

Reported tailings dam failures A review of the European incidents in the worldwide context

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Abstract

A detailed search and re-evaluation of the known historical cases of tailings dam failure was carried out. A corpus of 147 cases of worldwide tailings dam disasters, from which 26 located in Europe, was compiled in a database. This contains six sections, including dam location, its physical and constructive characteristics, actual and putative failure cause, sludge hydrodynamics, socio-economical consequences and environmental impacts. Europe ranks in second place in reported accidents (18%), more than one third of them in dams 10–20 m high. In Europe, the most common cause of failure is related to unusual rain, whereas there is a lack of occurrences associated with seismic liquefaction, which is the second cause of tailings dam breakage elsewhere in the world. Moreover, over 90% of incidents occurred in active mines, and only 10% refer to abandoned ponds. The results reached by this preliminary analysis show an urgent need for EU regulations regarding technical standards of tailings disposal.

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1. Introduction

Tailings dams are supposed to last forever, but past experience shows that minor and major spills pose a serious environmental threat that stay behind when the mine closes. A number of singular characteristics makes tailings dams more vulnerable than other type of retention structures (e.g. water retention type of dams), namely (1) embankments formed by locally collected fills (soil, coarse waste, overburden from mining operations and tailings); (2) dams subsequently raised as solid material coupled with a severe increase in effluent (plus runoff from precipitation); (3) lack of regulations on specific design criteria; (4) lack of dam stability requirements regarding continuous monitoring and control during emplacement, construction and operation; (5) high cost of maintenance works for tailings dams after closure of mining activities.

In Europe, public concern on the risk and potential impacts of the existing (in operation, inactive and abandoned) tailings

dams has been growing since recent incidents occurred: the Aznalcóllar large scale sulphide tailings dam spill on April 25th, 1998 [1–3], the Baia Mare (Romania) cyanide contaminated water released in January 2000 [4], the Baia Borsa (Romania) tailings contaminated by heavy minerals spill in March 2000 [5] and Aitik mine (Sweden) contaminated water released in September 2000 [6,7]. These and other past experiences show that emphasis should be put on prevention rather than reacting after the fact. By anticipating potential risk considerations, environmental impact can be minimised and true costs optimised.

Several investigations have attempted to summarise the causes of major tailings dam failures throughout the world. The most recent and comprehensive synthesis was performed by the International Commission on Large Dams (ICOLD) [8] (221 tailings dam incidents), based on the previous database by the U.S. Commission on Large Dams (USCOLD) [9], gathering a large amount of information on incidents in the USA (185 tailings dam incidents) that occurred during the period 1917–1989. This database was supplemented by the U.S. Environmental Protection Agency [10] with recent damage cases in USA, and by the United Nations Environmental Programme [11] (last updated on the 4th of March 2006), referring to the compilation of a selection

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of 83 major tailings dam failures. The analysis of tailings dam performance provides important information on key design factors of dam stability [8], including in situ characteristics (geology, seismicity, climate, upstream catchment area), selection of embankment and construction sequence types, as well as hazard factors identification (heavy rain, flooding, earthquake vulnerability).

These databases reflect the level of public reporting which is highly disparate, being satisfactory only in USA and Europe. The amount of reported information is related to the degree of national regulation requirements for reporting incidents. According to the European Union SEVESO II Directive [12], the National authorities should report to the Commission major accidents involving toxic and dangerous substances. Since 1984, industrial incidents have been collected in the Major Accident Reporting System [13], operated by the Major Accident Hazard Bureau (MAHB) and placed at European Commission Joint Research Centre in Ispra (Italy). However, incidents related to mining activities were only included since 2003, following the amended Directive 2003/105/EC [14]. Therefore, the official European database on historical mine incidents contains scarce information, which must be completed from the existing databases, published papers and reports.

In this paper, a detailed search and re-evaluation of the known historic cases of tailings dam failure in Europe and the World was carried out, in the scope of an EU project (e-EcoRisk, a regional enterprise network decision-support system for environmental risk and disaster management of large-scale industrial spills, contract no. EVG1-CT-2002-00068). The main objective of the study is to improve the understanding of tailings dam incident distribution, and to establish relationships and trends based on (known) historical tailings dam failures in Europe, as compared with the world's failure cases. Simple statistical representations and correspondence analysis were used to relate dam characteristics, failure causes and types of disasters that occurred in four groups of countries classified according to their environmental protection laws.

2. Methodology

2.1. Database construction

The e-EcoRisk database was fed with all available records, after a process of revision, cross-checking and information updating, using in first place bibliographic sources. In this process, a detailed literature review was conducted to gather as much information as possible. New data were added and information gaps were completed on the grounds of a detailed scrutiny of a number of journals, conference proceedings, reports, published and unpublished dissertations and web pages [15–29, among others]. Also the compilation of data from different European countries was achieved through the collaboration of the e-EcoRisk partners. As a result, 147 cases of tailings dam failures in the world were identified, 26 of them in Europe. For each case compiled, as much information as possible was extracted and documented, despite the above-mentioned difficulties in public consultation.

For each one of the reported cases, a data form was filled including the most relevant information related to the tailings dam, the accident and its consequences. The layout of the data form was divided into six sections or tables, containing the principal characteristics of the dam and the accident: dam location, tailings dam characteristics, tailings dam failure, sludge characteristics, impacted area—socioeconomical consequences and impacted area—environmental consequences.

To perform the statistical analysis, seven qualitative and quantitative variables were selected from the database: dam type (dam, ring-dyke impoundments, water retention and others), type of sequentially raised tailings dam (upstream, downstream, centreline and non-reported), state of activity (active, inactive but maintenance and abandoned), storage volume ($\leq 370,000$, $370,000$ – $2,000,000$ and $>2,000,000$ m³), tailings dam height (≤ 15 , 15 – 30 and >30 m), failure causes (management operations, seismic liquefaction, rise of the phreatic surface, mass movement/slope instability, fluvial undermining, inadequate/insufficient beach or free board, piping/seepage, dam overtopping/overflow, foundation failure, water level rise, snow melt, inadequate decant pipe construction, unusual rainfall event/period, insufficient perviousness of filter drain, mine subsidence and others) and type of failure (breach, hole, overtopping/overflow and others).

2.2. Correspondence analysis application

From the above described database, a set of 7 contingency tables was extracted, relating 4 groups of countries (Europe (26 cases), USA (57 cases), other countries with developed environmental laws at the moment of the failure (e.g. Canada, Japan) – WPD – (14 cases) and the rest of the world – WNPD – (50 cases)) with the available common attributes, that characterise each breakage case. Such attributes are in general qualitative variables (type of dam, failures causes, ...), divided into their modalities. Whenever quantitative variables are available (height and volume of the dam, ...), those are split into classes, being transformed into ordinal attributes that can be treated jointly with qualitative variables (nominal attributes).

In order to describe the database in term of the most relevant associations between country type and disaster attributes, a correspondence analysis was applied to the above-mentioned set of tables.

This specific factorial method allows to summarize qualitative information under simple and straightforward graphs that are easily interpreted according to the rules given in ref. [30]. The method was developed by Benzécri [31] for contingency tables and allows to project individuals (country groups) and variables (disaster attributes) in the same graph, the relevance of which is measured by the fraction of the total inertia assigned to each factorial plan, being the “inertia” the analogue of variance for qualitative variables.

In order to select the modalities associated with each axis, the “absolute contribution” criterion is applied: a variable is retained for interpretation if the ratio of its inertia by the axis eigenvalue exceeds the uniform distribution ratio.

3. Results

3.1. Geographical distribution of tailings dam incidents

It is worth noting that this database is the first attempt to put together the reported accidents in this matter, which can contribute to a better understanding of failure cases with special emphasis on the European incidents. Obviously, any effort to collect historical cases of tailings dam incidents would result in a very incomplete database, since the majority of tailings dam incidents remain unreported, especially in developing countries or in those countries where environmental legislation is, or has been, very lax. In those cases where a known accident did occur, it is often difficult to obtain basic information regarding the tailings dam and its condition prior to the incident (e.g. dam height, tailings volume, water content, etc.).

This lack of information affects strongly the representativeness of the database, since the major part of the compiled cases is taken from a few countries. In Fig. 1, the distribution of tailings dam incidents by country indicates that 74% of the cases come from a small number of countries: USA (39%), Europe (18%), Chile (12%) and Philippines (5%). In Europe, out of the 26 cases compiled, 38% occurred in the UK and 56% are distributed between 9 other countries (Bulgaria, France, Ireland, Italy, Republic of Macedonia, Poland, Romania, Spain and Sweden). The geographical distribution of the collected cases reflects the lack/abundance of information from individual countries and the uneven distribution of mine exploitations and corresponding tailings dams.

The analyses of the distribution of the world's tailings dam failures with regard to dam height (Fig. 2) show that 55.9% of the cases occurred in dams over 15 m in height and only 22.6% of incidents in dams higher than 30 m. The distribution is similar when considering only Europe, even though some differences are noticed (Fig. 2). 47.4% of European incidents occurred in dams over 15 m in height, while this figure is 43.2% for events elsewhere in the world. By contrast, there is a greater percentage of failures in dams of 15–30 m in Europe (42.1%) than in the rest

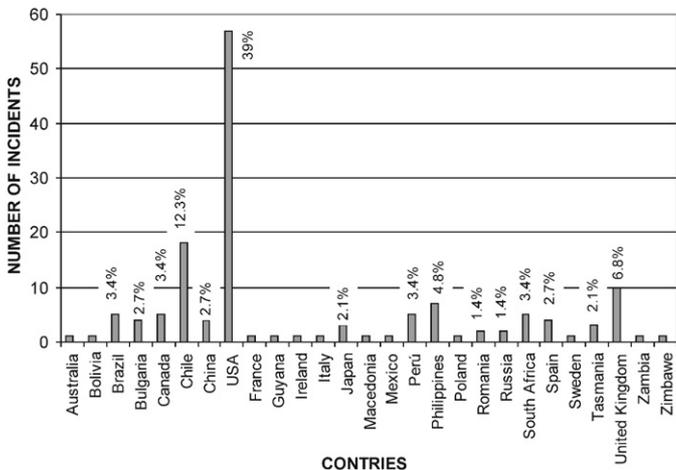


Fig. 1. Distribution by country of the tailing dam incidents recorded in the database.

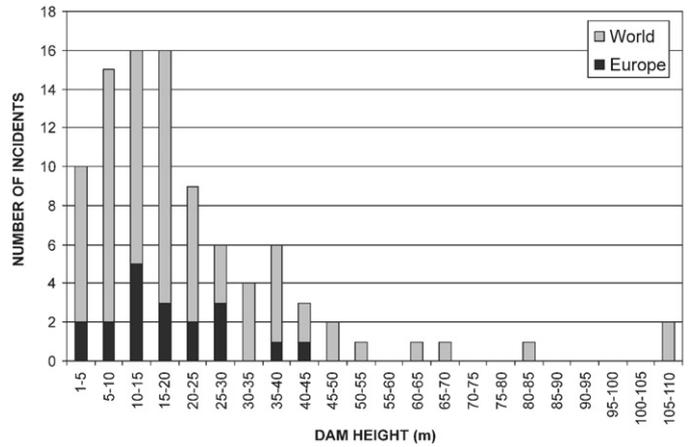


Fig. 2. Distribution of the number of incidents related to dam height.

of the world (31.1%). Furthermore, all European dam failures occurred in dams less than 45 m in height.

3.2. Tailings dam failure causes

In this database, 15 different failure causes have been spotted. In many cases (39%), the dam breaks resulted from a combination of different factors. For example, failures attributed to meteorological causes (intense rainfall, hurricanes, rapid snowmelt, ice accumulation in the tailings dam, etc.) may also be associated with overflow/overtopping, seepage, foundation failure or bad impoundment management. In this analysis, 11 “cause of failure” categories were differentiated (see Fig. 3), and each incident was assigned to a single category, which contributed the most to the dam break according to the dam failure description. The major fraction of incidents relates to meteorological causes (e.g. unusual rainfall events/periods and snow), accounting for 25% of worldwide cases and 35% in Europe.

The second most important cause in Europe is related to poor management and inadequate human activities at the tailings dam sites. Deficient management practice accounted for 10% of worldwide incidents and 12% of European cases. This

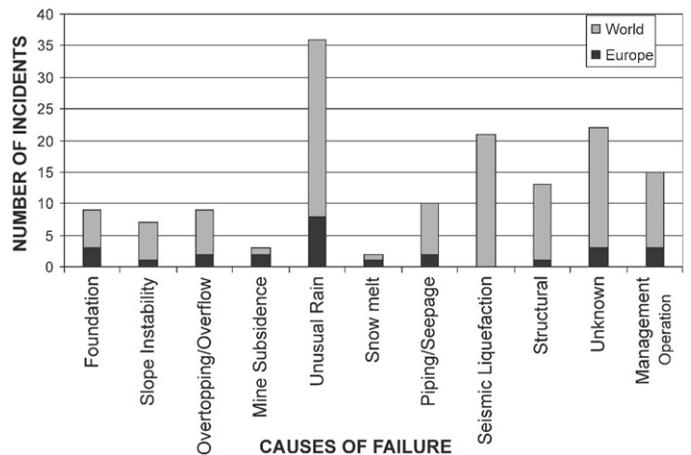


Fig. 3. Distribution of the number of incidents according to cause in the world and in Europe.

category includes the following specific causes: poor beach management, faulty maintenance of the dam drainage structures, inappropriate dam procedures (e.g. rapid dam growth, presence of heavy machinery in unstable dams). It is likely that the correct application of basic safety regulations would have prevented the accidents.

The following most common cause of dam break in Europe is related to failures of the dam foundations and, in most of the reported cases, this was due to a poor choice of dam placement and dam construction, accounting for 12% of European cases and 6% of all cases registered globally. Other causes that correspond to a greater number of events in Europe than in the rest of the world are seepage/piping, overtopping and mine subsidence accounting for, respectively, 8, 8 and 8% in Europe, against 7, 6 and 2% globally. The higher frequency of these types of failures in Europe, along with meteorological causes and poor management, is a relevant finding as compared with the worldwide situation. It is also worth noting the lack of incidents caused by earthquakes (seismic liquefaction) in Europe. This cause, for the rest of the world, accounts for 14% of total cases.

3.3. Accident statistics in relation to mining activity and dam construction methods

As soon as an impoundment has been filled or the mine production ceases, the tailings dam becomes inactive. In some cases, the infilled pond and dam continue to be maintained. However, in other cases, especially when mine production ceases, the tailings dam may be abandoned. For this reason, the tailings dams contained in the database were classified according to whether they were active when the accident occurred (ACT), inactive but still being maintained (INM) and abandoned (AB). In European countries, under the present environmental legislation, inactive dams are currently supervised and controlled. However, in countries without an appropriate environmental legislation, the majority of tailings dams are abandoned. Out of the total number of failure cases where the activity of the dam could be determined, 83% occurred when the dam was active, 15% in inactive and abandoned dams and only 2% of failures occurred in inactive but maintained dams. In active dams, the most frequent causes of failure are related to natural hazards (e.g. seismic liquefaction or heavy rainfall), followed by management operation and structural failures. Management operation and slope instability are only associated with active tailings dams. In Europe, 90% of incidents occurred in active dams and 10% in abandoned ponds. There is a lack of reported incidents in inactive-maintained dams.

Tailings dams are usually constructed in phases as the impoundment fills. New parts of the embankment are built on top of the previous structure with the new dam crest thus moving upstream, downstream or following a centerline (see ref. [32] for detail explanation). The method of dam construction that accounts for the highest number of incidents is associated with the upstream raised method (UPS), representing 76% of the cases in the world and 47% of failures in Europe (% referred to reported cases where available data on dam construction method exists). Downstream (DOWN) and centerline (CTL) raised tailings dams represent 15 and 5% of global cases, respectively,

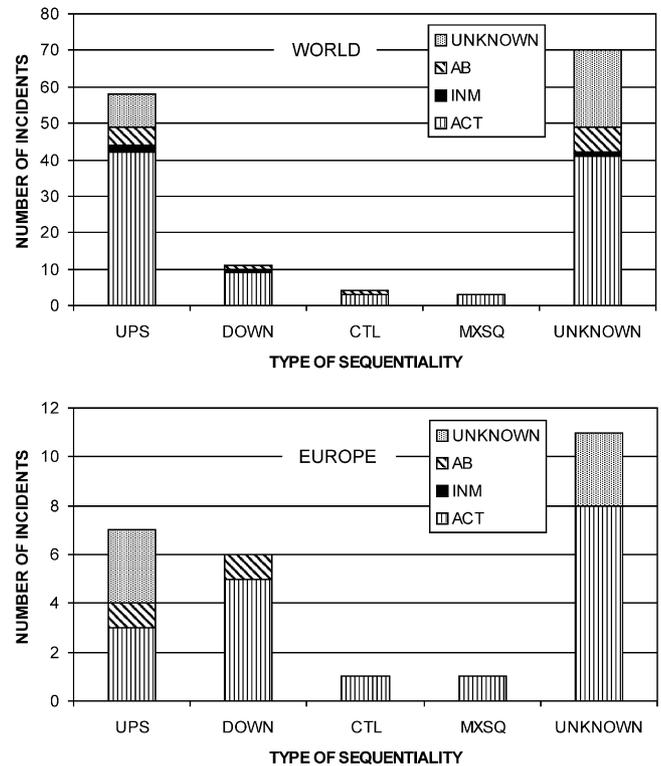


Fig. 4. Distribution of the number of incidents according to type of dam construction and state of activity in the world (above) and in Europe (below). (UPS, upstream; DOWN, downstream; CTL, centerline; MXSQ, mixed construction; ACT, dam active at the moment failure happened; INM and AB, dam inactive at the moment failure occurred, abandoned (AB) or inactive but maintained (INM).

whereas in Europe they correspond to 40 and 6.5% of known cases.

Dam constructed using more than one method was included under the category of mixed construction (MXSQ), which represents a 4% of global cases and 6.5% in Europe. In Fig. 4, the different construction types are presented alongside the state of activity at the dam. The figure shows that the greatest number of incidents worldwide occurred in active dams of upstream growth type. In Europe, a similar percentage of dam incidents occurred in dams with upstream and downstream raised methods (47 and 40%, respectively). There is a two-fold explanation for this feature: (1) downstream growth in Europe is more commonly used that elsewhere in the world, and (2) there is a lack of incidents related to seismic liquefaction which are known to affect especially dams with part of its structure lying on the tailings deposits. It is estimated that roughly half of the dam breaks could have been avoided with correct tailings dam construction (e.g. adequate site selection, correct dimensions, etc.) and appropriate management during its period of activity.

3.4. e-EcoRisk database correspondence analysis

A correspondence analysis was applied to the set of seven contingency tables, of which results are summarised in Fig. 5, accounting for 100% of the available information.

The interpretation of (Fig. 5(a)) is straightforward:

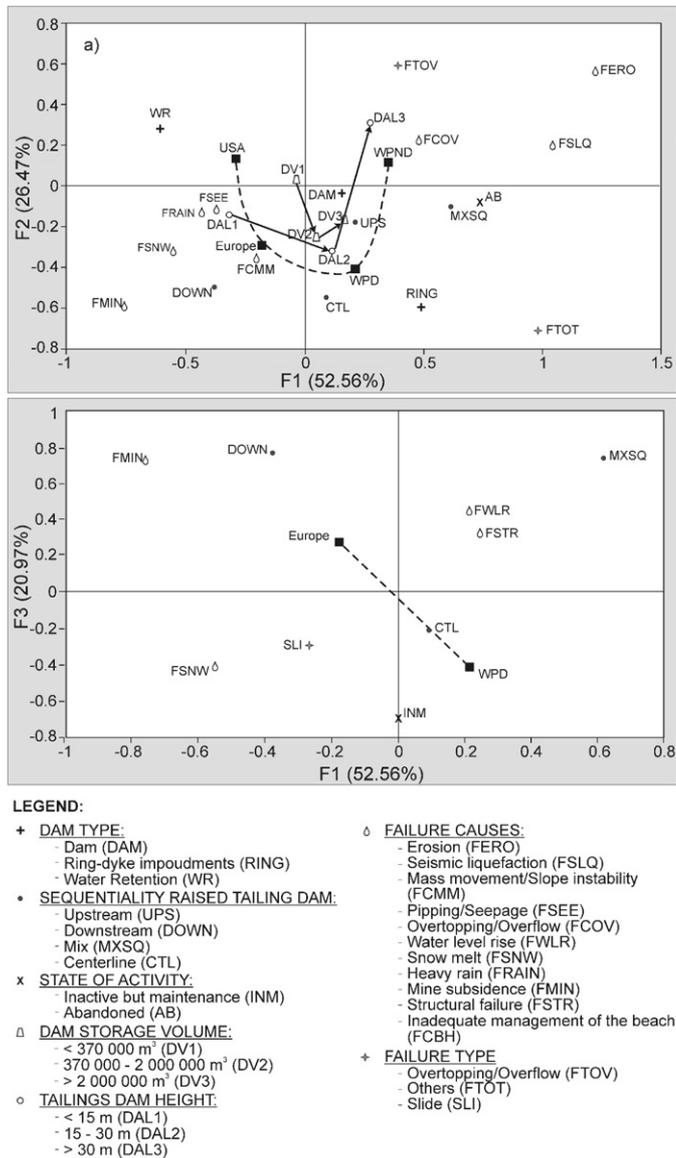


Fig. 5. Projection of attributes and groups of countries onto the first and second plane of correspondence analysis.

- Along axis 1 (from the negative to the positive side) are sequenced the groups of countries according to their “development level” in what environmental regulations are concerned (USA, Europe, WPD and WNPD).
- Regarding ordinal attributes, variables dam storage volume (DV) and dam height (DAL) follow the same sequence (from small to big impoundments), indicating that the more “developed” is a country, the smaller is the dam that breaks.
- Regarding nominal attributes, the modalities that contribute significantly to (USA + Europe) group, according to the above given (Section 2.2) “absolute contribution” criterion, are the following: water retention dam type (WR), downstream sequentially raised dam (DOWN) and failure causes, mine subsidence (FMIN), snow melt (FSNW), unusual rainfall event/period (FRAIN), seepage/piping (FSEE) and slope instability (FCMM). Conversely, for the (WPNP + WPD) group, contribute the following modalities: ring-dyke

impoundments (RING), dam-type impoundments (DAM), upstream sequentially raised dam (UPS), mix sequentially raised dam (MXSQ), abandoned impoundment (AB), seismic liquefaction failure cause (FSLQ), other failure types (FTOT), overtopping/overflow failure cause (FCOV) and overtopping/overflow failure type (FTOV).

- Axis 2 is not relevant for the interpretation of the cross-tabulation countries versus dam and failure attributes since it opposes the two extremes (USA + WPNP) to “intermediate” conditions (Europe + WPD) and no significant attribute modality is assigned to the opposition disclosed by this axis.
- In what concerns plane 1, 3 (Fig. 5(b)) gives a fair insight about the opposition Europe versus WPD, when projection onto axis 3 is interpreted in terms of nominal attribute modalities that contribute significantly to it. In fact, Europe is associated with downstream (DOWN) and mix (MXSQ) raised dams, and with the following failure causes: FMIN, FWLR (water level rise) and FSTR (structural failure); on the other hand, WPD is associated with centerline (CTL) inactive but maintained dams (INM), slide failure cause (SLI) and with the snow melt failure cause, FSNW.

4. Conclusions

In the scope of the EC-funded project e-EcoRisk, a worldwide database of historical tailings dam failures was collected. Most of the data compiled in the e-EcoRisk database have been obtained from newspapers, technical reports, scientific papers and from e-EcoRisk partners’ reports. A preliminary statistical analysis was carried out in order to gain knowledge on the causes of failure, vulnerable tailings dam geometries and geographic distribution of incidents.

Regarding to tailings dam incidents in Europe, the main conclusions are:

- Europe (14%) is the second world zone on tailings dam incidents, only exceeded by the USA (43%). The largest number of accidents in Europe is located in the UK (56% out of 14%).
- All the European tailings dam failures have occurred in dams of less than 45 m high, of which one third were in dams of 20–30 m in height.
- The major percentage of incidents is related to meteorological causes (26% to unusual rainfall and 3% to snow). There is a lack of incidents due to seismic liquefaction, which accounts for 14% of incidents elsewhere in the world.
- Over 85% of the accidents occurred in active tailings dams, and only 15% of the incidents were related to abandoned dams. In Europe, there are not reported incidents on inactive-maintained tailings dams.
- In Europe, there is an even number of reported incidents on dams with upstream and downstream construction methods (44% each), whereas worldwide the upstream growth is associated with up to 66% of the reported failures.
- A typical incident in Europe is, therefore, related to unusual rainfall events. This data is relevant to the growing number of inactive mine ponds in Europe, and shows the great importance

- of appropriate dimension of the dam's water drainage systems.
- In regard to the comparison of failure cases by groups of countries (USA, Europe, WPD, WNPD), this sequence is explained by an increase of dam volume and height and by a transition of modalities contributing to USA + Europe (which are the water retention (dam type); the mine subsidence, the snow melt, the heavy rain, the slope instability and the piping/seepage (failure causes) and the downstream (type of sequentially raised tailing dam)) and to WPD + WPND (which are the ring (dam type); the abandoned (state of activity); the seismic liquefaction, the overtopping/overflow (failure causes) and the upstream, the mix and the centerline (type of sequentially raised tailing dam)).
 - When Europe is compared with the WPD countries, the contrast is obviously smoother than the previous described sequence (in a ratio of 1:4). In any case, the modalities that contribute for the European "pole" are, in terms of type of sequentially raised tailing dam, the downstream and the mix, and in terms of failure causes, mine subsidence, water level rise and structural failure. For the opposite "pole" contribute the following modalities: snow melt and slide, in centerline and inactive but with maintenance dams.
 - Common EU Directives may contain different requirements taking into account the different environmental and economic conditions of the European Member State. New regulation is needed to establish technical standards on tailings construction as well as on incident reporting.

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