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Risk assessment of mine tailings/waste surface ponds

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Abstract

A general approach for risk assessment of surface tailings/waste storage facilities is presented using Event Trees based on typical failure modes. The relevant modes of failure involve either movement of large volumes of material, often in three-dimensions leading to dam breakage and uncontrolled release of the facility content, or to contamination of the environment with no structural failure. This paper focuses on the fact that natural materials are spatially variable and that a proper stochastic representation of this variability is crucial to achieving a realistic understanding of the geotechnical and hydro-geological safety issues. The risk model consists of products and sums of different risks described by their corresponding probabilities and associated consequences, some of which may be mutually correlated.

1 Introduction

The first documented attempt at geo-environmental risk analysis considered a petrochemical plant on Canvey Island in Essex, UK (HSE, 1978). In the 1980s, this kind of risk analysis was increasing applied across several industries, including chemical and petrochemical plants, automotive manufacturing, railway engineering, and water supply systems. Presently there is much greater public awareness of the rationale and motivation for risk assessment and management related to important engineering projects that may potentially affect public safety. At the same time, industry and government agencies are encountering financial and labour constraints which may limit initiatives and fall short of community expectations. In the important arena of tailing dams, public perception of risk often depends as much on political considerations as much as the quality of site investigation and the engineering sophistication of the risk analysis methodologies used.

Larger and larger volumes of industrial waste deposited into tailings ponds, or placed in storage yards, combined with reduced tolerance levels of local communities for these structures confirms the importance and need for improved risk assessment procedures. These procedures need to bond the multifaceted aspects of identification of hazards and their impacts, as well as determining effective and socially allowable means of hazard mitigation and prevention. The adoption of a combined multi-risk-oriented analysis which focuses on the interrelation between events and their possible consequences 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 TAILSAFE (2004) completed in 2004 by an international consortium. However, this valuable work does not indicate nor recommend 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.

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 utilise the data taken from at least three large sites from different European countries.

Unlike in previous works, the IRIS project offers an integrating of 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
- the path grouping analytical methods and measurement techniques useful for environmental risk assessment, for a case of possible soil/water pollution in accordance with the European regulations.

Each of the groups will utilise their own characteristic analytical and measurement methods. Finally the paths will be integrated leading to an assessment of the total risk involved. Selected parts of this approach, concerning in particular structural instability, will be highlighted further in this paper.

2 Current practice

2.1 Legislation and regulations on tailings facilities

The Waste Framework Directive 75/442/EEC of 15 July 1975 (amended by Council Directive 91/156/EEC of 18 March 1991, Council Directive 91/692/EEC of 23 December 1991, and Commission Decision 96/350/EC of 24 May 1996) lays down general provisions and principles for the handling of waste in European Union’s countries. 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) (LAMMIP, 2005).

The Directive concerning Landfill of Waste (1999/31/EC of 26 April 1999) outlined generally surveillance programmes for different media. 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 which said that safety assessment analysis must include several components, such as geological assessment, geomechanical assessment, hydro-geological assessment, geochemical assessment, biosphere impact assessment, etc. Moreover, the Decision presented more clearly the overview of landfill classes and options provided basically by the Landfill Directive.

In April 2006, Directive 2006/21/EC of 15 March 2006 on the management of waste from extractive industries has been passed. This Directive provides 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, among others, 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. According to this Directive, each operator shall, before the start of operations, draw up a major-accident prevention policy for the management of extractive waste. The accident prevention policy should consider, among others, identification and evaluation of major hazards arising from normal and abnormal operations and assessment of their likelihood and severity. The Directive 2006/21/EC is a base for the Polish Extractive Waste Act of 10 July 2008.

Local legislation and regulations applicable to tailings dams differ considerably amongst the countries and display very high level of generality. They cite different legal documents and acts concerning rather environmental, water treatment or structural design issues than "true" risk procedures and recommendations. However, there are no doubts that Directive 2006/21/EC on Extractive Waste may be treated as a first step which shall trigger wide and detailed research investigations on codes and procedures dealing with tailings dams risk assessment and management. As a point of departure to this work, a variety of more technically oriented documents, elaborated by professional dam safety organisations (e.g. International Commission of Large Dams ICOLD, Federal Emergency Management Agency FEMA, U.S. Army Corps of Engineers, etc.), may be used. For instance, the International Commission for Large Dams provided various recommendations on how tailings dam statutory legislation could be arranged, explaining complete provisions for commissions, registers, permission, construction, operations and maintenance, inspections and rehabilitation (ICOLD, 1989, 1996). Similarly, the Australian National Committee on Large Dams Incorporated published its guidelines (ANCOLD, 1999, 2003) which contain usable information on tailings dams design, construction and operation and methods for estimating the probability of failure for embankment-tailings dams. The Swedish hydropower industry has also developed their own guidelines for new and existing dam safety, RIDAS, revised in 2002. In 2007, these guidelines were extended by including embankment dam issues and as GruvRIDAS (SveMin, 2007) are being currently used by the mining industry.

2.2 Causes of tailings dam failures and incidents

The distinctive feature of the tailings storage structures is their susceptibility to different external effects and loads of different nature as well as on their own internal physical imperfections. A wide variety of the hazard resources results in a large number of different modes of possible structural failure and in different events which may be considered as the catastrophic ones. Presently the available data on vulnerability of property/people due to tailings ponds/storage yards damage is rather not scarce since hundreds of serious tailing dams accidents are reported, e.g. by USCOLD (1994), UNEP (1996), UNEP/ICOLD (2001), Rico et al. (2008).

Since each processing plants produce unique kinds of tailings which are further stored in surface storage facilities designed for operation also in unique geologic/topographic and technical/legal conditions, the causes of those structures' failures vary significantly. Among the main reasons of such events occurrences one may indicate:

- insufficient knowledge on material parameters and improper structure's physical model of behaviour resulting in inadequate theories and calculation models as well as wrong design concepts and errors in site selection. This also leads to improper understanding of the relations between the causes and the outer forms of structure's instability.
- inadequate site management including bad maintenance and control, operational departure from design criteria, lack of appropriate structure monitoring, related particularly to ground movement and water related phenomena.

Generally there are two main forms of tailings ponds' failure: (a) structural instability – construction failure, and (b) environmental disaster. Construction failure may be caused by direct types of external actions such as active environment (e.g. rain, snow melting, freeze, etc.), earthquakes and mining related seismicity or their derivatives such as excessive water flow manifested in a form of overtopping or a seepage of high intensity. Also structural inherent imperfections such as unsatisfactory foundation, difficult geological/geotechnical conditions and material defects may result in dam structural instability. Environmental disasters, however, may be caused independently as a polluted fluid seepage or as a consequence of structural failure followed by an uncontrolled wave of slurry. Both types of tailings ponds failure may result in a stopped production, water and soil mechanical/chemical contamination.

2.3 Currently applied risk assessment methods

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 Figure 1) indicates all recommended steps of such analysis. At the present moment however, only selected parts of PRA analysis are sufficiently recognised 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:

- 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 modelling of any deterministic phenomena associated with the object behaviour (e.g. finite element methods (FEM), finite difference methods (FDM) of stress/strain behaviour, 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.
- 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.
- Consequence analysis and vulnerability: (a) property, (b) people, (c) roads, (d) vehicles.
- Quantitative risk estimation (wherever possible should be based on a quantitative analysis).
- Risk evaluation: acceptable and tolerable risk.
- 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 as well as a lack of legal enforcement discourages owners from commissioning sophisticated analyses. Current practice therefore is confined to rather basic deterministic considerations and field monitoring. It must however be emphasised that the 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 by integrating risk assessment procedures as described in this paper.

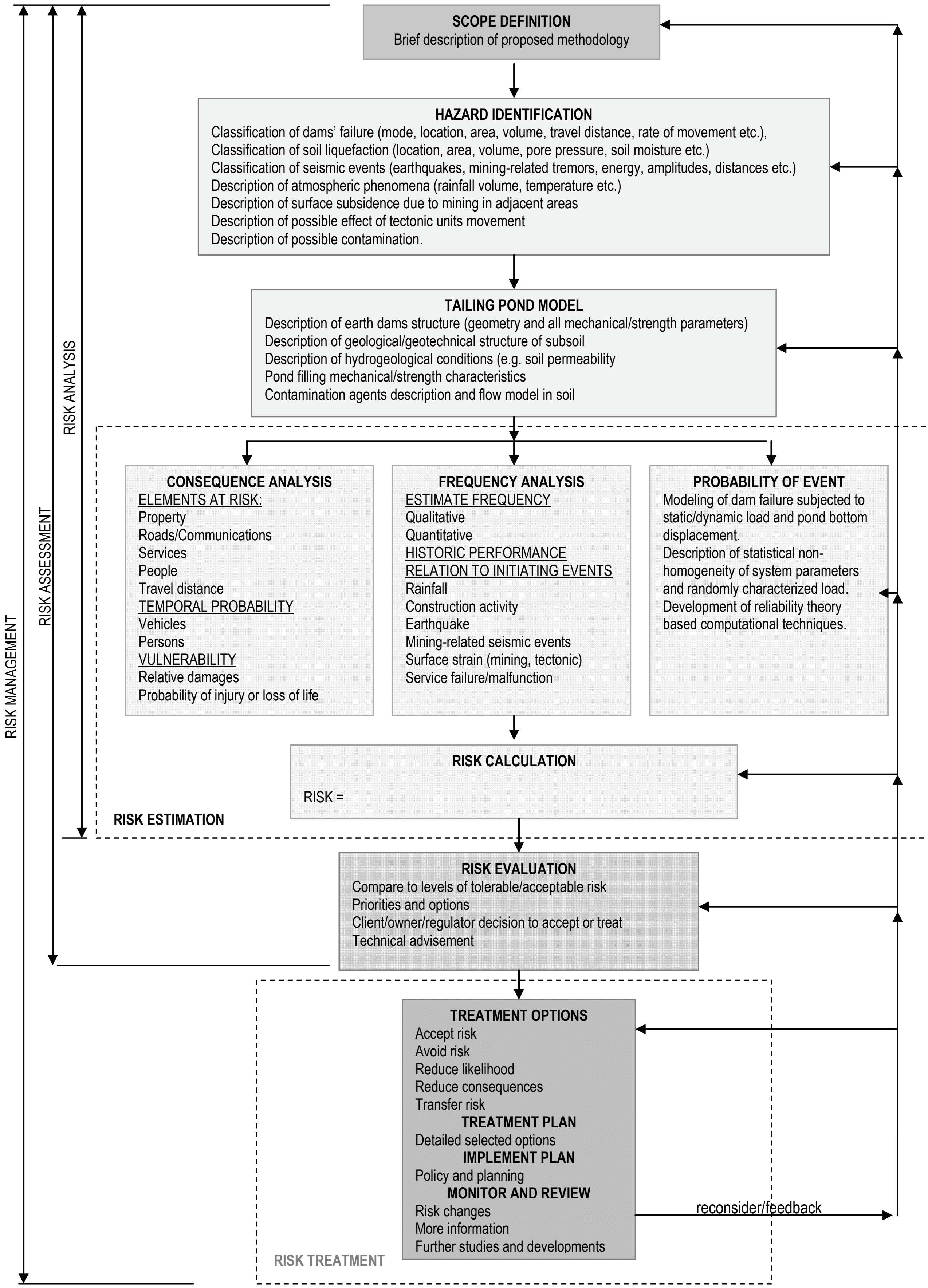


Figure 1 Flowchart of probabilistic risk assessment (based on AGS, 2000)

3 Proposed tailings ponds risk assessment procedures

3.1 General remarks

The risk model will consist of a product of different risks described by appropriate probabilities and associated consequences, some of which may be mutually correlated. This is one of the most important assumptions made by the author since previous methods of tailings facilities risk assessment have been based on a qualitative rather than a truly probabilistic quantitative approach. However, all risk assessment and management procedures should seek a compromise between purely engineering/scientific activity and public relations issues involving society's subjective risk perception. This may be related to the terms of accepted and marginally accepted risks as shown in Figure 2 (Baecher, 1987).

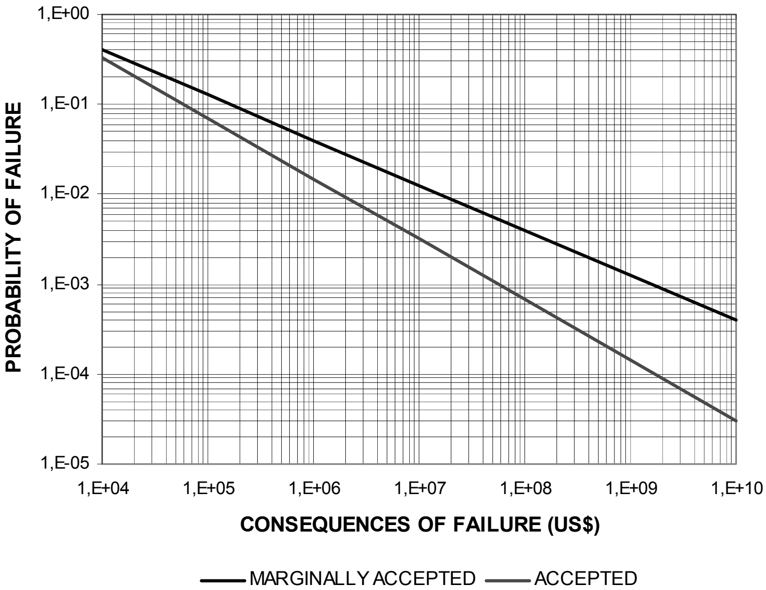


Figure 2 Accepted and marginally accepted probability of failure based on Baecher (1987)

From Figure 2 one may determine approximate ranges of annual probabilities of failure as well as the consequences of such events also in reference to tailings ponds where the failure event is usually associated with dam breakage. With moderate incident consequences assumed to be in the range from \$1m to \$10m, the respective acceptable probability of failure is within the range from $1.5 \cdot 10^{-2}$ to $2 \cdot 10^{-3}$ while the marginally accepted probability of failure is estimated to be between $3 \cdot 10^{-2}$ and $1.3 \cdot 10^{-2}$. All the estimated probabilities are relatively high however for very large financial loses (estimated as 1b\$) due to the damaged facility closure the appropriate accepted probability of failure could not be greater than $1 \cdot 10^{-4}$. To make any comparisons however the actual value of probability of failure should be calculated *a priori* and this paper basic goal is to show how it could be achieved.

Since tailings dam failure events may be related to structural stability problems or may be treated as an environment protection issues, different analytical tools and approaches should be employed. This may be obtained through statistical integrating the calculated partial risks governed by different failure modes and related parameters of random nature, into spatially distributed total risk values. Thus an effective risk management procedure should be developed as a methodologically-ordered measures' system which permits continuous identifying and measuring of hazard elements which tailings ponds and landfills may be subjected to, developing, selecting and implementing the appropriate and effective means for risk assessment, mitigation and prevention. Environmental risk assessment however may be based generally on the Bayesian statistical approach.

3.2 Random variables involved in tailings ponds risk assessment

3.2.1 Introductory remarks

Real engineering structure mode of failure can be represented by single criterion of failure, e.g. equation for slope/dam stability factor. In practice however, structures should fulfil satisfactorily a number of safety criteria, most of them inter-correlated by the same (mostly random) parameters. Each of the criteria may generate a different function of limit state. These criteria may be furnished in the row-type systems (all elements of the system could not fail if the system would survive), the parallel-type systems (at least one of the elements could not fail if the system would survive) and the mixed systems (combinations of the row- and parallel-type systems). However, the total reliability (or probability of failure) of complex structures may be calculated almost instantly only in the cases of the independency of the (sub)elements (Grosh, 1989). If the considered system elements representing instability events are dependent ones, the problem becomes more complicated since the joined probability distribution functions are then involved (Fenton and Griffiths, 2008) and special analytical methods have to be utilised in the analyses.

Assuming that the (sub)elements of the structure's reliability system represent different instability events it is necessary, at the preliminary stage of the analyses, to characterise all parameters governing different mechanisms of failure as well as different inherent and external loads influencing behaviour of the considered structure.

3.2.2 Soils and tailings

This paper focuses on the fact that natural materials are spatially variable (Figure 3) and that representation of this variability appears crucial in getting a realistic understanding of certain geotechnical and hydro-geological problems particularly in terms of structural (in)stability of tailings dams and possibility of ground water and soil contamination.

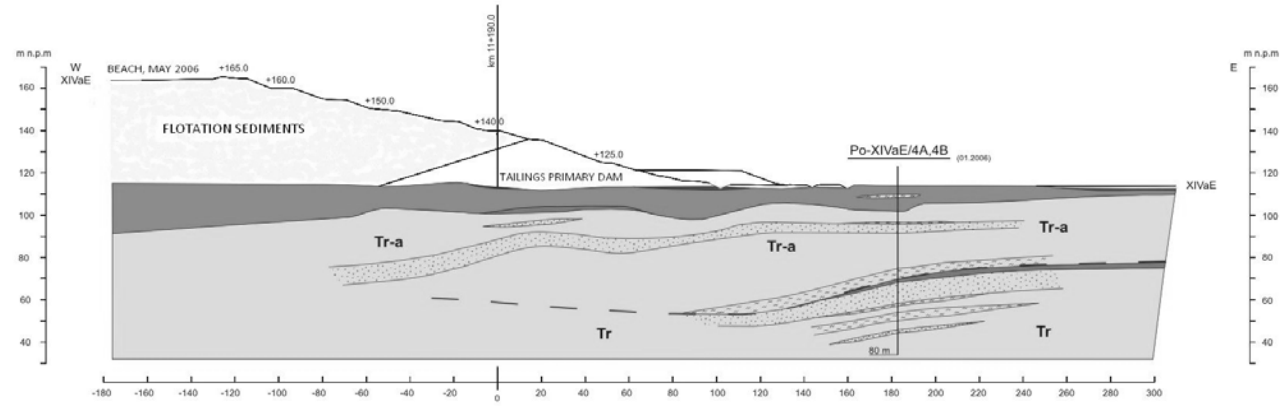


Figure 3 Selected geotechnical profile for upstream dams of Żelazny Most tailings pond (Poland)

In the literature relatively scarce data on the soil parameters' random distribution may be found presently (Rackwitz, 2000; Thao, 1984). It must be also emphasised that the available data obtained in a given location may not be appropriate for a different type of soil at the different space coordinates. Therefore the general conclusions on soil parameters statistical heterogeneity cannot be withdrawn independently on location and the unique technical characteristic of the earth structure. The field investigation (e.g. CPTs) should be performed in the place of interest with the sufficient number of the parameter sampling. Soil parameters distribution functions may be estimated based on field investigation in the analysis steps proposed by Rethati (1988) expressing the mathematical and the physical properties of the data series.

The following basic soil parameters seem to be the most important in dams' stability analysis: (a) soil density γ, (b) angle of internal friction ϕ, (c) cohesion c, and (d) stiffness module E. Parameters (a-c) are strongly related to stability problems, while the last one may be linked rather to deformability/settlement problems mostly, however in some earthquake problems, induced settlement may play significant role as a cause of instability events (e.g. overtopping). All of the mentioned parameters should be considered as random variables mutually correlated. Correlation coefficients may be determined based on well known statistical procedures such as regression analysis.

The properties of embankments' and filling's materials always vary in space, horizontally and vertically, and depend on the underground excavation site geology (e.g. artificial ground materials from processing/ enrichment plants) as well as on the entire structure's natural subsoil geological features. Based on the available large population of test results, one may decompose the general data on three components as follows (Agterberg, 1974):

$$y(x) = t(x) + p(x) + \varepsilon \tag{1}$$

where: $t(x)$ – the trend component, $p(x)$ – the periodic component, ε – stochastic component. The trend function is usually described by a straight line, however, a parabola or an exponential curve may be also used. The trend function may be built-in into the deterministic model of the structure as a set of parameters sufficiently describing its technical characteristics. The periodicity may be in turn verified using so called autocorrelation analysis, which enables to specify numbers describing the memory of the process and the mutual (in)dependence of the elements.

Having two corresponding empirical vectors of correlated variables (e.g. distance and cohesion, $\mathbf{d_1}$ and $\mathbf{c_1}$), numerical spacing(s) k_i may be chosen and the new correlated pairs of vectors $\mathbf{d_i}$ and $\mathbf{c_i}$ can be created for which coefficients of correlation r_i can be found. Furnishing the obtained data in the form of a diagram $r_k = f(k)$ (see Table 1), the so called autocorrelogram may be obtained.

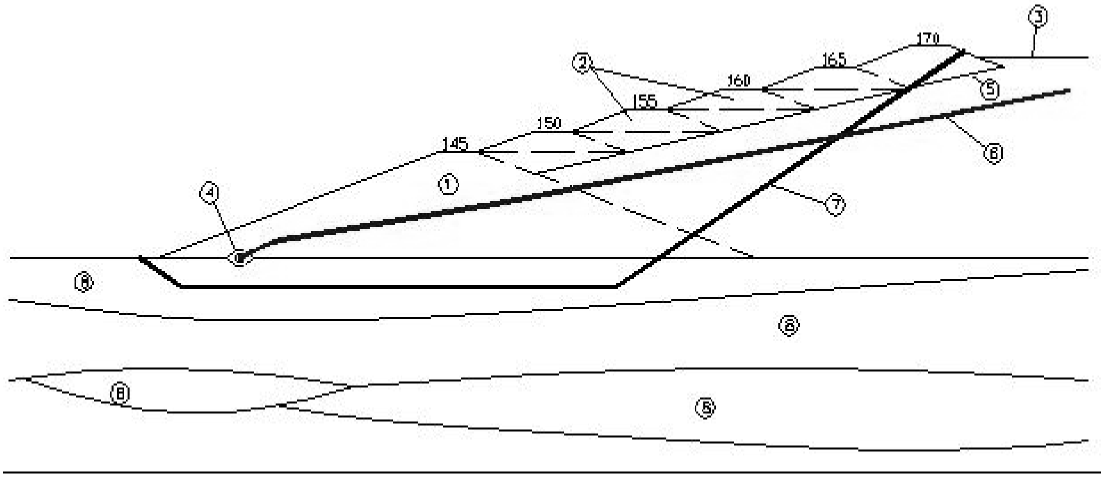
Table 1 Selected cases of autocorrelograms

General Case Description		
$t(x) = p(x) = 0$	All elements in the series are uncorrelated.	White noise
$t(x) = 0, p(x) \neq 0$	Every element depends only on the directly preceding element. The autocorrelogram may be written up as follows: $r_k = e^{-ak}$.	First-order Markov process
$t(x) \neq 0, p(x) \neq 0$	The autocorrelation function's distortion may be compensated by the constant c and then: $r_k = ce^{-ak}$.	First-order Markov process
Series contain also periodic elements	$r_k = e^{-\alpha k}[\cos k\omega_0 + (\frac{\alpha}{\omega_0}) \sin k\omega_0]$ where: $\omega_0 = 2\pi / T$, T – the length of the step, α – index of the memory.	Second-order Markov process

It is also generally accepted that any soil/material property X may be modelled as a random field formulated in n dimensions (Fenton and Griffiths, 2008). These functions describe spatial relationship of parameter value depending on a distance between two points where the parameters have been determined. Therefore, the correlation length (also known as correlation radius, scale of fluctuation or correlation distance) which may be assessed arbitrarily or from appropriate relationships (Fenton and Griffiths, 2008), is a convenient measure of the autocorrelation within the random field. Correlation length is utilised in the random finite element method (RFEM) on the routine basis.

3.2.3 Water table (phreatic surface)

Water table is one of the most important parameters affecting earth/tailings dams' stability. It may display relation to seasonal raining or technical conditions of the structure (e.g. drainage, see Figure 4). Field measurements indicate that most often the water level elevation is a parameter with non-Gaussian p.d.f. Since the phreatic surface locations changes with time (with seasons) the dam's stability analyses should be performed for several typical seasons (e.g. winter, fall etc.) each with specific p.d.fs.



1 – basic dam, 2 – particular stage dams, 3 – beach, 4 – dam's drainage, 5 – range of sediments of poor strength characteristics, 6 – predicted phreatic surface, 7 – slip surface of the minimum stability factor value acc. to GLE, 8 – subsoil strata with geological divisions.

Figure 4 Typical computational scheme (Żelazny Most tailings pond) including the water table presence

3.2.4 Seismicity

Tailings ponds may be subjected not only to natural seismicity effects but also to seismicity related to active mines located in close vicinity. Depending on depth, method of exploitation, kind of rocks within the overburden strata, and many other parameters, the seismic wave induced by instability events occurring within rock mass may be transferred to the surrounding underground and surface structures. Therefore, near the most important objects, seismic stations are established for monitoring of subsoil vibrations (Figure 5).

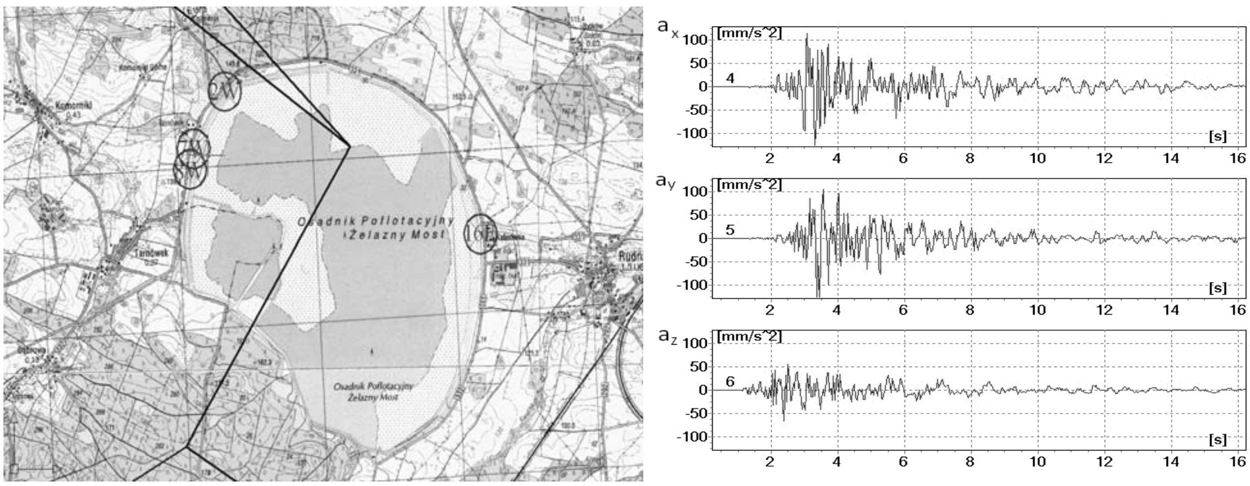


Figure 5 Location of seismic stations at Żelazny Most tailings pond (left), examples of recorded accelerograms (right)

From recorded seismograms/accelerograms one may find:

- acceleration/velocity amplitudes
- frequency
- duration of event.

One of the most commonly assessed parameters from the recorded seismic data are the maximum amplitudes of acceleration (*ppa* – peak particle acceleration) and the maximum velocity (*ppv* – peak particle velocity).

However, these data represent a kind of momentary phenomena insufficiently representing the entire process. Therefore, rather the “efficient acceleration” values are applied as a design seismic load:

$$\tilde{a}_{x,y,z} = \sqrt{\frac{1}{\tau}\int_0^{\tau} a_{x,y,z}^2(t)\,dt} \tag{2}$$

These parameters may be used for the ‘basic’ seismicity coefficients in three dimensions assessment, just related to (x_o, y_o) coordinates of seismic station where the accelerograms have been recorded:

$$s_{(x,y,z)} = \frac{\tilde{a}_{x,y,z}}{g} \tag{3}$$

where: g – the gravity acceleration. These values or their derivatives may be used for a typical slope stability analyses involving mining or the nature induced seismic load.

Since the basic seismicity coefficients by assumption are the elements of external load acting on pond’s dams and influencing their instability potential, they should be projected on the local coordinate system (x_k, y_k, z) established at all cross-sections of pond’s embankments which are considered in local stability analyses (Figure 7). Taking into account that the basic seismicity coefficients are determined based on a very large population of recorded accelerograms, they therefore may be treated as random variables. Performing probabilistic analyses based on the limit equilibrium method, additional random load, i.e. acceleration vectors determined acc. to Equation (3), may be involved. These vectors differ from each other since they depend on cross-section locations and the local coordinate systems’ azimuths:

$$s_{y,k} = s_y \cdot \frac{F_d(A, d_k, b)}{F_d(A, d_o, b)} \cdot \cos(\beta_o + \Delta\alpha_{o,k}) \tag{4}$$

$$s_{z,k} = s_z \cdot \frac{F_d(A, d_k, b)}{F_d(A, d_o, b)} \tag{5}$$

where: $s_{y,k}, s_{z,k}$ – seismicity coefficient components oriented along the local axes Y_k and Z_k, $\Delta\alpha_{o,k} = \alpha_o - \alpha_k$, d_k, d_o – distances (Figure 6), A, b – estimates of the acceleration damping modified function F_d. The remaining geometrical data may be found in Figure 6.

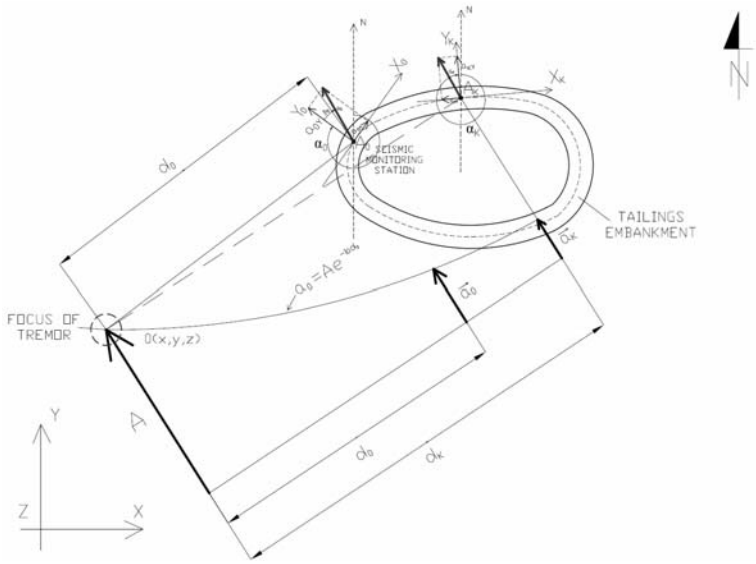


Figure 6 Schematic for local seismic coefficients assessment

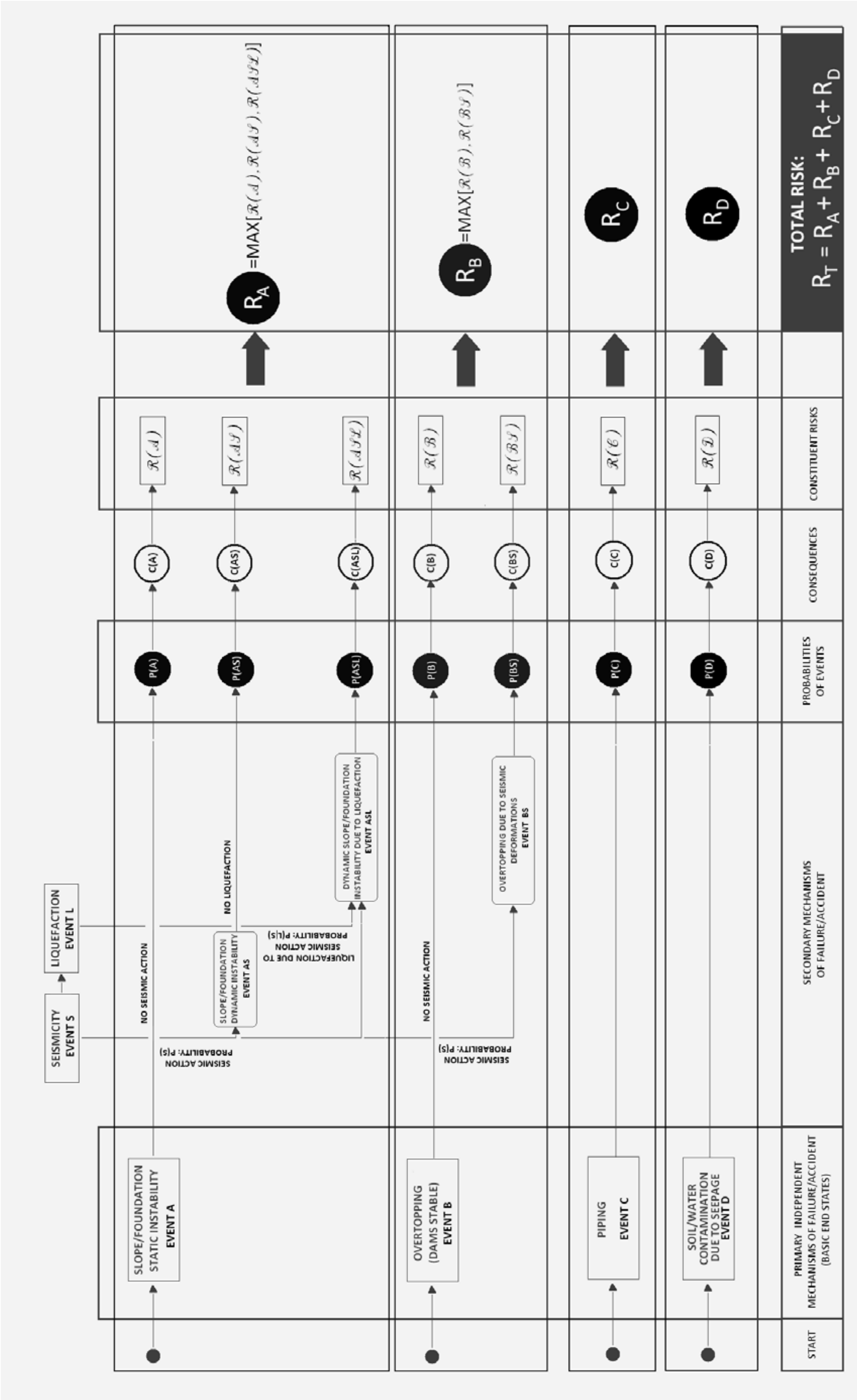


Figure 7 Example of event tree applied to tailings ponds risk assessment

The modified damping function F_d is based on Jaskiewicz (1999) approximation, appropriate for Polish copper mines area is as follows:

$$F_d = A \cdot d_k + b = -0.244 \cdot d_k + 1 \text{ for } 0 \leq d_k \leq 2.2\ km \quad (6)$$

$$F_d = A \cdot (d_k)^{-b} = 1.1675 \cdot (d_k)^{-1.1724} \text{ for } d_k \geq 2.2\ km \quad (7)$$

The probability of the assessed value of the efficient acceleration occurrence can be calculated using the Bayesian distributions (Benjamin and Cornell, 1970). Assuming that seismic events are the Poisson's events of average intensity of λ, variable X will be characterised by the Poisson's distribution of the average λt:

$$p_x(x|\lambda) = \frac{e^{-\lambda t}(\lambda t)^x}{x!} \qquad x = 0, 1, ...$$

where: x – number of seismic events of defined magnitude. Random parameter λ is characterised by gamma distribution $G(r_o+1,\ t_o)$ (*a priori* or *a posteriori*). The Bayesian distribution of X is therefore:

$$\tilde{p}_X(x) = \frac{t^x t_o^{r_o+1}}{(t_o+t)^{r_o+x+1}} \frac{(x+r_o)!}{x!\Gamma(r_o+1)} \quad for \quad x = 0, 1, 2, ... \quad (8)$$

Using the recorded seismic data one may estimate parameters t_o and r_o of λ-distribution. For instance, if event of the acceleration design value a occurred four times during 60 years, then t_o = 60 and r_o = 4. From the above presented equation the probability of x – times occurrences of event of a (acceleration) value in period time of t, can be determined.

3.2.5 Soil/tailings liquefaction

Liquefaction occurs when the structure of loose, saturated sand breaks down due to some rapidly applied loading, e.g. seismic event. Saturated rounded cohesionless soil (sands, silts) particles of uniform size are the most susceptible to liquefaction. Tailings grounded in processing plant's mills, usually do not provide significant resistance against liquefaction during strong dynamic excitation. Probability of liquefaction occurrence may be assessed using Moss et al.'s (2006) Bayesian updating approach based on 188 field case history data:

$$P\{FS > 1.0\} = \Phi\left[\frac{q_{c,1}^{1.045} + q_{c,1} \cdot 0.11R_f + 0.001R_f + c(1 + 0.85R_f) - 7.177 ln CSR - 0.848 ln M_w - 0.002 ln \sigma_v' - 20.923}{1.632}\right] \quad (9)$$

where:

CSR	=	simplified cyclic stress ratio.
M_w	=	moment magnitude.
σ_v'	=	effective stress.
$q_{c,1}$	=	corrected CPT tip resistance.
R_f	=	friction ratio
C	=	CPT normalisation exponent.

3.2.6 Rain falls

The probability of future rain falls, related to dams' overtopping probability, based on the data recorded in the past may be assessed using Bayesian distribution (Benjamin and Cornell, 1970). Particularly, we would like to know what is the probability that in the next m years, rain falls grater than a given number (mm) will occur y times, since from the available data one may notice that in the period of the last n years s such events have occur. Assuming bi-nomial p.d.f B(m,p) for Y variable (sum of the yearly events), Bayesian distribution of Y is as follows:

$$\widetilde{p}_Y(y) = \frac{n+1}{s+y+1}\binom{m}{y}\binom{n}{s}\left[\binom{m+n+1}{s+y+1}\right]^{-1}. \tag{10}$$

3.3 Tailings dam risk assessment

The main typical failure modes of tailings storage facilities are associated with the following, independent events (see Figure 7): (a) static slope/foundation instability – event A, (b) overtopping due to the overloading with precipitation water – event B, (c) internal erosion/piping – event C, and (d) (sub)soil and water contamination due to seepage – event D. All the modes of failure are usually confined within large volumes of materials moving in three-dimensional coordinates, and some of them are additionally related to time progress. They also lead to dam(s) break and following uncontrolled release of the facility content, or contamination of environment with no structural failures. The scale of failure increases due to the following additional effects:

- Seismicity (natural and mining-related), loading the structure with the additional load due to the acceleration acting in three-dimension from the external source (event S); this suggests to distinguish a new event – dynamic slope/foundation instability (event AS).
- Possible liquefaction (event L) of the structure's material resulting from the seismic action and causing extremely difficult conditions of maintaining of dams' stability; this may cause a new event such as dynamic slope/foundation instability due to liquefaction – event ASL.
- Intensive precipitation affecting positively the potential of overtopping and piping – this potential is represented in the water level data.
- Foundation static movement due to external influences (e.g. mining, tectonic processes, etc.).

The event tree for the potentially possible failure events are presented in Figure 7 below. The different modes' probabilities (see above) assessment constitutes the essential problem of tailings/waste storage facilities risk assessment. There are introduced the following assumptions concerned with particular, mentioned above events: (a) events A, AS and ASL exclude each other (mutually exclusive), (b) events B and BS also exclude each other, (c) events of groups: A(S,SL), B(S), C and D may occur independently, (d) the total risk may be calculated as a sum of particular risks created by different events. Furthermore, probabilities of the group AS, ASL and BS (related to seismic action) should be calculated for a number of different magnitudes of seismic event (with different probabilities of occurrence assigned). This may affects severity of expected consequences of possible failure modes or may influence different probabilities of soil/tailings liquefaction. Probabilities P(AS) and P(BS) may be assessed using different approaches: (a) using the model including seismic action (e.g. acceleration) treated as a random force/variable characterised by its own p.d.f – simulation methods, or (b) using the model with seismic action represented by a single number(s) (e.g. acceleration) associated with appropriate probability of occurrence P(S) – then:

$$P(AS) = P(\overline{A}) \times P(S) \tag{11}$$

where: $\overline{A}$ = event of the model failure involving seismic action represented by a single number(s). Probability P(ASL) may be calculated similarly as above using the following equation:

$$P(ASL) = P(\overline{A}\overline{S}) \times P(L) \tag{12}$$

where: $(\overline{A}\overline{S})$ = event of the model failure involving both seismic action and liquefaction characterised by probability of occurrence (L) – Equation (9) may be used.

4 Conclusions

The risk assessment of tailings ponds demonstrated in this paper has revealed some of the complexities faced by the analyst and explains the relatively slow progress in application of risk assessment tools to this important problem. Presently the authors are collecting the necessary data from Żelazny Most flotation tailings pond operated by KGHM Polska Miedź S.A., the largest producer of metallic copper in Europe. Having access to a very large computerised database such as this will facilitate the integration of structural and environmental risks posed by this type of tailings/earth structure. Due to limited space in this paper, more sophisticated numerical tools such as the random finite elements method (e.g. Griffiths and Fenton 2004) have not been included herein but progress in the approach described in this paper and other methods calibrated against the Żelazny Most demonstration site will be presented at IRIS Summer School which is held each year in Zell am See (Austria).

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