A review of the risks posed by the failure of tailings dams

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**Authors**

HR Wallingford: Marta Roca, Alex Murphy, Louise Walker and Sergio Vallesi.

**Contributors:**

Caitlin McElroy (Oxford University) and Olalla Gimeno (HR Wallingford).

**Acknowledgments:**

Darren Lumbroso (HR Wallingford)
Summary

Tailings dams are embankments constructed from waste rock to impound the tailings generated in a mine processing plant. Tailings often contain hazardous substances that can contaminate food chains, drinking water and the environment. Failure of tailings dams causes loss of lives, irreversible damages to ecosystems and large economic damages and therefore, there is a need for a cost effective service to both monitor operational and abandoned tailings dams, especially those in remote locations, and to help forecast potentially catastrophic failures.

This report provides an overview of risks associated to tailings dams, monitoring regulatory frameworks, methods and techniques and examples of tailings dams failures. It has been prepared in the context of the UK Space Agency supported project "Minimising the risk of tailings dams failures through the use of remote sensing data". The project aims to provide a proof of concept of a more cost effective way of remotely monitoring tailings dams and other tailings deposit areas utilising satellite technologies. The system will help reduce the risk of failure of tailings storage facilities and the consequent damage to population and ecosystem services downstream, upon which many vulnerable communities rely as a source of water and livelihoods. The project is being tested and applied in tailings dams in the mining region of Cajamarca in Peru.

The failure rate of tailings dams over the last one hundred years is estimated to be more than two orders of magnitude higher than the failure rate of conventional water retention dams (reported to be 0.01 %). Failures predominantly occur in small to medium size dams that are up to 30 m high and contain a maximum tailings volume of 5 Mm$^3$. Important factors that make the probability of tailings dam failure higher than that of other earth structures or dams include higher water levels, lack of understanding of behaviour of tailing materials, inappropriate site and geotechnical investigations and lack of monitoring (Berghe et al., 2011).

The appropriate characterisation of failure mechanisms is a key component in effective risk management as the understanding of failure mechanisms helps to assess the performance of a structure. The typical failure mechanisms (overtopping and overflowing, slope instability, earthquakes, foundations failure and internal erosion) are described in this report.
It is not possible to determine the actual level of monitoring used by the mining companies globally however, it appears that most, if not all, the large projects that are still active and operating tailing storage facilities are being monitored using at least regular visual inspections. Generally, there is also some form of in-situ instrumentation monitoring undertaken, which varies from site to site. However, it is probable that a very large number of small operating and non-operating tailings storage facilities are not monitored. A summary review of existing regulations in several countries is presented in the report.

Measurements and testing of all factors connected with the evaluation of dam stability at every stage of construction and operation and especially, as the final maximum height is approached, is fundamental. There is a range of methods and technologies available to assist owners of tailings dams to monitor the impoundment and reduce the probability of failure of the dam depending on the type of structure and the cause for potential failures. The instruments that are mostly used target the main parameters influencing the security of the dam: seepage, phreatic surface, pore-water pressure, seismicity, dynamic pore pressure and deformations. These instruments are discussed in the report.

While visual surveillance and in-situ measurements remain paramount to inspect tailings dams, the use of aerial photography and satellite imagery is becoming a reliable and cost-effective method to monitor the way the impoundment is developing and assist with detecting anomalies. Similarly, automated systems for the recording of monitoring data are also becoming very effective, as they assist with potentially reducing reading errors while increasing quality and frequency of data. The use of cloud computing is enabling a range of new applications toward real-time monitoring of tailings dams where monitoring information is being automatically collected remotely and processed in the cloud processing system. When combined with a suitable data processing and alerting system, they can contribute to effectively reduce the risk of dam failure.

The particular context of tailings dams in Peru a country with a long mining experience and where the UK Space Agency project develops, is described in this report. Peru has a very specific geology, with topographic, seismic and climatological extremes that make the construction and management of tailing dams a challenge. The report describes the different authorities involved in legislation, prevention, inspection and law enforcement of mining activities and their responsibilities. It also reviews the regulatory framework related to the management of operating, closed and abandoned tailings dams.

Failure of tailings dams continue to occur despite the available improved technology for the design, construction and operation. There are apparent deficiencies in design, operation and management which are repeated. It has been recognised that a large proportion of recent events implicate operation and management practice rather than poor or inadequate initial design and they can be related to the slow construction of tailings dams that can span many staff changes, changes of plant ownership and exceedance of original design heights. Examples of tailings dams failures worldwide and in Peru in particular are presented providing an overview of how different failure mechanisms develop and the large consequences that such events may have in terms of human lives and environmental and economic impacts.
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1. Introduction

Tailings dams are embankments constructed from waste rock to impound the tailings generated in a mine processing plant.

Tailings are the by-product of extractive industries and are mixtures of crushed rock and processing fluids that remain after the extraction of economic materials from the mine resource (Kossoff et al, 2014). Tailings are generally stored on the surface either within retaining structures (tailings dams) or in the form of piles (dry stacks) but can also be stored underground in mined out voids by a process commonly referred to as backfill. All these storage structures are referred as Tailing Storage Facilities (TSF). Tailings are conveyed as a slurry (mixture of water and solids) from the mining plant to the storage area. It is possible to apply several dewatering processes to the tailings before storage in order to minimize their environmental impacts (due to seepage and leakage). Depending on the percentage of remaining water and solids the tailings can be defined as slurry, paste, filtered or cake (from less to more percentage of solids).

Tailings dams are often constructed with readily available materials rather than the concrete used for example in water storage dams. Tailings dams also differ from water storage dams due to the fact that the construction phase of a tailings dam continues for the operating life of the mine processing plant, sometimes lasting several decades with many changes in operation and design parameters occurring during this period.

Figure 1.1 extracted from Kossoff et al (2014) shows the typical construction methods of tailings dams that include upstream, downstream and centreline raising. Upstream raising is achieved by placing the new material within the existing storage area, centre-line raising places new
material directly on top of the existing embankment and downstream raising places the new material outside the impoundment. The first method is the cheapest and most common raising method. Tailings are pumped from the mill to the storage area as slurry and dispersal methods are used to achieve size differentiation of the material: coarser, more porous material depositing in the structure itself and finer material forming an impermeable barrier. When depositing, the material gravitates away from the wall forming what is called an hydraulic-fill beach.

Some studies estimate that the number of mining sites in the world is in the order of 18,000 (Azam and Li, 2010) or 30,000, according to a more recent source (SNL, 2016). However, there is not an accessible global inventory of tailings dams. The National Inventory of Dams (2005) lists 1,448 tailings dams in the United States, and the worldwide total is estimated at over 3,500 (Davies et al, 2000). In addition to tailings dams, it is probable that a very large number of other small operating tailing storage facilities are not monitored including many non-operational large and small facilities. For example, Wei at al (2016) report that in China the number of TSFs increased from 1989 due to changes in environmental legislation requiring the construction of tailings ponds and reaching more than 6,000 of these structures in 2000. Expansion of the mining industry and the rapid economic development within China has increased the number of TSFs to more than 12,000 in 2008 (Wei et al, 2016).

Tailings often contain hazardous substances that can contaminate food chains, drinking water and the environment. Failure of tailings dams causes loss of lives, irreversible damages to ecosystems and large economic damages. There is a need for a cost effective service to both monitor operational and abandoned tailings dams, especially those in remote locations, and to help forecast potentially catastrophic failures. This report has been prepared in the context of the UK Space Agency supported project “Minimising the risk of tailings dams failures through the use of remote sensing data”. The project aims to provide a proof of concept of a more cost effective way of remotely monitoring tailings dams and other tailings deposit areas utilising satellite technologies. The system will help reduce the risk of failure of tailings
storage facilities and the consequent damage to population and ecosystem services downstream, upon which many vulnerable communities rely as a source of water and livelihoods. The project utilises Earth Observation including Interferometric Synthetic Aperture Radar and Global Navigation Satellite System technologies combined with real-time in-situ devices to provide a more cost effective way of remotely measuring displacements of tailing dams and other mining infrastructure. The project is being tested and applied in tailings dams in the mining region of Cajamarca in Peru.

This report provides an overview of risks associated to tailings dams (Chapter 2) describing the probabilities of failure of this type of structure and the consequences if such failure occurs. The typical failure modes are also described. Chapter 3 reviews the current monitoring approaches and instrumentation used in tailings dams. Chapter 4 focuses on the particular context of Peru, where the UK Space Agency project develops. The public bodies and regulatory framework in this country are reviewed. Finally, Chapter 5 presents examples of tailings dams failures worldwide and in Peru in particular. Descriptions of the failure event and its consequences are provided.
Chapter 2

2. Risks of failure of tailings dams

2.1 Introduction

Dam failure is an event that would clearly have catastrophic consequences as well as other higher-frequency incidents, such as seepage, which also have large impacts on the environment. ICOLD (2001) states that risk reduction methods for failures of tailings dams can be achieved through adequate application of available engineering technology for design, construction and operation. It also concludes that many of the incidents that occurred in the past (and summarised in ICOLD, 2001) could have been prevented.

Risk can be defined as the combination of the probability that an event, in this case the failure of a tailings dam, will occur and the consequences if such failure occurs. It is essential to consider both the probability (section 2.2) and the consequences (section 2.4), when conducting risk assessments and establishing measures to eliminate, reduce and mitigate for these risks. ICOLD (2001) also recommends that risk assessments should analyse failure modes to identify the most at risk facilities and optimise mitigation measures early on. The most typical failure modes for tailings dams are reviewed in Section 2.3.

2.2 Probability of failure

As discussed previously, latest estimates indicate that there could be 30,000 industrial mines globally (SNL, 2016). For a world inventory of 18,401 mine sites, the failure rate over the last one hundred years is estimated to be 1.2 % (Azam and Li, 2010). This is more than two orders of magnitude higher than the failure rate of conventional water retention dams that is reported to be 0.01 % (ICOLD, 2001).
Tailings dam failures currently amount to approximatively 20 events per decade (data from 1990s and 2000s). Failures predominantly occur in small to medium size dams that are up to 30 m high and contain a maximum tailings volume of 5 Mm$^3$. Upon dam breakage, the released tailings generally amount to about one-fifth of those contained within the facilities (Azam and Li, 2010).

Other more conservative sources estimate probabilities of failure as more than ten times more likely to fail than other conventional dams retaining water (Lemphers, 2010), but the difference between both types of structures is still vast. Important factors that make the probability of tailings dam failure higher than that of other earth structures or dams include higher water levels, lack of understanding of behaviour of tailing materials, inappropriate site and geotechnical investigations and lack of monitoring (Berghe et al., 2011).

Less severe incidents than dam failures occurring at tailings storage facilities (TSFs) are less well monitored and documented. It is likely that a very large number of small operating and non-operating TSFs, in the order of several thousands, are not currently monitored, resulting in potentially thousands of possible environmental incidents, most of which could be unreported. Using the USA EPA (2016) categories and definitions of a serious incident we found it reasonable to estimate the rate of serious environmental incidents over the last one hundred years to be at least twice the rate of dam failure presented above for the 18,401 world mine sites (1.2%), therefore around 2.4% (see Box Statistics from British Columbia, Canada).

In order to better estimate the probability of an incident occurring, the frequency of such events needs to be better monitored. Satellite images, aerial photos, high precision sensors mounted on UAVs can be used to detect changes in vegetation’s health that often reflect damage from seepages from tailings dams. Satellite images can also be used to assess whether environmental incidents have occurred at sites, leading to improved recording of such events.

**Statistics from British Columbia, Canada**

During the period 2000 to 2012 the number of officially reported dangerous tailings ponds incidents in British Columbia (BC) ranged from a high of nine in 2003 to a low of one (2005 and 2006) and totalled 23 (three dangerous occurrences in 2012, two each in 2010 and 2011, five in 2009, one each in 2005 and 2006, and nine in 2003). In an article published by the Vancouver Sun in 2014 following the Mount Polley accident (section 5.7), it is reported that there were another ’46 “dangerous or unusual occurrences” at tailings ponds at mines across BC between 2000 and 2012, according to annual reports of BC’s chief inspector of mines.’ (Vancouver Sun, 2014). According to the same article ‘the definition of dangerous occurrences in the context of the mine health, safety and reclamation code includes events that “might adversely affect the integrity” of dams and dikes. That includes cracking or caving in of a dam or dike, and unexpected seepage or appearance of springs on the outer face of a dam or dike. It also includes the loss of adequate freeboard (the distance between the water level and top of dam), and washout or significant erosion of a dam or dike.’ Clearly neither the 23 incidents nor the 46 dangerous occurrences would have caused anywhere near the release of 10 million m$^3$ of water and 4.5 million m$^3$ of toxic tailings which were discharged from the catastrophic accident at Mount Polley. However, it is fair to assume that in most cases at least serious contamination (US EPA rank 3 or above) must have occurred.

The above considerations support the estimate that the frequency of serious environmental incidents was probably twice that of dangerous failure incidents.
2.3 Failure mechanisms

The appropriate characterisation of failure mechanisms is a key component in effective risk management as the understanding of failure mechanisms helps to assess the performance of a structure.

Tailings dams vary greatly in their design and construction methods, the type of tailings they store and their characteristics and how they are operated, maintained, monitored and kept under surveillance. Their effectiveness and safety also depends critically on their foundation determined by the local geology. For example, Villavicencio et al (2014) identified four causes contributing to instability of Chilean sand tailings dams: construction method, poor compaction, high fine contents in the tailings and elevated degree of saturation.

The International Commission on Large Dams compiled a database of 221 tailings dam incidents (events potentially leading to failure) and failures (events in which dams stop retaining tailings as designed) that occurred from 1917 through 2000 (ICOLD 2001). Causes of incidents and failures were reported for 220 of these, comprising 85 incidents and 135 failures. Failure causes of the 135 reported failures are summarized in Table 2.1.

Table 2.1: Number and cause of tailings dam failures at active and inactive tailings dams.

<table>
<thead>
<tr>
<th>Failure mechanism</th>
<th>Number of Tailings Dam Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Active Dams</td>
</tr>
<tr>
<td>Overtopping</td>
<td>20</td>
</tr>
<tr>
<td>Slope instability</td>
<td>30</td>
</tr>
<tr>
<td>Earthquake</td>
<td>18</td>
</tr>
<tr>
<td>Foundation failure</td>
<td>11</td>
</tr>
<tr>
<td>Seepage and internal erosion</td>
<td>10</td>
</tr>
<tr>
<td>Structural failure</td>
<td>12</td>
</tr>
<tr>
<td>Erosion</td>
<td>3</td>
</tr>
<tr>
<td>Mine subsidence</td>
<td>3</td>
</tr>
<tr>
<td>Unknown</td>
<td>15</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td><strong>122</strong></td>
</tr>
</tbody>
</table>

Source: Data presented for 135 tailings dam failures for which causes were reported from 1917 to 2000 in ICOLD (2001)

In the study of Chilean sand tailings dams (Villavicencio et al, 2014) the dominant failure mechanisms were liquefaction (due to earthquakes), slope instability (with seismic induced deformations) and overtopping.

The following sections provide a description of five of the most common failure modes in Table 2.1: overtopping and overflowing, slope instability, earthquakes, foundation failure and seepage and internal erosion. Other failure modes identified in Table 2.1 are:

- Structural failure, due to design errors or failure of a designed component to function as designed. Failed decants (which drain water from the impoundments) are a common example;
- External erosion, erosion of a dam face, typically due to precipitation runoff that is not repaired. It could be in the form of local runoff on a mitre that results in erosion on the upstream or downstream side;
- Mine subsidence: when the dam or impoundment is built above an underground mine, collapse of the underground mine workings can lead to release of the impounding tailings;
- Unknown: Many of the older dam failures that were not sufficiently reported and documented may fall into this category. Similarly those that have recently occurred the cause of failure is still under investigation.
2.3.1 Overtopping and overflowing
In the context of reliability analysis of structures, overflowing (Figure 2.1) is the term referring to sustained overtopping over the crest of the dam due to water level increase behind the dam (in the reservoir). Water level increase until exceeding the dam crest can be caused by crest erosion, crest subsidence, poor management or major climatic events such as heavy rainfall.

Overtopping is the action of the waves washing over the crest of the dam. Overtopping from waves normally results from strong wind, landslide into the reservoir or design errors.

In general, sustained overtopping (or overflow) results in more catastrophic failure than wave overtopping. Overtopping is the primary cause for inactive tailings dam failure accounting for 80% of the recorded known cases. (Table 2.1)

![Schematic diagram of overflowing and wave overtopping](source: HR Wallingford, 2018)

2.3.2 Slope instability
Static slope instability failure occurs when shear stresses in a dam exceed the shear resistance of the dam material, most frequently resulting in a rotational or sliding failure of a portion of the downstream slope, leading to overtopping or breaching of the dam.

The shear stress of tailings increases as the density of the tailings also increases. Higher density can occur by densification, natural evaporation and consolidation after deposition. Over-consolidated tailings have lower void ratio and thus, their volume can increase with increasing shear. Compaction of tailings after deposition has a large influence on the stability of embankment slope. In the case of dewatered tailings, compaction can easily occur as the dam raises (due to deposition of new material) and therefore, the likelihood of static slope stability for dewatered, especially filtered tailings, will be lower than for slurry tailings.

The location of the phreatic surface (water level surface) in a tailings dam is also an important factor for static slope instability as pore pressure increases when phreatic surface rises. Resistance to shear failure decreases with higher pore pressures.

Table 2.1 shows that failures resulting from slope instability are higher in active tailings dams than in inactive ones. This suggests that the stability of tailings dams and impoundments may increase with time, as dewatering and consolidation of tailings occurs but additional loads are no longer applied.

Failures due to slope instability however, do still occur after operation. For example, the Gull Bridge Mine in Newfoundland, Canada, was rehabilitated in 1999 and in 2010, an inspection found that the tailings dam at the closed mine was deteriorating (Stantec Consulting 2011), and in 2012 the dam failed, leaving a 50 m gap the height of the dam (Fitzpatrick 2012).
2.3.3 Earthquake
Seismic events can cause:

- soil liquefaction: it is the excess pore-water pressures happening during a seismic event which in turn reduces the shear strength to almost zero. This type of failure is characterized by the short period of time that it takes (of the order of few minutes) and the large deformation of the tailings mass (Villavicencio et al, 2014)

- slope instability: even in the absence of sufficient high pore pressures to trigger liquefaction, dynamic stresses may result in slope instabilities

- seismic induced deformations: which may cause fissures that could compromise the retaining function of the dam or settlements of embankments, or may reduce crest elevation and therefore, the available freeboard, triggering overtopping.

Dams built by the upstream method and sandy dams are particularly susceptible to damage by earthquake shaking. Seed (1979) states that no failures have been reported in dams built of clayey soils even under strong earthquake conditions, and that all cases of slope failure reported have involved sandy soils.

One of the most well-known cases of tailings dam failure due to earthquake action is the Barahona Dam in Chile in 1929. On 1st December 1928 a magnitude 8.3 earthquake (that became known as the Talca Earthquake) struck the central zone of Chile. Located approximately 180 km from the epicentre, the Barahona tailings breached. The resultant flow of liquefied tailings sped down the courses of Barahona Creek and the Cachapoal River, leaving a trail of destruction in its path. Entire settlements were destroyed and 54 people lost their lives. An eye witness describing the event stated that ‘the dam stood during the occurrence of the earthquake and failed suddenly 2 or 3 minute after the end of ground motion’ (Troncoso et al., 1993). This incident helped to improve the general understanding of the potential for static and dynamic liquefaction of tailings materials.

2.3.4 Foundation failure
Foundation failure can occur if the soil or rock at shallow depth below the dam is too weak to support the dam. In that case, movement along a failure plane will occur, which can result in:

- the opening of joints in the foundation or damage to cut-offs, which creates seepage paths
- changes in relative levels of dams and appurtenant structures that cause them not to operate as designed
- differential settlement if the mining extraction is uneven or protection pillars are not large enough.

2.3.5 Seepage and internal erosion
Internal erosion is a mechanical process which occurs when soil particles within an embankment dam or its foundation are carried downstream by seepage flows. The process of internal erosion can be broken into four phases: initiation, continuation, progression to form an erosion pipe and initiation of a breach.

Internal erosion may lead directly to failure under constant loads or may weaken the dam to such an extent that it fails rapidly when subject to a change in external loads.

Potential failure modes for internal erosion can be classified into general categories with respect to the physical location of the internal erosion pathway. Internal erosion can take place in an embankment, foundation or contact area between embankment and foundation. In any case, the hydraulic gradient and specific material characteristics such as plasticity and particle graduation play a critical role.
Despite recent research, the physical mechanisms controlling initiation and the rate of development of internal threats are still not fully understood, but are believed to be controlled by material susceptibility, critical hydraulic load and critical stress condition (Figure 2.2).

**Figure 2.2: Venn diagram illustrating interaction of geometric, hydraulic and mechanical susceptibilities of soils to initiation of internal erosion**

Source: Garner and Fannin (2010)

Material susceptibility and hydraulic load relate to the hydraulic gradients and seepage velocities present in the embankment or foundation and whether they are sufficient to induce particle movement. The critical stress condition is related to the capacity to resist internal erosion depending on the magnitude of the effective stresses, recognizing that stresses vary spatially and/or temporally within the body of the dam.

Even if internal erosion initiates, it will not progress as long as the tailings dam has adequate filter layers designed with appropriate criteria. Without adequate filters, the probability of progression is virtually certain.

### 2.4 Consequences and impacts

Tailing dams can pose a threat to human health and the environment due to the presence of toxic substances such as arsenic, cyanide or heavy metals in the tailings. The release of these materials into the river systems increases concentrations of contaminants for many years. The rate of decline of contaminants varies as a function of the particular contaminant with arsenic, cadmium and lead declining at a faster rate than copper, manganese and zinc for example.

The presence of sulphides in the tailings exposed to oxygen and water causes the generation of sulphuric acid, known as Acid Mine Drainage (AMD) which can mobilise heavy metals and arsenic. AMD is recognised as one of the more serious environmental problems in the mining industry (Akcil and Koldas, 2006). Many old and abandoned TSFs were not designed, constructed or operated with an awareness of the environmental impacts of AMD and no provisions were made to minimise the generation of acid leachate or to prevent the leachate from entering the groundwater or surface waters.

Loss of life may happen during the first stages of a tailings dam failure as a result of drowning and suffocation. In the medium and long term, loss of life is related to the toxicity of the released materials during the failure that may enter the food chain and pollute water sources.
The impacts of tailings dams on fish and terrestrial animals are a combination of burial, direct impacts, mud blocking the gills and extreme changes in water chemistry. In general, after a tailings spill the pH of water decreases to very acid values.

The impacts on vegetation and arable crops are related to the concentration increase of contaminant elements in the floodplains, which are, in general, the fertile environments supporting animal husbandry and crop production.

River dynamics can have a major role in the rehabilitation of mining-affected catchments. Kossoff et al (2014) reports that the high sediment load and aggradation trends of the Pilcomayo river helped to dilute and store contaminants while failures in other more dry environments, such as the Aznalcollar failure in the Guadiamar river in Spain, still showed high rates of contamination in certain areas 10 years after the spill. In some catchments there is a potential of flow remobilization of historical contaminants already deposited in the area. Besides, flood events including bank erosion can remobilise contaminants from historically polluted floodplain sediments without the occurrence of a dam failure.

Table 2.3 provides a summary of the consequences documented in some of the more relevant tailings dam failures. These just provide a snapshot, reflecting the scale of the catastrophe, using the information available. More detailed information on consequences and impacts of failures is provided in the case studies compiled in Chapter 5.

Categorising the impacts of failures is subjective and the line between a serious failure and very serious failure, for example, is not clearly defined. Bowker and Chambers (2015) defined serious failures as ‘having a release of greater than 100,000 m$^3$ and/or loss of life’ and very serious failures as ‘having a release of at least 1 million m$^3$, and/or a release that travelled 20 km or more, and/or multiple deaths (generally ≥20)’.

Other definitions exist relating to the environmental impact of incidents. According to the US Office of Environmental Enforcement, environmental incidents are classified based on their effect or potential to impact on the environment (Table 2.2) (EPA US Office of Environmental Enforcement, 2016).

Table 2.2: Environmental Impact Assessment Criteria

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Classification</th>
<th>Impact on the environment</th>
</tr>
</thead>
</table>
| 1       | Minor          | ■ No contamination, localised effects  
|         |                | ■ Minor effect on air quality as evidenced by dust or odour complaint(s)  
|         |                | ■ ELV breaches  
|         |                | ■ An emission which does not comply with the requirement of the licence/COA (A pattern of repeated minor incidents should be taken into account when considering the level of response)  |
| 2       | Limited        | ■ Simple contamination, localised effects of short duration  
|         |                | ■ Local limited impact to water, land and air  
|         |                | ■ Notification to and short term closure of potable water extractors required  |
| 3       | Serious        | ■ Simple contamination, widespread effects of extended duration  
|         |                | ■ Significant effects on water quality  
|         |                | ■ Major damage to an ecosystem (e.g. significant impact on fish population)  
|         |                | ■ Longer term closure of potable water extractors  
|         |                | ■ Significant reduction in amenity value  
|         |                | ■ Significant damage to agriculture or commerce  
|         |                | ■ Significant impact on man  |
| 4       | Very serious   | ■ Heavy contamination, localised effects of extended duration  |
| 5       | Catastrophic   | ■ Very heavy contamination, widespread effects of extended duration  |

Bowker and Chambers (2015) analysed the trends in severity of TSF failures, using data from 1940 to 2010 and they found that there has been a clear increase in serious and very serious failures since 1980 (Figure 2.3).

Figure 2.3: Increasing severity of TSF failures globally 1940-2010
Source: Bowker and Chambers (2015)

Analysing historic mining metric indicators such as production costs and prices of various metals, Bowker and Chambers (2015) developed a correlation between these indicators and failure severity, enabling an estimation of projected future failures. The results forecast that if the present mining metric ‘driven by continuously lower grades in identified resources and continuously falling real prices of most metals’ continues, serious and very serious failures of TSF dams will also continue to rise.
### Table 2.3: Summary of impacts from some of the main tailings dam failures

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
<th>Waste/water released</th>
<th>Recorded impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 2018</td>
<td>Cieneguita mine, Urique, Chihuahua, Mexico</td>
<td>249,000 m³ of tailings and 190,000 m³ of embankment material</td>
<td>Tailings travelled 29 km downstream and were deposited along the course of the Cañitas River. Water in river turned white. Five workers were killed, several wounded, and four were reported missing. Machinery and vehicles damaged.</td>
</tr>
<tr>
<td>November 2015</td>
<td>Germano mine, Bento Rodrigues, distrito de Mariana, MG, Brazil</td>
<td>33 million m² of iron ore tailings slurry</td>
<td>Over 663 km of waterways polluted: North Gualaxo River, Carmel River and Rio Doce. 15 km² of land along the rivers smothered by slurry. Slurry reached Atlantic coast about a week later. 11 tonnes fish killed; 1,469 ha riparian forest destroyed; riverbed shallowed/dried out; increased turbidity of waterways; changes to water pH and temperature. Town of Bento Rodrigues flooded by wave of slurry, 158 homes destroyed, 19 people killed; 600 residents displaced; water supply disrupted for more than 400,000 people. Traditional livelihoods severely affected; fisheries, agriculture, tourism and freshwater resources disrupted. Interruption of mining activity affects economies of 37 villages/cities; possible increase in human exposure to heavy metals. Colonial monuments destroyed. Disruption of mining production; loss of tax revenue; cost of emergency services; loss of power generation; damage to infrastructure/property; harm to fishing and agricultural activities; harm to tourism; unemployment. Estimated micro-regional damages to infrastructure and public/private losses of BRL250 million (~ US$70 million) (Mariana, Barra Longa and Santa Cruz do Escalvado); BRL200 million (~ US$55 million) (industry/services sector Belo Oriente).</td>
</tr>
<tr>
<td>August 2014</td>
<td>Mount. Polley mine, near Likely, BC, Canada</td>
<td>7.3 million m³ of tailings, 10.6 million m³ of water, and 6.5 million m³ of interstitial water (containing arsenic, copper, nickel, lead)</td>
<td>Tailings flowed into adjacent Polley Lake, through Hazeltine Creek, into Quesnel Lake (Mitchell Bay). Increases in Quesnel Lake in conductivity and temperature; creation of high-turbidity layer persisting until early 2015; bioaccumulation of toxins. Drinking water quality affected for 300 residents; (restrictions in place); Quesnel Lake is an important commercial, recreational and aboriginal fishery; Chinook salmon fishery temporarily closed; long-term impact on fisheries and drinking water; social impacts of unemployment and loss of livelihood/income. At least 120 people made redundant. Other livelihoods indirectly affected by mine closure. Clean-up costs estimated at $31.5 million</td>
</tr>
<tr>
<td>September 2008</td>
<td>Taoshi, Linfen City, Xiangfen county, Shanxi, China</td>
<td>A mudslide several metres high was created.</td>
<td>The mud buried a market, several homes and a three-storey building. At least 254 people were killed and 35 injured.</td>
</tr>
<tr>
<td>Date</td>
<td>Event</td>
<td>Wastewater released</td>
<td>Recorded Impacts</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------</td>
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<td>----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>January 2007</td>
<td>Miraí, Minas Gerais, Brazil</td>
<td>2 million m$^3$ of mud and clay (&quot;red mud&quot;)</td>
<td>Environmental: Spill contained arsenic, mercury, lead, copper and chromium. 40 km of rivers turned an iridescent black. Fish killed in Tug Fork of the Big Sandy River. Social: Slurry released into Vassara River (tributary of Lina). Fears that salmon reproduction may be disturbed due to depleted oxygen levels. Economic: Drinking water intakes had to be closed in some towns along the Tug.</td>
</tr>
<tr>
<td>October 2001</td>
<td>Inez, Martin County Corp., Kentucky, USA.</td>
<td>950,000 million m$^3$ water / 118,500 m$^3$ coal waste slurry into local streams</td>
<td>Environmental: Spill contained arsenic, mercury, lead, copper and chromium. 40 km of rivers turned an iridescent black. Fish killed in Tug Fork of the Big Sandy River. Social: Slurry released into Vassara River (tributary of Lina). Fears that salmon reproduction may be disturbed due to depleted oxygen levels. Economic: Drinking water intakes had to be closed in some towns along the Tug.</td>
</tr>
<tr>
<td>September 2000</td>
<td>Aitik mine, Gallivare, Sweden.</td>
<td>1.8 million m$^3$ of liquid</td>
<td>Environmental: Slurry released into Vassara River (tributary of Lina). Fears that salmon reproduction may be disturbed due to depleted oxygen levels. Social: Slurry released into Vassara River (tributary of Lina). Fears that salmon reproduction may be disturbed due to depleted oxygen levels. Economic: Drinking water intakes had to be closed in some towns along the Tug.</td>
</tr>
<tr>
<td>March 2000</td>
<td>Borsa, Romania.</td>
<td>22,000 t tailings contaminated by heavy metals</td>
<td>Environmental: Protection of the Vaser stream, tributary of the Tisza River. Social: Contamination of the Vaser stream, tributary of the Tisza River. Economic: Contamination of the Vaser stream, tributary of the Tisza River.</td>
</tr>
<tr>
<td>Jan 2000</td>
<td>Baia Mare, Romania.</td>
<td>22,000 t tailings contaminated by heavy metals</td>
<td>Environmental: Protection of the Vaser stream, tributary of the Tisza River. Social: Contamination of the Vaser stream, tributary of the Tisza River. Economic: Contamination of the Vaser stream, tributary of the Tisza River.</td>
</tr>
<tr>
<td>April 1999</td>
<td>Placer, Surigao del Norte, Philippines.</td>
<td>700,000 t cyanide-contaminated tailings</td>
<td>Environmental: Protection of the Vaser stream, tributary of the Tisza River. Social: Contamination of the Vaser stream, tributary of the Tisza River. Economic: Contamination of the Vaser stream, tributary of the Tisza River.</td>
</tr>
<tr>
<td>December 1998</td>
<td>Huelva, Spain.</td>
<td>50,000 m$^3$ acidic and toxic water (phosphoric acid)</td>
<td>Environmental: Fertilizer company that owned mine fined €240,400. Social: Discharged into Ria de Huelva (part of tidal estuary). Economic: Fertilizer company that owned mine fined €240,400.</td>
</tr>
</tbody>
</table>
### Date | Event | Environmental | Recorded impacts | Economic
--- | --- | --- | --- | ---
April 1998 | Los Frailes, Spain. | Thousands of hectares affected. Nothing survived because of the high acidity of the waste. Fish and wildlife disappeared. | Thousands of hectares of farmland covered with slurry. (One commune alone lost 500 hectares). 250 farmers estimated to have "lost everything". | Clean up cost > €272 million (local government and Environment Ministry fund). The total cost of the disaster, up to May 2002, was estimated at €377.7 million. (Including €96 million that the mine operator spent on the clean-up of the spill and the cessation of mining activity during 1998). |
October 1997 | Pinto Valley, Arizona, USA. | 4.5 million m$^3$ toxic slurry water and slurry (including pyrite, lead, copper, zinc, cadmium and other metals, along with sulphide tailings) released | Tailing flow covered 16 hectares, including Tonto National Forest. Fish kill in Pinto Creek. | Tailings flow covered 16 hectares, including Tonto National Forest. Fish kill in Pinto Creek. |
August 1996 | El Porco, Bolivia. | 230,000 m$^3$ tailings and mine rock flowed into Pinto Creek. | Tailings flow covered 16 hectares, including Tonto National Forest. Fish kill in Pinto Creek. | Tailings flow covered 16 hectares, including Tonto National Forest. Fish kill in Pinto Creek. |
March 1996 | Marcopper, Philippines. | 4.2 million m$^3$ cyanide slurry | 12 killed. 14 vehicles lost. | 12 killed. 14 vehicles lost. |
September 1995 | Placer, Surigao del Norte, Philippines. | 50,000 m$^3$ Coastal pollution. Fish kill reported in Placer Bay. | 80 km of Essequibo River declared environmental disaster zone. The sludge destroyed fish and animal life in the close vicinity of the dam and contaminated drinking holes for animals in the forest. | 80 km of Essequibo River declared environmental disaster zone. The sludge destroyed fish and animal life in the close vicinity of the dam and contaminated drinking holes for animals in the forest. |
August 1995 | Omai, Guyana. | 2.5 million m$^3$ cyanide slurry | Drinking supplies contaminated. Mining supplies contaminated. | Drinking supplies contaminated. Mining supplies contaminated. |

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A review of the risks posed by the failure of tailings dams | 15
<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
<th>Waste/water released</th>
<th>Recorded impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>February 1994</td>
<td>Harmony, Merriespruit, South Africa.</td>
<td>500,000 m³ slurry</td>
<td>Flowed 4 km downstream. 17 people killed, extensive damage to residential township. 80 houses destroyed, 200 houses severely damaged.</td>
</tr>
<tr>
<td>July 1985</td>
<td>Stava, Italy</td>
<td>180,000 m³ tailing (sand, slime and water) plus a further 40,000 to 50,000 m³ from erosion and buildings destroyed by the flow.</td>
<td>A layer between 20 and 40 cm thick covered 435,000 m² over 4.2 km. Flowed up to 8 km downstream. 269 lives lost; 3 hotels, 53 homes, 6 industrial buildings, 8 bridges destroyed. &gt;€155 million</td>
</tr>
<tr>
<td>January 1978</td>
<td>Arcturus, Zimbabwe.</td>
<td>20,000 m³</td>
<td>Flowed 300 m downstream. Extensive siltation to waterway. 1 life lost. 1 injured. 2 pole-and-mud huts destroyed Extensive siltation of rough pasture</td>
</tr>
<tr>
<td>November 1974</td>
<td>Bafokeng, South Africa.</td>
<td>3 million m³ slurry</td>
<td>Flowed 45 km downstream. 12 people killed in a mine shaft inundated by the tailings.</td>
</tr>
<tr>
<td>February 1972</td>
<td>Buffalo Creek, USA.</td>
<td>500,000 m³</td>
<td>Flowed 27 km downstream. 125 lives lost, 1,121 people injured, over 4,000 left homeless., &gt;500 homes destroyed, in addition to 44 mobile homes and 30 businesses. 16 towns affected. Property and highway damage exceeded $65 million.</td>
</tr>
<tr>
<td>September 1970</td>
<td>Mufulira, Zambia.</td>
<td>68,000 m³ into mine workings</td>
<td>89 miners killed</td>
</tr>
</tbody>
</table>
3. Monitoring of tailings dams

3.1 Introduction

Notwithstanding the advances made in the mining sector tailings dams still fail. For example, between 2014 and 2017 there have been seven catastrophic failures significant enough to make international news in Canada (Section 0), Mexico, two in Brazil (Section 5.2), China, USA and Israel (Roche et al., 2017). Therefore, efforts to maintain an oversight of these structures through reliable and up-to-date monitoring techniques is vital to try to reduce their risk of failure.

The objectives of tailings dams instrumentation and monitoring are (ICOLD, 1996):

- continuous checking of the structure’s safety
- checking the assumed properties of the materials
- testing the validity of the design assumptions
- assessment of the calculation methods
- study of the influence of the various parameters on the behaviour of the structure
- collection of data during the construction period to determine the actual properties of the materials in situ and the evaluation of the effect of various factors.

It is not possible to determine the actual level of monitoring used by the mining companies globally however, it appears that most, if not all, the large projects that are still active and operating tailing storage facilities are monitoring them using at least regular visual
inspections. Generally, there is also always some form of in-situ instrumentation monitoring undertaken, which varies from site to site. However, it is probable that a very large number of small operating and non-operating tailings storage facilities (TSFs) are not monitored. A summary review of existing regulations in several countries is presented in section 3.2.

There is a range of methods and technologies available to assist owners of tailings dams to monitor the impoundment and reduce the probability of failure of the dam depending on the type of structure and the cause for potential failures. In most instances, the adopted methods and technologies to monitor large tailings dams are similar to what is used for water storage facilities and include:

- Regular visual inspections
- In-situ or remote measurements
- Dam safety reviews by technical specialists done regularly every year, every few years or following large flood or earthquake events or incidents that may affect dam safety.

Visual inspections and monitoring are paramount to ensure safety of tailings dams. However, the quality of monitoring data is still relying heavily on personnel skills to understand the relation of the observed changes to site-specific failure modes, and to promptly communicate the change.

Measurements and testing of all factors connected with the evaluation of dam stability at every stage of construction and operation and especially, as the final maximum height is approached, is also fundamental. This includes the distribution and zoning of the deposited tailings.

While visual surveillance and in-situ measurements remain paramount to inspect tailings dams, the use of aerial photography and satellite imagery is becoming a reliable and cost-effective method to monitor the way the impoundment is developing and assist with detecting anomalies. Similarly, automated systems for the recording of monitoring data are also becoming very effective, as they assist with potentially reducing reading errors while increasing quality and frequency of data. The use of cloud computing is enabling a range of new applications toward real-time monitoring of tailings dams where monitoring information is being automatically collected remotely and processed in the cloud processing system. When combined with a suitable data processing and alerting system, they can contribute to effectively reduce the risk of dam failure.

It is essential that the information collected from regular visual inspections and available monitoring instrumentation is reviewed by an assessor with sound knowledge of the behaviour of tailings dams. It is also critical that additional visual inspections and instrumentation readings are immediately available when requested, to confirm the nature of the observed changes, assess potential risks and take decisions. Without a robust evaluation process, collected information can be highly counterproductive as it might end up giving to management a false sense of reassurance.

Tailings storage facilities, including tailings dams that are apparently well monitored can still fail without previous notice. This can be explained by a number of reasons related to the quality of monitoring and management. Some of them are:

- Monitoring is not focused on potential failure modes;
- Poor quality monitoring because of poor equipment, poorly trained staff or monitoring is not undertaken because of lack of resources or financial constraints;
- Monitoring is not interpreted by technical specialists and regular independent reviews by appropriate specialists are not undertaken;
- Potential dam safety risks are not escalated to people in the organisation who have authority to act;
- Dam safety concerns are ignored because of financial pressures;
Regulators do not ensure that conditions relating to dam safety are enforced;

Many of the above issues arise because a comprehensive dam safety plan is not in place. A comprehensive dam safety plan ensures that monitoring is focused on potential failure modes, monitoring is undertaken by personnel that are trained and data is interpreted by appropriate technical personnel. The plan also ensures that management procedures are in place that ensure dam safety concerns are escalated to people in the organisation that have responsibility to ensure appropriate actions are undertaken.

Two examples where well monitored tailings dams have failed are presented in chapter 5 (sections 0 and 5.8).

The choice for the right monitoring techniques and instrumentation to use depends on the type of tailings dam and failure modes. However, often this is not the case owing to the lack of understanding of the potential failure modes, insufficient instrumentation installed during construction, limited budgets, non-availability of technology or contractors or negligence. A review of current monitoring techniques is presented in section 3.3.

3.2 Worldwide monitoring frameworks

There are few countries globally that have in place robust guidelines and regulations for monitoring tailings dams. Generally speaking, monitoring of tailings dams is better in western countries. The main reason for this are:

- There are statutory requirements or conditions associated with permits or regulatory approvals that require monitoring and they are enforced by the regulators;
- Large corporations understand the corporate risks of not having in place effective dam safety programmes (of which monitoring is an important part). Dam safety incidents can have distressing reputational effects and negatively impact their share values.

The following sections review how tailings dams are monitored in different countries. The information is extracted from the document ‘Tailings Management Facilities: Legislation, Authorisation, Management, Monitoring and Inspection Practices’, issued by the Finnish Environment Institute (Kreft-Burman et al 2005).

3.2.1 European region

- In Poland tailings dams are outside the scope of the Geological and Mining Law Act. They are regulated mainly by the Construction Law and the Polish Norms (on design and construction). Annual inspections of tailings dams are to be performed, as well as regular inspections should take place at least every five years.
- In Hungary, the mining authority is obliged to perform an annual inspection of tailings dams. According to the Mining Act, the mining company has to appoint an expert called a responsible technical leader to perform weekly inspections.
- In Romania specific regulations on tailings ponds are covered by the law and special orders are issued by the Ministry of Water and Environment Protection and the Ministry of Industry and Resources.
- In the United Kingdom tailings dams are regulated by the Reservoir Act 1975. It applies to tailings dams which still contain water and are capable of holding more than 25,000 m³ of water above natural ground level. Spoil heaps and lagoons of liquid wastes at mines and quarries are subject to the Mines and Quarries (Tips) Act 1969 and the related 1971 regulations, which lay down detailed requirements concerning their stability and safety.
However, no tailings dam guidelines or codes of practice exist. Other laws applicable to tailings management facilities are the Health & Safety at Work Act 1974, the Mines & Quarries (Tips) Act 1969, the Mines & Quarries (Tips) Regulations 1971, the Environment Act 1995 and the Record of refuse deposited on active classified tips, Regulation 14 ‘A’.

- The Swedish dam safety guidelines, which are also applicable to tailings dams, require that all tailings facilities have appropriate instrumentation to register changes, control the operation of the facility, check the stability and evaluate the status of the dam.

- In Finland, the safety surveillance programme of a tailings or other dams is prepared in accordance with the Dam Safety Code of Practice. According to it, the safety surveillance programme includes regular inspections (every five years) by a competent expert, annual inspections (in the intermediate years) by maintenance personnel and surveillance between inspections according to the programme defined in the basic inspections. A safety monitoring programme or its amendments are approved by an authority.

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

3.2.3 Canada
British Colombia (BC) in Canada has guidelines in place which suggest that periodic inspections and reviews, audits, independent checks and comprehensive independent reviews are the main part of the surveillance programme (CDA, 2018).

3.2.4 Australia
In Australia the legislation concerning mining includes the Mining Act and the Mines Safety and Inspection Act. In some cases, additional Acts (Aboriginal Heritage Act, Conservation 9 and Land Management Act, Land Administration Act, Local Government Act, Soil and Land Conservation Act, Wildlife Conservation Acts, Native Title Act) are also adapted. All tailings storage facilities (TSFs) in Western Australia are categorised as a Category 1, 2 or 3 facilities. The TSF categorisation is based on its “hazard rating”, coupled with the maximum embankment height. All TSFs over 15 m in height are considered to be Category 1 facilities, i.e. those requiring the most stringent attention.

3.2.5 South Africa
Mining in South Africa is regulated by the Water Act, 1998, the Minerals Act, 1991 and the Mine Health and Safety Act, 1996. The Department of Minerals and Energy (DME) is responsible for implementing the provisions of the Acts. Government Mining Regulations had come into force in 1976 and they require a minimum freeboard of 0.5 m to be maintained at all situations for a tailings dam, in order to store the 1 in 100 year rainfall occurring without overtopping.

3.2.6 Peru
In Peru, monitoring approaches for tailings dams make use of geotechnical instrumentation with data sent by telemetry. Installed instruments include inclinometers, settlement cells, accelerometers and vibrating wire piezometers. Open wells to monitoring water flows, control of seepage from the dam and water samples are also considered. The situation is very different when it comes to smaller and non-operating tailings storage facilities (TSFs) where there is often little surveillance and nearly no instrumentation monitoring. Further explanations on the regulatory framework in Peru are provide in Chapter 4.
3.3 Current monitoring methods and technologies

As already stated in the introduction, visual inspections (section 3.3.1) and monitoring techniques are paramount to ensure the safety of tailings dams. The use of specific instruments to monitor the performance of a dam is widely used in the case of water storage dams and the same instruments are also often used to monitor tailings dams (ICOLD, 1996).

The International Commission on Large Dams (ICOLD) Tailings Committee is currently working on a new Monitoring and Surveillance Bulletin which will provide a compendium of best practices and guidelines for monitoring tailings dams and ultimately reduce the risk of failures. Table 3.1, courtesy of ICOLD, presents a summary of the most common preventative control monitoring methods and technologies. A description of the most common monitoring methods and technologies is presented in the following sections.

Table 3.1: Common preventative control and monitoring methods

<table>
<thead>
<tr>
<th>Threat/Causes [failure mode]</th>
<th>Parameter to control</th>
<th>Monitoring methods or instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Foundation</strong></td>
<td>Dam design</td>
<td>Site investigation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peer review</td>
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<tr>
<td></td>
<td></td>
<td>External review boards</td>
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<tr>
<td></td>
<td>Deformation</td>
<td>Inclinometers</td>
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<td></td>
<td></td>
<td>Ground penetrating radar (GPR)</td>
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<td></td>
<td>Pore pressure</td>
<td>Piezometers</td>
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<td></td>
<td></td>
<td>Dam Safety Inspection</td>
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<tr>
<td></td>
<td>Static stability – based on design</td>
<td>Peer review</td>
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<tr>
<td></td>
<td></td>
<td>External review boards</td>
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<tr>
<td></td>
<td>Seismic stability – based on design</td>
<td>Dam Safety Reviews</td>
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<tr>
<td></td>
<td></td>
<td>Load cells to measure stress and strain changes</td>
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<tr>
<td><strong>Dam Slope</strong></td>
<td>Material characterization</td>
<td>As-constructed records</td>
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<tr>
<td></td>
<td></td>
<td>Data records</td>
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<tr>
<td></td>
<td></td>
<td>Dam Safety Inspection</td>
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<tr>
<td></td>
<td>Static stability – based on design</td>
<td>Peer review</td>
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<td></td>
<td></td>
<td>External review boards</td>
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<tr>
<td></td>
<td>Seismic stability – based on design</td>
<td>Dam Safety Review</td>
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<tr>
<td></td>
<td>Pore pressure</td>
<td>Piezometers</td>
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<td>Dam Safety Inspection</td>
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<tr>
<td></td>
<td>Deformations</td>
<td>Slope surveys</td>
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<td>Lidar</td>
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<td></td>
<td></td>
<td>Inclinometers,</td>
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<td>Drones</td>
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<td></td>
<td>Satellite images</td>
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<td></td>
<td></td>
<td>Dam Safety Inspection</td>
</tr>
<tr>
<td>Threat/Causes (failure mode)</td>
<td>Parameter to control</td>
<td>Monitoring methods or instrumentation</td>
</tr>
<tr>
<td>------------------------------</td>
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<td>----------------------------------------</td>
</tr>
<tr>
<td><strong>Piping</strong></td>
<td>Limiting hydraulic gradients— based on design</td>
<td>Peer review</td>
</tr>
<tr>
<td></td>
<td>Filter compatibility— based on design</td>
<td>External review boards</td>
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<tr>
<td></td>
<td>QA/QC of filters</td>
<td>Dam Safety Review</td>
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<tr>
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<td>As constructed records</td>
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<tr>
<td><strong>Overtopping</strong></td>
<td>Design criteria</td>
<td>Peer review</td>
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<td>Flood storage capacity— based on design</td>
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<td>Spillway capacity— based on design</td>
<td>Dam Safety Review</td>
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<td></td>
<td>Water levels</td>
<td>Level recorders, cameras</td>
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<tr>
<td></td>
<td>Flows</td>
<td>Cameras</td>
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<tr>
<td></td>
<td></td>
<td>Dam Safety Inspection</td>
</tr>
<tr>
<td><strong>Decant</strong></td>
<td>Decant structure— based on design</td>
<td>Peer review</td>
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<tr>
<td></td>
<td>Operations and maintenance procedures</td>
<td>External review boards</td>
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<td></td>
<td></td>
<td>Dam Safety Review</td>
</tr>
<tr>
<td></td>
<td>Flows</td>
<td>Level recorders, cameras</td>
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<tr>
<td></td>
<td>Deformation</td>
<td>Cameras</td>
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<tr>
<td></td>
<td></td>
<td>Dam Safety Inspection</td>
</tr>
<tr>
<td><strong>Erosion</strong></td>
<td>Erosion controls— based on design</td>
<td>Peer review</td>
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<tr>
<td></td>
<td></td>
<td>External review boards</td>
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<tr>
<td></td>
<td></td>
<td>Dam Safety Review</td>
</tr>
<tr>
<td></td>
<td>Inspection and maintenance</td>
<td>Dam Safety Inspection</td>
</tr>
<tr>
<td><strong>Geohazards</strong></td>
<td>Geohazard controls— based on design</td>
<td>Peer review</td>
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<td></td>
<td>Slopes</td>
<td>External review boards</td>
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<td></td>
<td>Snowpack</td>
<td>Dam Safety Review</td>
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<tr>
<td></td>
<td>Deformations</td>
<td>Level recorders, cameras</td>
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<tr>
<td></td>
<td></td>
<td>Cameras</td>
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<td></td>
<td></td>
<td>Dam Safety Inspection</td>
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<tr>
<td><strong>Water Contamination</strong></td>
<td>Waste and water characterization</td>
<td>Peer review</td>
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<tr>
<td></td>
<td>Seepage controls— based on design</td>
<td>External review boards</td>
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<td></td>
<td>Filters for ARD precipitates— based on design</td>
<td>Dam Safety Review</td>
</tr>
<tr>
<td></td>
<td>Water quality</td>
<td>Peer Review</td>
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<td></td>
<td></td>
<td>Real time sensors, e.g. pH, EC, Neutron probes</td>
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<td>Lysimeters</td>
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<td>Sampling and testing</td>
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<tr>
<td></td>
<td>Water flows</td>
<td>Stream gauges</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seepage collection weirs</td>
</tr>
</tbody>
</table>

Source: Courtesy of ICOLD Tailings Committee, adapted from Table 8.1 in ICOLD (2007)
While the use of monitoring instruments in the mining sector is increasing, the use of critical controls and trigger action response plans is required if the risk of failure is to be effectively reduced. The collection of quality data is also an essential requisite for dam safety professionals to be able to review dam performance and undertake calibration of critical controls.

The main factors directly influencing the actual security of the dam are (ICOLD, 1996):

- Seepage discharge through the dam itself, through the foundation and abutments;
- Position of the phreatic surface and any danger that it might emerge on the slope;
- Pore pressure;
- Seismicity and induced dynamic pore pressure
- Horizontal and vertical movement of the starter dam crest and of the down-stream slope;
- Amount that the dam crest is above pond water level (freeboard);
- Beach width, which should be as large as possible;
- All tailings placement procedures;

Therefore, the instruments that are mostly used to monitor tailings dams target the following parameters: seepage, phreatic surface, pore-water pressure, seismicity and dynamic pore pressure and deformations. These instruments are briefly discussed in the following sections. More details about the importance of these parameters in failure mechanisms is provided in section 2.3.

Regardless of the type of instruments, their durability is critical, not only owing to the changing nature of tailings dams, but also due to the presence of strong chemicals, which requires all parts of instruments to be resistant to chemical attack.

### 3.3.1 Visual inspections

Visual inspections consist of undertaking visual reconnaissance, via personnel site inspections or with the use of drones or satellite images, on a continual or periodic basis, to check for early indicators of potential failure modes.

It is paramount that the personnel undertaking the inspections of tailings dams have received sufficient training and are able to relate any observed changes to site-specific identified failure modes. Ongoing reviews of potential failure modes is also exceptionally important since conditions of the dam and the loadings to which the dam is subjected are constantly changing.

Owners of tailings dams often rely on external consultants for ongoing advice, and undertaking visual inspections is only one of the many duties for operational staff. The situation is different in the case of water storage dams, where there is a well-established dam safety culture and surveillance is undertaken by proficiently trained personnel, and changes are promptly notified to dedicated dam safety engineers who are trained to make quick decisions on their significance. This approach provides continuity of advice and clear communications.

### 3.3.2 Seepage monitoring

A close monitoring of seepage flows is essential, together with the presence of a good drainage system, to reduce pore pressures and decrease the risk of failure.

Similar to water storage dams, known seepage points from tailings dams are generally individually collected, as this provides a good indicator of common failure modes such as internal erosion. Discharges are measured with the use of monitoring weirs. Automatic systems are also available, which provide increased quality and frequency of data and allow for better interpretation of dam behaviour in case of abnormalities.
Recorded measured flows also provide a means of monitoring dangerous contaminants entering the water bodies downstream of the dam.

The use of electric resistivity surveys has proven successful in water storage dams to assist with defining the water table, detecting seepage zones, and identifying potential heterogeneous conditions. These methods are becoming common also for tailings dams, especially to monitor the conditions and time changes of the condition. In particular, geophysical investigations can be used to detect seasonal resistivity variations in the tailings dams which can be assessed against water table fluctuations and pattern of observed seepages.

To be more effective, measurements can be repeated with constant time interval to determine changes and identification of possible leakage zones, depending on electrical properties of the filling materials and the environment of the dam (Mainali, 2006).

3.3.3 Phreatic surface monitoring

Keeping a low phreatic surface level is of crucial importance for the stability of tailings dams. The most commonly used instruments for measuring the phreatic level are open standpipe piezometers, which can be read manually or automatically. Installation of these instruments in tailings dams is not as straightforward as it is in the case of water storage dams. Piezometers that do not reach the foundation tend to settle, and regular assessments are required to check the elevation of the bottom end and to ensure the screening zone is still functioning. The installation of new standpipe piezometers is also often required, especially to follow the ongoing increase of dam height.

The inner diameter of standpipe piezometers varies depending on the location of the instrument. Generally smaller diameters are used in instances with finer and less permeable materials, or where the phreatic surface varies rapidly. Closed piezometers can also be used to determine the phreatic surface, however they tend to require more maintenance than standpipe piezometers which remain the preferred option, as long as they can be easily accessed. To increase data quality and frequency, automation can be easily achieved with the use pressure transducers installed inside the piezometric tubes.

3.3.4 Pore pressure monitoring

Pore pressure monitoring is also critical for tailings dam, especially in the presence of poor drainage. Pore pressure is also generally measured with the use of standpipe piezometers, by reading the water level. When pressures are too high, for example in the inner part of the tailings dams, the tubes are capped, and gauges are installed to read the pressure. This arrangement can be easily automated.

In case of existing high pressures, different types of piezometers can be used, including electrical resistance, vibrating wire, pneumatic and hydraulic. All of these systems are ideal to read pressures remotely, and to provide a reliable means of monitoring. In some cases, especially with upstream tailings dams, the use of piezometers to monitor pore pressure can be ineffective, and often this method fails to predict failures, such as static liquefaction. Furthermore, these instruments tend to be more problematic when maintenance is required. Generally, vibrating wires are preferable as they are more robust and not as susceptible to electrical disturbance like in the case of electrical resistances. Vibrating wire piezometers are also widely used to measure dynamic pore pressure, which is of critical importance in case of seismic events, due to the rapid response they are able to offer.

Table 3.2, courtesy of ICOLD, presents a summary of the most common preventative control monitoring methods and technologies for pore pressure monitoring.
Table 3.2: Monitoring instrumentation for pore pressures or moisture changes (from ICOLD, internal communication)

<table>
<thead>
<tr>
<th>Equipment Measuring Device and Methods</th>
<th>Parameters Measured</th>
<th>Application</th>
<th>Research / Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric piezometers with telemetry to process plant or phone</td>
<td>Pore pressure and temperature</td>
<td>Monitor pore pressure changes due to loading and changes in hydrogeological conditions.</td>
<td>Standard practice at many mines. Strings at multiple depths is preferred.</td>
</tr>
<tr>
<td>TDR, Neutron Probes</td>
<td>Saturations levels and temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self Potential</td>
<td>Passive electrical method which is sensitive to the flow of seepage water.</td>
<td>Electrodes are placed on the dam surface both for investigation and monitoring.</td>
<td>Research and long-term field measurements have been performed especially in US, Canada, France and Sweden.</td>
</tr>
<tr>
<td>Distributed Fibre Optic sensing</td>
<td>Temperature and strain are measured in optical fibres using laser light.</td>
<td>Cables are installed in new or old dams for seepage evaluation using temperature and strain analyses to assess movements.</td>
<td>Basic research since 1996 in Germany and Sweden. Further research especially in France, Austria, the Netherlands, UK and US. Challenges are calibrating measurements to site conditions.</td>
</tr>
</tbody>
</table>

3.3.5 Seismicity and dynamic pore pressure

In seismic regions, large tailings dams can be monitored with “strong motion accelerographs” to register earthquakes above a certain given threshold. Two of three accelerographs should be used as a minimum. They provide the data needed for calibrating seismic models and calculating the earthquake response of the dam as construction advances.

Liquefaction may occur when dynamic pore pressure is very high and the effective stresses are reduced to zero. To monitor dynamic pore pressure, vibrating wire piezometers, which have a rapid response, can be used.

3.3.6 Monitoring of deformation

For tailings dams, most surfaces are not to be considered as permanent. Vertical movements, which are often significant, are due to compaction from the weight of the material and consolidation. Sudden changes in vertical movements could be an indicator of a failure mode, including internal erosion.

External vertical movements are usually measured with the use of Global Positioning System (GPS) via a survey network consisting of:

- A control network of geodetic datum points independent from the dam;
- A network of geodetic points typically located along the crest of the dam and on its berms.

Internal vertical movements can also be measured, in terms of differential settlements within the embankment, with the use of electromagnetic probes deployed within standpipes equipped with stainless steel plates or rings.

Horizontal movements are mainly caused by non-uniform settlement of the different sections of the dam. External horizontal movements are usually measured with the use of GPS at the same geodetic points that are used for surveying the vertical movements. The use of stereoscopic aerial photography to detect changes is also often adopted.

The use of aerial photography, satellite images and Unmanned Aerial Vehicles (UAVs) is becoming an effective means to monitor vertical and horizontal displacements, as well as the downstream slope of the dam. As for GPS and total stations, ground checkpoints need to be surveyed first.
before assessing the vertical accuracy of the models. The accuracy obtained indicated that UAV-assisted monitoring of tailings dams is sufficiently accurate for supporting management operations, undertaking volume calculations, and for tracking surface displacements in the decimetre range.

In the case of satellite technologies, the accuracy is also suitable for monitoring displacement and is in the order of millimetres. In particular, Permanent Scattered Synthetic Aperture Radar (SAR) Interferometry (PSInSAR) technology works best for hard highly reflective targets, including rock filled dams and tailings dams, whereas the main strength of Intermittent Small Baseline Subset (ISBAS) InSAR technology is that it enables to determine land motion parameters over all land cover classes, urban or rural. For example, over an agricultural site ISBAS would be able to obtain 50 times more points than SAR techniques using the same data.

Table 3.3, courtesy of ICOLD, presents a summary of the most common preventative control monitoring methods and technologies for monitoring deformations.

Table 3.3: Monitoring instrumentation for monitoring deformations (from ICOLD, internal communication)

<table>
<thead>
<tr>
<th>Equipment Measuring Device and Methods</th>
<th>Parameters Measured</th>
<th>Application</th>
<th>Research / Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration Measurements</td>
<td>Dynamic response (modes and frequencies)</td>
<td>Long term monitoring of the integrity of concrete structures</td>
<td>Either forced or natural ambient loads are used for excitation. Change in dynamic response under the same loading conditions indicate changes in the integrity of the structure.</td>
</tr>
<tr>
<td>Borehole Instruments (inclinometers)</td>
<td>Electro-Mechanical devices used to measure deformation</td>
<td>Devices are placed where movements/ tilts may occur</td>
<td>Recent developments allow continuous monitoring both in vertical boreholes as well as longitudinally within the dam.</td>
</tr>
<tr>
<td>Settlement plates</td>
<td>Change in elevation</td>
<td>Monitoring of dam settlement</td>
<td>Common practice at dams sensitive to settlement and to understand the deformation and stress state of the dam.</td>
</tr>
<tr>
<td>Global Navigation Satellite System (GNSS)</td>
<td>Accurate distance measurements between orbits and sensor.</td>
<td>Local monitoring of movements.</td>
<td>Extensive research with improved accuracy for different applications.</td>
</tr>
<tr>
<td>Laser scanning and digital imagery</td>
<td>Accurate distance measurements using laser with high spatial resolution over surfaces.</td>
<td>Provide a three-dimensional geometric model of dam. Deformations can be detected by regular measurements.</td>
<td>Technology continuously improving by lasers, sensors and digital image processing. Method is used in several countries as a normal procedure.</td>
</tr>
</tbody>
</table>

Source: Courtesy of ICOLD Tailings Committee, adapted from ICOLD (2007) Table 8.1
4. Tailings dams in Peru

4.1 Introduction to the mining industry

Peru is a country with a long mining experience. It’s the second world producer of copper, silver and zinc and the first producer of gold, zinc and lead in Latin-America. It also has the world’s largest reserves of silver and the third ones of copper, zinc and molybdenum (MINEM, 2018).

Most of the country is in the Andean mountain range, which extends from south to north along South America. Almost 80% of the water in the country concentrates in the east side of the Andes while 70% of the population lives on the west (or Pacific) side. Mining activities concentrate in the Andean region and in the Amazon basin towards the south of the country (Figure 4.1).

In 2016, the Peruvian mining industry contributed to 12% of GDP, 59% of total country exports and its related taxes represented 22.8% of Government revenues (SNMPE, 2017).

There are approximately 200 metal mines in operation in the country, and thousands of closed, abandoned and illegal mines, which have no state permission meaning no land rights, mining license, exploration or mineral transportation permit. In abandoned mines, acceptable mine closure and reclamation has not taken place or is incomplete. In most cases, mine owners of closed or abandoned mines cannot be found or are financially unable or unwilling to carry out the proper closure and clean-up of the mine site.
Since 2000 and with the contribution of the expansion of mining activities, Peru has come to be seen as one of the world’s leading emerging markets, with a good base of economic stability, low inflation and steady GDP growth. It is the sixth-largest economy in South America, which has enabled the country to reduce unemployment and poverty, and it has even started to be talked of as a potential middle-income country (EY, 2017).

Local governments in mining regions have obtained large rents derived from mining activities as the central government transfers 50% of the taxes levied on mining companies to them (known as the Mining Canon). Despite a decline in poverty, the expansion of mining activities has been accompanied by rising social tensions (Loayza and Rigolini, 2018). According to the Peruvian Ombudsman Office, active social conflicts have tripled in Peru since 2010. Seven out of every ten conflicts are mining-related expressing environmental concerns, mostly about water usage and quality but also related to compensation for land purchases and relocations, perception of unmet commitments or demands for implementation of infrastructure projects not provided by local governments (MINEM, 2018).

MINEM (2018) highlights that two of the main environmental impacts related to the mining industry in Peru are the pollution of rivers and coastal water from municipal and mining wastes and deforestation and habitat destruction by illegal gold mining. For example, Bebbington and Williams (2008) report that every year mining and metallurgy release over 13 billion cubic meters of effluents into Peru’s watercourses. As most of the mining projects are set at the upper reaches of the catchments, in the headwaters, there is an easy transfer of any possible impacts downstream, to the whole catchment. Scourrah (2008) also highlights that although water demand by the mining industry is relatively small in comparison with agriculture (5% compared to 80%), it happens in areas of the
country with water shortage. As example, there are conflicts in Moquegua, in the South of the country, since the 1980s between a mine corporation and the cities of the area for the access of surface and ground water. The conflict ended with a resolution of the International Water Tribunal in The Hague in 1992 against the mining company for irrational use of water in the region.

### 4.2 Context of tailings dams in Peru

Peru has a very specific geology, with topographic, seismic and climatological extremes that make the construction and management of tailing dams a challenge. The likelihood of tailings dams failures is high due to these challenges and because, in most cases, tailings dams were constructed without a proper engineering design or the design did not take into account seismic factors due to lack of knowledge and tools and/or regulatory frameworks, mainly on the environmental side. It should also be noted that was not until the 1960's and 1970's that tailings dams design was developed as a formal engineering discipline (Martin and Davies, 2000).

In Peru, tailings dams and other tailings deposit are considered environmental mining liabilities, “Pasivos ambientales mineròs” in Spanish (PAMs), which are defined as those installations, effluents, emissions, remains or waste deposits produced by mining operations currently abandoned or inactive that can cause a permanent risk to the population, the surrounding ecosystem and the property (based on Article 2 of Law 28271). The types and subtypes of PAMs are detailed in the following table:

<table>
<thead>
<tr>
<th>Table 4.1: Types and subtypes of PAMs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td>Works</td>
</tr>
<tr>
<td>Tailings</td>
</tr>
<tr>
<td>Infrastructure</td>
</tr>
</tbody>
</table>

Source: Extracted from Chavez (2015)

The National Water Authority identified 113 tailings dams in operation in Peru in 2015 as part of its national inventory of operating dams. This figure corresponds to 15% of the total dams identified in the country (MAR&ANA, 2015). OSINERGIM identifies in its interactive map (OSINERGIM, -) 183 tailings deposits. Its current status and the type of tailings based on its percentage of solids is shown in figure below.

![Figure 4.2: Distribution of the 183 tailings deposits (relaveras in Spanish) based on their status (left) and the type of tailings (right). Data from OSINERGIM website](image)

<table>
<thead>
<tr>
<th>Type of tailing (% of solids)</th>
<th>% of Tailings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slurry (35-55%)</td>
<td>52</td>
</tr>
<tr>
<td>Paste (65-75 %)</td>
<td>1</td>
</tr>
<tr>
<td>Filtered (&gt;70%)</td>
<td>9</td>
</tr>
<tr>
<td>Filtered and slurry</td>
<td>2</td>
</tr>
<tr>
<td>Coarse tailings</td>
<td>2</td>
</tr>
<tr>
<td>Mixed</td>
<td>2</td>
</tr>
<tr>
<td>No data</td>
<td>32</td>
</tr>
</tbody>
</table>

Typical raising methods of tailings dams include upstream, downstream and centreline approaches (Kossoff et al 2014) (Figure 2.1).
Upstream tailings dams have been built for over hundreds of years. They are progressively built upstream of the first dam by controlled deposition of tailings materials. Their design has evolved with improved construction practices and a better understanding of the potential for static and dynamic liquefaction of tailings materials following several failures including the well documented case of Barahona tailings dam in Chile in 1928. Upstream tailings are best suited for arid climates where less water is stored in the impoundment, and in non-seismic regions. This type of raising is not allowed in Peru, but they are the most common type because their construction costs are reduced by using tailings as construction material.

In addition, most of the Peruvian mines are located in the upstream areas of the catchments, with steeper slopes and higher risks of mudslides and flash floods, which also threaten the stability of the dams.

### 4.3 Environmental impacts

The largest environmental impacts of PAMs are related to surface and ground water pollution, discharge of polluted sediments and pH reduction, which are related to Acid Mine Drainage (AMD). For example, Scurrah (2008) reports the case of Mantaro River and its tributaries in a main central valley of Peru, an important agricultural area considered the “bread basket” of Lima. A study of water quality determined that most of the tributaries did not meet the World Health Organisation quality standards for acidity, turbidity, lead, cadmium, chromium and arsenic. This meant that rivers were virtually “dead” in terms of life forms, unsuitable for human or animal consumption and posed a threat to agriculture.

Other environmental impacts of PAMs are related to the reduction of soil quality due to pollutants being transported by water or wind, or increase of air pollution due to sediment entrainment. In the example of the Mantato river, Scurrah (2008) reports levels of lead of 1,000 to 3,000 parts per million in soil samples compared to the maximum allowable level of 230. All these impacts have clear influence on human health due to the use of contaminated water supply sources or irrigation water, which also impacts the food chain.

### 4.4 Public bodies

Table 4.2 describes the different authorities involved in legislation, prevention, inspection or law enforcement of mining activities and their responsibilities.
### Table 4.2: Key government and regulatory authorities with their function and responsibilities

<table>
<thead>
<tr>
<th>Authority</th>
<th>Responsibilities</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINEM - Ministerio de Energía y Minas (Ministry of Energy and Mines)</td>
<td>Responsible for writing and approving regulatory policies, as well as promoting sustainable development of mining activities in the country. It performs these functions through two departments:  - La Dirección General de Minería (DGM)  - La Dirección General de Asuntos Ambientales Mineros (DGAAM)  - DREM (Dirección Regional de Minería) is the regional division of MINEM, with representation in Cajamarca.</td>
<td>Legislation</td>
</tr>
<tr>
<td>MINAM - Ministerio del Ambiente (Ministry of the Environment)</td>
<td>Responsible for  - Development and direction of the National Environmental Policy.  - Enforcement of the national environmental legal framework among public and private entities.  - Imposing sanctions in the event of infringement of national environmental laws.  - Directing climate change policies.  - Directing the National System of Natural Protected Areas.  - Elaborating and updating of environmental quality standards (EQSs) and maximum permissible limits (MPLs).  - Directing the National System of EIAs</td>
<td></td>
</tr>
<tr>
<td>OEFA - Organismo de Evaluación y Fiscalización Ambiental (Agency for Environmental Assessments and Enforcement)</td>
<td>Governing institution for environmental evaluation and inspection under the authority of the Ministry of Environment. Responsible for:  - Monitoring and controlling environmental regulations.  - Supervising and verifying compliance with environmental regulations.  - Verifying the performance of national, regional and local environmental regulators.  - Investigating and sanctioning breaches of environmental obligations.  - Implementing the Environmental Inspection Regime.</td>
<td>X</td>
</tr>
<tr>
<td>Authority</td>
<td>Responsibilities</td>
<td>Function</td>
</tr>
<tr>
<td>--------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>OSINERGMIN - Organismo Supervisor de la Inversión en Energía y Minería</td>
<td>National regulatory authority for mining safety under the authority of the Ministry of Energy and Mining.</td>
<td>X X</td>
</tr>
<tr>
<td>(Supervisory Agency for Investment in Energy and Mining)</td>
<td>In charge of supervision of energy and mining sector and responsible for physical stability and safety of tailings dams</td>
<td></td>
</tr>
<tr>
<td>RENAMA - Gerencia Regional de Recursos Naturales y Medio Ambiente</td>
<td>Responsible for environmental management at the regional level formulating, approving, executing, evaluating, directing, controlling and administering the plans and policies in environmental matters, or implementing and controlling the regional environmental management system.</td>
<td>X X</td>
</tr>
<tr>
<td>(Regional department on natural resources and the environment)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FEMA - Fiscalía Especializada En Materia Ambiental</td>
<td>Under the authority of the Ministry of Justice.</td>
<td>X</td>
</tr>
<tr>
<td>(Environmental Prosecuting Authority)</td>
<td>Responsible for investigating environmental incidents from a legal standpoint.</td>
<td></td>
</tr>
<tr>
<td>DGAAM - Dirección General de Asuntos Ambientales Mineros</td>
<td>Department of the MINEM in charge of proposing and evaluation the environmental policies of the mining sector.</td>
<td>X</td>
</tr>
<tr>
<td>(General Directorate of environmental mining issues)</td>
<td>It also promotes the execution of activities oriented to the conservation and protection of the environment related to the development of mining activities.</td>
<td></td>
</tr>
<tr>
<td>ANA - Autoridad Nacional del Agua</td>
<td>National authority of water resources under the authority of the Ministry of Agriculture and Irrigation. Its responsibilities are:</td>
<td>X X</td>
</tr>
<tr>
<td>(National Water Authority)</td>
<td>- Suggesting and approving regulations about the integral management and sustainable use of water resources.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Granting, modifying or extinguishing water rights.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Supervising and evaluating the activities, impacts and fulfilment of the National System of Water Resources Management objectives.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Issuing prior technical opinion about the availability of water resources for hydraulic infrastructure projects.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Managing, supervising, controlling and sanctioning activities to preserve natural water resources and hydraulic infrastructure.</td>
<td></td>
</tr>
<tr>
<td>Activos Mineros S.A.C</td>
<td>Public company responsible for providing environmental remediation in cases of abandoned mines (when the owners cannot be located) and providing services for mine closure for state owned mines.</td>
<td>X</td>
</tr>
<tr>
<td>Authority</td>
<td>Responsibilities</td>
<td>Function</td>
</tr>
<tr>
<td>----------------------------------------------------</td>
<td>----------------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>DIGESA</td>
<td>Inspection authority of water resources quality</td>
<td>X</td>
</tr>
<tr>
<td>INGENMET – Instituto geológico, minero y metalúrgico (Geological, mining and metallurgical Institute)</td>
<td>Responsible for the investigation of mineral resources in Peru and to manage the mining concessions process, including reception and granting of petitions</td>
<td>X</td>
</tr>
<tr>
<td>FONAM – Fondo Nacional del Ambiente (Environmental National Fund)</td>
<td>Institution created in 1997 by the Congress to promote and facilitate funds for the protection of the environment. It carries out studies related to environmental mining liabilities (PAMs)</td>
<td>X</td>
</tr>
</tbody>
</table>

Source: Modified from Table 4.1.3 in Brooks et al (2018)
4.5 Regulatory framework

Under Peruvian law, all natural resources including metal and non-metal minerals are the Nation's property and the State is sovereign over the exploitation of natural resources. The State sets the conditions for its use, grants concessions to individuals and shall promote their sustainable use. Through mining concessions, individuals have the right to explore and exploit the mineral resources of soil, subsurface and sea located within the area granted by the concession. Once extracted, minerals are privately owned by the concessionaires, who in exchange must pay royalties to the State. Marketing, sales prices as well as treatment and refining charges of the extracted mineral products are free and established according to international prices, by supply and demand. The General Directorate of Mining (DGM) grants concessions for medium and large-scale mining. In the case of small-scale mining, concessions are granted by the Regional Directorate of Energy and Mines (DREM).

A regulatory framework to mitigate the environmental negative impacts of mining activities was established in the 1990s and a framework for the closure of mines and environmental liabilities in the early 2000s. Permits and environmental studies required on each stage of the mining process are summarised below.

Table 4.3: Permits and Environmental studies required in each stage of mining

<table>
<thead>
<tr>
<th>Stage</th>
<th>Permits</th>
<th>Environmental studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploration</td>
<td>■ Mining concession is not required but there are some restrictions</td>
<td>■ Environmental impact statement</td>
</tr>
<tr>
<td></td>
<td>■ EIA semi-detailed</td>
<td>■ EIA semi-detailed</td>
</tr>
<tr>
<td>Exploitation / Benefit</td>
<td>■ Mining concession, environmental studies and permits are required for surface and water use.</td>
<td>■ Environmental impact study</td>
</tr>
<tr>
<td></td>
<td>■ Since applying for a mining concession, title holder has a social responsibility, which includes contributing to local sustainable development and</td>
<td>■ Program environmental compliance and management</td>
</tr>
<tr>
<td>Closure</td>
<td>■ Mine closure plan</td>
<td>■ Mine closure plan</td>
</tr>
<tr>
<td></td>
<td>■ Closure plan for mining environmental liabilities</td>
<td>■ Closure plan for mining environmental liabilities</td>
</tr>
</tbody>
</table>

All the regulations related to the PAMS are detailed in Grufides (2015) and are not repeated here. One of the most important laws is the Regulation Law of Environmental mining liabilities Law 28271 (from 2004 and modified in 2005 and 2008) that establishes the mechanisms for identification, responsibility and financing or remediation operations of PAMS and elaboration of Closure Plans.

One of the main problems in Peru, and worldwide, is handling environmental liabilities left unsolved when mining companies abandoned the sites or went bankrupt. The main challenges are related to identifying the responsible of the site and costs and payments of the remediation works.

The Ministry of Energy and Mines (MINEM) developed in 2001 a plan to eliminate environmental mining liabilities and in 2010 designed a methodology to manage those environmental liabilities (PAM) based on four stages:

■ Stage 1: Update of the inventory
  The Ministry of Energy and Mines (MINEM) through the Mining Department (Dirección General de Minería, DGM), is in charge of producing the inventory based on field visits and information provided by mine owners

■ Stage 2: Identification of those responsible for tailings deposits
  Using this inventory, the DGM undertakes an investigation of mining companies
and/or individual responsibilities. Once those who are responsible for the sites are identified, they receive a notification, having a year to sign a contract of remediation and to present a closure plan. In the absence of an identified responsible entity, it is up to the State to carry out site remediation activities.

- **Stage 3: Development of technical studies**
  Whether the responsible is the private owner identified in Stage 2 or it is the Government, who takes ownership of the PAM, technical studies are developed to proceed to the closure of the PAM. Activos Mineros S.A.C is the public company responsible for providing environmental remediation when the State is responsible to carry out those activities, as well as providing mine closure services for state owned mines.

- **Stage 4: Implementation of works**
  This methodology is updated by the Ministry of Energy and Mines (MINEM) in subsequent management plans of PAMs, being the latest the one corresponding to the period 2017-2019.

Since 2006, MINEM updates the National Inventory of PAMs and the latest figure, from 2017, registers 8,794 liabilities in Peru. Based on (MINEM, 2018) 50% of them present very high and high risk. Of the 4,292 very high and high risk liabilities, the State, in its subsidiary role, has intervened from the remediation of 40% of these in the period 2010 to 2014. The total number of active and inactive tailing dams in the country is unknown.

Chavez (2015) states that public information about PAMs is still insufficient as for example, it does not describe the activities associated to each PAM, which ones are being restored, what are their environmental, social and economic impacts, whether they are close or in contact with water sources, etc.

Closure of PAMs is a two stage process:

- **Remediation or closure**: development of activities detailed in the Closure Plan including engineering designs, demolition, field measurements, physical, chemical and hydrological stabilization works, revegetation, rehabilitation and restoration of area and transference of land ownership. The steps to follow for remediation or closure of a PAM are defined in the PAM law as:
  - Identification of mining site owner
  - Presentation of the Closure Plan by the mining site owner
  - Evaluation of the Plan
  - Execution of the Plan and implementation of measures post-closure
  - Certification of Final Closure

- **Post-closure**: maintenance, monitoring and surveillance programme done for the owner of the Closure Plan that needs to be done for at least 5 years after the closure

OEFA is the institution in charge of supervising the activities related to the Closure Plans and to issue the certificate of conformity of termination of activities (after closure and post-closure activities). In 2015 none of the identified PAMs had executed and finished a closure plan (Chavez, 2015). Figure 4.4 shows as example, some of the remediation works undertaken by Activos Mineros S.A.C.
Obligations relating to the continuous monitoring of tailing dams are contained in the environmental management instruments and the environmental certificates approved by DGAAM, the Environmental Department of the MINEM. The law requires mining companies to present a study on the physical stability of the tailings dam every two years. The company is also in charge of informing the authorities of any incident observed in their site, and allowing site access to the controlling bodies at any time.

The community can also participate in the control of mining activities by informing the public bodies of any incident observed. RENAMA, the regional department on natural resources and the environment, when informed of possible incidents, verifies the complaint by traveling to the contaminated areas, taking samples and sharing reports with the bodies in charge of monitoring and sanctions.

OSINERGMIN is the body responsible for controlling the physical and chemical stability of medium and large-sized mines while OEFA controls the environmental impacts of the mining activity and sanctions those responsible for any observed infraction. FEMA is involved when a crime is alleged to have been committed, for example, if mining activities are illegal.
5. Case studies of tailings dams failures

5.1 Introduction

Failure of tailings dams continue to occur despite the available improved technology for the design, construction and operation. There are apparent deficiencies in design, operation and management which are repeated. It has been recognised that a large proportion of recent events implicate operation and management practice rather than poor or inadequate initial design and they can be related to the slow construction of tailings dams that can span many staff changes, changes of plant ownership and exceedance of original design heights.

One of the main well-documented failures in the 20th century is the one at Barahone in Chile, a 61 m high dam built by the upstream method with downstream slopes of 1 in 1. The dam failed during the Talca earthquake of magnitude 8.3, producing a breach 460m wide. The released tailings flowed down the valley killing 54 people. This failure helped to improve construction practices with a better understanding of the potential for static and dynamic liquefaction of tailings materials. Unfortunately, and disturbingly for the industry, records also indicate certain common features amongst the major failures which imply that lessons are not being learnt from the past. The history of engineering failures teaches engineers of all disciplines that we ignore history at our peril.

Reporting of tailings dam failures around the world is highly disparate, being only satisfactory in USA and Europe. The amount of reported information is related to the degree of national regulation.
requirements for reporting incidents. Several investigations have attempted to summarise the causes of major tailings dam failures throughout the world, including the ICOLD Bulletin 121, Tailings Dams: Risk of Dangerous Occurrences (ICOLD, 2001) which provides details of accidents and failures.

There have been a number of notable failures around the world that have led to loss of life, a cost to the environment and valued assets. Table 5.1 gives examples of some of the tailings dams failures around the world. The majority of tailings dams incidents remain unreported, especially in developing countries or in those countries where environmental legislation is, or has been, very lax.

In addition to ICOLDs findings, Figure 5.1, also highlights the discrepancy of distribution of tailings dam incidents by country, indicating that 74% of cases come from a small number of countries. Rico et al (2008) noted the geographical disturbances of their collected cases and identified the lack of or abundance of information from individual countries and the uneven distribution of mine exploitations and corresponding tailing dams.

Table 5.1: Examples of tailings dam failures around the world

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martin County Corporation, Kentucky, USA</td>
<td>October 2001</td>
<td>0.95 million m$^3$ coal waste slurry released into local streams, Fish kill in River Tug and drinking water intake had to be closed.</td>
</tr>
<tr>
<td>Aitik mine, Sweden</td>
<td>September 2000</td>
<td>1.8 million m$^3$ water released.</td>
</tr>
<tr>
<td>Bors, Romania</td>
<td>March 2000</td>
<td>22,000 t tailings contaminated by heavy metals released.</td>
</tr>
<tr>
<td>Baia Mare, Romania</td>
<td>Jan 2000</td>
<td>100,000 m$^3$ cyanide contaminated water with some tailings released.</td>
</tr>
<tr>
<td>Place, surigao del Norte, Philippines</td>
<td>April 1999</td>
<td>700,000t cyanide contaminated tailings released. 17 home buried.</td>
</tr>
<tr>
<td>Haelva, Spain</td>
<td>December 1998</td>
<td>50,000 m$^3$ acidic and toxic water released.</td>
</tr>
<tr>
<td>Aznalcollar, Spain</td>
<td>April 1998</td>
<td>4-5 million m$^3$ toxic water and slurry released.</td>
</tr>
<tr>
<td>Pinto Valley, USA</td>
<td>October 1997</td>
<td>230,000 m$^3$ tailings and mine rock.</td>
</tr>
<tr>
<td>El Poroco, Bolivia</td>
<td>August 1996</td>
<td>400,000 t involved.</td>
</tr>
<tr>
<td>Marcopper, Philippines</td>
<td>March 1996</td>
<td>1.5 million t tailings released.</td>
</tr>
<tr>
<td>Placer, Philippines</td>
<td>September 1995</td>
<td>50,000 m$^3$ released. 12 killed.</td>
</tr>
<tr>
<td>Omai, Guyana</td>
<td>August 1995</td>
<td>4.2 million m$^3$ cyanide slurry released.</td>
</tr>
<tr>
<td>Merriespruit, South Africa</td>
<td>February 1994</td>
<td>500,000 m$^3$ slurry flowed 2km. 17 lives lost.</td>
</tr>
<tr>
<td>Stava, Italy</td>
<td>July 1985</td>
<td>269 lives lost, tailing flowed up to 8km.</td>
</tr>
<tr>
<td>Arcturus, Zimbabwe.</td>
<td>January 1978</td>
<td>1 life lost, 20,000 m$^3$ flowed 300m.</td>
</tr>
<tr>
<td>Bafokeng, South Africa</td>
<td>November 1974</td>
<td>12 deaths. 3 million m$^3$ slurry flowed 45km.</td>
</tr>
<tr>
<td>Buffalo Creek, USA</td>
<td>February 1972</td>
<td>125 lives lost, 500 homes destroyed.</td>
</tr>
<tr>
<td>Mufiliira, Zambia</td>
<td>September 1970</td>
<td>89 deaths. 68,000 m$^3$ into mine workings.</td>
</tr>
<tr>
<td>Hokkaido, Japan</td>
<td>1968</td>
<td>A 12m high dam built by the upstream method with a 1 in 3 downstream slope, failed during the Tokachi-Oki earthquake of magnitude 7.8. 90,000m$^3$ tailings flowed from the breach, crossing and blocking a river near the downstream toe.</td>
</tr>
</tbody>
</table>

Source: (Main) ICOLD Bulletin 121
Relevant failures in Peru are summarised in Table 5.2. Some of the incidents are related to earthquakes, one of the main threats for tailings dams in Peru. Detailed descriptions are presented for some of the of the main and more recent failures of tailing dams in Peru: Amatista mine in 1996 (5.9), Hachocolpa in 2010 (5.10) and two recent cases from 2018 (5.11 and 5.12).

Table 5.2: Summary of tailings dams incidents

<table>
<thead>
<tr>
<th>Mining site</th>
<th>Height (m)</th>
<th>Year</th>
<th>Possible cause of failure</th>
<th>Operating status of mining site</th>
<th>Damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casapalca (Lima)</td>
<td>60</td>
<td>1952</td>
<td>Earthquake</td>
<td>Abandoned</td>
<td>Pollution of Rimac River and several people missing</td>
</tr>
<tr>
<td>Milpo (Pasco)</td>
<td>60</td>
<td>1956</td>
<td>Earthquake</td>
<td>Reconstruction</td>
<td>Road closure (Cerro De Pasco-Huánuco) environment and human damages</td>
</tr>
<tr>
<td>Almivirca (La Libertad)</td>
<td>40</td>
<td>1962</td>
<td>Earthquake (causing liquefaction) / heavy rainfall</td>
<td>Abandoned</td>
<td>Environmental damages, agriculture, livestock and infrastructure</td>
</tr>
<tr>
<td>Marsa mine</td>
<td>-</td>
<td>1963</td>
<td>Overtopping</td>
<td>-</td>
<td>6 casualties</td>
</tr>
<tr>
<td>Yauliyacu (Lima)</td>
<td>80</td>
<td>1968</td>
<td>Earthquake</td>
<td>Abandoned</td>
<td>Pollution of Rimac River, closure of Central Road</td>
</tr>
<tr>
<td>Recuperada Buenaventura</td>
<td>-</td>
<td>1969</td>
<td>Unknown</td>
<td>-</td>
<td>Important pollution. Agricultural damages</td>
</tr>
<tr>
<td>(Huancavelica)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quiruvilca (La Libertad)</td>
<td>40</td>
<td>1970</td>
<td>Earthquake</td>
<td>Abandoned</td>
<td>Pollution of River San Felipe.</td>
</tr>
<tr>
<td>Atacocha (Pasco)</td>
<td>-</td>
<td>1971</td>
<td>Drainage</td>
<td>Abandoned</td>
<td>Pollution of River Huallaga (estimated 100,000 T of tailings)</td>
</tr>
<tr>
<td>Ticapamza / Alizanza</td>
<td>20</td>
<td>1971</td>
<td>Structural and drainage</td>
<td>Abandoned</td>
<td>3 casualties, houses destroyed and interruption of Huaraz-Lima road; release of 9,000 T of tailings</td>
</tr>
<tr>
<td>San Nicolas (Cajamarca)</td>
<td>-</td>
<td>1980</td>
<td>Structural</td>
<td>Abandoned</td>
<td>Pollution of River Tingo (Hualgayoc) and agricultural damages</td>
</tr>
</tbody>
</table>
### Table 5.3: Summary of case studies

<table>
<thead>
<tr>
<th>Dam</th>
<th>Country</th>
<th>Year</th>
<th>Comments</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minas Gerais</td>
<td>Brasil</td>
<td>2015</td>
<td>One of the biggest mining-related accidents in the world with serious</td>
<td>Section 5.2 on page 41</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>environmental and social consequences</td>
<td></td>
</tr>
<tr>
<td>Baia Mare</td>
<td>Romania</td>
<td>2000</td>
<td>Example of overflowing failure and the devastating consequences of cyanide</td>
<td>Section 5.3 on page 43</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>spill</td>
<td></td>
</tr>
<tr>
<td>Merriespruit Virginia</td>
<td>South Africa</td>
<td>1994</td>
<td>Example of slope instability failure and lack of emergency management plans</td>
<td>Section 5.4 on page 45</td>
</tr>
<tr>
<td>Los Frailes</td>
<td>Spain</td>
<td>1998</td>
<td>Example of foundation failure with impacts on a protected natural area</td>
<td>Section 5.5 on page 47</td>
</tr>
<tr>
<td>Val di Stava</td>
<td>Italy</td>
<td>1985</td>
<td>Example of structural incident with a large number of victims</td>
<td>Section 5.6 on page 49</td>
</tr>
<tr>
<td>Mount Polley Dam</td>
<td>Canada</td>
<td>2014</td>
<td>Highlights the importance of increasing the regulations required for a</td>
<td>Section 5.7 on page 52</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>proper design, as well as the need to improve the way information is</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>collected and communicated to management</td>
<td></td>
</tr>
<tr>
<td>Manila mining</td>
<td>Philippines</td>
<td>1995</td>
<td>The same as above</td>
<td>Section 5.8 on page 54</td>
</tr>
<tr>
<td>Amatista-Nazca</td>
<td>Peru</td>
<td>1996</td>
<td></td>
<td>Section 5.9 on page 54</td>
</tr>
<tr>
<td>Caudalosa Chica, Huachocolpa</td>
<td>Peru</td>
<td>2010</td>
<td></td>
<td>Section 5.10 on page 54</td>
</tr>
<tr>
<td>Huanacapati</td>
<td>Peru</td>
<td>2018</td>
<td></td>
<td>Section 5.11 on page 58</td>
</tr>
<tr>
<td>Sulliden Shauindo</td>
<td>Peru</td>
<td>2018</td>
<td></td>
<td>Section 5.12 on page 59</td>
</tr>
</tbody>
</table>
5.2 The Germano mine storage facility failure, Minas Gerais, Brazil, 2015

The main sources of information from this case study are Salinas (2016) and Roche et al. (2017).

The Germano mine, close to the city of Mariana in south eastern Brazil, is one of over 300 mines operating in the so-called “Iron Quadrangle” of the state of Minas Gerais. On 5 November 2015, at around 4 pm, its Fundão dam failed, and approximately 33 Mm$^3$ of mine waste was released down the valley. More than 600 people were working in the Germano complex at the time. Witnesses described having seen ‘the dam dyke moving on its plateau and carrying vehicles that were on it at the same time it collapsed’.

The waste travelled around 650 km through 39 cities, destroying people, buildings, historical heritage, and infrastructure, and causing irreversible environmental damage, along its way to the Atlantic Ocean. The catastrophe is considered by many to be Brazil’s greatest environmental disaster, and one of the biggest mining-related accidents in the world.

Nineteen people lost their lives that day. Hundreds of people were made homeless, hydroelectric power plants were destroyed and water supply cut off for thousands of homes. Indigenous communities were affected by the immense damage to natural resources, and fishing and agricultural activities were banned across affected areas for an indefinite period. The damage to the Rio Doce basin will affect several generations to come.

The wave of mud released from the dam swept downstream rapidly. Thankfully, it was contained temporarily at a second dam, the Santarém dam, to allow most of the community of Bento Rodrigues, 2.5 km further downstream, to evacuate. However, with no alarm system, and warnings being conveyed only by word of mouth, five residents were killed. The town was flooded with mud, up to 10 m high in places, and its road access was completely cut off.

Figure 5.2: Town of Bento Rodrigues after the disaster.
Source: Salinas (2016)

The mud continued for 55 km through the River Gualaxo, then a further 22 km along the Rio do Carno into the Rio Doce. Along these stretches the mud exceeded the capacity of the rivers, thus became most destructive as it flowed out of channel, and destroyed bridges, roads, buildings and infrastructure in the cities of Mariana Barra Longa, Rio Doce and Santa Cruz do Escalvado. There was also strong erosion of the narrow river banks. In Rio Doce, about 30% of the tailings were retained by a hydroelectric plant, where power generation was halted. Between this power plant and another further downstream, sedimentation occurred.
in the Rio Doce, altering the channel’s geomorphology. Further downstream, in the lower reaches of the Rio Doce, turbidity increased significantly in the water, and supplies to 12 cities were cut off for a few days. One indigenous community, the Krenak community, had to be evacuated from their reserve due to the contamination caused by the tailings.

On 11 November the pollution reached the Atlantic Ocean. Peaking on 21 November, the slurry coloured the ocean orange over an area of approximately 7 km$^2$.

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**Figure 5.3: Mud runout map. Numbers are the communities affected in Minas Gerais (beige) and Espírito Santo (pink)**


The social, environmental and economic impacts of the dam failure were tragic. Death, unemployment, destruction of heritage, homelessness, displacement, psychological effects, poor health, disruption to education, and loss of livelihoods are among the many social consequences. Environmentally, water and soil quality in the affected area were severely degraded, natural vegetation was destroyed, water bodies suffered siltation and morphological change, fish and other aquatic organisms were killed and the balance of aquatic ecosystems was disturbed. Economic impacts of events such as these are hard to quantify, as they are multi-faceted, but include clean-up costs, emergency service provision, losses due to disruption of mining activity, loss of tax revenue, loss of hydroelectric power generation, damage to merchants affected by sea of mud, damage to infrastructure, losses in activities dependent on water quality, harm to fisheries, harm to agricultural activity, damage to property, impact on tourism and unemployment. The damages to infrastructure and public/private losses in one region alone (Mariana, Barra Longa and Santa Cruz do Escalvado) were estimated at BRL250 million (~ US$70 million). Total costs would have been in the billions.
5.3  Baia Mare, Romania, 2000

The information of this case study have been extracted from UNECE (2007), ICOLD (2001), Blog NUS (2015), Cunha (2015 and Pitta (2015).

On 30th January 2000, a 30-year-old tailings dam operated by AURUL SA, and located near the residential area of the city of Baia Mare, overflowed. AURUL had only started working on the mine in May 1999, with the intention of processing solid waste from prior mining operations to recover precious metals.

An embankment wall approximately 25 m long and 2.5 m deep collapsed, triggering the release of approximately 100,000 m³ of tailings water (Figure XX) containing an estimated 120 tons of cyanide and heavy metal that flowed into the Lapus River, a tributary of the Szamos River. The release continued for two to three day, until the team was successful in stopping the spill, and the focus could move onto the clean up operation.

The contamination flowed through the Lapus and Szamos Rivers, and onwards into the Tisza and the Danube, upstream of Belgrade. Almost a month after the initial spill, it was detected in the Danube Delta, on its way into the Black Sea. Traveling at 2.1 km/h to 2.4 km/h, the pollution took 14 days to reach Tisza, some 800 km away. Pollution continued for a further 1200 km at 2.4 km/h to 2.9 km/h before entering the Black Sea. The map below illustrates the route of the pollution, and its complex transboundary nature.

![Spread of the cyanide spill from Baia Mare dam](image)

Figure 5.4: Spread of the cyanide spill from Baia Mare dam. Extracted from Blog NUS (2015).

Cyanide is highly reactive and can be fatally toxic to humans. It prevents the body from using oxygen for cellular processes, especially in the heart and brain, which can lead to suffocation. Acute exposure to cyanide can have immediate effects on the heart and brain, leading to sudden collapse, seizure or coma. Although the spill did not result in any human loss of life, the cyanide had devastating consequences for the region’s ecological systems, as well as significant social and economic impacts.
A 30 to 40 km long contaminated pollution plume wiped out aquatic flora and the fauna of the central Tisza River. Acute effects, typical for cyanide, occurred for long stretches of the river system down to the confluence of the Tisza with the Danube: phyto- and zooplankton were down to zero when the cyanide plume passed and fish were killed in the plume or immediately after. Rare and unique species both of flora and of fauna have been endangered (UNECE, 2007).

The impact on aquatic wildlife was widespread. Estimates of the quantity of fish affected vary, but were reported in multiple countries: tonnes of dead fish were reported in Yugoslavia (now Serbia); thousands of tonnes of dead fish estimated in Hungary; smaller numbers reported in Romania. No major fish kills were reported from the Danube. On one stretch of the Tisza, virtually all living species were killed, and further south, in the Serbian section, 80% of the aquatic life was killed. 62 species of fish were affected, 20 of which were protected species.

Heavy metals pose another threat to humans and animals. In the presence of UV light, cyanide can be quickly broken down in water, stabilising heavy metals such as mercury and lead. Bioaccumulation of heavy metals in fish and the subsequent food chain can easily occur, which in this case led to the hospitalisation of children who consumed contaminated fish. Drinking water supplies for more than 2 million Hungarians were contaminated. The impact on the socio-economics of the area was perhaps most severe for the region’s fishermen. Two years after the disaster, fishermen in Hungary were reporting catches at only a fifth of pre-spill levels.

In 2000, the Hungarian government lodged a compensation claim against the mine operator, amounting to US $179 million. The damages however, are thought to be far greater.

Figure 5.5: Baia Mere breach
Source: http://baiamare-romania.blogspot.com/
5.4 Merriespruit Virginia, South Africa, 1994

Information from this case study has been extracted from Wagener (1997), Strydom and Williams (1999), Van Rooyen (1994) and SAWDOS (2013).

Merriespruit tailings dam in the Harmony goldmine complex in Virginia, Free State, was a 31 m high dam constructed just up slope of the township of Merriespruit. Dampness on the downstream slope and some small slips had caused the impoundment to be closed. It continued to be used for the occasional discharge of waste water containing some tailings with the extra tailings slowly pushing the pond further towards the dam and reducing the freeboard.

The movement of the pond was recorded by satellite imagery (by chance a satellite passed over the site on a regular basis) and it was seen that the decant became isolated so that no further discharge could come from the pond.

On the afternoon of 22nd February 1994, an intense thunderstorm and downpour occurred over the goldmine complex: 30 to 55 mm fell in half an hour. Later that evening, dam number 4A failed, and over half a million cubic meters of liquid flowed downhill towards the suburb of Merriespruit. The nearest houses were located 300 m downslope of the dam and were hit by a wave of water and tailings 2.5 m high. Seventeen people lost their lives. The damage to the environment and the township was devastating. Eighty houses were destroyed and 200 severely damaged. The flow was eventually halted more than 2 km downstream of the dam, where it was contained by an ornamental lake. One report stated that the extent of the groundwater contamination following the spill rendered it impossible to clean the entire area.

‘An eyewitness reported a strong stream of water entering the town downstream of the dam at 7 o’clock on the evening of the disaster, and that was not the first time this had occurred. One person reported seeing water flowing over the top of the dam wall. When the mining company and contractor arrived at the site that evening one of the contractor’s employees found water lapping the top penstock ring, he then removed rings from the two penstock outlets. Another employee saw blocks of tailings toppling from the tailings buttress. Before they could warn the inhabitants of the town they heard a loud bang and a wave of tailings and water flooded the town’ (SAWDOS, 2013).

![Figure 5.6: Merriespruit tailings engulf the town](http://www.tailings.info/assets/images/accidents/merriespan.jpg)
The failure could have been prevented if a suitable operating manual and emergency plan had existed and been implemented successfully. The operation of the facility leading up to the major failure was outside the designed operating procedures. The lack of understanding of the operational procedures and the seriousness of the events prior to the main failure had not been realised. If a well-structured and executed operational plan had existed then the tailings operator(s) would have known to intervene, continually monitoring the closed impoundment for change and preventing further discharge to the facility.

The position of the supernatant pond and its ability to decant had been lost which suggests that the monitoring procedures had been inadequate to notice the change in the pond geometry and location. Alternatively the tailings operators may not have been trained to realise the consequences of pond migration as a result of single point deposition of the processed water and tailings. A management structure documenting individual responsibilities, operating procedures and contingency measures would have been sufficient to identify and prevent the initial localised slips and how the facility was to be managed thereafter. Having a suitable tailings management system implemented could have prevented this failure from occurring.
5.5  Los Frailes, Aznalcóllar, Spain, 1998

The main sources of information of this clear example of foundation failure are UNECE (2007), ICOLD (2001) and Barcelona Field Studies Centre (2018).

On 25th April 1998, the tailings dam (27 m high) at the Aznalcóllar mine extracting lead, zinc and copper, in the province of Seville, failed. The mine had been operated by Boliden-Apirsa since 1987. During the event a length of the dam about 600 m swung forwards like a door, forming a breach about 45 m wide and releasing 5 Mm$^3$ of toxic slurry into the River Agrio, a tributary of the River Guadiamar. The sludge travelled around 40 km and covered an area of approximately 4,500 hectares threatening the Doñana National Park, a UN World Heritage Area.

The dam was founded on about 4 m thickness of alluvium, overlaying marlstone which may have contained preformed slip surfaces. According to Eriksson and Adamek (2000) the cause of the failure was a fault in the marlstone 14m below ground surface. Bodily movements of the marl, carrying with it the intact dam towards the river, were assisted by the reduction of effective stress on the horizontal line caused by high pore pressure. Piezometric heads in the marlstone after the event were found to be above the dam crest indicating that the high density of the impounded tailings increased pore pressures in the heavily overconsolidated marl that migrated horizontally towards the river. River flow measurements downstream detected two peaks which suggests that the failure occurred in two stages.

Figure 5.8: Dam failure from foundation failure (Aznalcóllar, Spain)


No damage to humans was reported but the environmental impact of the disaster was immense. Emergency work was undertaken immediately to contain the sludge and waters and protect the national park downstream. Workers moved the sludge and contaminated soil into an old Aznalcóllar mine pit. The clean-up continued throughout the whole 1998, with some additional works and re-cleaning taking place in 1999 and 2002.

The Coto Doñana Natural Park, at the mouth of the River Guadiamar, bore the brunt of the damages from the Aznalcóllar disaster. The park consists of three distinct ecosystems: the marismas (wetlands), the Mediterranean scrublands and pine forests, and the shifting coastal sand dunes and beaches. It is one of Europe's largest reserves (over 75,000 hectares) and most important wetland habitats, home to a wide variety of bird species and a stopover for large numbers of migrating birds. Thousands of hectares of parkland were affected by the
release of the highly acidic waste. Acidity levels in the river rose and river bank vegetation died. Heavy metals in the soil and water worked their way up the food chain, impacting the local wildlife and malformations and tumours were noted in the stork population. Around 300 species of birds are estimated to have stopped migrating to the park, almost 2,000 birds, chicks, eggs, and nests were killed or destroyed and 25,000 kg of dead fish were collected. Impacts on society were also huge, with 10,000 hectares of farmland adjacent to the river contaminated by the sludge. Thousands of farmers’ crops were destroyed. One commune (Aznalcazar) lost 3,500 hectares of fields growing rice, cotton and citrus fruit. Around 250 farmers and 500 day-jobbers were estimated to have “lost everything”. The tourism sector experienced reduced income as visitor numbers to the park decreased. Some water sources (wells and groundwater) were contaminated. As the toxic metals do not break down naturally, it is estimated that the recovery time for the farmlands and wetlands may be around 40 years.

The costs of cleaning up the disaster were high. Up to May 2002 the total cost was calculated at €377.70 million including:

- €96 million that Boliden spent on the clean-up of the spill before the cessation of mining activity
- €145 million from the Andalucía Government for the clean-up and the purchase of polluted grounds
- and €136.70 million from the Environment Ministry for the clean-up and river restoration.

Mine operations were authorised to restart in April 1999, one year after the incident, but with restrictions on disposal volume. The mine closed in September 2001 when the mining company filed for insolvency. The following year, the Environment Department of the Andalusian Government completed the removal of the muds (~10,000 m³) that still were stored in the river basin of the Guadiamar.

![Figure 5.9: Los Frailes tailings dam breach (Aznalcóllar, Spain)](http://edafologia.ugr.es/donana/recursos/presa.jpg)

Source: Extracted from http://edafologia.ugr.es/donana/recursos/presa.jpg
5.6 Val di Stava, Italy, 1985

The main sources of information for this case study area ICOLD (2001), Luino and De Graff (2012), Govi and Luino (2003) and Roche et al., (2017).

The Val di Stava dam failure occurred on 19th July 1985, when two tailings dams above the village of Stava in Northern Italy failed. It was one of Italy’s worst disasters, killing 268 people, destroying 63 buildings and demolishing eight bridges.

The upper dam broke first, leading to the failure of the lower dam. The upstream dam suffered a rotation slip when it reached 29 m and subsequently breached. The release of the tailings caused the downstream dam to fail. The dams are thought to have failed as a result of poor management as the margins of safe operations were minimal.

The two dams were built one above the other on a sloping ground formed by fluvial and glacial sediments. Dams were raised by the upstream method. In order for the downstream slope to be built at an inclination of 1 to 1.2 the tailings contained a coarse angular sand. Pipes encased in concrete were laid on the ground to be under the lower impoundment and upward facing openings were made in each pipe length to act as decants for tailings water. As the construction height of the tailings increased the pipes were plugged.

The upstream dam was constructed on natural ground, with similar concrete pipes to act as decants. Before completion of construction a blockage occurred in the decants pipe on the upstream dam and a new steel by-pass pipe was installed and connected to the concrete pipe.

![Figure 5.10: Aerial view of the dams before failure](http://www.tailings.info/assets/images/accidents/stava-dams.jpg)

Around 180,000 m$^3$ of mud, sand, and water were released into the Stava valley and flowed towards the Stava village at a speed of around 90 km/h. Leaving a trail of destruction in its path, the sludge continued through Stava village and onwards for another 4.2 km, where it reached the Avisio River. A thick layer of mud measuring between 20 and 40 cm in thickness covered an overall 435,000 m$^2$ surface.

Hundreds of trees (spruce and larch) were actually cut down by the shock wave of air created from the moving flow. This air blast also led to rock falls.
Although the mudflow lost some volume as it deposited material on its journey through the valley, it also gained some, from the debris created in its path. The additional volume created by the eroded material (with destroyed buildings and infrastructure and trees cut down or uprooted by the flow), is estimated at around 40,000 to 50,000 m$^3$. By the time the flow reached Tesero (approximately 3 km downstream Stava) the mudflow still had a huge amount of force. An eyewitness in Tesero saw some superstructures from the saw mill “go flying”, just before the wave of mud hit them.
The mudflow finally came to rest at the confluence of the Stava and Avisio Rivers, where the mud spread out was deposited over an area of around 100,000 m$^3$. The mud that accumulated in the Avisio River formed a dam upstream of the confluence, leading to the formation of a lake 500 m long.

The human loss of life resulting from this incident was tragic. On top of the fatalities, there were an additional 100 people injured. There were devastating consequences for the environment too: habitats were smothered and rivers contaminated causing changes to water chemistry and increasing suspended sediment loads. Sediments got trapped in fish gills and had subsequent effects on semi-aquatic and terrestrial species. Aquatic and riparian nursery habitats buried in deposits.

The cost of repairing the damage caused by the Stava disaster is estimated at €155 million. The long-term social costs, relating to poor health, loss of income and livelihoods, and environmental degradation, however, are impossible to quantify.
5.7 Mount Polley dam, Canada, 2014

The Mount Polley tails dams failure in Canada is a good example of a modern tailings dam that failed despite robust monitoring and regular external reviews. The main sources of information of this case study are Roche et al. (2017), Byrne et al. (2018), CBC (2017) and the British Colombia Government and the Province of British Colombia websites (Province of British Colombia, 2015).

On 4 August 2014, a breach occurred at the tailings dam at the Mount Polley mine near the town of Likely releasing 10 Mm$^3$ of water and 4.5 Mm$^3$ of toxic tailings.

The breach occurred within the perimeter embankment. At the time of the breach, the tailings dam was permitted under the Ministry of Energy and Mines, with approval to raise the crest by 2.5 metres. The breach occurred early on 4 August 2014 at a crest elevation 1 m short of its permitted elevation. Loss of containment was sudden, with no warning. The recorded pond elevation at 6:30 pm on 3 August 2014 was 2.3 m below the crest. While some piezometers provided very useful information (e.g. the tailings piezometers provided pore pressure values that could be applied to slope stability analyses), the perimeter embankment instrumentation overall could not have provided any warning of the looming failure. Nor did provide any relevant information of the critical failure mode. The failure was sudden without any surface evidence. In the design for the proposed Stage 10, BGC anticipated this issue and recognized that a berm would be required for perimeter embankment.

Shortly afterwards of the failure, three separate investigations into this incident were launched: an independent expert engineering panel was established to determine the root cause of the breach, the Chief Inspector of Mines and the British Columbia Conservation Officer Service conducted different investigation. Both the expert panel and the Chief Inspector found that the Mount Polley tailings dam failed because the strength and location of a layer of clay underneath the dam was not taken into account in the design or in subsequent dam raises. The Chief Inspector also found...
other factors including the slope of the perimeter embankment, inadequate water management, insufficient beaches and a sub-excavation at the outside toe of the dam exacerbated the collapse of the dam and the ensuing environmental damage (British Colombia Government, 2015)

Although the response to the accident was swift, the environmental impact was disastrous. Tailings initially flowed north into Polley Lake, then formed a plug, preventing the flow of water from Polley Lake. Subsequent tailings flowed southeast into Hazeltine Creek, before reaching the west basin of Quesnel Lake, one of the world’s deepest glacial lakes, supporting populations of sockeye salmon, rainbow trout and a range of other fish species. The flow eroded the valley, before depositing layers of sediment up to 3.5 m thick. Deposits were found up to 100 m from Hazeltine Creek.

The environmental impacts of the disaster have been described as ‘immeasurable’ and ‘long lasting’, with the area still not having recovered two years on. Although trees have been planted along Hazeltine Creek, ‘nothing is growing’ said one resident of the area. Another described it as a ‘debris field of toxic sludge…knee deep and waste deep in some places’. The full extent of the environmental damage, however, may not be known for years, as the toxic waste from the tailings build up in the environment and may bioaccumulate in the food chain.

![Image of Hazeltine Creek](source: Jacinda Mack in CBC (2017))

Figure 5.14: Hazeltine Creek, pictured 22 September 2016, over two years after the disaster.

Like most disasters of this scale, the economic cost of the Mount Polley catastrophe cannot be accurately quantified. Clean-up costs by the Government of British Columbia are estimated at approximately $31.5 million. The financial impact of the mine closure would have had an enormous impact on the local community: at least 120 people employed by the mine owners were made redundant. Much of the rest of the community in this Cariboo region are also indirectly dependent on mining for their livelihoods, so also felt, and are still feeling, the economic, and consequent social effects, of the disaster greatly.
5.8 Manila Mining Corporation’s Tailing Pond No 5, Philippines, 1995

The following summary is extracted from ICOLD (2001).

Manila Mining Corporation’s Tailing Pond No 5 is located in Placer Bay, Surigao del Norte, Philippines. The dam was built in 1985-1986 and it was filled to its capacity by July 1995, when dam crest was 17 m above sea level. The crest was about 10 m wide and was used as a two-way road for the heavy plant. The closed impoundment began being used as a dump for mine waste rock.

At 9:30 am on 2nd Sept 1995, about 50,000 m$^3$ of material was released into the sea, extending 200 m seawards. When collapsed, the impoundment contained more than a million cubic metres of mine waste, earth, boulders, rock and leach pad debris plus several trucks and other machinery. Failure was thought to be due to high rainfall raising the phreatic level although the toe of the dam was over reclaimed land and the breached portion coincided with the former shoreline. Daily inspection reports of the impoundment indicated no signs of failure.

Seventeen people were working on the tip at the time and two people were walking along the shore. Of these, 12 were killed.

Previously, on 21st Dec 1986, Typhoon Ameng washed away a portion of the dam at the seafront and another collapse occurred on 9th July 1987, both incidents releasing effluent with high levels of cyanide resulting in fish kill.

5.9 Amatista in Nazca, Peru, 1996

On 12th November 1996, a 6.4 magnitude earthquake with an epicentre 135 km south-east of the site occurred causing liquefaction failure of the upstream-type tailings dam 45 m high. More than 300,000 m$^3$ of tailings were released. Two other inactive tailings dams in the area did not fail.

The tailings flow runout about 600 m downstream and spilled into the river contaminating downstream croplands. Remediation works were limited to the re-excavation of the river channel.

5.10 Caudalosa Chica, Huachocolpa, Peru, 2010

Caudalosa Chica mine (owned by Caudalosa Chica Mining Company), near the cities of Huachocolpa and Lircay, in the Huancavelica region was in a very remote location at 4250 m above sea level.

On 25th June 2010 at 18:10 the tailings dam failed releasing 58,000 m$^3$ of tailings. Expedient N° 024-10-EO from OSINERGMIN provides a description of the failure process:

- 9 January: Seepage near the chimneys and low reinforcement of supporting construction of chimney
- 16 January: Water accumulation behind the floating dike and seepage in the dike by the chimneys
- 15 February: Increased seepage in dike
- 22 March: No retaining walls in the drainage chimney
- 17 April: Very low operating height of supporting construction of chimney (by the dike)
- 19 May: Very low operating height of supporting construction of chimney (by the dike)
- 5 June: Seepage at the dike near the chimneys. It is necessary to increase the crest of dike A
- 25 June: Breach

Based on the report elaborated by OEFA, the main factors contributing to the failure of the tailings dam were related to design and operation. In relation to design, it was state the following:
There was no technical study nor permit for raising the height of the Dike A. A study from 2006 assessed a life span of 10 months of the structure.

- Heterogeneity of embankment materials (tailings, aggregates, etc)
- Lack of supporting structures
- Crest width variable (from 3.20 m to 3.40m) and different from design (4m)
- Freeboard of 0.1-0.2 m (1m minimum by law)
- Embankment slopes (35°-40°) higher than design (26°)

In relation to operation:

- Water impoundment was close to the embankment with no tailings beach
- No actions were taken to reduce seepage, liquefaction and piping
- There was no monitoring of geotechnical conditions or groundwater levels
- The drainage system was partially filled with mud
- There were no Environmental contingency plans or tailings management plan

In conclusion, the main cause of failure identified by OEFA was excess of hydraulic gradient due to the lack of proper drainage. Contributing factors were the height of the embankment, which was raised although its unstable condition had been reported, and the lack of monitoring.

As the toe of the tailings dams run parallel to the Escalera River the material released travelled downstream affecting more than 110 km of rivers, with thousands of dead fishes and impacts to agricultural land and livestock in the downstream villages along the rivers of Escalera, Huachocolpa, Opamayo, Lircay, Urubamba, Cahimayo, Cahis and Mantaro.

The remediation measures involved the construction of several large trenches backfilled with angular and pervious mine waste fill at the downstream toe. To ensure the long-term stability of the dam, a compacted downstream buttress fill was implemented.

The Agencies involved in the management of the incident were MINEM, OSINERGMIN, ANA, DIGESA, OEFA, Regional Government, Local Government and Local Authority (section 4.4 for further details).

In January 1998 during an exceptionally heavy rainy season, the mining company already reported large deformations and slumping activities in the reservoir area and the downstream slopes of the two tailings dams. Garga and de la Torre (2002) reported instabilities in the foundation of the Caudalosa tailings dams, with large deformations in progress at the time of their study and emergency stabilization works being performed.
Figure 5.15: Pictures from OEFA showing different stages before and after the failure.
g) Built weirs to try to trap tailings

h) Cleaning of tailings by local communities
(on the left top of the picture)

i) Fencing to stop cattle accessing the polluted river

Figure 5.15 (continued): Pictures from OEFA showing different stages before and after the failure
5.11 Huancapati, Peru, 2018

Huancapati dam in the Recuay province, Ancash region is owned by Licuna Mining Company (Picasso Group). On 3rd of March 2018 at 00:15, 80,000 m³ of tailings were released to the downstream watercourses Sipchoc creek and Santa river.

The failure was caused by the partial failure of the edge and base of the dam (Dam number 2) after heavy rain (Source: http://www.wise-uranium.org/mdaf.html)

The impacts were being assessed by OEFCA.

Figure 5.16: Images of the consequences of the failure (top) and at the dam (bottom) extracted from OEFA website
5.12 Sulliden Shauindo, Peru, 2018

The Sulliden Shauindo mining plant is located in Condebamba Valley, in Cajamarca.

In January 2018 OEFA reported the collapse of a lateral drainage channel of the mining site due to intense rainfall. This caused soil erosion and sediment material filling the tailings dam flowing downstream in the Higueron creek and finally ending in the Condebamba river.

Damages occurred in the downstream villages of Liclipampa Bajo and Chingol in the Cachachi District including houses, fields and local wells. Inspectors from government found mud deposits 0.3-0.5 m thick with intense odours that caused skin irritations.

Figure 5.17: Images of the consequences of the failure extracted from RENAMA website
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