

# Anomalies in design for mining dams

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*The design of dams for mining projects requires processes and technology that are unfamiliar to many mine owners and managers. Dam designers rely on ANCOLD assessments of Consequence Category, commonly leading to a High rating for mining dams due to a combination of potential loss of life, impact on environment and damage to assets such as mine voids, process plants, workshops, offices, roads, railways etc.*

*From this High Consequence Category the relevant annual exceedance probabilities for design parameters and loading conditions such as earthquakes and floods are selected.*

*Mining companies have sophisticated methods available for assessing risk, yet for their assets they often adopt an order of magnitude lower security for earthquake and floods even though the consequences in terms of lives at risk and impact on project are similar.*

*The discrepancies in the design standards lead to situations where extreme dam loads are adopted to prevent damage and loss of life in assets that theoretically would have already collapsed under much lower loads.*

*One difference may be that some mining dams exist in an environment which is controlled by a single entity. Unlike other dams, failure of these mining dams would therefore impact only individuals and assets which fall under the responsibility of the same entity.*

*This paper discusses the discrepancies between the design of mining dams and the design of other mine infrastructure. The paper considers the impact of discrepancies on the overall risk to the mine and compares the degree of protection offered by a factor of safety and the influence of reliability of design input parameters, alternate load paths and design redundancy.*

**Keywords:** Dams, tailings dams, mining, acceptable risk, factors of safety

## Problem Definition

Public perception is that tailings storage facilities and other mining dams pose one of the greatest risks in the mining industry. This is because past failures of such facilities have, in some broadly publicised examples, had devastating impacts on people, infrastructure and environment both within and outside the mine area.

At many mine sites, the people who would be directly exposed to floods from a dam break (referred to as Population at Risk - PAR) are often limited to those working at the mine. Depending on the location of the dam, the PAR can be found in the mine voids, process plants, administration buildings and other mine infrastructure.

The PAR or the number of people from the PAR who could lose their lives in the event of dam failure (referred to as Potential Loss of Life – PLL), along with the “Severity of Damage and Loss”, determine the Consequence Category of a given dam. In turn, the Consequence Category governs the selection of the design loads and contingencies adopted for the dam design. The Consequence Category framework is outlined in the Australian National Committee on Large Dams (ANCOLD) Guidelines on Consequence Categories for Dams (ANCOLD, 2012b), and has been adopted in the ANCOLD Guidelines on Tailings Dams (ANCOLD, 2012a).

Due to the importance of mining dams for the mines’ operation, most of the dams are classified as having a “High” to “Extreme” Consequence Category, depending on the PAR and/or PLL. Where the risks are realistically lower, then they could be classified as Significant or even Low.

On mine sites the people accounted for in the dam break PAR are also exposed to other risks, including the risk of engulfment as a result of:

- Slope, wedge, bearing capacity or other types of soil and rock failures in mine voids, cuts and underground workings
- Waste dump failure
- Structural failure in the process plant, workshop and other mine buildings and infrastructure

The design of dams for mining projects requires processes and technology that are often unfamiliar to many mine owners and managers. The design procedures, allowances for uncertainties and required Factors of Safety (FOS) used for the design of the dams are significantly different from those used for the design of the other mine infrastructure. As a result of these differences, comparatively high loads are often adopted in the design of mining dams to prevent damage and loss

of life in assets that were designed and constructed for much lower loading conditions and thus would have already collapsed before a dam failure.

## Design approaches used in mining

### Open pits

The design of open pits, which often would be flooded in part by mining dams failures, is depicted by generic guidelines such as the General Considerations in Open Pits Mines Guideline provided by the Department of Mines and Petroleum in Western Australia (DMP, 1999), the Guidance Material for the Assessment of Geotechnical Risks in Open Pit Mines and Quarries provided by the Victorian Department of Economic Development, Jobs, Transport and Resources or the Codes of Practice provided by the National Mines Safety Framework.

While the Guidelines on Tailings Dams (ANCOLD, 2012a) recommend different magnitude of loading for different Consequence Categories, the Open Pit Guidelines (DMP, 1999) allow for either a minimum recommended FOS or a Probability of Failure (POF) depending on the consequence of failure and the degree of uncertainty. These guidelines are shown in Table 1. A similar approach, based on the Probabilistic Stability Analysis of Variable Rock Slopes (Priest and Brown, 1983), has been adopted for other industry guidelines and codes of practice.

**Table 1 General Considerations in Open Pits Mines Guideline Table 1**

| Wall Category | Consequence of failure | Design FOS     | Design POF | Pit wall examples   |
|---------------|------------------------|----------------|------------|---|
| 1             | Not Serious            | Not applicable |            | Walls (not carrying major infrastructure) where all potential <sup>#</sup> failures can be contained within containment structure |
| 2             | Moderately Serious     | 1.2            | 10%        | Walls not carrying major infrastructure   |
| 3             | Serious                | 1.5            | 1%         | Walls carrying major mine infrastructure (e.g. treatment plant, ROM pad, tailings structure)                                      |
| 4             | Serious <sup>##</sup>  | 2.0            | 0.3%       | Permanent pit wall near public infrastructure and adjoining leases  |

# Potential failures have been defined as those modes of pit wall failure that have either a FOS of less than 1.2 or a POF of greater than 10%.

## Where a mutually acceptable agreement to allow mining cannot be made between the mining company and the "owner" of the adjoining structure or plot of land. Note that a higher standard of geotechnical data is required for the design of category 3 and 4 slopes compared to category 1 and 2 slopes.

The Open Pit Guideline (DMP, 1999) and other mining guidelines and codes do not consider either the PAR or PLL as a measure of consequences. This is because the PAR group consists of mine workers and as such their safety management is governed by occupational health and safety (OHS) practices.

The OHS practices include the as low as reasonably practicable (ALARP) principle to determine the acceptable residual risks. Given that ALARP is a deterministic approach, the OHS practices do not consider a quantitative risk assessment or suggest tolerable levels of risks for workers. The minimum safety standards and policies, guided by the OHS practices and regulated by several specific Australian Standards and Jurisdictional legislative requirements, are established by the mining companies themselves. These safety policies include training and induction programs to assist the workers to recognise hazards, apply appropriate safe work practices and appreciate other preventive measures reducing the overall occupational risk.

As a result of the different approaches to the safety management, the acceptable POF values are at least an order of magnitude greater than the equivalent POF that would be derived from the Annual Exceedance Probability (AEP) for various loads and acceptable FOS provided in the ANCOLD Guidelines. If earthquakes are considered in the loading conditions, the design earthquake is frequently limited to a 1:100 AEP event.

### Waste dumps

The design of waste dumps does not appear to be regulated in Australia. The construction of waste dumps frequently follows in-house mining company guidelines with a focus on constructability and safety of the operating personnel.

Commonly the dumps have exterior slopes near to the angle of repose of the loosely dumped material. Consequently, a waste dump typically has a very low margin of safety and may present a significant hazard to any assets and people in its vicinity during flood and earthquake events.

The potential risks posed by the waste dumps are deemed acceptable as the waste dam slopes are commonly considered as temporary structures only. A similar view is applied to various other batters and cuts on mine sites. A thorough design and stability assessment is frequently only applied as part of the mine closure.

### Structures

Most items of built mining infrastructure (process plants, workshops, stores, conveyors, administration buildings) are steel frame structures and thus are designed under AS/NZS 1170 Structures Code (AS/NZS 1170). Major mining

companies have their specific requirements but generally follow this 1170 code. The buildings are usually sited to be above a 1:100 AEP flood level.

The loads to be used in design are defined in part by the “importance level” (AS/NZS 1170, Table F1), which is a combination of potential loss of life (although no numbers are given) and economic, social and environmental consequences. In some ways this is similar to ANCOLD Consequence Categories and uses Low, Ordinary, High (in two levels) and Exceptional categories, which are given Importance Levels from 1 to 5, respectively. In most mines the majority of structures are designed to the “Ordinary” Level 2 which is referred to as “medium consequence for loss of life”.

The loads are further defined by the “Design Working Life” with AS/NZS Table F2 giving AEP figures for design lives of 5, 25, 50 and 100 years as shown in a condensed version in Table 2.

In practice many mines have a working life in the order of 25 years, or alternatively the processes, market requirements or changing ore grades will require modifications to structures or buildings in that time. Hence most structures are designed for a 25 year life at an importance level of 2.

**Table 2 Extract from AS/NZS 1170.0 Table F2**

| Design Working life                       | Importance Level | Wind AEP      | Earthquake AEP |
|---|------------------|---------------|----------------|
| <b>5 years (if no risk to human life)</b> | 1                | 1/25          | 1/25           |
|   | 2                | 1/50          | 1/50           |
|   | 3                | 1/100         | 1/100          |
| <b>25 years</b>                           | 1                | 1/100         | None           |
|   | 2                | 1/200         | 1/250          |
|   | 3                | 1/500         | 1/500          |
|   | 4                | 1/1,000       | 1/1,000        |
| <b>50 years</b>                           | 1                | 1/100         | 1/250          |
|   | 2                | 1/500         | 1/500          |
|   | 3                | 1/1,000       | 1/1,000        |
|   | 4                | 1/2,500       | 1/2,500        |
| <b>100 years or more</b>                  | 1                | 1/500         | 1/250          |
|   | 2                | 1/1,000       | 1/1,000        |
|   | 3                | 1/2,500       | 1/2,500        |
|   | 4                | Risk analysis | Risk analysis  |

Mining dams are often considered to remain in place in perpetuity and in fact closure requirements (ANCOLD, 2012a) suggest a nominal life exceeding 1,000 years. However, the mining dam is used for mining purposes for a period only slightly greater than the life of the project. After that, it should be rehabilitated and closed. Post closure the loading conditions and consequence, including PAR, can be quite different to those in its working life.

A comparison of design requirements for a mining structure and a mining dam is shown in Table 3. The comparison is based on a design life of 25 years, importance Level 2 for a typical mining structure and a mining dam of Consequence Category High B, which is typical of many mining dams where the greatest risk to life is to persons associated with the mining and processing operations.

**Table 3 Comparison of design requirements, Annual Exceedance Probability**

| Design requirement | Mine structure<br>(expected life 25 years) | Tailings dam<br>(expected life undefined) | Tailings dam closure<br>(expected life >1000 years) |
|--------------------|--|---|---|
| Flood              | 1/100                                      | 1/1,000                                   | PMF   |
| Wind               | 1/200                                      | 1/50                                      | Not Applicable                                      |
| Earthquake         | 1/250                                      | 1/10,000                                  | MCE   |

The differences in design requirements during the operation life are significant. The wind loading for a dam is influenced by the time taken to develop waves as compared with a gust loading on a structure. Closure is a special case with the dam then receiving less attention from the owner and being potentially in the public domain in perpetuity.

### **The role of Factor of Safety**

Mining structures and dams use limit state analyses by reference to a yield point of materials such as steel, concrete and soil. The structures code provides an extra margin by applying a factor of 0.9 to the nominated yield strength of steel and 0.8 for concrete, effectively introducing a safety margin of 1.1 and 1.25 respectively to cover the possibility of below standard materials whilst recognising different post yield strengths.

For soils and particularly for the variable strengths of tailings, most designers do not use average properties but instead use the lower quartile of test results. Some others use the lower limit, which introduces an effective margin of perhaps 1.1

to 1.5 depending on the shape of the critical failure path relative to the position of weaker zones in the soil. The variability of material properties would be largely covered in this approach rather than in an extra margin included within the Factor of Safety (FOS). In addition, the design of earthfill dams is commonly based on strength properties of fully saturated soils whereas the downstream shoulders are not expected to be saturated. The shear strength of partly saturated soils is generally much greater than fully saturated strength, so the assumption of full saturation provides an additional and sometimes significant level of conservatism in dam design.

The structures code provides a safety margin against yield failure by multiplying the design loads by a Load Factor which varies according to different combinations of loads. Often used load factors would be 1.2 for dead loads whilst maximum design live loads can have a factor of less than 1.0 if in combination with other short term loads such as wind or earthquake. Wind loads usually have a factor of 1.2 and the earthquake factor is 1.0 for dead loads and 0.1 for live loads.

The effective FOS for mining structures is therefore of the order of 1.2, not counting the extra margin as above. In practice, serviceability requirements such as deflection limits can lead to larger structural members and a higher effective FOS.

For mining dams, a FOS is recommended as compared with a load factor since the major loads are dead loads and an application of a load factor can lead to a calculated increase in friction resistance on the failure plane where it would not exist in reality. The usual FOS for static loads is 1.5 with the exception of 1.3 during construction when remedial actions can be quickly implemented if a potentially unstable situation occurs. This lower FOS can only be used where there is no risk to life or release of tailings or water to the environment in the event of failure.

From the above it can be seen that the FOS for mining structures can be significantly lower than for mining dams, in addition to the loadings having lower AEPs in recognition of the comparatively short lives of mines. The effect of lives at risk is recognised in both types of structures and in many cases the same lives are potentially at risk from either dam or infrastructure failure.

### **Fall-back vs. risk-based approach**

A major difference between mining dams and other dams is their change in design conditions during and after mining operations. Mining dams have an operational life measured in years or tens of years, whilst the design life of a water supply, irrigation or hydropower dam is typically one or two orders of magnitude longer. Therefore, the cumulative probability of occurrence of loading conditions with the same AEP during the operational life of mining dams would also differ by one or two orders of magnitudes, reverting to a similar life at closure.

Due to the limited design life, structures such as cuts, quarries, waste dumps and underground workings are considered as temporary only. The long term performance of these structures is only considered in the planning and implementation of the mine closure. The temporary character of the mine structures is projected in the perception of the acceptable risks, which leads to the discrepancies when the ANCOLD Guideline principles and recommendations are applied.

Current practices in dam design, selection of loading conditions and determining allowances such as freeboard are governed by the Consequence Category of the dam without reference to the life of the structure. The actual design can be developed using either a risk-based approach or by using fall-back methods, also known as standard-based methods.

The risk-based approach is described in the ANCOLD Guidelines on Risk Assessment (ANCOLD, 2003) and referenced in other ANCOLD guidelines including the Guideline on Tailings Dams (ANCOLD, 2012a). The approach divides the dam into components such as embankments, spillways and outlet works, evaluates the likely failure modes of each component and the initiating events that might lead to failure. This process includes consideration of the probability of each event (such as a design flood) occurring and therefore considers probabilities in the context of the required design life of the component. The process then considers the behaviour under each loading and estimates the probability of failure, sometimes by reference to historical frequencies of similar failures. Event trees (failure pathways) are used to calculate the risk.

The risk-based approach can be time consuming but leads to a rational evaluation that defines the risk of possible events. The risk is then compared with company acceptable levels of risk, hopefully also with reference to published criteria and standards for acceptable societal and individual risk levels.

The alternative fall back methods are defined in various tables in ANCOLD Guidelines. The tables prescribe specific requirements for various aspects of dam design, including earthquake loading, freeboard requirements, spillway capacity and FOS. Many owners and designers use the ANCOLD tables as a quick and convenient method for determining a design that is unlikely to be challenged by peer review or by a government agency; even though the guidelines clearly state that this is not the intended use of the tables. This practice does not necessarily achieve a design that is economic and in line with the mining company's risk acceptance criteria.

Application of the fall-back approach and adoption of the minimum recommended loading conditions prescribed in the ANCOLD tables can lead to the risk discrepancies discussed earlier in this paper.

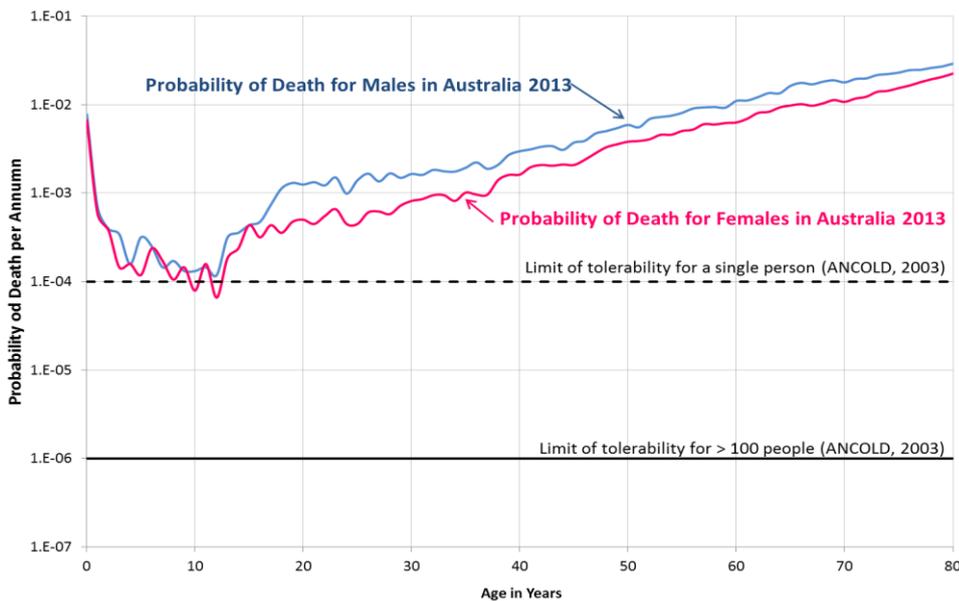
## Perception of acceptable risk

The ANCOLD Guidelines on the Consequence Categories for Dams (ANCOLD, 2012b) were prepared to “provide consistent method of categorising the consequence of dam failure so that resources can be allocated according to the potential effects of failure on the general community”.

Some mining dams do not directly influence the general community but perform in, and impact on, an environment that is controlled by a single entity (the mine owner). All site risks, including the risks posed by the dam are borne and managed by the same entity. Failures of these mining dams would impact mostly on people working at the mine and mining assets rather than on the wider community. The above does not apply for mining dams that have an impact zone affecting the general public and/or with significant and long lasting environmental consequences.

Guidelines on Risk Assessment (ANCOLD, 2003) provide background information relating to acceptable risks in the community. Figure 1 shows the annual probability of death taken from the Australian Bureau of Statistics Report 3302.0 (ABS, 2013) and the limits of tolerability suggested by Guidelines on Risk Assessment (ANCOLD, 2003).

It can be seen that the accepted limit for tolerability for probability of a single death is  $1 \times 10^{-4}$  per annum. The broadly acceptable risk is two orders lower, being for a risk imposed on a number of people (more than 100) in the wider community by an external party. These two parameters are carried into the recommended societal risk imposed by new dams as per Guidelines on Risk Assessment (ANCOLD, 2003), Fig 7.5. Interestingly, for an existing dam, the existence of which is presumably known by the public, the acceptance levels are one order higher. This is also a practical acceptance of the cost effect associated with upgrading numerous dams.



**Figure 1 Average background risk (Bureau of Statistics, 2013) and tolerability levels**

PAR used in consequence assessments account for all people in the potential dam break failure inundation zone at the time of the failure, assuming they do not take any action to evacuate. No consideration is given as to awareness of being within the potential inundation zone. Therefore, the Consequence Category of a mining dam as presented in the ANCOLD Guidelines on the Consequence Categories for Dams (ANCOLD, 2012b) does not take into account the risk awareness of the people in the dam failure impact zone. In contrast, the OHS standards and policies put emphasis on the workers' awareness of the risks and the risk mitigation measures as the key risk management principles. This should also include awareness of the risk posed by a dam where relevant.

The assessment of Severity of Damage and Loss outlined in the Guidelines on the Consequence Categories for Dams (ANCOLD, 2012b) includes partly subjective measures such as “impact on dam owner's business”. For companies with only one or a few mines, the failure can lead to closure if only for repairs and clean up, but sufficient loss of cash flow for the company to consider this being “Catastrophic”. When this classification is chosen in any of the Severity of Damage and Loss measurements, the consequence category of the dam cannot be lower than “High C” irrespective of the PAR or PLL values.

Given the importance of the dams for the mining operation, most of the dams are classified as having “High C” or higher Consequence Categories driven by the impact of failure on the owner's business. For these Consequence Categories, the Guidelines on Tailings Dams (ANCOLD, 2012a) recommend adopting design parameters and loading conditions with very low probabilities of occurrence, including a 1:10,000 AEP earthquake event as the Maximum Design Earthquake. Yet, the mine owners are frequently exposed to, and accept, much greater business risks such as market fluctuations but has to view this in context of his responsibility to the public..

## Conclusion

Application of the fall-back method in the design of mining dams, as discussed in this paper, can lead to higher design loads including earthquake loads as compared with other mining infrastructure.

Differences in the design approaches and the loading conditions that may result in dam failure can be several orders of magnitude greater than loading conditions used for the design of the very assets that would be impacted by the dam failure. The concept of consequence and thus PAR and PLL driven design, developed for dams impacting the general public, collides with the OHS practices implemented on mine sites and can lead to discrepancies in perceptions of acceptable risks.

The use of much greater loadings for the design of mining dams as compared with the loading used for the design of other mine infrastructure can in some cases result in significant additional costs to the mine owners. Where this is recognised, a risk-based design approach can be used, as allowed for and encouraged by ANCOLD Guidelines. The risk-based approach can take into consideration the changing conditions in the life of the mining dam and the assets in its vicinity along with the differences in perception of the acceptable risk to the owner. The risk based design approach, with target tolerability limits, may still result in discrepancies due to the application of PLL to workers acting under the OHS practices.

Where it is considered that the fall back methods may lead to increased dam costs, the design of mining dams should be based on the ALARP principle. In addition, an incremental damage and loss approach for the earthquake-induced dam failure assessment, similar to flood-induced failure, may also be appropriate in some circumstances.

The particular nature of mining dams, including their changing operational conditions over time and the controlled environment in which they operate should be taken into account in preparation of the revised ANCOLD Guidelines on Risk Assessment. This would include careful consideration of the risk profiles used by mining companies for other infrastructure and for OHS workers policies, which in some cases may be considered as non-conservative.

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