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

Rico, M.[1]; Benito, G.[2], Salgueiro, A. R.[3], Díez-Herrero, A.[4] & Pereira, H.G.[3]

[1]CSIC – Instituto Pirenaico de Ecología, Zaragoza, Spain

[2]CSIC – Centro de Ciencias Medioambientales, Madrid, Spain

[3]CERENA – Centro de Recursos Naturais e Ambiente of IST, Lisboa, Portugal

[4]Geological Hazards Unit, Spanish Geological Survey (IGME), Madrid, Spain

Corresponding author:

Rico, M.

e-mail: mayterico@ipe.csic.es

Telephone: (34) 976716118

Fax: (34) 976716019

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.

Keywords: *Environmental hazards, Tailings dam failures, Europe, Mine Tailings, Mono and multi variate statistical analysis.*

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 [1,2,3], 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 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 Data Base 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 [15,16,17,18,19,20,21,22,23,24,25,26,27,28,29, 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 m^3, 370 000 to 2 000 000 m^3 and > 2 000 000 m^3), tailings dam height ($\leq$15m, 15-30 m and >30m), 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 data base, 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 (heigh 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 data base 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 [30]. The method was developed by J.P. 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 data base 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 data base, 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, whilst 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 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 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 cause 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 [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, whereas in Europe they correspond to 40% and 6.5% of known cases.

Dam constructed using more than one method were 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 twofold 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 7 contingency tables, which results are summarised in Fig. 5, accounting for 100% of the available information.

The interpretation of Fig. 5a) is straightforward:

- 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 (WPND+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 vs. dam and failure attributes since it opposes the two extremes (USA+WPND) 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. 5b)) gives a fair insight about the opposition Europe vs. 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 are 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.

Acknowledgments

This research has been funded by the European Commission through the project “A regional enterprise network Decision-Support System for environmental risk and disaster management of large-scale industrial Spills”, e-Ecorisk Project (contract no. EVG1-2002-0068) and by the Spanish Ministry of Science and Education (HP2006-0072). The authors are very grateful to Varyl Thorndycraft for the critical review of the original manuscript, and for his very useful comments and suggestions.

References

[1] E. López-Pamo, D. Barettino, C. Antón-Pacheco, G. Ortiz, J.C. Arránz, J.C. Gumiel, B. Martínez-Pledel, M. Aparicio, O. Montouto , The extent of the Aznalcóllar pyritic sludge spill and its effects on soils, The Science of the Total Environment 242(1-3) (1999) 57-88.

[2] F. Gallart, G.Benito, Martín J.P. Vide, A. Benito, J.M. Prió, D. Regüés, Fluvial geomorphology and hydrology in the dispersal and fate of pyrite mud particles released by the Aznalcóllar mine tailings spill, The Science of the Total Environment 242 (1999) 13-26.

[3] G. Benito, A. Benito-Calvo, F. Gallart, J.P. Martín-Vide, D. Regües, E. Bladé, Hydrological and geomorphological criteria to evaluate the dispersion risk of waste sludge generated by the Aznalcollar mine spill (SW Spain). Environmental Geology 40(4/5) (2001) 417-428.

[4] UNEP/OCHA, Cyanide spill at Baia Mare, Romania. UNEP/OCHA Assessment Mission. UNEP/Office for the Co-ordination of Humanitarian Affairs, OCHA, 2000.

[5] UNEP/OCHA, Mining waste spill from the Baia Borsa processing complex in Romania. Assessment Mission to Hungary and Romania. UNDAC Mission Report. United Nations Environment Programme, UNEP/Office for the Co-ordination of Humanitarian Affairs, OCHA, 2000.

[6] T. Göransson, A. Benckert, M. Lindvall, R. Ritzén, Dam failure at the Aitik mine: Investigations, conclusions and measures taken, in: Proceedings of Securing the future: International Conference on Mining and the Environment, June 25-July 1 2001, Skellefteå, Sweden (appendix), Sweden, 2001.

[7] R. Holmgren, Experiences from the tailing dam failure at the boliden Mine Aitik and the legal consequences, Internal report, County Administration of Norrbotten, Sweden, 2000.

[8] ICOLD, Tailings Dams - Risk of Dangerous Occurrences, Lessons learnt from practical experiences, Bulletin 121, Published by United Nations Environmental Programme (UNEP) Division of Technology, Industry and Economics (DTIE) and International Commission on Large Dams (ICOLD), Paris, 2001.

[9] USCOLD, Tailings Dam Incidents, U.S. Committee on Large Dams - USCOLD, Denver, Colorado, 1994.

[10] EPA, Damage Cases and Environmental Releases from Mines and Mineral Processing Sites, U.S. Environmental Protection Agency, Office of Solid Waste, Washington DC, 1997.

[11] UNEP, Environmental and Safety Incidents concerning Tailings Dams at Mines: Results of a Survey for the years 1980-1996 by Mining Journal Research Services; a report prepared for United Nations Environment Programme, Industry and Environment, Paris, 1996.

[12] European Council, Council Directive 96/82/EC on the major accident hazards of certain industrial activities ("SEVESO II"), Official Journal of the European Communities, No L 10/13-10/33, 1997.

[13] MARS, Web site: http://mahbsrv.jrc.it/mars/Default.html. Major Accident Reporting System (MARS), 2006.

[14] European Council, Council Directive 2003/105/CE of the European Parliament and of the Council of 16 December 2003 amending Council Directive 96/82/EC on the control of major-accident hazards involving dangerous substances, Official Journal of the European Communities, L 345, 2003.

[15] G.E. Blight, Destructive mudflows as a consequence of tailings dyke failures, Proc. Instn. Civ. Engrs. 125 (1997) 9-18.

[16] S.C. Bourcy, R.E. Weeks, Stream morphology and habitat restoration of Pinto Creek, Gila County, Arizona, in: Tailings and Mine Waste '00, Proceedings of the

Seventh International Conference on Tailings and Mine Waste '00, Fort Collins, Colorado, USA, 23-26 January 2000, Balkema, Rotterdam, 2000, pp. 467-475.

[17] D. Brink, The long-term repair of the Merriespruit Tailings Dam, in: Tailings and Mine Waste '98: proceedings of the Fifth International Conference on Tailings and Mine Waste '98, Fort Collins, Colorado, USA, 26-28 January 1998, Balkema, Rotterdam, 1998, pp. 953-957.

[18] R.J. Chandler, G. Tosatti, The Stava tailings dams failure, Italy, July 1985, Proc. Instn. Civ. Engrs. 113 (1995) 67-79.

[19] R. Dobry, L. Alvarez, Seismic failures of Chilean tailings dams, Journal of the Soil Mechanics and Foundations Division 93 (1967) 237-260.

[20] A.B. Fourie, G. Papageorfiou, G.E. Blight, Static liquefaction as an explanation for two catastrophic tailings dam failures in South Africa, in: Tailings and Mine Waste '00, Proceedings of the Seventh International Conference on Tailings and Mine Waste '00, Fort Collins, Colorado, USA, 23-26 January 2000, Balkema, Rotterdam, 2000, pp. 149-158.

[21] L.A. Hansen, N.J. LaFronz, M.B. Yasin, Stabilization of the Pinto Valley tailings impoundment slide, in: Tailings and Mine Waste '00, Proceedings of the Seventh International Conference on Tailings and Mine Waste '00, Fort Collins, Colorado, USA, 23-26 January 2000, Balkema, Rotterdam, 2000, pp. 477-487.

[22] J.K. Jeyapalan, J.M. Duncan, H.B. Seed, Investigation of flow failures of tailings dams, Journal of the Geotechnical Engineering Division 109(2) (1983) 172-189.

[23] R.N. Kostaschuk, J.M.T. Wilkinson, Predicting the deformation of tailings dams resulting from earthquake liquefaction, in: Tailings and Mine Waste '99, Proceedings of the Sixth International Conference on Tailings and Mine Waste '99, Fort Collins, Colorado, USA, 24-27 January 1999, Balkema, Rotterdam, 1999, pp. 237-248.

[24] G. McPhail, R.J. Stuart, D. Venter, The disaster of Merriespruit and its consequences: Remediation-Making safe, in: Tailings and Mine Waste '98: proceedings of the Fifth International Conference on Tailings and Mine Waste '98,

Fort Collins, Colorado, USA, 26-28 January 1998, Balkema, Rotterdam, 1998, pp. 959-957.

[25] D.J. Miller, Failure modes and effects analyses of potential ground movements at Golden Sunlight Mine, in: Tailings and Mine Waste '99, Proceedings of the Sixth International Conference on Tailings and Mine Waste '99, Fort Collins, Colorado, USA, 24-27 January 1999, Balkema, Rotterdam, 1999, pp. 335-344.

[26] A.D. Penman, Risk analyses of tailings dam construction, in: Conference proceeding: Safety of Mining Dams Seminar, Gällivare, 20-21 September 2001, Swedish Mining Association, Natur Vards Verket, European Commission, Technical Papers, 2001, pp. 37-53.

[27] H.J. Van Niekerk, M.J. Viljoen, Causes and consequences of the Merriespruit and other tailings-dam failures, Land degradation & development 16 (2005) 201-212.

[28] F.v.M. Wagener, H.J. Craig, G. Blight, G. McPhail, A.A.B. Williams, J.H. Strydom, The Merriespruit tailings dam failure, in: Tailings and Mine Waste '98: proceedings of the Fifth International Conference on Tailings and Mine Waste '98, Fort Collins, Colorado, USA, 26-28 January 1998, Balkema, Rotterdam, 1998, pp. 925-952.

[29] M. Willow, C. tenBraak, Survey of three hard-rock acid drainage treatment facilities in Colorado, in: Tailings and Mine Waste '99, Proceedings of the Sixth International Conference on Tailings and Mine Waste '99, Fort Collins, Colorado, USA, 24-27 January 1999, Balkema, Rotterdam, 1999, pp. 759-767.

[30] M.J. Greenacre, Theory and applications of Correspondence Analysis, Academic Press, London, 1984.

[31] Ch. Bastin, J.P. Benzecri, CH. Bourgarit, P. Cazes, Pratique de l’analyse des données, Vol. 2, Abrégé théorique. Etudes de cas modèles, Dunod, Paris, 1980.

[32] S.G. Vick, Planning, design, and analysis of tailings dams, BiTech. Publishers, Vancouver, 1990.

LIST OF FIGURES

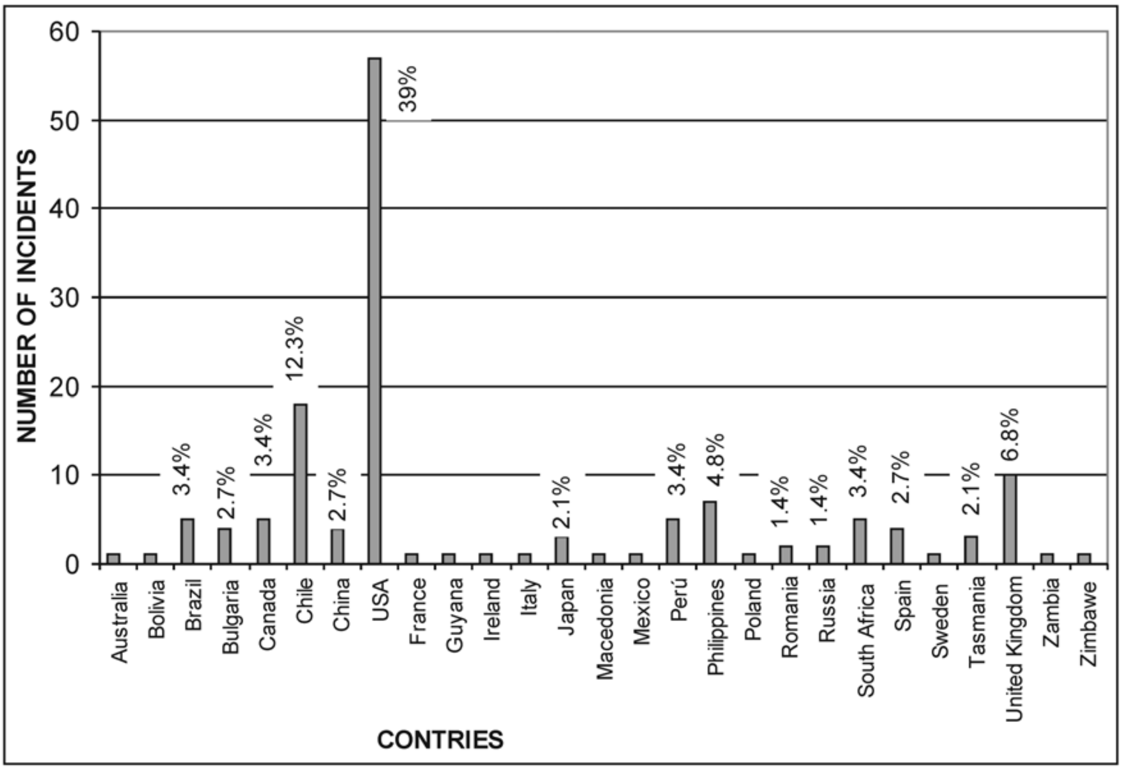
NUMBER OF INCIDENTS
60
50
40
30
20
10
0
39%
12.3%
3.4%
2.7%
3.4%
2.7%
2.1%
3.4%
4.8%
1.4%
1.4%
3.4%
2.7%
2.1%
6.8%
Australia
Bolivia
Brazil
Bulgaria
Canada
Chile
China
USA
France
Guyana
Ireland
Italy
Japan
Macedonia
Mexico
Perú
Philippines
Poland
Romania
Russia
South Africa
Spain
Sweden
Tasmania
United Kingdom
Zambia
Zimbawe
CONTRIES

Figure 1

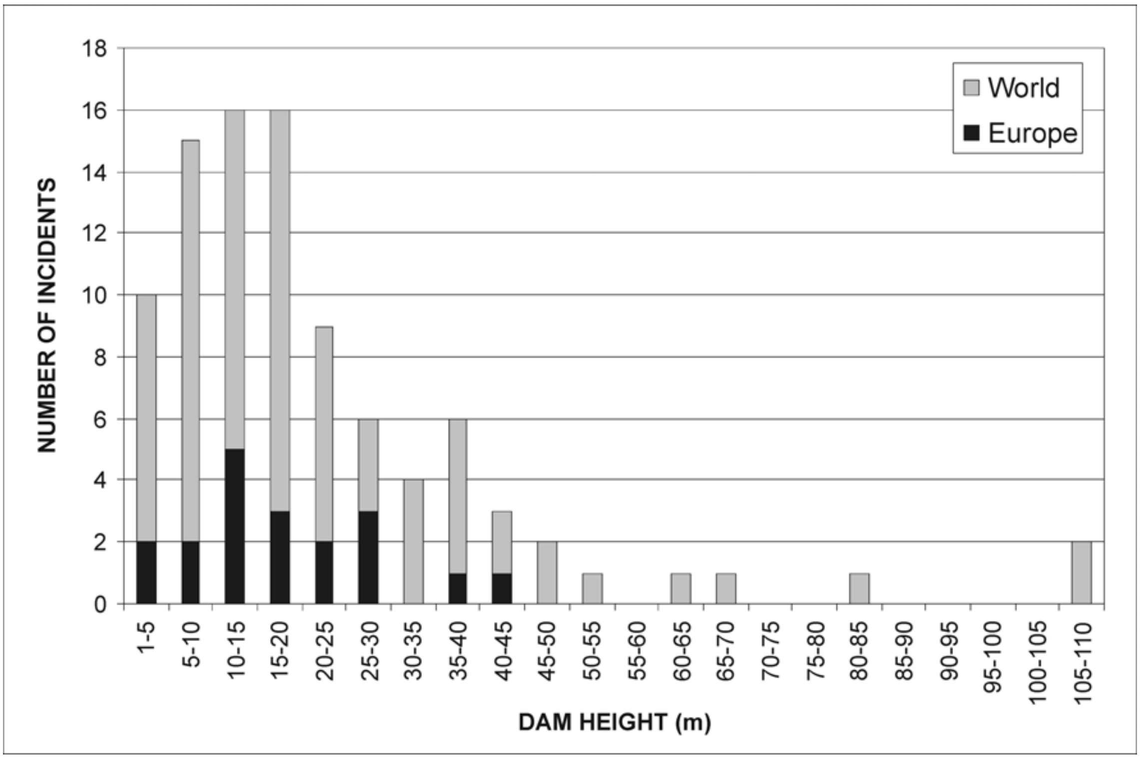
World
Europe
NUMBER OF INCIDENTS
0
2
4
6
8
10
12
14
16
18
1-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-55
55-60
60-65
65-70
70-75
75-80
80-85
85-90
90-95
95-100
100-105
105-110
DAM HEIGHT (m)

Figure 2

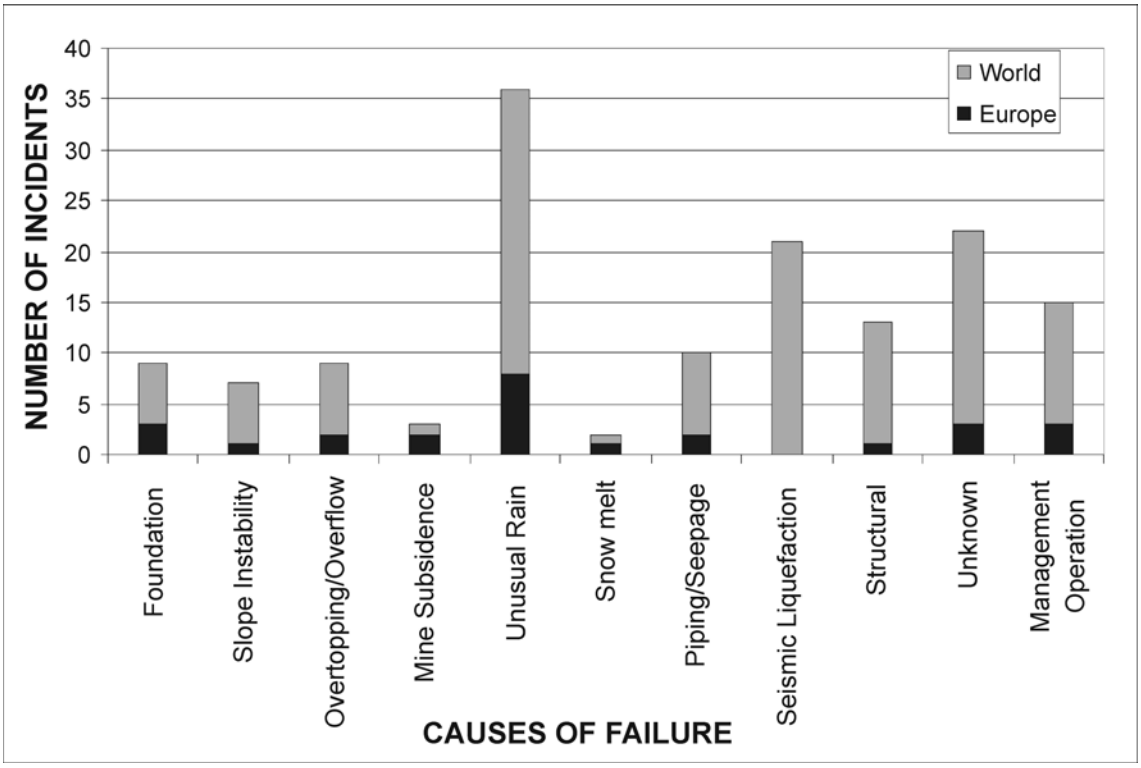
NUMBER OF INCIDENTS
40
35
30
25
20
15
10
5
0
World
Europe
Foundation
Slope Instability
Overtopping/Overflow
Mine Subsidence
Unusual Rain
Snow melt
Piping/Seepage
Seismic Liquefaction
Structural
Unknown
Management Operation
CAUSES OF FAILURE

Figure 3

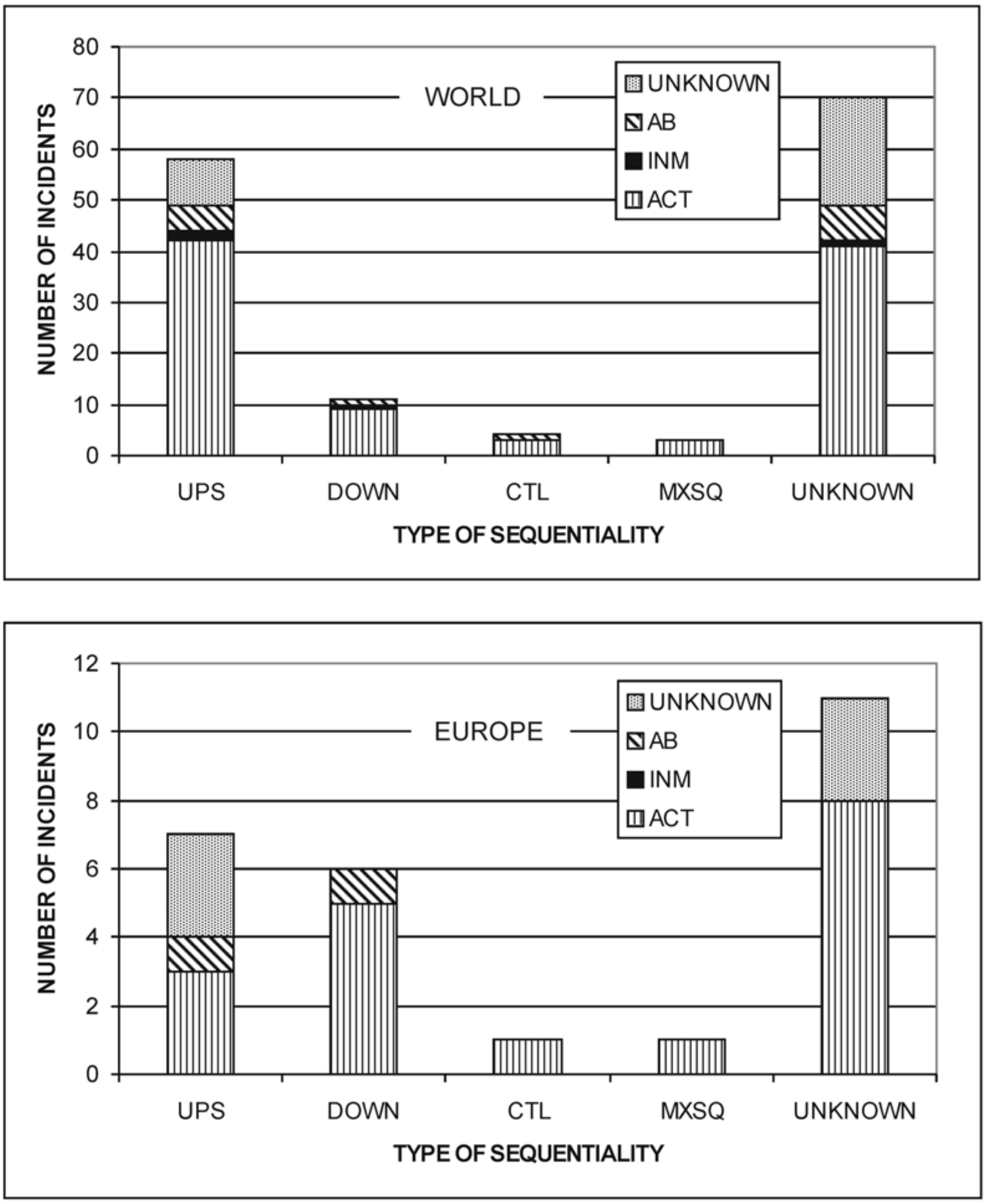
WORLD
NUMBER OF INCIDENTS
80
70
60
50
40
30
20
10
0
UNKNOWN
AB
INM
ACT
UPS
DOWN
CTL
MXSQ
UNKNOWN
TYPE OF SEQUENTIALITY
EUROPE
NUMBER OF INCIDENTS
12
10
8
6
4
2
0
UNKNOWN
AB
INM
ACT
UPS
DOWN
CTL
MXSQ
UNKNOWN
TYPE OF SEQUENTIALITY

Figure 4

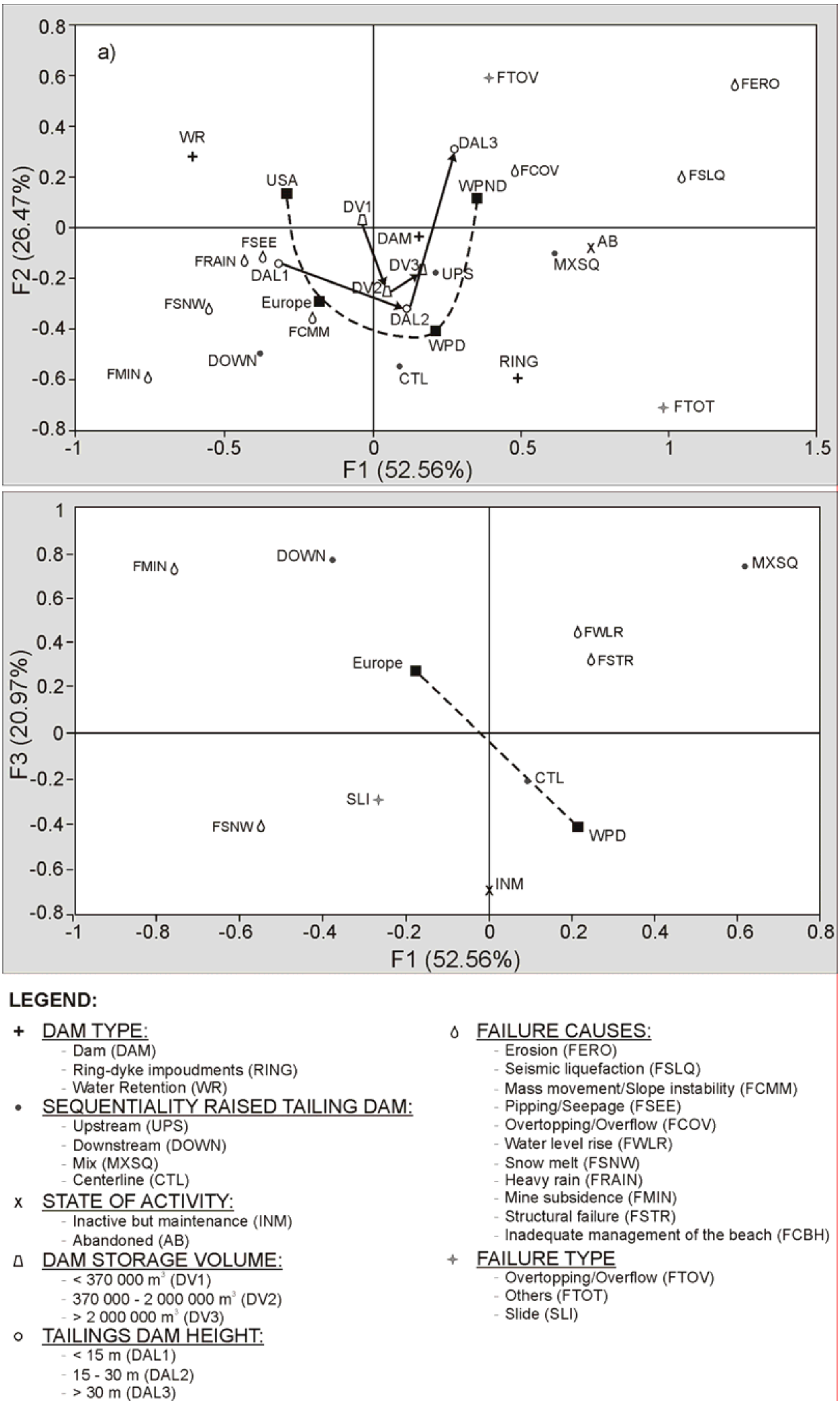
a)
F2 (26.47%)
F1 (52.56%)
FTOV
FERO
WR
DAL3
FCOV
FSLQ
USA
WPND
DV1
DAM
AB
FSEE
FRAIN
DAL1
DV3
UPS
MXSQ
DV2
FSNW
Europe
DAL2
FCMM
WPD
DOWN
RING
FMIN
CTL
FTOT
F3 (20.97%)
F1 (52.56%)
FMIN
DOWN
MXSQ
FWLR
FSTR
Europe
CTL
SLI
FSNW
WPD
INM
LEGEND:
DAM TYPE:
- Dam (DAM)
- Ring-dyke impoudments (RING)
- Water Retention (WR)
SEQUENTIALITY RAISED TAILING DAM:
- Upstream (UPS)
- Downstream (DOWN)
- Mix (MXSQ)
- Centerline (CTL)
STATE OF ACTIVITY:
- Inactive but maintenance (INM)
- Abandoned (AB)
DAM STORAGE VOLUME:
- < 370 000 m³ (DV1)
- 370 000 - 2 000 000 m³ (DV2)
- > 2 000 000 m³ (DV3)
TAILINGS DAM HEIGHT:
- < 15 m (DAL1)
- 15 - 30 m (DAL2)
- > 30 m (DAL3)
FAILURE CAUSES:
- Erosion (FERO)
- Seismic liquefaction (FSLQ)
- Mass movement/Slope instability (FCMM)
- Pipping/Seepage (FSEE)
- Overtopping/Overflow (FCOV)
- Water level rise (FWLR)
- Snow melt (FSNW)
- Heavy rain (FRAIN)
- Mine subsidence (FMIN)
- Structural failure (FSTR)
- Inadequate management of the beach (FCBH)
FAILURE TYPE
- Overtopping/Overflow (FTOV)
- Others (FTOT)
- Slide (SLI)

Figure 5