

# Columbia Water Center

## Assessing Risks of Mine Tailing Dam Failures

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# Contents

Abstract.....	1
1. Introduction .....	2
2. TSF reported failures.....	5
2.1 Causes of TSF failure.....	8
3. TSF Design and risk management .....	10
3.1 Design .....	10
3.2 Risk Management.....	13
3.3 Monitoring and Management .....	14
4. An example of TSF exposure rating .....	15
4.1 Data.....	17
4.2 Methods.....	17
4.2.1 Calculation of $V_F$ and $D_{max}$ .....	17
4.2.2 Affected area .....	19
4.2.3 Calculate $H_R$ .....	19
4.2.4 Results .....	20
5. Recommendations.....	23
Appendix I .....	26
References .....	27

# Abstract

Tailings dams are some of the largest man-made structures in the world. The consequences of tailings dam failures can be catastrophic for communities and ecosystems in the vicinity of the dams. Almost three hundred tailings dam failures have been reported in the last hundred years. Failures are usually caused by extreme events (precipitation, earthquakes), faulty design and construction, bad operational and management practices, or a combination of them.

The number of total reported failures has steadily decreased since the 1970s but despite significant advances in the design and management of tailings dams, failures still occur. The breach of the Fundão dam at the Samarco mine in 2015 killed 19 people and was declared the worst environmental disaster in Brazil's history. The incident has caused significant legal and financial repercussions to the company. The risks posed by tailings dams to the population, environment, and the mining companies need to be better assessed and disclosed.

This paper reviews historical tailings dam failures, failure mechanisms, and current design and risk assessment practices. Risk analyses for tailing impoundments are still largely deterministic due to the large uncertainty around the failure modes and the characteristics of the dams, and generally do not consider the costs of failure. Therefore, the financial magnitude of the risk assumed is likely misrepresented. On the exposure side, dam breach analyses are now required in many places to estimate the damages downstream in the event of a tailings dam failure, but these require a lot of data and are also subject to large uncertainty in the parameter selection. We compile data on past reported tailings dams failures, their causes, and design aspects from literature sources.

We present a methodology to do a qualitative assessment of the exposure to tailings dams considering dam attributes and characteristics of the area downstream to obtain a hazard rating index ( $H_R$ ). The calculation of  $H_R$  does not need very detailed information and can be estimated for multiple dams simultaneously. This provides a rapid assessment of potential damages that can be updated overtime.  $H_R$  also gives better granularity on the characteristics of the hazards than existing dam hazard classification schemes, which usually classify dams in only a few categories but smooth important differences across them.  $H_R$  can be used as a guide to assess potential risks to downstream communities, and can be part of a strategy for elicitation of potential financial risk information for investors but it is not a substitute of formal inundation analyses. A test case of the calculation of  $H_R$  is presented using 179 tailings dams located in Minas Gerais, Brazil.

Finally, some recommendations are given to improve risk assessments and management of tailings dams.

# 1. Introduction

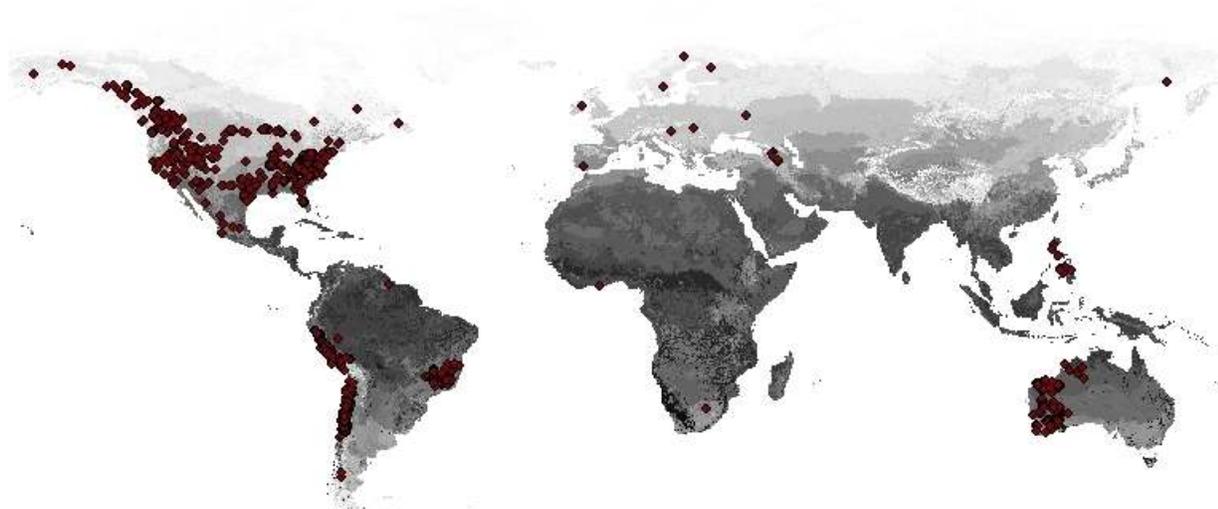
Tailings are the waste resulting from the extraction of minerals and metals. Tailings can be disposed in various ways but the most common practice is to deposit them as slurry in impoundments behind dams. This form of tailings storage facility is the focus of this paper, and the term TSF is used hereafter to refer to tailings dams.



**Figure 1** Santo Antonio tailings dam, Minas Gerais, Kinross Brasil Mineração (Google Maps image).

TSF failure can have disastrous consequences to nearby communities, the environment, and to the mining companies, who may face high financial and reputational costs. In 2015, the breach of the Fundão TSF at Samarco mine in Minas Gerais (jointly owned by BHP Billiton Brasil and Vale S.A.) resulted in 19 fatalities, and was declared the worst environmental disaster in Brazil's history. The company entered an agreement with the Federal Government of Brazil and other public authorities to remediate and compensate for the impacts over a 15 years period. Jointly, BHP and Vale recognized a US\$ 2.4 billion provision for potential obligations under the agreement (BHP Billiton, 2016; Vale, 2016). Twenty-one company executives were charged with qualified murder, and up until August 2017 the mine had not resumed operations. The losses to ecosystems caused by a TSF failure can have detrimental effects that can last for many years depending on the nature of the tailings. Samarco is in the process of recovering 5,000 streams, restoring 16,000 hectares of Permanent Conservation Areas along the Doce River basin, and 1,200 hectares in the riverbanks are being remediated with bioengineering and reforestation, amongst other remediation and monitoring activities (Wood, 2017). It is estimated that the livelihoods of more than 1 million people were affected because of the failure (Fernandes et al., 2016).

TSFs are some of the largest man-made structures in the world. Some of them can be higher than 200 meters (e.g., the Bruno Creek Tailings Impoundment in the United States) and can store more than 400 million cubic meters of tailings (e.g., the Santo Antonio tailings dam in Minas Gerais Brazil, Kinross Brasil Mineração; Figure 1). Martin & Davies (2000) estimated that there are around 3,500 TSFs worldwide, but the real number is much higher. There might be several thousand tailings impoundments in the U.S. alone, associated with active non-coal mining and tens of thousands of inactive or abandoned TSFs (EPA, 1994). In Hungary, more than 1,000 inactive mining waste impoundments have been identified (Inventory of closed mine waste facilities for Hungary, 2012), close to 1,900 in the United Kingdom (Potter & Johnson, 2014), and around 12,000 in China (Wei et al., 2012). There are thousands of abandoned impoundments dating as far back as the 1800s that have not been properly reclaimed or maintained, and that were built with very different standards than what it is required today (e.g., U.S., Nash, 2003; Sardinia Italy, Di Gregorio & Massoli-Novelli, 1992; Ghana, Kofi Bempah et al., 2013; Chile, Oyarzún et al., 2013 and Villavicencio et al., 2014; Hungary, Inventory of closed mine waste facilities for Hungary, 2012). Figure 2 shows the locations of approximately 2,700 tailings dams in countries where information was available (retrieved from multiple sources); many mining-intensive countries are not pictured. With so many TSFs around the world, it becomes important to understand what could be damaged in the event of failure.



**Figure 2** Sample of TSFs around the world (data from multiple sources).

Geographical Information Systems (GIS) can be used to assess risks in many sectors, including the mining industry. A study by the World Resources Institute focused on developing and mapping indicators to measure the environmental and social vulnerability of mining using publicly available data in a GIS (WRI, 2003). One of the conclusions was that nearly a third of all active mines and exploration sites in the world overlap or are located within a 10 km radius of a strictly protected ecological area (WRI, 2003). Gindy et al., (2007) developed a GIS model to assess the effects of water

dam failures in the State of Rhode Island, US, and used the level and severity of the potential impacts for dam hazard classification in a case study. In this paper, we use GIS to do a qualitative assessment of the exposure to TSFs considering dam attributes (such as height, storage volume, and elevation) to obtain a hazard rating index with the following steps:

- 1) An estimation of the volume of tailings released in the event of failure is obtained using similar empirical relationships as in Rico et al., (2008).
- 2) The affected area is calculated using elevation data and an estimation of the maximum distance traveled by the tailings, also obtained from empirical relationships.
- 3) The extent of the potential damage in case of failure is used in the computation of a hazard rating index ( $H_R$ ), which depends on the affected population, land use, and proximity to high conservation value areas.

We recognize that this approach has limitations, as it does not consider dam breach analysis to route the flow and obtain the inundation area. Very detailed information is needed to conduct such analyses, and often it is not available in places where TSFs are located. Mining companies produce dam breach analyses as part of their environmental impact assessments for new projects or TSF expansions, but even in those cases, there is large uncertainty surrounding the definition of the parameters, as explained by Martin and Akkerman (2017).  $H_R$  does not need very detailed information and can be calculated for multiple dams simultaneously. Therefore, the application of the  $H_R$  methodology provides a rapid assessment of potential damages that can be updated overtime taking into account changes in the characteristics of the TSFs (such as increases in volume/height), population shifts, and changes in land use. A test case of the calculation of  $H_R$  is presented using 179 TSFs located in Minas Gerais, Brazil.

*The approach presented here is not a substitute for a formal probabilistic risk analysis associated with a TSF. However, formal TSF risk analyses using event and fault trees require detailed information not available to investors. They also require a significant set of design and operational assumptions, that are difficult to test in practice, since operational maintenance, inspection and system practices may be at variance from those considered in the design phase. Consequently, the purpose of our rapid assessment tool is to help investors prioritize where it may be more or less important to pursue inquiry into a more detailed risk quantification process.* In related work, we are developing tools based on remote sensing and machine learning to monitor TSFs and the associated exposure from their failure, as a function of the state of filling and raising of the TSF and the potential for overtopping due to an extreme hydrometeorological event.

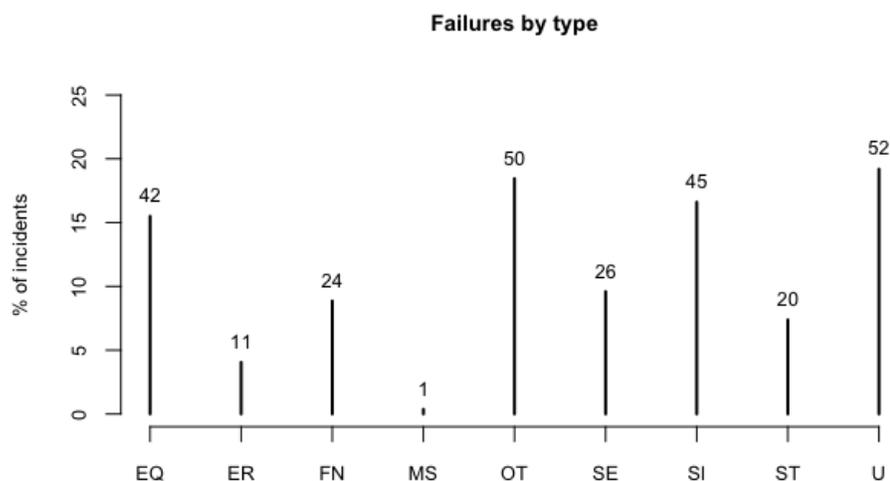
In order to provide a context about the risks posed by TSFs, the first two sections of this paper review historical TSF failures and their mechanisms, and discuss the evolution of design practices and risk management. The following section is dedicated to explain the methodology of the  $H_R$  calculation and the results obtained in the Minas Gerais test case. The last part focuses on recommendations and conclusions.

## 2. TSF reported failures

Tailings dams have unique characteristics that make them riskier than dams intended for water storage (Kossoff et al, 2014). Unlike water dams, TSFs embankments are often raised in multiple stages during the operational life of the mine. TSFs are usually built with local soil, coarse rock, and tailings. Operationally TSFs require strict monitoring, especially for controlling water in the impoundments. Additionally TSFs frequently contain materials that can contaminate the soil and water bodies. Other factors increase the risk of failure of TSFs. Their construction, maintenance, and closure costs provide no tangible returns for mining companies; therefore, there is limited effort to address factors of concern (Kelly et al., 2016). Variations in regulations, enforcement, and compliance can also contribute to variations in the risk profiles of TSFs (Martin & Davies, 2000).

Around three hundred tailings dam failures have been reported from 1915 to 2016 (Chambers and Bowker, 2016), but there is no complete database of all historical failures, and the information on individual failures has gaps in most cases (Rico et al., 2008; Kossoff et al., 2014; Martin & Davies, 2000). Many of the incidents go unreported for fear of legal repercussions and bad publicity (Kossoff et al., 2014). However, there have been attempts to study the causes and consequences of TSF failures worldwide using the available information (ICOLD, 2001; Rico et al., 2008; Martin & Davies, 2000; Chambers and Bowker, 2016). Some of the conclusions are:

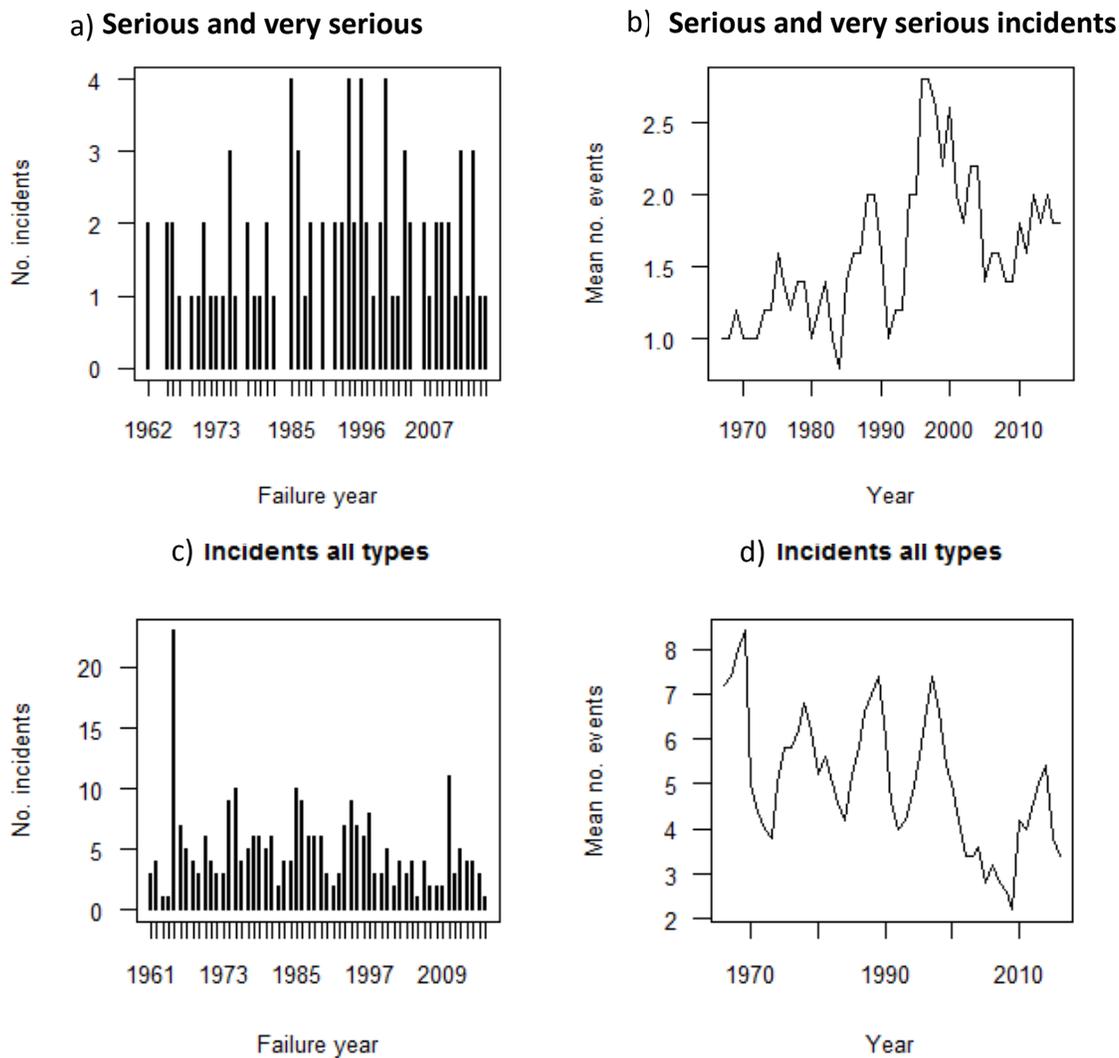
- (1) Active dams are more likely to fail than inactive dams (ICOLD, 2001).
- (2) The leading modes or mechanisms of failures identified from reported incidents in the past 100 years have been earthquakes (EQ), slope instability (SI), and overtopping (OT), (ICOLD, 2001; Chambers and Bowker, 2016). Refer to Figure 3.
- (3) Dams with the upstream construction method are more likely to fail, especially in seismic areas (Villavicencio et al., 2014).
- (4) The volume of tailings released is correlated with the run-out distance and the volume of tailings stored, so that an estimation of the potential flood and damages in case of failure can be made (Rico et al., 2008).
- (5) The safety of TSFs is inextricably linked to the management and operation practices of mining companies, and the trend of number of failures is likely to decrease due to an increase in company stewardship, better oversight, and regulations (Martin & Davies, 2000; Kelly, 2016).



**Figure 3** Reported TSF failures by cause 1915-2016. The number above each bar is the number of failures attributed to a category, and the y-axis is the percentage of each type within the sample of 271 failures (data retrieved from Chambers and Bowker, 2016, news and reports). EQ= earthquakes, ER=erosion, FN=foundation, MS=mine subsidence, OT=overtopping, SE= seepage and piping, SI=slope instability, ST=structural, U= undefined.

From the conclusion in point 5, better design, regulations, and oversight should have reduced TSF failures. However Bowker and Chambers (2015) argue that there is a positive trend in the number of high impact TSF failure incidents since the 1960's, in spite of improvements in engineering and management. They classified such events as very serious (multiple loss of life) and serious (loss of life and or release of  $>100,000 \text{ m}^3$  of tailings). Using the data compiled by Chambers and Bowker (2016) complemented with news and reports (data available in the supporting documentation), the trend in the number of serious and very serious events is significant (Kendall tau=0.45, p-value =  $7.82e^{-06}$ , Figure 4b), but when all the historically reported events are taken into consideration, a significant downward trend is observed (Kendall tau= -0.38, p-value =  $8.51e^{-05}$ , Figure 4d). The spike in the number of events around the 1960s (Figure 4c), was caused by earthquakes that occurred from 1960 to 1970 in Chile (Villavicencio et al., 2014) and Japan (Shigeyasu, So, & Hiromu; Marcuson, 1979). These trends however, do not inform if the proportion of serious and very serious failures in relation to the number of existing TSFs has actually increased (i.e. if the probability of failure has increased). That proportion is needed to assess the effectiveness of better design practices, regulations, and reporting. The challenge to do such an assessment is that many TSFs are not registered in publicly available databases and there is little information about their current physical state. Nash (2003) estimated that less than ten percent of tailings sites are included in databases, and information about their physical attributes (size, composition, stability, age, etc.) is hard to find or inexistent. However, there are efforts to compile TSF data in many countries (e.g. Australia, Canada, Chile, Brazil, the United States, members of the European Union, and others), and the International Commission of Large Dams (ICOLD) is in the process of adding TSFs to the world registry of dams, but this is a work in process. Regardless of the trend, the

consequences of a large TSF failure, even if the probability of occurrence was indeed decreasing, can be devastating and a better understanding of the causes and consequences of failure, and improvements in risk management at the mine level are needed.



**Figure 4** a) Number of type 1 and 2 incidents per year, b) mean number of events type 1 and type 2 with a 5 year moving window, c) number of incidents (all types) per year, d) mean number of events of all types with a 5 year moving window.

## 2.1 Causes of TSF failure

The term cause of failure in this paper refers to the mechanism by which a TSF ultimately failed. Examples of causes of failure are earthquakes (EQ), erosion (ER), foundation failure (FN), mine subsidence (MN), overtopping (OT), seepage and piping (SE), slope instability (SI), and structural damages (ST). All the causes of failure can be related to faulty design, construction, poor management, extreme events, or a combination of them.

The basic factors that influence the stability of a dam are the foundation conditions, the properties of the embankment materials, the rate of deposition and properties of the tailings (operational practices), the height of the dam, the angle of the outer slope, the design seismic event and storm event, and the overall water management (e.g. the control of the pheratic surface relative to the downstream slope, and control of pore water pressure); ICOLD, 2001; Zhang et al, 2009. Extreme floods, earthquakes, and operational practices can trigger failure events. Table 1 shows some causes of failure that result from those triggers (other causes of failure and triggers may also apply).

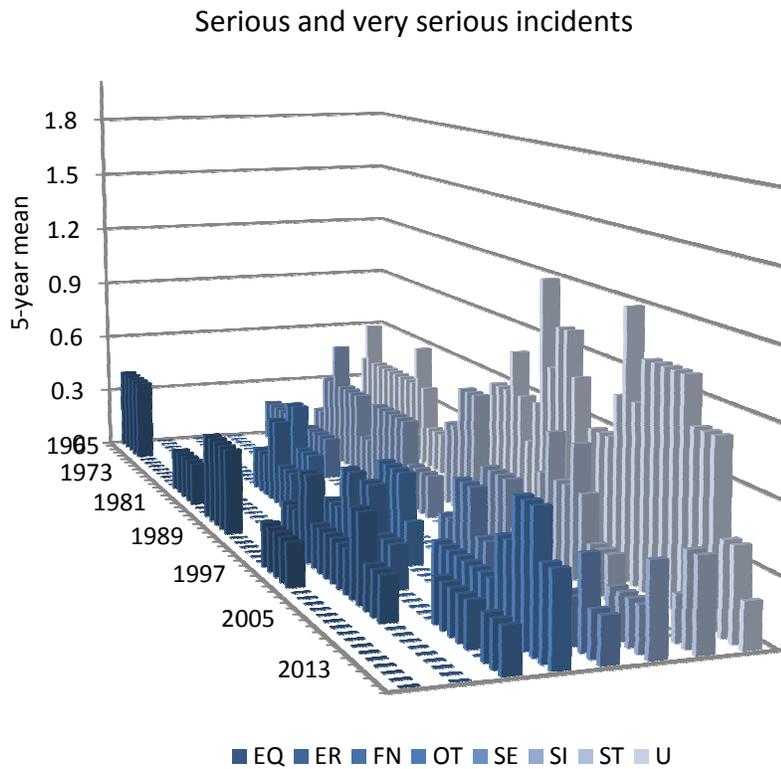
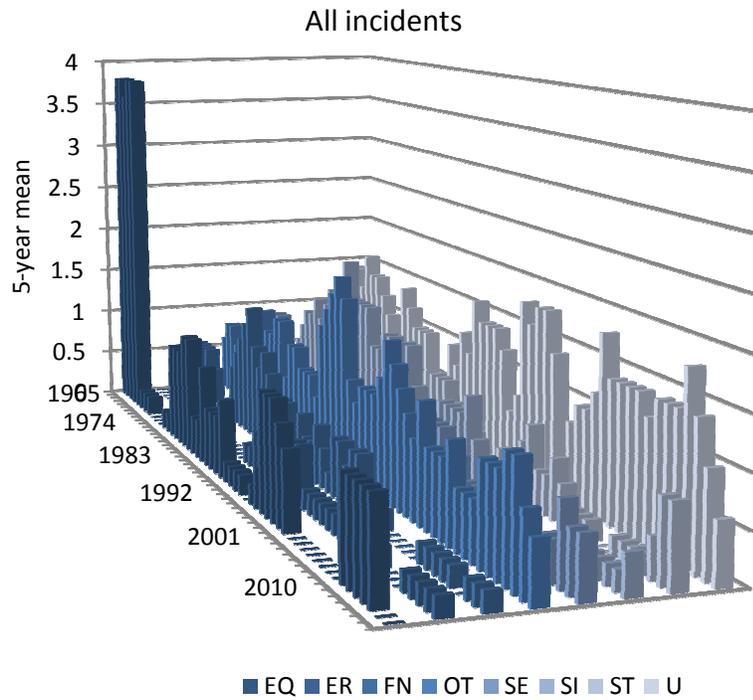
**Table 1** Common triggers and leading causes of failure. Adapted from Gindy et al., (2007)

Floods	Earthquakes	Operations
Overtopping	Foundation failure	Overtopping (WM)
Erosion	Structural damages	Erosion (WM & CM)*
Seepage and piping	Slope instability	Seepage and piping (WM & CM)
Slope instability		Slope instability (WM & CM)
Structural damages		Structural damages (CM & others)
		Foundation failure (CM & others)

\*WM= Water management, CM=Construction materials

In terms of historical events, the causes of failure have not changed dramatically since the 1960s. Considering a 5-year mean moving window, the trends in the reported mean number of events per cause of failure are mostly not significant (Figure 5 top). The only failure modes with any significant trends using Kendall's rank correlation are: **FN decreasing** ( $\tau=-0.37$ ,  $p\text{-value} = 0.0003$ ), **SI decreasing** ( $\tau= -0.52$ ,  $p\text{-value} = 2.214e^{-07}$ ).

If only the serious and very serious incidents are considered, some significant trends are found in the mean number of events (Figure 5 bottom): **EQ decreasing** ( $\tau=-0.35$ ,  $p\text{-value} = 0.001$ ), **OT increasing** ( $\tau=0.51$ ,  $p\text{-value} = 2.015e^{-06}$ ) although very slightly (when doing a linear regression the trend coefficient is 0.007, but significant), **U increasing** ( $\tau=0.38$ ,  $p\text{-value} = 0.00016$ ).



**Figure 5** Five-year mean TSF failures (moving window) by cause. Causes of failure with significant trends are presented in bold lines. EQ= earthquakes, ER=erosion, FN=foundation, OT=overtopping, SE= seepage and piping, SI=slope instability, ST=structural, U= undefined. Data from Chambers and Bowker (2016), news, and reports.

However, the reported type of failure has to be interpreted carefully since as mentioned before, many incidents are a combination of different causes (Villavicencio et al., 2014) and the assigned type of failure can be misleading (e.g. liquefaction of the foundation due to an earthquake or erosion leading to overtopping), and a large number of failures fall in the undefined (U) category. In the case of serious and very serious events, the decrease in earthquake failures can be a product of better design practices (e.g. improved stability simulations, the use of centerline and downstream construction versus upstream in seismic areas) after the earthquakes in Chile and Japan. The increase in overtopping events on the other hand, may show deficiencies in design (storm event) and water management. As Morgenstern (2011) points out, although progress has been made in the design tools, regulations, oversight and corporate responsibility, failures still occur. The next section reviews the evolution of design and risk management in TSFs.

## **3. TSF Design and risk management**

### **3.1 Design**

The design of tailings dams has changed significantly from the 1930s to the present (Davies et al., 2002). Construction of the early TSFs was done by trial and error (Stratchan et al., 2011). During the 1960's and 1970's geomechanical engineering started to be used to assess the behavior of the tailings and the stability of the impoundments (Stratchan et al., 2011). Geochemical concerns related to water quality and reclamation were first addressed in regulations related to uranium tailings in the United States in 1978 (Morgenstern, 2011). Many changes in the design methodology and testing occurred in the past five decades (Table 2 contains some examples). Currently, various studies are required to approve a TSF design and increasingly the plans for remediation and closure of the impoundments have to be included since the feasibility phase (Stratchan et al., 2011). Local and regional geology, geohydrology, seismicity, climate, surface and subsurface characterization, and the properties of local construction materials and tailings are evaluated. Risk assessments and peer reviews should also be produced in the feasibility phase (Stratchan et al., 2011). During the detailed design phase the following assessments are recommended: foundation and slope instability analyses, water and chemical mass balances, settlement and consolidation analyses, hydraulic analyses for the embankment freeboard, and the spillway capacity (Stratchan et al., 2011). The level of detail in the analyses and compliance to these requirements varies by country, company, and by project.

**Table 2** Changes in design and management

<b>Design</b>	<b>Prior to 1970s</b>	<b>1970s -1980s</b>	<b>1990s-2000s</b>
Earthquakes	Design mainly used the upstream construction regardless of local conditions.	Design for a certain return event (deterministic approach).  Seismic probabilistic risk analysis proposed but still not practiced widely (Vick et al., 1985).  Centerline and downstream construction in seismic zones	Design mainly based on return periods/ deterministic approach such as the maximum credible earthquake (MCE).  Advanced seismic stability calculations (e.g. the finite difference geomechanics modeling program FLAC) Caldwell and Van Zyl (2011)  Well established methods to assess seismic hazards (Morgenstern, 2011). Deterministic seismic hazard assessments (DSHA) and probabilistic seismic hazard assessment (PSHA); Wong et al., 2013)
Water Management	No formal water balances.	Design for a certain return event (deterministic approach).    Long computational time needed to do water balances	Deterministic design parameters such as the probable maximum flood (PMF) Trautwein (2009)  Use of stochastic climate data generating techniques. Proposal to assign probability distributions for the water balances (Truby, 2011)
Seepage	Rate of seepage estimated with conventional net flow analyses assuming steady state conditions (Mittal and Morgenstern, 1976)	Methods for seepage rate calculation not assuming steady state are proposed (Mittal and Morgenstern, 1976)  Improvements in field test methods (Mittal and Morgenstern, 1975)	Seepage modeling using finite element and finite difference computer models (Davies et al., 2002). Seep detection systems and improved liners Caldwell and Van Zyl (2011) Electronic piezocone technology (Davies et al., 2002)
Tailings management	Lack of control in tailings deposition	Improvements in the deposition of tailings.  Better understanding of the tailings geomechanics and geochemistry	Alternatives for tailings management and delivery (thickening, dry stacking, etc.)
Slope design and stability	No real stability analyses Some field and lab measurements (relative density tests). Caldwell and Van Zyl, (2011)	Probabilistic slope stability assessment (PSSA) first introduced. (El-Ramly et al, 2002)  Main design element: safety factor	Limit equilibrium and stress deformation analysis (Prodromos et al., 2008).  Probabilistic slope stability assessment. (El-Ramly et al, 2002). Gives higher credibility to the calculated factor of safety  Main design element: safety factor

Despite of the advances in TSF design, issues remain related to the assumed risk embedded in design parameters and decisions:

- Some deterministic parameters used in the design (such as the PMF or MCE) are still defined with reference to the largest events “reasonably possible” based on physical processes. The likelihood of occurrence is assumed to be very low but the numerical value is usually undetermined (Vick, 1985). Furthermore, there is variable practice in assessing the PMF and floods for design against extreme events (Morgenstern, 2011). One of the issues is the selection of the appropriate storm event (6-hr, 24-hr, 72-hr, etc.) that will provide the right level of conservatism for the specific case. Another issue is that historical precipitation data is usually limited at the mining sites (sometimes only two or three years long, in which case interpolation from the nearest stations is needed). Since it is usually not a probabilistic measure of the risk, its implications for loss are not properly translated into the expected net present value of the design. In general, deterministic parameters such as safety factors neglect the importance of the uncertainty inherent to geologic materials and processes, which probabilistic assessments consider (Van Zyl, 1987). However, recent trends in dam safety are favoring the use of probabilistic approaches for defining seismic design and ground motions (Wong et al, 2013) or a combination of deterministic (DSHA) and probabilistic (PSHA) seismic hazard assessments.
- Design decisions usually favor the option with the lowest capital costs, and although the modes of failure are analyzed, the cost optimization that takes place in this phase generally does not account for the potential economic losses in the event of dam failure.
- There is still a tendency to underestimate the consequences of failure due to earthquakes during operations and to adopt an earthquake loading that is too low, especially in areas of minor and moderate seismicity (Morgenstern, 2011).

The following section presents examples of risk management approaches for tailings dams.

### 3.2 Risk Management

Risk can be defined as the product of the probability of occurrence of an event and the damage or consequence resulting from that event. Therefore, risk analyses are a systematic process of identifying and quantifying possible outcomes and their associated probabilities (Vick, 2017). Fault and event trees are commonly used (an example for uranium tailings is shown in Van Zyl, 1987). Limit equilibrium methods, and more recently, advanced linear and non-linear finite element calculations (Hariri-ardebili, 2017) can be performed to provide input for the fault trees. However, risk analysis in dams (water or tailings) deals with many uncertainties, and analyses often end up being deterministic because complex models are time consuming (Hariri-ardebili, 2017). That is one of the reasons why although the benefits of probabilistic analysis over safety factors have been presented since the 1980's (Vick et al., 1985; Van Zyl, 1987), tailings dam engineers have been slow in adopting the techniques (El-Ramly et al., 2002). Sensitivity analyses are perceived to be more valuable in the TSF design process than estimating the probability of failure. These analyses are usually done by changing one parameter at a time (e.g. angle of friction, permeability, density, etc.), covering a range of variation of the parameter based on the soil type and testing. The same ranges could be used in a probabilistic approach.

Some mining companies use the qualitative failure mode and effect analysis (FMEA) to evaluate risk associated with one or more TSF options, and discounted cash flow (CDF) for site-specific cost analyses (Vick, 2017). FMEA starts with the outcome of an event and regresses to possible causes. The probability of occurrence of each failure mode and the effect can also be included in the process (Gindy et al., 2007), although the analyses are mostly qualitative for TSFs (Samarco used this methodology; Vick, 2017).

The TSF design selection and risk assessment process consists primarily of decision matrices or expert analyses evaluating capital costs, environmental and community impacts, operational complexity, and other metrics (some examples in Wardrop, 2007; Knight Piésold Consulting, 2010; Johnson et al., 2013; Roşia Montană Gold Corporation, 2006). Although dam break and flood inundation studies are now required by many jurisdictions as part of the permitting process (Rourke and Lupnow, 2015), the environmental impacts assessed are generally related to land disturbance (TSF footprint) or direct influence in local wildlife under normal TSF operations, but not to losses in the event of failure. Similarly, impacts to the communities are related to displacements and not to other problems derived from a potential failure such as infrastructure damage, interruptions to the water supply, and most importantly, loss of life. Therefore, the capital costs considered in the decision do not always reflect potential externalities so the “tolerable risk” is not accurately represented. Additionally, there are still many uncertainties in the current methods to do tailings dam inundation analyses, as discussed in Martin and Akkerman (2017).

A rational design decision approach would be one that considers a probabilistic framework to assess costs and benefits for each mechanism of failure to determine an optimal level of protection as exemplified by Vick et al.,

1985 for tailings dams and for river dams in Bowles et al., (1998), Bowles et al., (1999). The risk of each design option can be quantified multiplying the total probability of failure ( $P_f$ ) by the costs (C), where C includes the cost of construction and the cost of failure (Vick et al., 1985). One of the barriers to do such assessments is that considerable knowledge of a process or failure mode is needed. Some failure modes such as flood-induced overtopping or foundation liquefaction due to earthquakes (Yener Ozkan, 1998; Vick et al., 1985; Truby, 2011) are better understood and easier to analyze than others such as piping, or slope instability, although methods have been developed to estimate the likelihood of the latter (El-Ramly et al, 2002, 2003, 2006). Still, expert judgment is a key part in the estimation of probabilities of failures, even for overtopping and earthquake loads (Fell et al., 2000; Silva et al., 2008). Assessing the variability of the parameters requires a lot of data, and the selection of a probability distribution may be complicated. Other barrier is the calculation of the failure costs, especially when there is a potential loss of life (Vick et al., 1985). However, as more data becomes available (product of improved testing and monitoring technologies and practices), the adoption of probabilistic methods for design and decision making may increase. This approach facilitates communication of the significance of dam safety issues in relation to changes in a TSF, and could be used for portfolio management, providing a financial justification for each decision (Bowles et al., 1999b; Silva et al., 2008).

### **3.3 Monitoring and Management**

All the design options consider an assumption of best operational and management practices, but this is not guaranteed to take place. The initial design concept of the Fundão dam (Samarco) was robust according to the panel of experts reviewing the failure (Morgenstern, 2016), but it relied on efficient drainage and a specific ratio of sands to slurry delivery. Modifications to the design done afterwards, serious construction flaws of the drainage system, and operation issues (poor beach control, changes in sand production, and continuously raising the dam even when problems had already been detected) led to the incident (Morgenstern, 2016). Examples such as the Fundão TSF, where the integrity of the dam was compromised by deficient construction or management practices are abundant (Buena Vista del Cobre in Mexico, 2014; Kolontar in Hungary, 2010; Herculano Iron Mine in Brazil, 2014; Padcal in the Philippines, 2012, and many others included in the supporting documentation), so even when the design process followed the best practices including external peer reviews, the correctness in construction and operation have to go through similar oversight on a regular basis. This calls for a regular process for updating the failure risk and consequence estimates.

The quantitative risk assessment is not exclusive to the design phase as probabilities of failure change over-time in a TSF and the consequences of failure can also change over time (e.g. new population settlements downstream). Continuous monitoring using drones and aerial images can be used to update and detect potential failure mechanisms. Some mines are already using these technologies to monitor their TSFs, although the data generated

is not usually linked to a probabilistic risk assessment. An example is the Peñasquito mine in Mexico where aerial imagery at various resolutions is used to conduct topographic surveys of the TSFs. This allows tracking the evolution of the tailings to measure storage availability, and to detect potential issues such as a reduction on beach length (Schmidt, Malgesini, & Reinson, 2015). In the case of Peñasquito this type of analysis has proven to be inexpensive, safer and faster than ground monitoring (Schmidt, Malgesini, & Reinson, 2015). In other studies, soil pH maps of mines have been created to detect and predict acid drainage from tailings using satellite images, and soil moisture content has been monitored using remote sensing to prevent failures such as piping and seepage (Eo, 2009). The information generated through these monitoring practices could be integrated into models to perform probabilistic risk assessments. In terms of the evaluation of the potential consequences of failure, a methodology is proposed in section 4 to obtain hazard classifications that can be updated overtime.

Lastly, external audits, combined with risk analysis using regular monitoring of the operations, and adherence to the best industry practices (such as the guidelines developed by the Mining Association of Canada, the International Commission of Large Dams, the Australian National Committee on Large Dams, the Canadian Dam Association, the U.S. Army Corps of Engineers and others) could reduce incidents, but expert enforcement is needed. For example the three dams in Samarco were graded as “guaranteed stability” by an external auditor in 2015 just before the failure, but according to the failure report, the failed dam had long standing problems after a faulty construction (Morgenstern, 2016). Audits are a useful prevention tool to the extent that they are properly conducted.

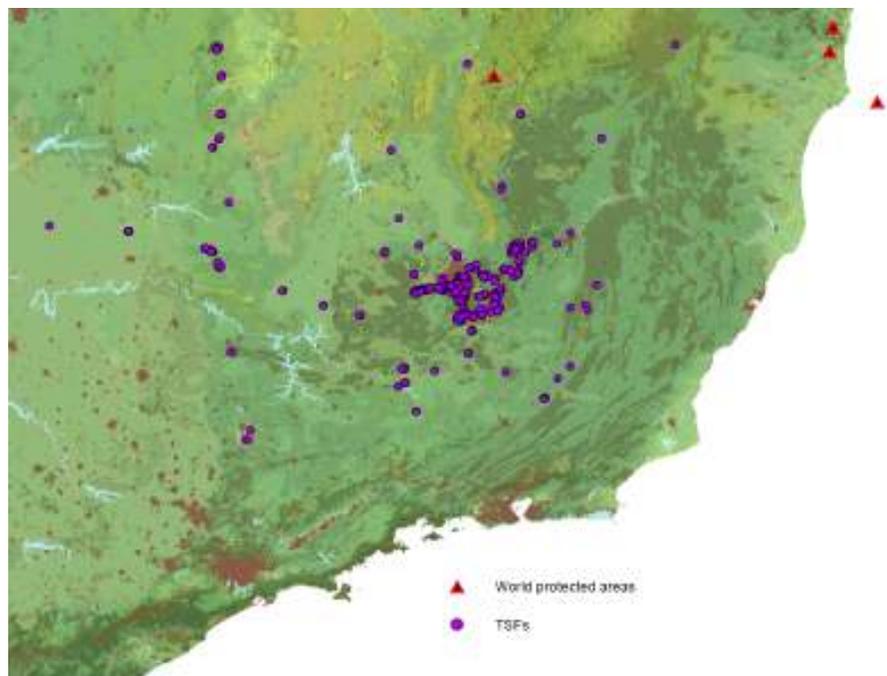
## 4. An example of TSF exposure rating

A new hazard rating index ( $H_R$ ) was developed using ArcGIS to assess and compare the potential damage that TSFs failures may cause downstream.  $H_R$  considers some attributes of the tailing dams (height and storage capacity), and information about the areas around them (population, land use, and proximity to high conservation value areas).  $H_R$  can be updated with a few inputs over the life of a TSF to reflect changes in exposure from changing characteristics of the TSF (e.g. incremental storage), and changes in the conditions downstream (e.g. population increase). *The index can be used by investors to prioritize where it may be more or less important to pursue inquiry into a more detailed TSF risk quantification process, but it is not a substitute for a formal risk analysis.*

Hazard classifications of dams are common in many countries and determine the frequency of inspections both for water and tailings dams. Brazil’s Deliberação Normativa COPAM nº 62 (Appendix I) has three dam classifications according to height, volume, population, environmental interest, and infrastructure close to the dams. Category III is the most risky and audits are conducted every year; for categories II and I, audits take place every two and three years respectively. In general, dam hazard classifications include components such as population at risk, loss of life,

infrastructure damage, and environmental damage (Gindy et al., 2007), but the terminology used to classify the dams can be subjective. Brazil's classification contains parameters such as "little concentration" of nearby infrastructure but does not define how to determine what is regarded as little or nearby. Here, we attempt to create a standardized index to compare the potential hazards of TSF failures within a company or country. The idea is to present a hazard exposure index in the event of failure accounting for some of the uncertainties in the estimation of the potential impact.

Our calculation of  $H_R$  does not consider dam breach or inundation analyses to obtain the potential affected areas. We use an empirical approach applied to historical failure data that does not explicitly account the uncertainty in such analyses. At site conditions may vary considerably and information from the ensemble of past failures can only be expected to cover some of these conditions in a broad sense. The information needed to conduct detailed inundation analyses for TSFs is usually not readily available to those outside the mining company or its contractors. Further, even the analyses conducted by the mining companies rely heavily on expert judgment for the selection of the dam break and inundation model parameters (Martin and Akkerman, 2017). We expect that the empirical methodology proposed here for the calculation of  $H_R$  can be more informative for hazard classification than other methods currently used, while using information that is generally available. We selected 179 TSFs located in Minas Gerais (Figure 6) as a test case from the tailings dams dataset compiled by FEAM, (2015).



**Figure 6** Tailings dams in Minas Gerais, Brazil.

## 4.1 Data

The following datasets were used for the calculation of  $H_R$  in Minas Gerais:

1. Population: Gridded Population of the World version 4 dataset 30 arc-sec resolution, ~ 1km at the equator; GPW4, 2015.
2. Land use: Global Ecosystems gridded database at 250m resolution; USGS, 2014. The ecological land units (ELU) description were used to assess damage by type of land use.
3. High conservation value areas: HCV areas dataset; WRI, 2003.
4. Elevation: Hydrosheds 15 arc-sec DEM data (Hydrosheds, 2006)
5. Historical tailings dams failure information compiled from Chambers and Bowker (2016), Chambers and Bowker (2017), and Rico et al (2008); (refer to Attachment I).

## 4.2 Methods

The methodology for rating the potential hazard exposure associated with a dam consists of four steps:

1. Calculate the volume of potential released tailings ( $V_F$ ) and the distance travelled by the tailings in case of failure ( $D_{max}$ ) using a regression approach relating these two variables and TSF height using historical failure data.
2. Estimate the affected area ( $A$ ) using digital elevation data in the proximity of the TSF site.
3. Obtain information about the potential land use, water bodies and population in the affected area.
4. Calculate Hazard Rating Index ( $H_R$ ) as the integration of these processes

A description of each of the steps is presented below.

### 4.2.1 Calculation of $V_F$ and $D_{max}$

In the first step, the potential outflow in case of failure ( $V_F$ ) and the maximum distance travelled by the tailings ( $D_{max}$ ) were estimated by updating the empirical relationships developed by Rico et al, (2008) (Eq. 1 and Eq 2) using a new data set. The 22 complete observations (including height, storage volume in  $m^3$ , released volume in  $m^3$ , and distance traveled) originally used by Rico et al, (2008) were corrected and updated with additional information from Chambers and Bowker (2016) and Chambers and Bowker (2017) to have a total of 29 complete cases (refer to Attachment I).

$$V_F = 0.354 \times V_T^{1.01} \quad R^2 = 0.86 \quad \text{Eq.1}$$

where  $V_F$  is the waste outflow volume and  $V_T$  is the storage volume in  $10^6 \text{ m}^3$  at the time of failure.

$$D_{max} = 1.61 \times (H \times V_F)^{0.66} \quad R^2 = 0.57 \quad \text{Eq. 2}$$

where  $D_{max}$  is the maximum runoff distance in kilometers,  $H$  is dam height at the time of failure in meters, and  $V_F$  is the waste outflow volume in  $10^6 \text{ m}^3$ .

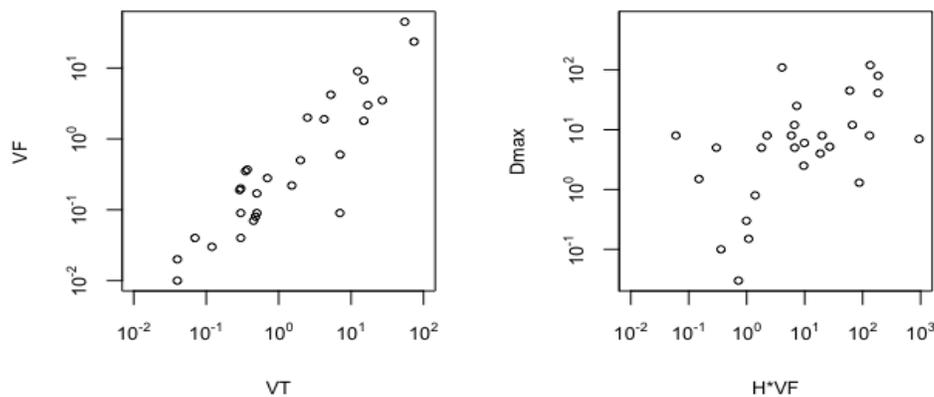
The linear regressions fitted with the new data correspond to Eq.3 and Eq.4. The scatterplots of the dependent and independent variables are shown in Figure 7.

$$\log(V_F) \sim a + b \cdot \log(V_T) \quad \text{Eq. 3}$$

The coefficients are:  $a = -0.515$ ,  $b = 0.924$ ; with  $R^2 = 0.81$  and  $p\text{-value} = 1.466 \times 10^{-11}$ . In Rico *et al.*, (2008) notation that translates to  $V_F = 0.305 \times V_T^{0.92}$

$$\log(D_{max}) \sim c + d \cdot \log(H \times V_F) \quad \text{Eq. 4}$$

The regression coefficients are:  $c = 0.255$ ,  $d = 0.511$ ; with  $R^2 = 0.36$ , and  $p\text{-value} = 3.569 \times 10^{-4}$ . In Rico *et al.*, (2008) notation that translates to  $D_{max} = 1.8 \times (H \times V_F)^{0.51}$



**Figure 7** Left: Relationship between  $V_F$  and  $V_T$  in  $10^6 \text{ m}^3$  (plotted in the log scale), Right:  $D_{max}$  in km in relation to height and released volume (plotted in the log scale).

It is important to note that these are empirical regression equations with significant uncertainty about the mean. Many investigators directly use such regression equations in a deterministic way to specify exposure. However, at

site conditions vary significantly, and there is considerable uncertainty that needs to be quantified. It is important to account for the uncertainty in these estimates to derive a probabilistic measure of risk that also accounts for how well the regression fits in a certain range of values of the predictors. Therefore, the prediction interval of  $D_{max}$  is reported at the 5<sup>th</sup> and 95<sup>th</sup> percentiles (Attachment II); this approach is reasonable as the residuals are normal in the log-log space.

The importance of considering the uncertainty distribution around the regression, rather than using it directly is illustrated by the following example. The mean value of the predicted  $D_{max}$  for the Fundão dam (Samarco) is 108 km if the observed  $V_F$  is used in the calculation or 65 km if  $V_F$  is the predicted mean of Eq. 3, while the predicted 95<sup>th</sup> percentile is 2878 km with  $V_F$  observed (1607 km with  $V_F$  predicted). The  $D_{max}$  reported from the actual failure was 637 km downstream, which based on the uncertainty distribution associated with the regression equation, has a probability of exceedance of approximately 18% with  $V_F$  observed (12% with  $V_F$  predicted). In this case the tailings were deposited directly in the Doce River (Fernandes et al., 2016), transporting the tailings all the way to the Atlantic Ocean, whereas for other TSF failures an immediate river receptor may not be there limiting the travel distance. Consequently, if regression equations such as those developed by Rico (2008), are to be used it is important to consider the uncertainty distribution around the regression since it at least accounts for the variability in the potential  $D_{max}$  considering the data that was available. For a probabilistic risk evaluation then, for Samarco, the concern would have been the greater than 600 km impact with a 12% chance rather than the very modest 65 km indicated by the regression considering the predicted mean  $V_F$  from Eq.3. Of course, the lower limit of  $D_{max}$  corresponding to a 5% level could also be of interest (4.02 km with  $V_F$  observed; 2.6 km with  $V_F$  predicted for Samarco), and hence providing the 95% prediction interval in addition to the regression prediction is important.

#### **4.2.2 Affected area**

The affected area ( $A$ ) below the tailings dams was estimated using ArcGIS in the following way:

1. Create a buffer with radius equal to  $D_{max}$  for each tailings dam.
2. Obtain the elevation at the tailings dam with Hydrosheds 15 arc sec digital elevation model (DEM).
3. Discard all the areas in the buffer where elevation is higher than the elevation of the TSF.
4. Use the remaining polygons to extract information from the population and land use layers.

The extent of potential damage included in the index is based on ( $A$ ) computed with  $D_{max}$ .

#### **4.2.3 Calculate $H_R$**

The proposed hazard rating index is then defined as:

$$H_R = \sum w_i * M_i \quad \text{Eq.3}$$

where  $w_i$  is a user specified weight and  $M_i$  is a measure of a specified variable of interest such as population, land use, etc. within the affected area. For our example, we used the following variables:

$M_1 = \log(\text{population in } A)$ ,  $M_2 = \log(\text{cropland in } A)$ ,  $M_3 = \log(\text{urban area in } A)$ ,  $M_4 = \log(\text{water surface in } A)$ ,  $M_5 = \log(\text{forests in } A)$ ,  $M_6 = \log(\text{Grassland in } A)$ , and  $M_7 = \text{number of high conservation value areas within } A$ . All areas are in  $\text{km}^2$ . The first set of attributes was log transformed here since the effects of the release may not increase linearly with  $D_{\max}$  given dilution, and retardation, and the decreasing adjacency of the potential affected area to the TSF release.

For the test case all  $w_s$  are equal to one (Eq.4) but these can be assigned differently (for example, more assigning weight on population).

$$H_R = M_1 + M_2 + M_3 + M_4 + M_5 + M_6 + M_7 \quad \text{Eq.4}$$

Other important parameters that could be included are the toxicity and concentration of the tailings. For the TSFs in Minas Gerais that information was not available, but it is a relevant component for hazard estimation (as in Liu et al., 2015).

#### 4.2.4 Results

$H_R$  was calculated for 179 TSFs (results included in Attachment II) using the median of  $D_{\max}$  in each case and the locations and results are pictured in Figure 8. The concentration of TSFs with large  $H_R$  (>15) in Minas Gerais is evident in Figure 8, and it doesn't include all the TSFs in the region.

The hazard ratings can be compared in a region or within a company to decide on specific actions such as inspections, monitoring, expansions, etc.  $H_R$  ratings for a sample of tailings dams of the Companhia Vale do Rio Doce are presented as an example in Table 3, where it is evident that dams of the same Brazil hazard classification can have different  $H_R$ . In general, the spread in  $H_R$  values within the Brazil hazard classification is large (Figure 9, total sample set), so the classification doesn't really account for the differences within the dams of a particular class. These differences can be important in terms of the inherent hazards and can be prioritized with a more granular measure such as  $H_R$ . Still, a better way of reporting  $H_R$  would be to include the 5<sup>th</sup> ( $H_{RQ5}$ ) and 95<sup>th</sup> ( $H_{RQ95}$ ) percentile to account for the uncertainty of the potential damages. An example is shown in Figure 10, where the distribution of  $H_R$  is calculated based on predicted values of  $D_{\max}$  at different probabilities.

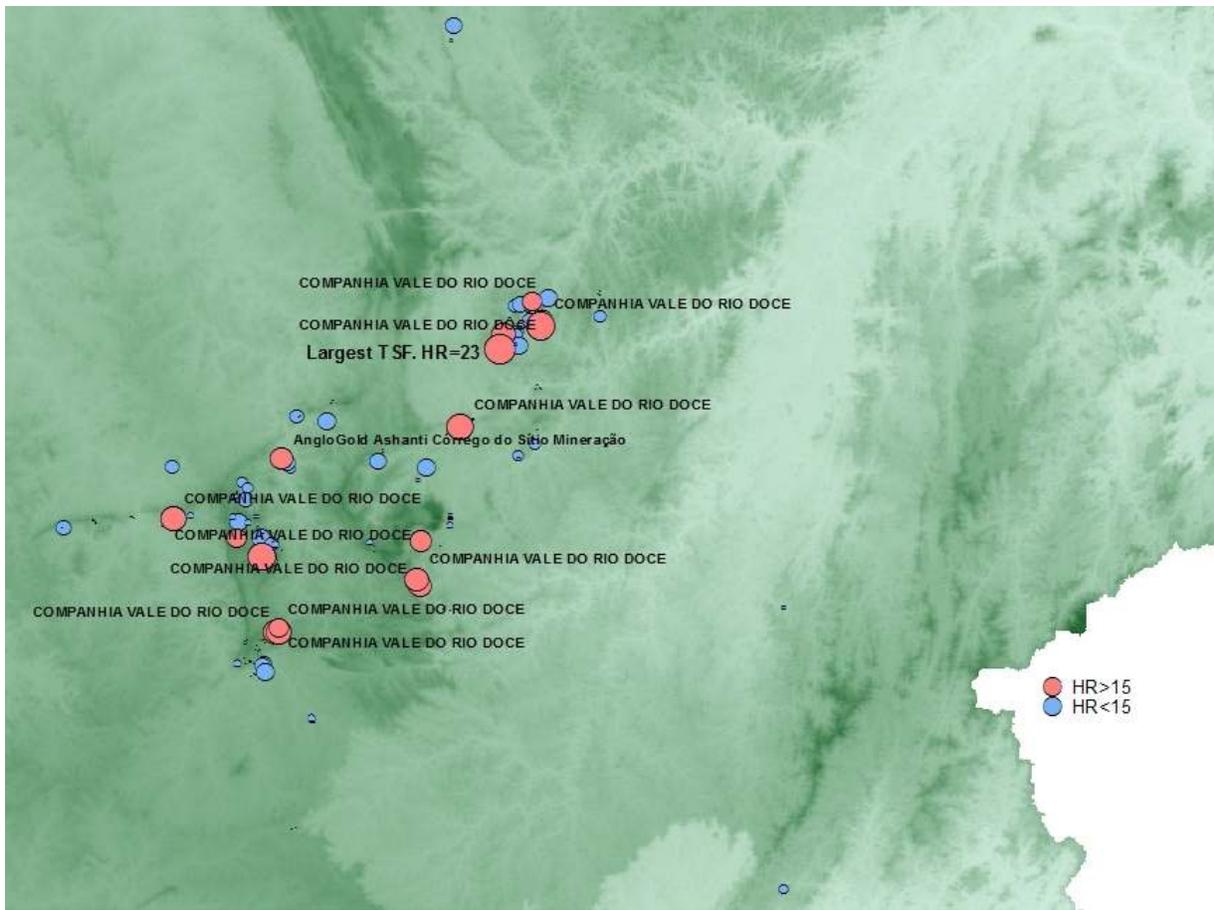


Figure 8  $H_R$  results pictured by the size of the circle. The company names of TSFs with  $H_R$  larger than 15 are labeled in the map.

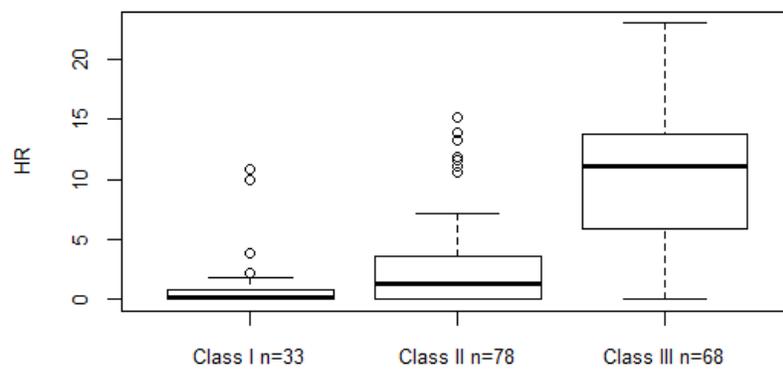
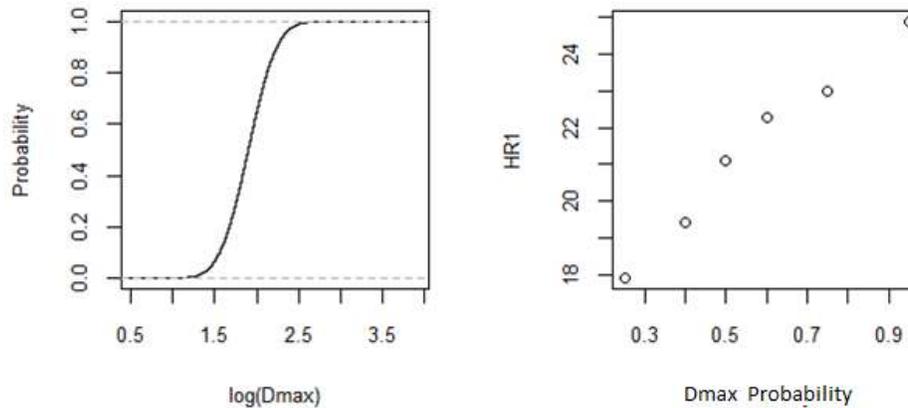


Figure 9  $H_R$  values per class according to Brazil's dam hazard classification; n is the number of dams in each class.

**Table 3** Hazard rating of the Companhia Vale do Rio Doce sample tailings dams in Minas Gerais.

TSF	Class	H (m)	V <sub>T</sub> Mm <sup>3</sup>	Q <sub>95</sub> D <sub>maxx</sub>	Q <sub>50</sub> D <sub>maxx</sub>	M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>	M <sub>4</sub>	M <sub>5</sub>	M <sub>6</sub>	HR
BARRAGEM ITABIRUÃ#U	III	68	230.0	1409.5	126.8	6.7	3.1	3.2	3.4	4.4	2.1	23.0
BARRAGEM PONTAL	III	69	122.5	1020.2	91.2	6.6	2.9	2.9	3.3	4.1	1.9	21.8
BARRAGEM MARAVILHAS II	III	80	76.3	840.5	75.7	6.5	2.9	2.8	3.1	3.7	1.6	20.6
CÓRREGO DO CANAL (SUL)	III	80	53.2	745.1	67.2	6.6	2.8	2.8	3.2	3.9	1.3	20.6
FORQUILHA I	III	84	26.0	542.2	52	6.2	2.5	2.9	3.2	3.7	1.4	19.9
FORQUILHA II	III	88	24.0	514.2	47.6	5.8	2.3	2.8	3.1	3.6	1.2	18.9
BARRAGEM I	III	87	12.7	392.6	35.3	6.3	2.6	2.5	2.8	3.1	1.5	18.8
BARRAGEM CONCEIÇÃO	III	60	40.6	556.7	51.4	5.6	2.2	2.5	2.9	3.7	0.9	17.9
BARRAGEM TIMBOPEBA	III	64.9	34.0	478.9	41.5	5.5	2.1	2.6	3.1	3.5	1.2	17.8
BARRAGEM DOUTOR	III	73	34.2	530.6	48.1	5.4	1.9	2.4	2.8	3.5	1.0	17.1
BARRAGEM CAMPO GRANDE	III	97	20.6	480.8	42.8	5.4	1.9	2.3	2.9	3.4	1.0	16.8
BARRAGEM PIABAS	II	21	59.7	385.4	34.2	5.2	1.8	2.0	2.3	3.2	0.5	15.1
FORQUILHA IV	III	90	3.9	213	19.7	5.1	1.6	2.4	2.5	2.7	0.8	15.1
BARRAGEM CEMIG II	II	22.35	12.3	184.6	17.2	5.1	1.7	1.6	2.1	2.8	0.6	13.9
BARRAGEM SANTANA	III	52.4	11.0	272	24.8	5.0	1.5	1.8	2.0	2.9	0.5	13.7
BARRAGEM RIO DO PEIXE	III	31	13.1	237.8	22	5.1	1.6	1.5	2.0	2.9	0.5	13.5
SUL SUPERIOR	III	85	3.2	185.4	17.1	4.9	1.4	1.7	2.4	2.7	0.0	13.1
BARRAGEM JIRAU	II	15	6.2	109.3	9.8	5.0	1.6	1.0	1.7	2.2	0.3	11.8
CORDÃO NOVA VISTA	III	17	10.0	142.1	12.6	4.9	1.5	1.3	1.5	2.1	0.5	11.7
DIQUE MINERVINO	III	17	6.5	115.9	10.3	4.9	1.5	1.2	1.3	1.9	0.5	11.3
BARRAGEM CAPÃO DA SERRA - MIO DO TAMANDUÁ	III	43	2.1	114.4	10.4	4.6	1.3	2.0	2.1	1.3	0.0	11.2
BARRAGEM CEMIG I	II	32.5	1.6	89.1	8	4.8	1.4	1.0	1.7	2.0	0.3	11.2
BARRAGEM MARAVILHAS I	III	34	2.0	97.2	9	4.5	1.0	2.0	1.9	1.1	0.2	10.7
BARRAGEM ALCINDO VIEIRA	II	27	2.8	95.9	8.3	4.8	1.5	0.8	1.6	2.0	0.0	10.6
BARRAGEM VARGEM GRANDE	III	38	2.5	112.8	10.1	4.4	0.6	1.9	2.1	1.1	0.3	10.3
BARRAGEM GALEGO	III	35	1.0	69.5	6.4	5.0	1.3	1.0	1.5	1.5	0.0	10.3
BARRAGEM CAMBUCAL I	III	15.4	2.2	67.5	5.9	5.0	1.6	1.0	1.1	1.2	0.0	9.9
BARRAGEM CAMBUCAL II	III	17.5	1.6	57	5.1	5.0	1.5	0.8	0.9	1.0	0.0	9.2



**Figure 10** Uncertainty distribution of Dmax for a hypothetical TSF (left) and the calculated  $H_R$  using different probabilities of Dmax (right).

$H_R$  only relates to the expected consequences in case of failure but a similar approach could be followed to address the likelihood of a failure in the form of a “failure trigger” index. This index could consider combinations of variables that make a TSF riskier based on past failures and current knowledge. The components of the trigger index could include physical characteristics: seismic hazard, type of construction (upstream, downstream, centerline), status (active, inactive), material of construction, and management practices: are the roles and responsibilities well defined, are the operators and designers experienced and knowledgeable, are there well established and followed critical controls, grade in past inspections, etc. This way a dam could be classified in two ways: a dam is risky based on triggers rating and a dam’s failure impact is high /low based on the hazard rating scores. Again, this approach would not substitute a formal probabilistic risk assessment but could be used as an initial screening to decide on having detailed evaluations at particular sites. The hazard ratings could be complemented with the estimation of monetary losses in case of failure, as information is available (Vick et al., 1985). This would provide a clearer direction and justification for monitoring, and maintenance.

The Columbia Water Center developed an application that calculates  $V_f$ ,  $D_{max}$ , and  $H_R$  for TSFs anywhere in the world. The required inputs are the volume, height and coordinates of a given TSF. The application allows calculating the probability of exceeding a certain value of  $V_f$  or  $D_{max}$  following the approach described in section 4.2.1.  $H_R$  in the application is reported including the 25<sup>th</sup> ( $H_{RQ25}$ ), 50<sup>th</sup> ( $H_{RQ50}$ ), and 75<sup>th</sup> ( $H_{RQ75}$ ) percentile to account for the uncertainty of the potential damages. This application will be available on line in 2018.

## 5. Recommendations

Based on the findings from the previous sections we provide a list of actions that are needed to better understand the risk of TSFs, and recommendations to mitigate them.

*a) Create databases of TSFs locations and attributes around the world.*

Data availability is a primary limitation for understanding the exposure and risks of TSFs around the world. Some countries have already launched programs to compile information about tailings dams (e.g. Chile, Brazil, B.C. Canada, Ireland, the U.S., the E.U.), but the information included in the databases is not standardized. The International Commission of Large Dams (ICOLD) has a registry of more than 50,000 dams worldwide that includes details on their characteristics and is updated regularly, but it has not completed the process of including tailings dams. The minimum information that a TSF database should include is: mine name/owner, type of ore, TSF coordinates, current and design height, information about rises (year and height), year of construction, projected life, current and design storage capacity, type of construction (e.g. upstream, downstream, centerline), material of construction, information about the nature of the tailings (inert, acid drain generating, toxic, etc.), status (active, closed, abandoned), and information about any past incidents.

The TSF database would be used for indicative analyses (in the absences of detailed information) to:

1. Perform qualitative exposure analyses such as the one presented here. These analyses can be done at multiple scales depending on the intended use (asset, portfolio, regional, country, or global).
2. Inform the initial stages of risk assessment, particularly for portfolio management.
3. Inform communities about the potential risks posed by TSFs.
4. Improve the existing methodologies to estimate probabilities of failure modes.

*b) Understand what interventions are needed to reduce the risks of TSF failures in terms of the design process, operations, and risk mitigation strategies.*

1. Implement probabilistic risk assessment during the design and operation of TSFs. Current decision matrices do not reflect the losses associated with the potential risk of failure and this has to be addressed starting with the definition of the design parameters, transitioning from a purely deterministic approach (e.g. PMF) to incorporating probabilistic methods. Understanding the probability of failure during operations is also important, for example studying the risks associated with dam rises out of the design schedule, or the volume of the supernatant pond.
2. Ensure that an Independent Review Board was involved in the design process (Morgenstern, 2011).
3. Complement external audits and compliance to best practices with new monitoring technologies. The use of satellite and aerial images to track changes in the TSFs is gaining popularity. Successful cases are included in Schmidt, Malgesini, & Reinson, 2015 and Eo, 2009.
4. Calculate cost increases for additional risk assessment and oversight. The lack of understanding of the potential financial benefits of avoiding a TSF failure in the long term makes it difficult to decide if investing in better monitoring and management practices is worth it. In retrospective, recent failures such as the one occurred in Samarco show that it may be.

5. Educate the communities near to mines by bringing independent third parties, so they understand the risks imposed by mine facilities, including TSFs, and allow them to participate or see the results of some of the key monitoring activities.

*c) Financial disclosure of potential liabilities from TSFs and their probability*

1. Use the quantitative risk assessments to disclose the liabilities associated with potential TSF failures. Liabilities related to TSFs are included in the balance sheets of mining companies as part of the asset's cleanup and reclamation costs and are annually disclosed. These estimates should be updated to reflect the changes in the mine operations, including potential changes in the TSF design, construction and operation, and reclamation activities. The closure liabilities should also consider external factors, such as construction of new roads, community activities downstream of the TSFs, as well as implementation of mitigation measures (sometimes these liabilities are updated with input from the quantitative FMEA). There is no reporting standard for the total expected closure costs, so the detail provided by each company is discretionary. If a mining company has several assets, closure liabilities are aggregated in the balance sheet and therefore detail for individual mining projects is lost. Besides, these costs are not segmented in the balance sheets so typically there is no visibility to shareholders of the fraction corresponding to tailings impoundments nor of the expected value of the loss in case of a TSF failure. Further, the insurance maximum corresponding to the TSFs is generally not disclosed. A framework that identifies the probabilities of each mode of failure, the exposure, and the corresponding costs could be used to update and disclose the TSFs liabilities. The mining companies therefore would have an incentive to improve TSF design and management (justify cost increase in operational oversight) and the shareholders would be better informed on the risk they are taking. A remaining challenge however would be to achieve consistency in the assessment and reporting of the TSF liabilities across mining projects and companies.
2. Perform portfolio risk analyses of TSFs across a company's assets considering different failure mechanisms, exposure, and a history of their asset management and design practices. In large mining companies with multiple assets around the world, the management and operational practices may differ at the asset level. Portfolio assessments understanding dam safety risk across assets and feeding into a safety program can be used to prioritize risk reduction actions (Fell et al., 2000).

## **Acknowledgements**

We would like to thank Lindsay Bowker and David Chambers from the Center for Science in Public Participation for their insightful reviews, and to members of mining companies who provided feedback for the document.

# Appendix I

Dam risk classification in Brazil. Translated from the Deliberação Normativa COPAM nº 62, de 17 de dezembro de 2002 ( <http://www.siam.mg.gov.br/sla/download.pdf?idNorma=5008>, last accessed in May 2017).

**Dam risk classification in Brazil**

Height (H in m)	Volume (Vr in 10 <sup>6</sup> m <sup>3</sup> )	Nearby human population	Nearby sites of environmental interest	Nearby Infrastructure
Small (H<5) V=0	Small (Vr<0.5) V=0	Inexistent V=0	Little significance V=0	Inexistent V=0
Medium (15<H<30) V=1	Medium (0.5<Nr<5) V=1	Eventual V=2	Significant V=1	Little concentration V=1
High (H>30m) V=2	Large (Vr>5) V=2	Existent V=3	High V=3	High concentration V=2
-	-	Large V=4	-	-

**Low potential damage, Class I:** When the sum of V is equal or less than 2

**Medium potential damage, Class II:** When the sum of V is greater than 2 but less than 5

**High potential damage, Class III:** When the sum of V is equal or greater than 5.

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