison of the proposed technological solutions with other available solutions applied in national or world practice from the point of view of cleaner production
  - a concise summary of the information contained in the audit in a non-technical language.

Presently the Directive on the management of waste from the extractive industries 2006/21/EC is under adoption process which includes among others:

- definition of the waste facility
- classification system waste facilities depending on their hazard potential
- permit for a construction of a waste facility
- waste management plans
- emergency plan, etc.

In Germany not all tailings ponds are amendable to the Mining Law. Planning, construction, maintenance and operation of tailings dams are defined in the Water Act (different for different states). Furthermore, the selected German Industry Norms (DIN-Normen) are applicable to tailings dams.

No specific legislation concerning tailings dams exists but Ireland has adopted the UK legal System. The UK's Reservoirs Act 1975 works as an operational law, although it is not legally binding. ICOLD recommendations concerning safety of tailings dams has had an impact on the practice in Ireland as well as the Canadian and Australian guidelines. All instructions and issues connected to safety of the TMF are included in the operational permit of a mine. The authorization process for mining activities includes, inter alia, the Integrated Pollution Control License (IPC). Since 1994 this license has been required to be obtained from the Irish Environmental Protection Agency (EPA) for most large industrial activities in order to commence or continue operations. The requirements of the IPC license corresponds 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 the mining as well as the processing of minerals into the IPC licensing net. One of the documents central to the license 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.

In 1997 the Swedish hydropower industry have developed their own guidelines for new and existing dam safety RIDAS, revised in 2002. In 2007 however, these guidelines have been extended into GruvRIDAS form

including embankment dams issues which are using by mining industry at the moment.

## 4. Currently applied risk assessment methods

### 4.1. Introduction

The problem of risk created by tailings ponds, landfills and waste stockpiles is known widely for many years, particularly as an issue of earth dam's stability. These structures work in statistically non-homogeneous natural and man-made environment subjected to various randomly defined external natural inter-correlated influences such as floods, rainfalls, earthquakes, tectonic movement of surface geological deposits (rocks and soil). These effects in conjunction with possible mining-related static and dynamic influences are extremely complex and therefore their analytical (numerical) solutions are unavailable in literature in a complete form.

Although the "true" risk assessment analysis for tailings ponds has been not required by the existing law in the past, the present knowledge of the subject is already sufficient for its "partial" development. This may be done using the principles of probabilistic risk assessment (PRA) theory addressed to earth/tailings surface structures. The presented flowchart (see Fig. 3) indicate all recommended steps of such analysis. At the present moment however, only selected parts of PRA analysis are sufficiently recognized and theoretically developed to be ready for instant application. Nevertheless current practice in risk analyses of tailings ponds/storages is already able to consider in deep the following aspects of the problem :

#### A. Object description and hazard identification:

- (a) mechanical/functional model of the object (e.g. geometry, material within embankments, filling and foundation, drainage, water flow etc., methods of parameters' description and determining);
- (b) identification of direct and indirect (complex) hazards and associated phenomena, e.g. dam failure modes with relevant parameters and methods of measurement/estimation, moving mass volume, velocity and distance of movement, soil liquefaction, seismicity, forced displacement, etc.;
- (c) analytical methods and computer programs selection for appropriate modeling of any deterministic phenomena associated with the object behavior (stress/strain distribution – FEM,FDM, water flow and seepage, filling flow, debris movement, etc.);
- (d) soil and surface water contamination (chemistry, range of pollution, etc.);
- (e) laboratory and field investigation, measurements and tests following internationally recommended procedures.

#### B. Frequency/probability of failure events assessment:

- (a) analytical methods selection: first-order, second-moment approach (FOSM), first- and second-order reliability methods (FORM and SORM), Monte-Carlo simulation techniques, event tree and fault tree analyses, Bayesian updating approach, etc.
- (b) random variables and their distribution functions and estimators.
- C. Consequence analysis and vulnerability:
  - (a) property,
  - (b) people,
  - (c) roads,
  - (d) vehicles
- D. Quantitative risk estimation (wherever possible should be based on a quantitative analysis).
- E. Risk evaluation: acceptable and tolerable risk.
- F. Risk treatment:
  - (a) treatment options (methods for reducing of probability or consequences, monitoring and warning systems, transfer the risk);
  - (b) treatment plan – how the options will be implemented;
  - (c) surveillance, monitoring and inspections.

However, mathematical complexity of “full solution” as well as a lack of law enforcing strict requirements in this matter discourage owners to perform such analysis in a truly extended formulation. Therefore currently practiced so called “risk analyses/assessments” are confined rather to the basic deterministic considerations/solutions and field activities described in the following chapters.

It must be however emphasized that the A-F list of topics mentioned above, applied for the rare and very important objects, has also a large number of shortcomings concerned with lack of advanced solution and procedures. Since the earth/tailings structures work in statistically non-homogeneous natural and man-made environment subjected to various randomly defined external natural inter-correlated influences, risk assessment procedures become extremely complex due to inter-correlated and conditional probabilities and therefore their analytical (numerical) solutions are unavailable in literature yet. IRIS WP4 will offer these probabilities integrating procedures permitting the total risk assessing.

#### **4.2. Technical characteristics of waste facilities**

There are two basic types of structures used to retain tailings in impoundments:

- the retention dams (Fig. 4), and
- the raised embankment dams (Fig. 5).



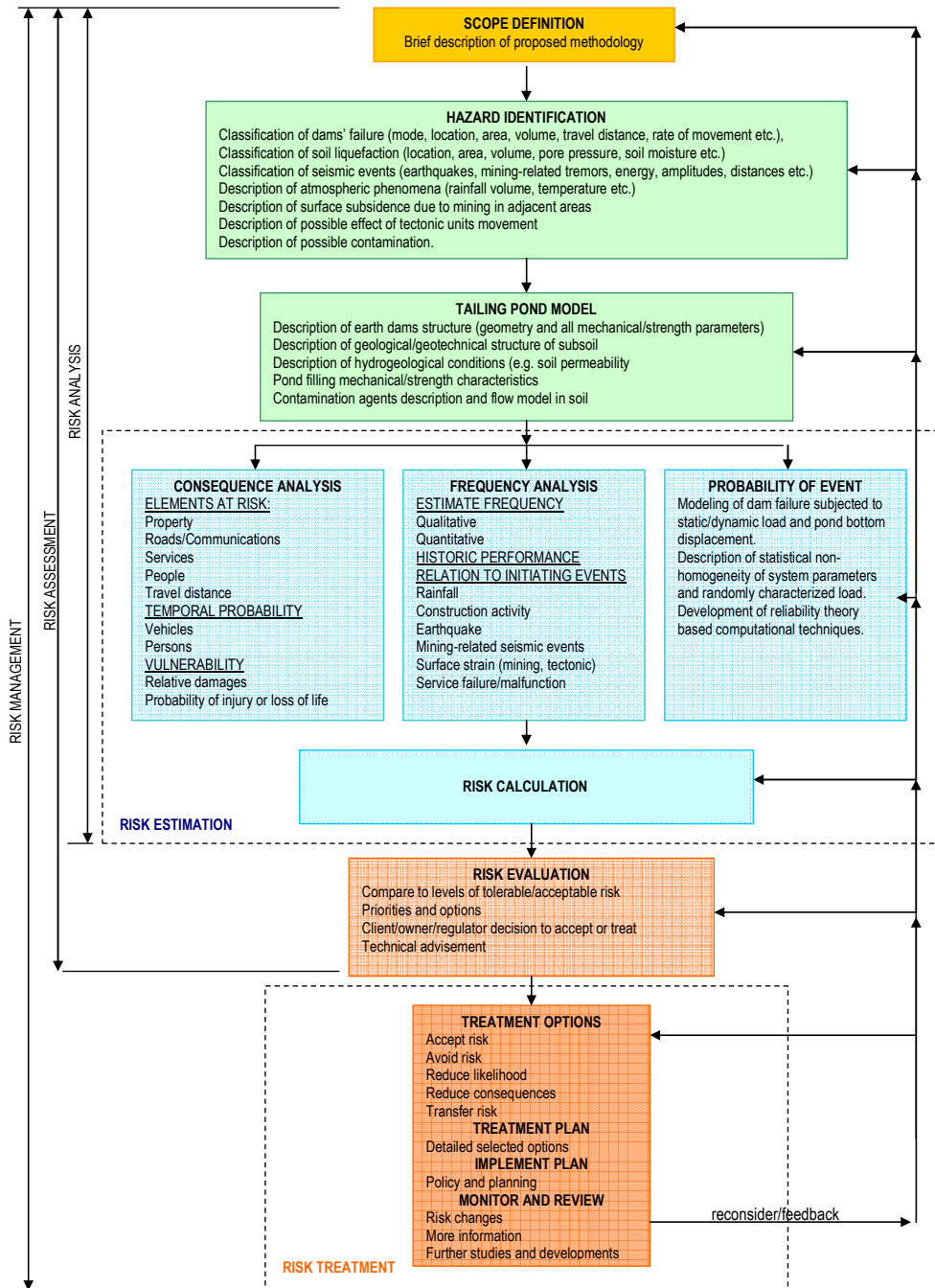


Fig. 3. Flowchart for probabilistic risk assessment (based on Landslide Risk Management, 2000)

Because raised embankments are much more common than retention dams, they are emphasized in this report. Either type of structure, raised embankments or retention dams, can be used to form different types or configurations of tailings impoundments. The four main types of impoundments include:

- Ring-Dike (Fig. 6)
- In-Pit
- Specially Dug Pit (Fig. 7), and
- Valley design (Fig. 8).

The design choice is primarily dependent upon natural topography, site conditions, and economic factors. Most tailings dams in operation today are a form of the Valley design. Because costs are often directly related to the amount of fill material used in the dam or embankment (i.e., its size), major savings can be realized by minimizing the size of the dam and by maximizing the use of local materials, particularly the tailings themselves. Retention dams are constructed at full height at the beginning of the disposal whereas raised embankments are constructed in phases as the need for additional disposal capacity arises. Raised embankments begin with a starter dike with more height added to the embankment as the volume of tailings increases in the impoundment.

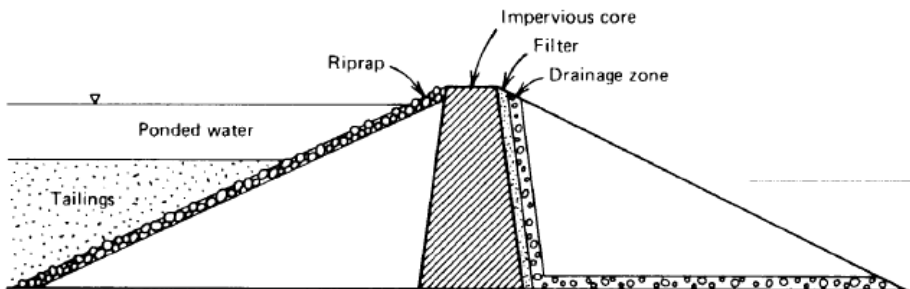


Fig. 4. Water-retention type dam for tailings disposal

Source: [7]

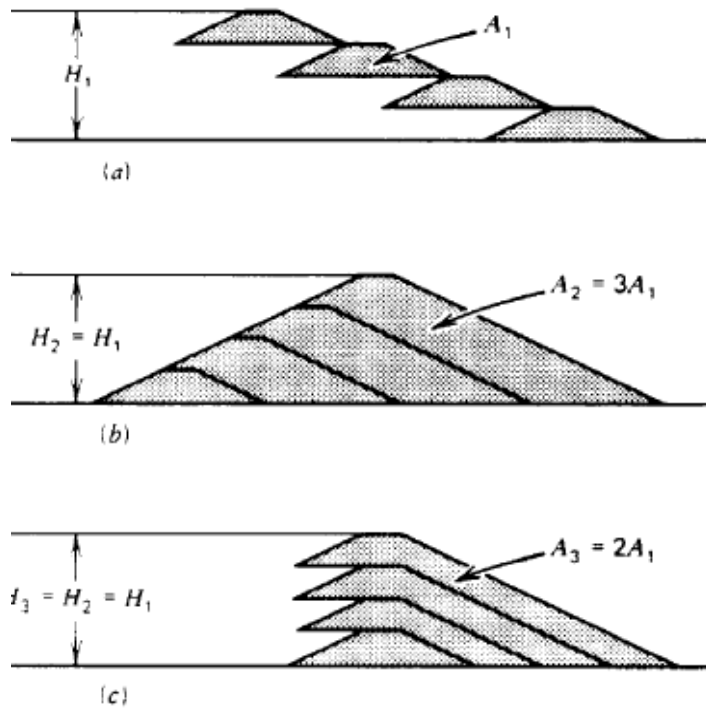


Fig. 5. Embankment types: (a) upstream, (b) centerline, (c) downstream  
Source: [7]

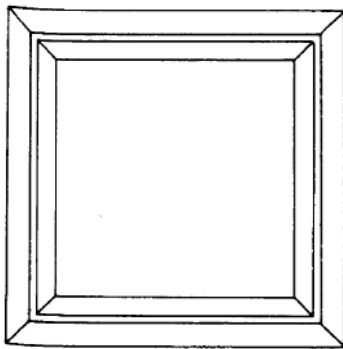


Fig. 6. Ring-Dike type of impoundment structure (left), tailings pond Želazný Most (right)

Source: [17]



Fig. 7. In-Pit type of tailings pond

Source: Angel Faz Cano. Risk assessment and restoration possibilities of some abandoned mining ponds in the Murcia region, SE Spain, SP4 Meeting, Wroclaw, 2009

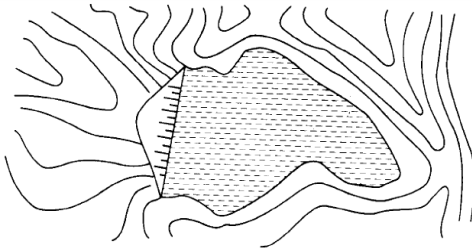


Fig. 8. Cross-valley impoundment type

Source: Vick, 1990 (left), Angel Faz Cano. Risk assesment and restoration possibilities of some abandoned mining ponds in the Murcia region, SE Spain, SP4 Meeting, Wroclaw, 2009 (right)

Tailings retention dams are similar to water retention dams in regard to soil properties, surface water and ground water controls, and stability considerations. They are suitable for any type of tailings and deposition method.

Upstream method of tailings dam construction, while available at low cost, implies a number of specific hazards for dam stability. These hazards require a thorough assessment and continuous monitoring and control during siting, construction, and operation of the dam. Experience shows that these conditions often are not maintained. Typical modes of such kind dams failure are presented below.

### 4.3. Tailings impoundment design

The actual design of a tailings dam and impoundment occurs after the site has been selected. The site and embankment type as well as the impoundment configuration are however strongly effected by a number of design principles and physical parameters or phenomena. The following section describes them briefly. It should be emphasized that the major issues in the design process are: structural stability, cost, and environmental performance.

#### 4.3.1. Basic design concepts (EPA, 1994)

Tailings impoundments and their dams are designed basically using the data on tailings' physical and strength-deformation characteristics, available construction materials, site's hydro-geological conditions, local topography. Water presence and its flow and table level location belong to the most important parameters governing dam stability and in-time performance. The maintenance of the phreatic surface (the surface along which pressure in the fluid equals atmospheric pressure – water table) as low as possible near the embankment face is the fundamental principle in the embankment design process. This permits maintaining a pore pressure at the face of the embankment lower than atmospheric pressure plus the weight of the embankment particles what enables the face of the dam to be stable. The basic methods of maintaining a low phreatic surface near the embankment face is to increase the relative permeability of the embankment in the direction of flow (see Fig. 9) and/or using an appropriate drainage system (see Fig. 10). The most important factors influencing the phreatic surface location are:

- permeability, compressibility, and grading of tailings,
- embankment internal structure, and
- site-specific features such as foundation characteristics and the hydrogeology of the impoundment area.

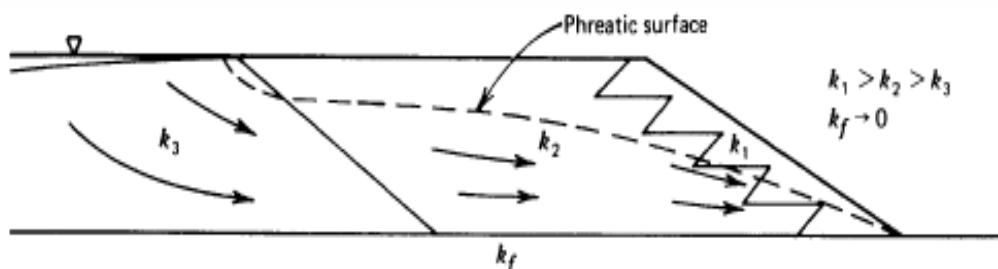


Fig. 9. Phreatic Surface Through a Tailings Impoundment

Source: [3]

The phreatic surface in a waste embankment may change due to a number of reasons, among them:

- malfunction of drainage systems
- freezing of surface layers on the downstream slope of the dam
- changes in construction method (including the characteristics of the placed material)
- changes in the elevation of the pond, and
- externally induced subsidence (e.g. mining related).

In addition to maintaining the phreatic surface for stability purposes, dam design includes also factors related to environmental impacts associated with tailings seepage which may be controlled by the use of liners, drains, and pump back systems. The design should also address the future reclamation of the site.

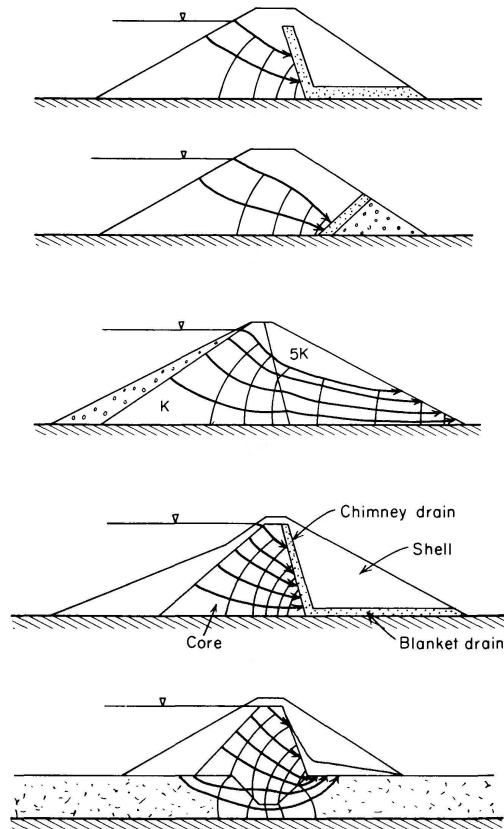


Fig. 10. Design features for earth and rockfill dams

Source: [4]

### 4.3.2. Design variables

#### 4.3.2.1. Tailings-specific factors (EPA, 1994)

The tailings' physical characteristics are evaluated in the design of tailings impoundments from the following points of view:

- the potential use of tailings sands in constructing the embankment
- the potential impact on structural stability and seepage characteristics, and
- the potential chemical aspects of seepage or other discharges from the impoundment.

The best method of deposition of tailings into the impoundment should be also examined within this stage of design.

Tailings sands are often used as an inexpensive source of material for embankment construction; by removing the sands for embankment construction the volume of tailings to be disposed of is reduced. Basically tailings are considered to be soils (with subtle differences) and subject to traditional soil mechanics patterns of behavior. Index physical properties (gradation, specific gravity, and plasticity) may be determined by relatively simple tests. The properties that impact design, stability and drainage of the impoundment include among others:

- in-place and relative density
- permeability (hydraulic conductivity) varying in both horizontal and vertical directions
- plasticity which may be expressed by the Plasticity Index - the range of moisture content over which a soil is plastic (tailings with a high Plasticity Index are finer-grained and have low permeability and drainage characteristics, while tailings with a low Plasticity Index are more coarse and have high strength and permeability drainage properties)
- consolidation and compressibility displaying the ability to change in overall volume over time due to dewatering and/or added load (depends on particle size, void ratio etc.)
- shear strengths and stress parameters affect dam stability and depend on the value of pore pressure.

These factors mutually interact in a complex way producing the unique phreatic surface inside impoundment and embankment.

In addition to tailings characteristics that affect stability and seepage quantity, tailings can be analyzed to determine seepage water quality. Besides process chemicals (e.g., cyanide) that may be present, metal mine tailings may contain an array of minerals originally present in the host rock that can contaminate tailings seepage. Contaminants including arsenic, copper, lead, manganese, selenium and other metals. Tailings also can have significant levels of radioactivity. Tailings and effluent may be acidic or caustic, and in some cases are neutral but later become acidic. The

oxidation of sulphides, particularly pyrite ( $\text{FeS}$ ) and pyrrhotite ( $\text{Fe}_{1-x}\text{S}$ :  $\text{Fe}_6\text{S}_7$  to  $\text{Fe}_{11}\text{S}_{12}$ ) can result in the generation of acid drainage. In the presence of free oxygen, the pyrite oxidizes to produce acidic conditions. The chemical reaction is the combination of metal sulfide and water to produce a metal hydroxide and sulfuric acid. In addition to chemical oxidation, a bacterium (*thiobacillus ferrooxidans*) causes bacterial oxidation which may become the dominant process in the later stages of acid production. The acidification of tailings ponds can occur in tailings that were initially alkaline; as water levels drop within the tailings impoundment, they introduce air into the void spaces and the subsequent oxidation produces acids. Analysis of the ore and tailings prior to disposal is useful in anticipating water quality problems and the need to adjust seepage flows (EPA 530-R-94-038, 1994).

#### 4.3.2.2. Site-specific factors

Site-specific factors include:

- volume of tailings and area required by the dam
- cost of fill material
- water controls
- tailings depositional methods, and
- flood control, ground water and surface water contamination, and wildlife habitats.

#### 4.3.2.3. Mill/processing plant location

Typically, tailings are transported from the processing plant (mill) in form of slurry with water content of 45-85 percent by weight. (see Fig. 11), by extensive piping systems. Therefore sites close to the mill are favored on a cost basis over those further away. Furthermore, sites should be if possible located downhill from the mill to allow gravity flow of the tailings to the impoundment and to minimize slurry pumping costs.



Fig. 11. Slurry transporting system between KGHM mines and Želazny Most tailings pond



#### 4.3.2.4. Topography

Since the basic aim of impoundment effective design is the maximum storage capacity with the least amount of embankment volume, the natural topography is one of the main considerations for the given impoundment volume required. It is generally accepted rule that embankment heights should be kept below 60 m since higher embankments often pose design and construction problems that could be avoided by better siting (see Fig. 12).

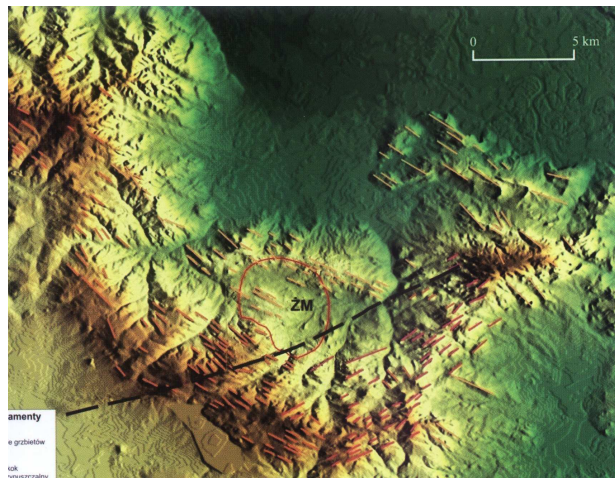


Fig. 12. Terrain numerical model with the major tectonic structures in the vicinity of Želazny Most tailings pond [2]

#### 4.3.3. Geology and ground water

Once the site screening criteria of mill location, topography, and hydrology have been applied, the number of siting options usually has been considerably reduced. Geologic considerations then assume a critical role (see Fig. 13). Different observations can assess broad geologic factors, including drainage conditions at the site, and apparent ground stability of the site (such as slumping, evidence of weak planes within the rock, faulting, etc.). Test pits and trenches may be dug and test holes may be drilled to obtain soil and/or rock samples. In situ permeability tests also may be run in holes drilled at the site of the proposed tailings impoundment area (Fig. 14).

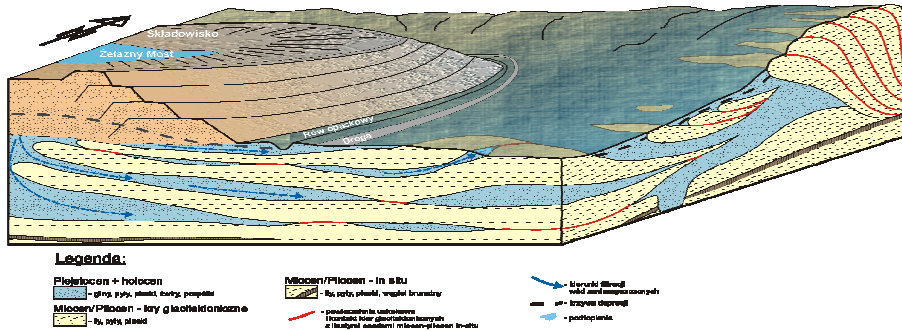


Fig. 13. General view on Żelazny Most tailings pond geology [13]

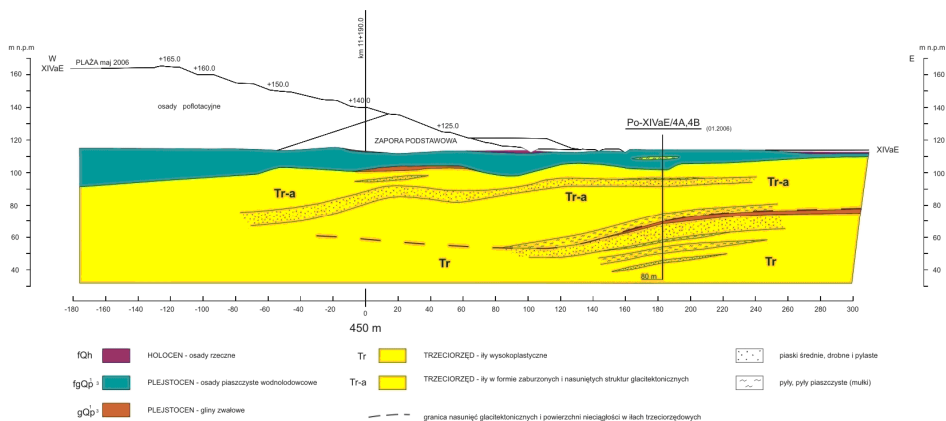


Fig. 14. Żelazny Most tailings pond selected cross-section with foundation geotechnical structure [17]

In particular, site geology and geotechnical conditions affect the foundation of the embankment, seepage rates, and the availability of borrow materials for embankment construction (see Fig. 15). Soft foundations, for example, may limit the allowable rate of embankment build-up in order to allow for adequate pore pressure dissipation. Sloping foundations and the presence of weak layers in the foundation will need to be investigated since they may contribute to slope failure of the embankment.

Ground water conditions are usually related to the geology, and also affect siting conditions. A high water table limits the amount of dry borrow material available for construction, and shortens the distance for seepage to enter the ground water system. In addition, shallow ground water can infiltrate tailings and increase the amount of water in the impoundment.

A proposed site has to undergo a geotechnical site investigation. The investigation will assess site geology, including the depth, thickness, continuity, and composition of the strata (Fig. 14), and site hydrogeology; geotechnical properties of soil and rock affecting design.

Geotechnical testing on soils is generally undertaken to determine water content, grain-size distribution, Atterberg limits (moisture content in soil as measured in the boundary stages of four states of soil: liquid, plastic, semi-solid, and solid), consolidation, shear, permeability, and ion exchange capacity (of clays considered for liners). For rocks it is usually necessary to know the shear strength along weak layers, and the permeability and strength of the various strata. These tests are usually performed in combination with in situ tests such as standard penetration (see Fig. 16), static cone, vane shear, and pressure meter, in order to obtain useful data on field properties. While estimates of soil permeability may be determined in the laboratory, these values need to be confirmed through field testing, which may include borehole in situ methods, and large scale pumping methods. In addition, ground water measurements, including piezometric pressures in the underlying soil/sand rocks, and water sampling are usually undertaken to establish baseline conditions prior to construction of the impoundment.

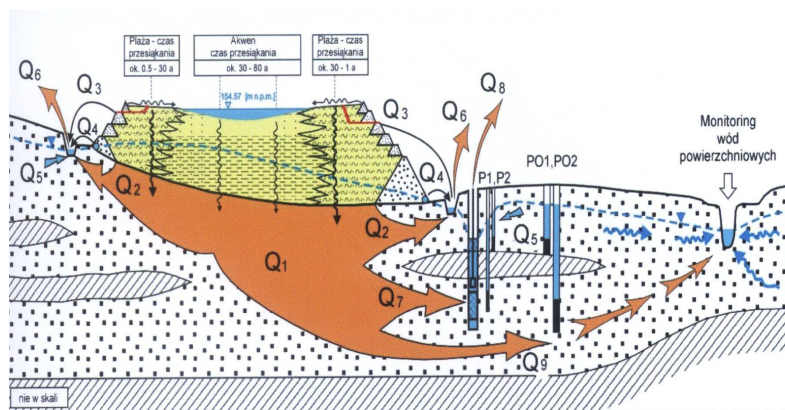


Fig. 15. Conceptual model of water flow in Żelazny Most tailings pond and foundation [20]

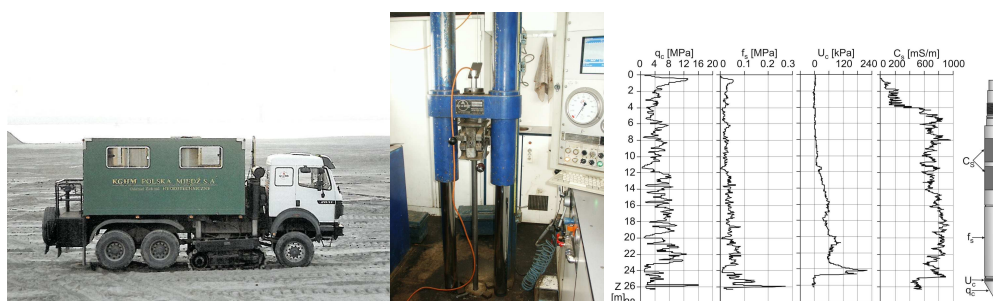


Fig. 16. CPT field measurements within Żelazny Most tailings pond using self propelled laboratory (on the right, selected depth-dependent profiles for: cone resistance, friction on the probe surface, pore pressure, electric conductivity) [18]

#### 4.3.4. Foundations

The foundation area beneath the embankment is assessed using the geotechnical methods. Compression or consolidation of the foundation can cause appreciable settling of the overlying material, sometimes causing cracks in tailings embankments that can lead to seepage or piping.

The permeability of the foundation significantly affects the stability of an embankment. When an embankment is constructed on a foundation of saturated impervious clay, for example, the loading of the embankment will create excess pore water pressure in the foundation material. Because the immediate loading is taken by the water phase in the foundation material, there is no increase in shear strength and the rapid increase in loading can precipitate embankment failures extending through the foundation. If the foundation material beneath the tailings dam is pervious, excessive seepage can lead to piping failure. All of these foundation factors are taken into account during design.

#### 4.3.5. Seismicity

The design of tailings impoundments usually has to consider potential seismic activity at the site, particularly located in close vicinity of the areas of mining operations. This requires continuous measurements of mining-related seismicity (see Fig. 17) which results will create a basis for further studies concerned with dynamic effects on structure/embankment (in)stability.

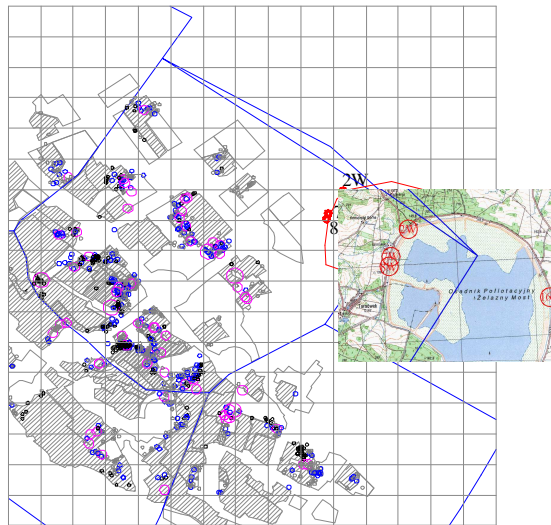


Fig. 17. Seismic monitoring stations established on Żelazny Most dams and mining-related seismic events focuses in its vicinity

#### 4.4. Typical causes and modes of tailings dam failure

The first step in the design or evaluation of any dam is the development of an understanding of the way the dam can fail. The dams' capacity to remain stable in common or unusual/challenging load conditions is the most important characteristic of such earth/tailings/rock structures. Below typical modes of dams failures are presented.

##### 4.4.1. Hazard from weak foundation (1/3 of all dam failures globally)

If the soil or rock at shallow depth below the dam is too weak to support the dam, movement along a failure plane will occur. This may result in partial or complete failure of the dam (see Fig. 18).

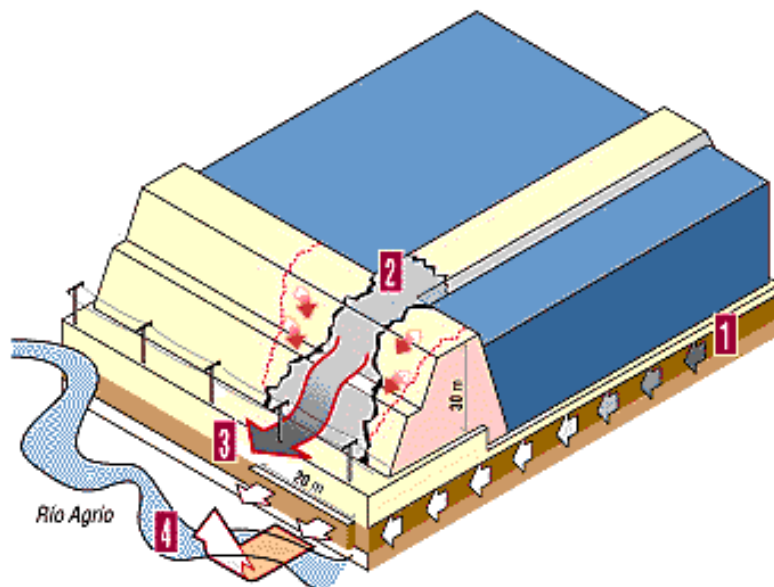


Fig. 18. A tailings dam failure of the Los Frailes lead-zinc mine at Aznalcóllar near Seville, Spain on April 25, 1998

Source: El País of May 14, 1998

#### 4.4.2. Hazard from seismic events

Upstream tailings dams are known to have very poor properties during seismic events. During cyclic mechanical stress, as experienced during seismic events, the tailings slurries (including the material used for the dam) may liquefy (see Fig. 19).



Fig. 19. Dam failure due to embankment liquefaction after seismic event – San Fernando, California, February 1971

As a consequence, large parts of the impounded tailings may be released in a slurry wave, causing catastrophic devastation in the downstream area. In case of marginal dam stability, liquefaction even may occur from vibrations caused from heavy equipment (for example scrapers travelling along the dyke crest or the dam toe), from nearby mine blasting, or the like.

#### 4.4.3. Hazard from piping (1/5 of all dam failures globally)

Piping occurs, if seepage within or beneath the embankment causes erosion along its flowpath. Excessive piping may result in local or general failure of the embankment (see Fig. 20).

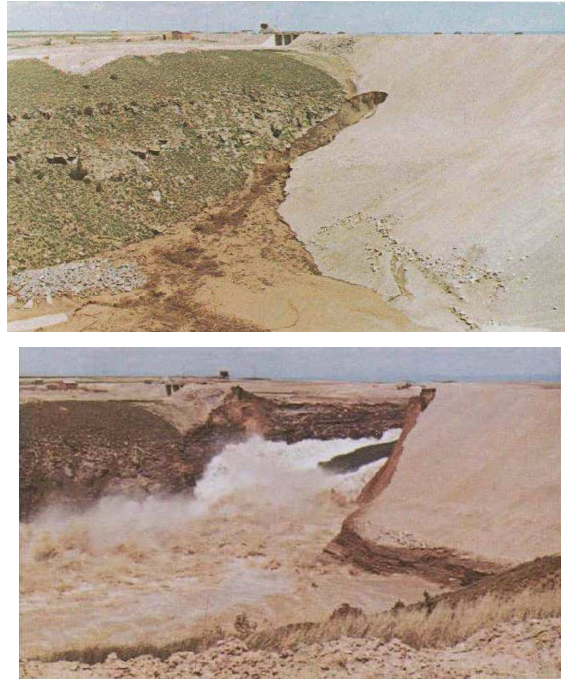


Fig. 20. The piping type failure of the Teton Dam during initial filling of the reservoir on June 5, 1976; initial stage of failure - left, final stage of failure – right

Source: [15]

#### 4.4.4. Hazard from excessive water level rise

Excessive rises in the level of the water ponding on the slurries in the impoundment can also cause failures of upstream dams – even if no overtopping occurs. This level rise can be caused by inflow from heavy precipitation events or by inappropriate water management of the mill operator. If the exposed beach width becomes too small, the phreatic surface within the embankment rises and causes the toe of the dam to become unstable: The whole dam can collapse, starting from the toe of the embankment.

#### 4.4.5. Dam failure from overtopping (1/3 of all dam failures globally)

If, the water level rise results in water overtopping the dam crest, complete breaching of the embankment is very likely. The overtopping water erodes the embankment within a very short time and can lead to a failure of the overall impoundment within minutes.

#### 4.4.6. Hazard from excessive dam rising rate

If an upstream dam is raised too fast, dam failure can occur from excessive pore pressure within the dam.

#### 4.4.7. Hazard of instability of earth/rock dams in normal conditions

Presently earth dams/embankments instability is considered to be the first cause of environmental disasters referred to tailings ponds and different industrial storage objects. Currently practiced analytical tools applied for so called „safety” assessment are limited mostly to stability index or factor of safety analysis based on deterministic models. This kind of investigation can not be however treated as a truly risk oriented approach.

The currently applied computational algorithms may be divided into two groups depending on involved procedures:

- methods based on limit equilibrium approach, and
- numerical methods.

This conventional slope stability analyses investigate the equilibrium of a mass of soil bounded below by an assumed potential slip surface and above by the surface of the slope. Forces and moments tending to cause instability of the mass are compared to those tending to resist instability. Most procedures assume a two-dimensional (2-D) cross section and plane strain conditions for analysis. Successive assumptions are made regarding the potential slip surface until the most critical surface (lowest factor of safety) is found (see Fig. 21 ).

If the shear resistance is insufficient, the mass is unstable. The stability or instability of the mass depends on its weight, the external forces acting on it (such as surcharges or accelerations caused by dynamic loads), the shear strengths and pore-water pressures along the slip surface, and the strength of any internal reinforcement crossing potential slip surfaces (see Fig. 21).

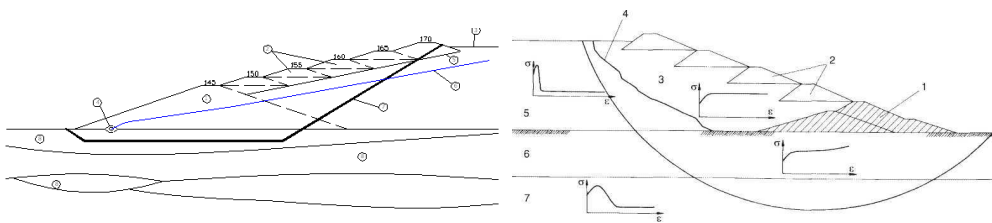


Fig. 21. Examples of the limit equilibrium method performed for Želazny Most Tailings Pond dams [13]



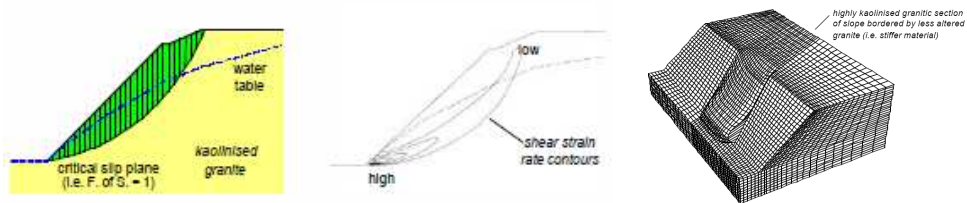


Fig. 22. Analysis of slope using limit equilibrium to find the critical slip plane (left) and finite-difference method (FDM) to model shear strain development (center) and 3D slope instability model using FDM (right)

Source: [16]

Due to advances in computing power and the availability of relatively inexpensive commercial numerical modeling codes means that the simulation of potential rock/earth slope failure mechanisms involving complexities relating to geometry, material anisotropy, non-linear behaviour, in situ stresses and the presence of several coupled processes (e.g. pore pressures, seismic loading, etc.) can be currently solved. Such a numerical methods of analysis used for rock slope stability may be divided into three main approaches: continuum, discontinuum and hybrid modeling (see Fig. 22).

#### 4.4.8. Seismic action (earthquakes /mining related dynamic load)

##### 4.4.8.1. Overtopping of the embankment

Seismic safety of embankment dams often depends on the magnitude of expected deformations. If the embankment crest moves below the level of the reservoir surface, erosion from overtopping can cause the dam to fail. There are available direct and indirect methods of assessing deformation due to earthquake. If the post-earthquake factor of safety is high, the deformations should be limited to a few feet except under very severe loading. The magnitude of deformations strongly depends on strengths of the materials involved. If the dynamic stresses temporarily exceed the available strength during shaking small permanent deformations may occur. In saturated very loose, contractive soils however, there is frequently observed loss of shearing resistance due to significant increase in pore water pressure (**liquefaction**). This leads to very large deformations, even of hundreds meters of displacement. Overtopping leading to failure of the dam can also result from the movement on a fault through the reservoir or through the embankment foundation, and from an earthquake-induced landslide that displaces a significant volume of water.

#### 4.4.8.2. Cracking and internal erosion

If a dam is deformed by earthquake excitation or fault displacement, the deformations can cause cracks in the dam and/or disrupt internal filters, either of which could lead to failure of the dam by erosion. There is also evidence that shaking could precipitate piping even without formation of a crack if the dam is already on the verge of piping. Should there be conduits through the embankment, deformation of the dam can rupture them or cause joints to separate, leading to erosive failure by either creating an unfiltered exit for seepage or exposing the embankment or foundation to full reservoir head where not intended. Erosion along intact conduits has also caused dam failures.

#### 4.4.8.3. Methods of analysis

For a dam and foundation not subject to liquefaction, minor deformation may take place but should not lead to failure if some specified conditions are satisfied. Otherwise more detailed analysis should be performed – (1) assessment of liquefaction potential, (2) post-earthquake stability analysis, and/or (3) deformation analysis. If there are no potentially liquefiable materials present, this can usually be done by the simple Newmark sliding-block approach. When excess pore pressure could develop, it may be necessary to conduct more rigorous FEA or finite-difference analyses which should prove whether plausible movements would be sufficient to allow overtopping by the reservoir, or if cracking at critical locations could result in failure by internal erosion.

Eurocode 8 recommends to represent seismic motion at a given point at the surface by an elastic ground acceleration response spectrum („elastic response spectrum”, see Fig. 23) and then seismic action may be simplified to the so called „pseudo static analyses”.

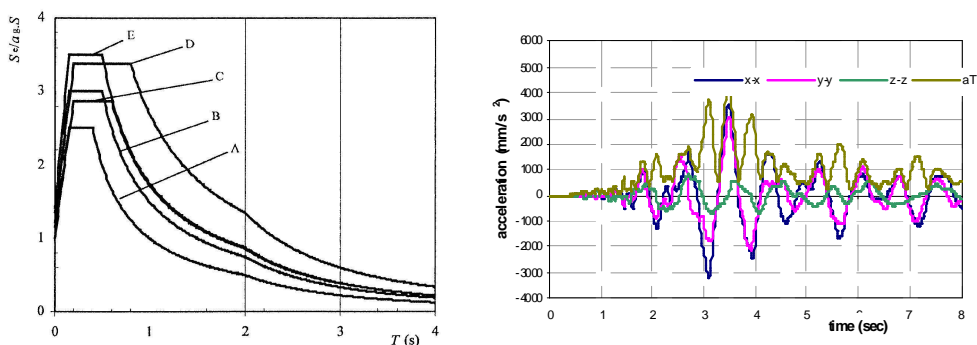


Fig. 23. Acceleration response spectrum acc. to Eurocode 8 (left), selected accelerogram monitored at Želazny Most Tailing Pond seismic station

The response of ground slopes to the design earthquake shall be calculated either by means of established methods of dynamic analysis, such as finite elements or rigid block models, or by simplified pseudo-static methods subjected to defined limitations.

Time-history representations of the earthquake motion may be also used as:

- artificial accelerograms, or
- recorded or simulated accelerograms (Fig. 23).

#### **4.4.8.4. Liquefaction evaluation**

For existing dams/foundations, as well as for the foundations for proposed new dams, the most important part of a liquefaction investigation is adequate subsurface investigations (mapping, drilling, sampling, geophysical) so that the extent of any weak material is identified. In general, sands, gravels, and fine-grained non-plastic soils should be evaluated for susceptibility to liquefaction. Soil grains characteristics such as distribution of sizes, shape, composition etc., affect significantly the susceptibility of a soil to liquefy. Consequently, saturated rounded cohesionless soil (sands, silts) particles of uniform size are the most susceptible to liquefaction. Similarly, non-plastic soil fines with a dry surface texture, e.g. rock flour like tailings grounded in processing plant's mills, usually do not provide significant resistance against liquefaction during strong dynamic excitation. More detailed criteria for soil liquefaction development are presented in Ferrito 1997 and Moss et al. 2006 [9,14].

The analysis approach concerning a soil/tailings dam for liquefaction resistance may be performed in the following steps:

- (a) predict of soil/tailings type using SPTs (Standard Penetrometer Tests) and/or CPTs (Cone Penetrometer Tests) performed on the embankment; provide samples for laboratory tests (e.g. grain size, Attenberg limits etc.); establish soil dynamic properties (e.g. shear moduli);
- (b) using a two-dimensional finite element program establish the effective stresses existing in the embankment and pond's filling;
- (c) prepare seismic load – e.g. ground motions described by acceleration vs. time, and using FEM calculate the seismicity-induced stresses in the embankment and its foundation;
- (d) evaluate the liquefaction resistance of the embankment and calculate factor of safety against liquefaction; if this factor is near or below 1.0, perform a static post-seismicity slope stability analysis.

## **5. Conclusions**

In Poland operational manuals for the tailings facilities are required by the Construction Law. Each tailings impoundment is required to have its own

operational manual but at present moment however there are not detailed requirements in this matter available. Nevertheless it seems to be reasonable to adopt the following Operational Safety Manual (OSM) elements recommended by Martin 2002:

- project administration,
- design overview and key design criteria,
- tailings deposition and water management plans,
- planning requirements,
- training and competency requirements,
- operating systems and procedures,
- dam surveillance (signs of unfavorable performance, responses to unusual observations),
- reporting and documentation requirements,
- emergency action and response plans,
- construction and quality assurance/ quality control requirements,
- standard formats for status reports in certain times, performance reviews,
- reference reports and documents.

This is the most important and basic measure concerning the tailings dams/ponds safety. Tailings dams are usually inspected annually by independent experts. During the surveillance the following observations should be made:

- Investigation of the visible parts of the dam structure.
- Observation of the internal inspection galleries and wells.
- Visual observation of the collection wells and discharge points of the dam filter system (function of drains and color of seepage)
- Reading of the stand pipes, measuring weirs and other monitoring instruments.
- Inspection of the drains in the downstream area and abutments.
- Inspection of the inflow pipes, pumping lines and outlet channels.
- Checking the inspection of the monitoring and collecting wells.
- Quality control of the building and work to increase the height of the dams.
- Evaluation of environmental impacts.

Parameters of monitoring and inspections includes:

- stability and settlements/displacements,
- seepage and pore water pressure,
- structures in the dams,
- condition of the dams,
- impounded tailings characteristics.

Surveillance, monitoring and inspections are presently the most important and ultimate measures performed for tailings structures “risk assessment”. Any rapid changes in the structure behavior (e.g. displacements, cracks etc.) or significant changes in its output (e.g. volume and color of water out-

flow) are treated as the alarming events. At this moment the emergency action and response plans are being introduced:

- A. Investigations on the possible causes of unexpected or unexplainable phenomena development are commenced,
- B. The appropriate counter-measures against undesirable tailings structure behavior are selected and initiated,
- C. If necessary, emergency plan is announced by the Crisis Committee.

Therefore a basic activity at the existing tailings impoundment structures is presently confined rather to field measurements, monitoring and surveillance understood as a basic source for a "real time risk assessment".

### Acknowledgements

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## **Współczesna praktyka w zakresie szacowania ryzyka funkcjonowania stawów osadowych**

*Słowa kluczowe: stawy osadowe, stateczność, określenie ryzyka*

*W pracy przedstawiono zarys współczesnej praktyki w zakresie szacowania ryzyka funkcjonowania stawów osadowych. Obejmuje on omówienie obowiązujących w tym zakresie regulacji na terenie państw Unii Europejskiej i w świecie, a także podstawy dotyczące projektowania składowisk odpadów przemysłowych. Wykazano, że obecnie stosowane metody oceny ryzyka ograniczone są generalnie do pomiarów polowych i obserwacji stanu technicznego obiektów, przez co nie mogą być traktowane jako „prawdziwe” oszacowanie ryzyka obejmujące prawdopodobieństwo zdarzenia awaryjnego z towarzyszącymi mu konsekwencjami.*