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Design criteria for upstream raised tailings storage facilities

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For more than 100 years upstreaming has been the dominant raising method for tailings storage facilities in Southern Africa. However, there is a growing view worldwide that upstreaming is inherently less safe than centreline or downstream raising of tailings storage facilities. Considering that more than 90% of the 250 plus operational tailings storing facilities in Southern Africa are upstream raised and cannot economically be converted to, or replaced by, downstream raised facilities, the arguments for and against upstreaming were examined in this study. It was found that no compelling reason exists to ban upstreaming in Southern Africa, provided that failure mechanisms are thoroughly considered to prevent serious design omissions. The ALARP (**a**s **l**ow **a**s **r**easonably **p**racticable) approach is introduced as a practical method to deal with the risk of failure, and its hierarchical application is illustrated.

INTRODUCTION

Upstreaming has been the dominant raising method for tailings storage facilities in Southern Africa for more than 100 years. Many of the facilities were positioned in the densely populated towns and cities that were built around the Witwatersrand gold reefs and the eastern and western limbs of the platinum belt. Since 1886, when gold was discovered in South Africa, there have been several concerning incidents and two significant failures which claimed lives, namely the Bafokeng failure in 1974 (Jennings 1979) and the Merriespruit failure in 1994 (Wagener 1997). Since the introduction of the South African National Standard (SANS) 10286 code of practice (SANS 1998), which focuses on improving management of tailings storage facilities, there have been no further failures of significance. (The Jagersfontein failure occurred since writing this paper and has therefore not been considered). In the same period, upstreaming has been banned in at least two countries where seismicity is low, and probably not strong enough to pose a risk to tailings facilities. Hence there is a growing view worldwide that upstreaming is inherently less safe than centreline or downstream raising of tailings storage facilities. Some are going as far as suggesting that the practice should be banned across the globe.

Morgenstern (2018) stated in his De Mello lecture: *"At this time, there is a crisis associated with concern over the safety of tailings dams and lack of trust in their design and performance. This crisis has resulted from recent high-profile failures of dams at locations with strong technical experience, conscientious operators and established regulatory procedures."* It is therefore indisputable that we must side with initiatives to regain trust. To do so we need to focus on changing those things that will make a difference and not on those that will not.

Banning of upstreaming is in most instances promoted by practitioners from the western coastal countries of South and North America where seismic activity is intense. In regions with extreme seismicity, such as Chile, Peru and British Columbia, the ban makes sense, but the reasons are not that clear for Brazil, where upstreaming has been banned following the sequence of failures of their upstream dams ending with the Brumadinho failure which had catastrophic consequences. Banning of upstreaming in the seismically active regions on the eastern extremes of the Americas in the 1970s has been shown to have been prudent, but it remains to be seen whether the ban in Brazil will deliver improved trust based on a reduced incidence of failures. Although the Brazilian regulators thought so

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at the time, it is not clear whether it is both necessary and sufficient to ban upstreaming to regain public trust. It is also possible that banning of upstreaming is taking attention away from the more important interventions such as improved governance and mitigation of weak engineering for all types of facilities that should be implemented by the mining industry, including its consultants, as a matter of urgency.

Morgenstern (2018) in his lecture went further to say: *"I side with the views of Martin and McRoberts (1999), and others before them (Lenhart 1950; Vick 1992), that there is nothing wrong with upstream tailings dams, provided that key principles are adhered to in the design, construction and operation of such dams."* Boswell and Sobkowicz (2018) corroborated this view by stating that, *"For every failed tailings dam, there exists a large number of stable, well managed tailings facilities around the world. These structures do not achieve stability by chance, coincidence or serendipity. Their stability is the result of sustained effort over many years by the engineers that design and build them …"*

Where does that leave the Southern African mining industry? Should Southern Africa follow suit and eliminate upstreaming? More than 90% of the 250 plus operational tailings storage facilities (TSFs) in Southern Africa are upstream raised and cannot economically be converted to, or replaced by, downstream raised facilities. The local industry is therefore reluctant to follow the call to move away from upstreaming. Although there are significant consequences for the industry which is substantially invested in upstreaming, the argument against elimination of upstreaming for economic reasons is not sufficient on its own, since safety must take priority. In this regard, the author sides with the views of Martin and McRoberts (1999) and McRoberts *et al* (2017), and with Morgenstern's (2018) conclusion that upstreaming is not inherently flawed, provided that key principles are observed. This paper therefore serves to examine where we have gone wrong with our upstreaming practices and what needs to be done to ensure that we can build upstream facilities in a safe and sustainable way in future.

ARGUMENTS FOR AND AGAINST UPSTREAM RAISING

There are good arguments both for and against upstreaming. The arguments are, however, not always placed in context, since those who are against may well be correct that upstreaming cannot be safely done in the regions with which they are familiar, for legitimate reasons. Some of the arguments for and against are discussed in the following paragraphs in the context of performance in the modern era since 2000 for both existing and new dams. It is important to focus on the modern era since much has changed and tailings management is now widely characterised by much improved governance and more thorough engineering.

Arguments against upstreaming

The first of the arguments is that upstreaming is unsafe since the failure rate is higher than for centreline and downstream raised facilities. There have been several papers which examine the statistics since 2000 and do not show a definitive difference in failure rate between upstream, centreline and downstream raised facilities in the modern era. The United Nations Environmental Programme (UNEP) (Roche *et al* 2017) provides statistics for the incidents that have been recorded across the globe since 2000. One of the interesting observations from the UNEP study is that there have been no significant incidents or failures in Southern Africa (excluding Jagersfontein) where there are more than 250 operational tailings facilities of which 90% or more are raised by upstreaming.

The second argument is that management rigour is insufficient to sustain consistent standards and that failures will occur because of management failure. This statement has merit since there has been a loss of skill in the Southern African mining industry and there are emerging weaknesses in tailings operations. This is an area where the Southern African industry will need to strengthen capacity to minimise risk.

The third argument is that if tailings can liquefy, it must be assumed that it will liquefy (Robertson 2021a), and that upstream raising is therefore flawed since the tailings of which the outer embankment is formed will always have a propensity to liquefy. This is one of the most controversial restrictions that has emerged from the recent standards (Robertson 2021b) and will be one of the most difficult to satisfy. Furthermore, if this requirement is applied strictly, many facilities in Southern Africa will not satisfy the safety criteria. However, dealing with this requirement is not impossible for upstream facilities, as we shall see later in the paper.

The fourth argument is that raising with tailings does not meet with international standards. Although this requirement does not appear in most standards, it is implicit in the European Union guidance (Cusano *et al* 2017). The justification for the standard is, however, based on environmental considerations and should not preclude the Southern African practice of using tailings for raising from continuing, provided that the environmental consequences are mitigated.

Arguments for upstreaming

The first argument for upstreaming is that it has been practised relatively safely in Southern Africa for more than 100 years. The two failures that have occurred can be attributed to excess water retention and overtopping, and not for any of the reasons cited by those against upstreaming.

The second argument is that Southern African management practice has evolved to suit labour and management intensive requirements for upstreaming. In this, the Southern African practices, reinforced substantially by SANS 10286 (SANS 1998), are, in the author's opinion, world-class, albeit at a practice rather than governance level.

The third argument is that there are no known cases of static or dynamic liquefaction as the initiating cause of failure in Southern Africa, and no failures of any kind have been reported since SANS 10286 was published in 1998 (SANS 1998) (one unreported case is known to the author). In this period many significant failures have occurred elsewhere in the world, including significant failures in downstream and centreline raised facilities. These failures have also usually been followed by liquefaction of the tailings.

The fourth argument is that the regions where mining takes place in Southern Africa have low seismic activity, being located on a stable craton. The statistically probable peak ground acceleration for a 1:10000 event (which is extrapolated from a known database of seismic events) is unlikely to exceed 0.15 g, although it is acknowledged that this is currently being challenged on theoretical grounds. According to Vick (1983), based on case histories, this level of acceleration is unlikely to bring about liquefaction.

The fifth and last argument is that the Southern African climate is favourable for upstreaming. Use can be, and has been, made of the natural climatic deficit to desiccate and stabilise the tailings to eliminate liquefaction potential.

No compelling reason to ban upstreaming in Southern Africa

The arguments for and against do not provide a clear direction, but it is evident that there is no compelling reason to ban upstreaming in Southern Africa. There are, however, conditions for proceeding. Morgenstern (2018) refers to these conditions as the key principles that must be adhered to in the design, construction and operation of tailings facilities. So, what are these principles and how should we be applying them? The following section presents the principles to which Professor Morgenstern was referring to, as ten rules.

TEN RULES FOR UPSTREAM RAISING

The following rules for upstreaming have been derived based on experience and with reference to the published work of Lenhart (1950), Vick (1992) and Martin and McRoberts (1999). The rules have in some instances been modified and summarised by the author, and reference should therefore be made to the original publications for the full descriptions.

1. A sufficiently wide beach, relative to the ultimate height of the dam, must be maintained to form a strong, wide, drained (unsaturated), and/or dilatant (non-contractive) outer shell (prism).
2. The prism upon which the stability of the dam relies must not be compromised by underlying tailings that are contractive or weak which, when subjected to excess strain or seismic loading, can either weaken or liquefy to the point where the factor of safety is insufficient.
3. The prism must be of sufficient width to retain "bursting pressures" (Casagrande & McIver 1970) of the contractive tailings that may be located upstream of the prism.
4. Where the tailings prism is relied on to provide stability, the rate of raising of the dam must be sufficiently slow, such that there is a sufficient dissipation of excess pore pressures and desaturation in the supporting prism.
5. There must be sufficient underdrainage (drainage blanket, finger drains, etc) and/or a pervious foundation to maintain the prism in a drained and desaturated condition, and to prevent seepage from issuing from the face of the tailings dam.
6. Design analyses must include both undrained strength analysis and effective stress analysis, with design controlled by the analysis type that best represents the anticipated behaviour of the tailings. A wide range of factors, including material type, degree of consolidation, loading rate and stress path, must be assessed in selecting the appropriate analysis method.
7. A high degree of regular performance monitoring, reviews and ongoing involvement by the designer (or another engineer formally appointed to assume this role) is essential to confirm that design intent is being satisfied.
8. Conventional upstream dams cannot be considered for areas of moderate seismicity without improved upstream construction, involving a combination of compaction or other means of densification (such as desiccation) of the outer shell and good internal drainage. Upstream dams should not be considered in areas with high seismicity.
9. The design must be consistent in terms of design requirements (e.g. minimum beach width) versus operational requirements (e.g. pond size required for clarification, storm storage and freeboard). The geotechnical design of upstream tailings dams should not be carried out in ignorance of operating constraints.
10. Seepage conditions within the dam must be well-defined, requiring a good understanding of hydraulic properties, pore pressure profiles and hydraulic gradients.

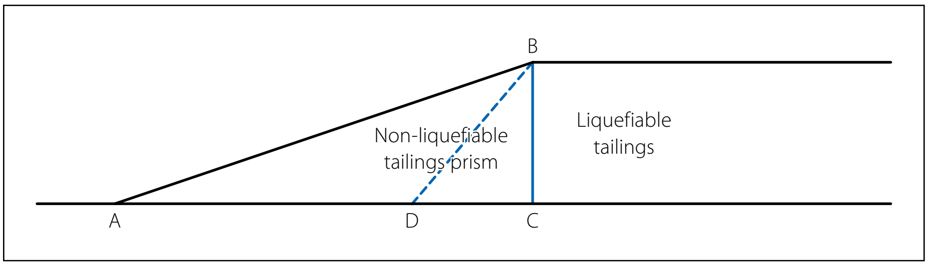

Figure 1 Illustration of supporting prism

Although these rules have not been prescribed by South African guidance and regulations, they are generally understood and followed. However, the author has been exposed to a large proportion of the operational Southern African tailings facilities over the past 15 years – firstly, as an operator with Fraser Alexander, and secondly, in the role of independent tailings review board member. This experience has shown that designers have begun to deviate from the rules, often in minor ways, and sometimes in significant and important ways. For example, in the time before designs were prepared by professional engineers, facilities were limited to a maximum height of 30 m based on empirical rules. This limit made it relatively easy to achieve a desaturated prism with width approximately equal to the final height. However, as the height of facilities has increased well above 30 m, the reason for the empirical rule has been forgotten and the required desaturated prism width has not been maintained. This has been particularly prevalent and concerning for facilities raised with cyclones in the upstream mode. There is a need therefore always to refer to the ten rules, and to explicitly adopt them in design.

The ten rules discussed

The outer shell or prism

The dimensions of the outer shell, which must be maintained in a partially saturated or dilatant state, need to be determined by analysis. As a starting point, a supporting prism that forms a triangle extending downstream from the final crest will be adequate in most cases (illustrated as triangle ABC in Figure 1). Optimisation may reduce the required prism dimensions to the triangle ABD, including repositioning of B to prevent topping failures. The extended prism has implications for drain design which go beyond the current guidance as offered in ICOLD Bulletin 97 (ICOLD 1994). This point also addresses the second rule insofar as having a stable prism will preclude the presence of underlying tailings that are contractive or weak.

Bursting pressure

The prism must be of sufficient width to retain "bursting pressures" which can build up behind upstream raises, as described by Casagrande and McIver (1970) and

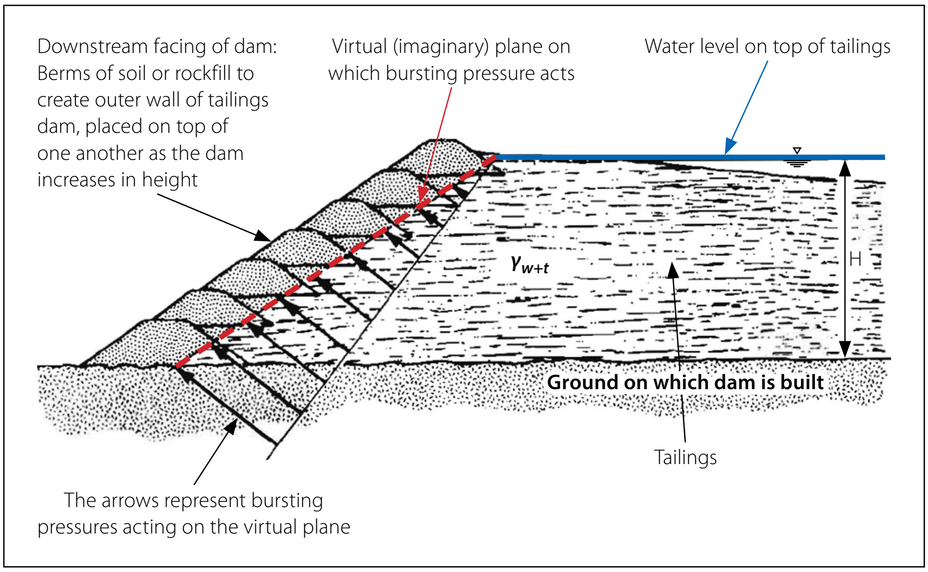

Figure 2 **Illustration of bursting pressures (adapted from Casagrande & McIver (1970))**

illustrated in Figure 2. This mechanism is seldom evaluated but needs specific attention, especially for existing upstream raises which are formed from earth or other materials against which hydrostatic pressure can develop. Casagrande and McIver (1970) go on to say that *"… the practice of raising tailings dams by a series of dykes, each supported in part by the underlying dyke and in part on soft or loose tailings, does not assure adequate safety. This construction practice can provide safe dams only when the sand fractions of the effluent … are separated and compacted to at least the axis of the final dike of the dam."* The axis of the final dike referred to by Casagrande and McIver (1970) is illustrated by line BC in Figure 1.

Rate of rise

Rate of rise, tailings layer thickness and cycle management are determinants of the rate of desiccation of tailings in a particular climatic setting. The rate of rise and the layer thickness and cycle time must be established to achieve the required degree of desaturation to preclude liquefaction. The degree of desaturation that is required to ensure that contraction during shearing does not result in pore pressure build up when subjected to straining or seismic loading is not well established. Hence a maximum degree of saturation of 85% is usually assumed, unless a higher percentage can be demonstrated to suffice.

Internal drainage

Sufficient underdrainage must be provided to maintain the prism in a drained state. The facility geometry and location of the pond play an important role in determining the extent and arrangement of drainage. Drainage needs to be more extensive to bring about drawdown where the pool is located close to the crest, and where layering, which leads to higher horizontal than vertical permeability, may require the use of chimney or curtain drains that interrupt the continuity of the horizontal layers to intercept seepage moving laterally. To provide for the required drainage, seepage conditions must be well defined and understood. This requires comprehensive analysis by specialised personnel.

Analysis

The analyses must include both undrained and drained analysis as a starting point.

A drained analysis provides a measure of the margin of safety against conventional loading conditions in the absence of any events that might trigger undrained behaviour. It remains the most reliable method to establish the margin of safety.

An undrained analysis, on the other hand, indicates the margin of safety against abnormal loading conditions causing a failure. The most conservative approach is to assume that the worst-case loading conditions can arise, and to design accordingly. In many cases with existing facilities, it is not practicable to assume the worst case, and it becomes necessary to examine the probability of occurrence of abnormal loading conditions. Seismic loading is one of the loading conditions that can induce undrained behaviour, and hence, where the tailings can liquefy, upstreaming should not be considered in seismically active areas without improved upstream construction.

Performance monitoring

It goes without saying that a high degree of regular and rigorous performance monitoring is required for upstream raised facilities to provide assurance that the development of the facility is in conformance with the design requirements. Monitoring should be designed to measure performance for all possible failure mechanisms and to provide early warning of developments that indicate a trend towards non-conformance. Monitoring cannot provide early warning of undrained failure and therefore the monitoring system should be designed to measure the parameters that must change to initiate an undrained failure. Monitoring of earthquakes is, however, not useful as an observational tool.

Consistency between design requirements and operational outcomes

The design requirements must be explicitly stated by the designers so that performance indicators can be set and monitored during operations. For example, a minimum beach width is assumed for the drainage design and stability analysis but is often only shown on cross-sections that appear in the appendices of design reports. The minimum dry beach width therefore does not get to be established as a formal performance requirement. The process of crystalising design assumptions into operational performance criteria requires a good understanding of the design models and of the upset conditions that could result in non-conformance. Senior oversight of design is particularly important for identifying these requirements before operations commence.

MEETING THE REQUIREMENTS IN SOUTHERN AFRICA

The ten rules can be met for new upstream designs without too much additional cost. It is therefore strongly advocated that designers should fully internalise the rules and ensure that they are built into future designs. Independent reviewers should also focus on the rules and should be specifically requested to provide opinion on whether the rules have been incorporated into the design and, if not, what the risks are.

Many of the existing facilities in Southern Africa will not meet the requirements, principally because they will fail on rules 1 and 2. The prisms that have been designed to support the weak tailings in the interior are often undersized owing to incorrect positioning of the drains, failure of the drains or inadequate gradients. This then leads to a situation where the critical failure surface passes through tailings that have inadequate peak and/or post-peak undrained shear strength and where the factor of safety criteria are not met.

The real risk is, however, somewhat different. Several tailings facilities exist in Southern Africa with undrained factors of safety of less than 1 for peak undrained strength with an implied probability of failure of close to certainty but have never failed even after exposure to the largest mining induced tremors of the Free State and Witwatersrand. This fact clearly calls into question the approach that is currently adopted globally to deal with the undrained condition. The shortcoming, in the author's opinion, is associated with a fixation on "compliance" or rule-based approach as opposed to a risk-based approach. A risk-based approach would recognise that a low factor of safety for an undrained condition is a flag which prompts the designer to examine the triggers that could bring about an undrained condition, and to assess the potential for these conditions to develop. Thus, in moderate and high seismic regions the designer would most likely conclude that the probability of occurrence of an earthquake of sufficient magnitude that would lead to failure is too high, while elsewhere the designer might conclude that the probability of occurrence of triggers for undrained behaviour, such as removal of support (associated with a conventional failure) or a rapid increase in phreatic surface that could trigger an undrained failure, are just too low to warrant concern. Unfortunately, the rule-based approach is prevalent and is favoured by many non-Southern African reviewers. This requires a concerted effort by Southern African engineers to demonstrate that risks associated with upstreaming are within reasonable limits.

The Global Industry Standard on Tailings Management (GTR 2020) makes provision in Requirement 4.7 for resolution of the impasse when target factors of safety are not met. Requirement 4.7 states that existing tailings facilities shall conform to the minimum requirements, except for those aspects where the Engineer of Record (EoR), with review by the Independent Tailings Review Board or a senior independent technical reviewer, determines

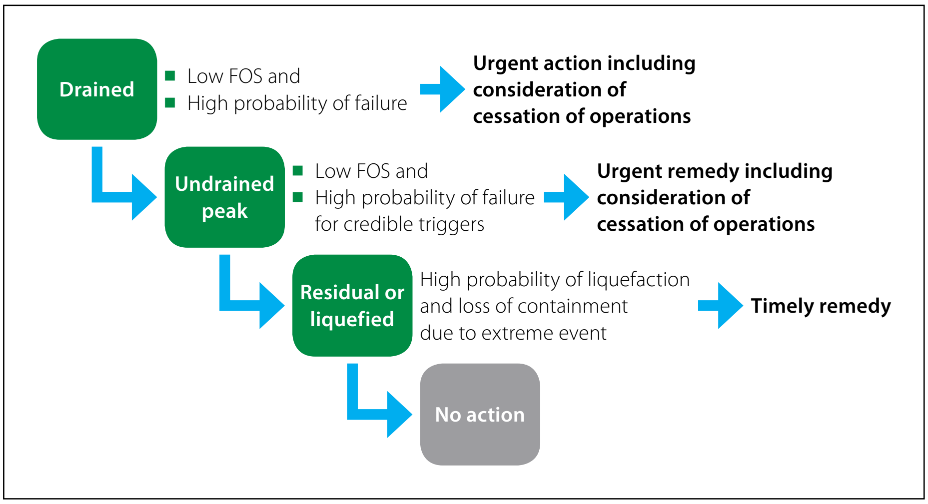

Figure 3 Hierarchical process for stability evaluation

that the upgrade of an existing tailings facility is not viable or cannot be retroactively applied. In this case, the Accountable Executive shall approve and document the implementation of measures to reduce both the probability and the consequences of a tailings facility failure to reduce the risk to a level as low as reasonably practicable (ALARP). The basis and timing for addressing the upgrade of existing tailings facilities shall be risk-informed and carried out as soon as reasonably practicable.

Most Engineers of Record are having difficulty in implementing Requirement 4.7 since there is not an established process to do this and very little thought has been given as to how to assess the probability of occurrence of most of the trigger mechanisms. The process should, however, not be complicated and should follow the hierarchical approach which is illustrated in Figure 3 to facilitate stability evaluation and interpret factors of safety (FoS) in context.

The process follows a series of steps beginning with confirmation that either the factor of safety exceeds the target threshold or that probability of failure for conventional drained stability is low (say <1:1000 to 1:10000). This would represent the lower bound for engineering reliability and may be taken to demonstrate that, but for unforeseen circumstances, the facility safety is adequate. If the target factor of safety is not adequate, then the probability of failure should be determined to decide whether mitigation is required to increase the factor of safety.

If the drained factor of safety or the probability of failure is found to be adequate, then proceed to the next step to determine the undrained factor of safety. As for the first step, if the factor of safety is not adequate, confirm that the probability of triggers exceeding a level that would induce undrained behaviour (say again <1:1000 to 1:10000) would be acceptable and, if not, develop and implement remedial measures.

If the undrained factor of safety is adequate or the probability of inducing undrained behaviour is low enough, then proceed to the last step. If the tailings cannot liquefy or if the probability of liquefaction is low enough, then no further action is required. If the tailings can liquefy, then the risk should be mitigated by an ALARP process. The term "can liquefy" should be defined as being possible with a probability of >1:1000 to 1:10000.

Actions which can be considered in the ALARP process include increasing the factor of safety to >1.1 for post-earthquake shear strength by buttressing, strengthening or slope flattening; providing for protection of people by early warning; physical containment and or diversion infrastructure; or, as a last resort, resettling people and relocating infrastructure in the inundation zone.

PRACTICAL APPLICATION OF THE ALARP PROCESS

GISTM Requirement 4.7 stipulates that the Accountable Executive shall approve and document the implementation of measures to reduce both the probability and the consequences of a tailings facility failure to reduce the risk to a level as low as reasonably practicable (ALARP). The basis and timing for addressing the upgrade of existing tailings facilities shall be risk-informed and carried out as soon as reasonably practicable.

ALARP requires that all reasonable measures be taken with respect to 'tolerable' or 'acceptable' risks to reduce them

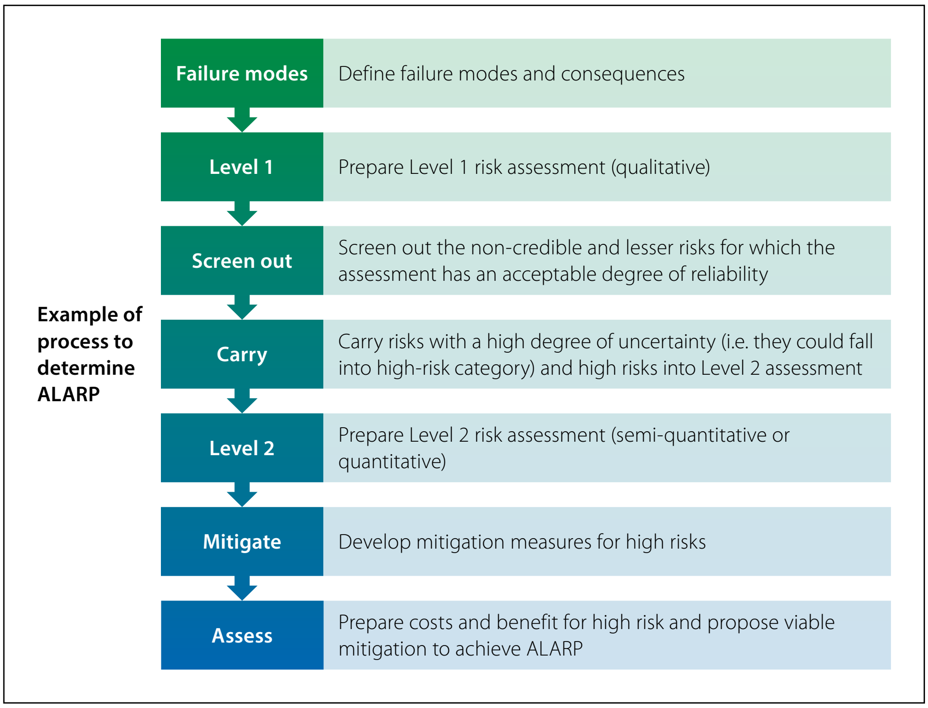

Figure 4 **Simplified ALARP process**

even further until the cost and other impacts of additional risk reduction are grossly disproportionate to the benefit.

The ALARP process must be carried out in a systematic manner and should be documented to provide an audit trail and serve as the basis for justification to regulators and stakeholders that the process has been thorough, and that the outcome is defensible. The principles defining the process are not yet settled and there are many ways in which an outcome could be achieved. Wates (2021) proposed a simplified process that is illustrated in Figure 4.

In the context of ALARP, tolerable risk, as defined in ICOLD Bulletin 130 (ICOLD 2005) and adapted from the United Kingdom Health and Safety Executive definition, is *"... a risk within a range that society can live with to secure certain net benefits. It is a range of risk that we do not regard as negligible or as something we might ignore, but rather as something we need to keep under review and reduce it still further if we can."*

In any assessment as to whether risks have been reduced to ALARP, measures to reduce risk can be ruled out only if the sacrifice involved in taking them would be grossly disproportionate to the benefits of the risk reduction.

CONCLUSION

The call to eliminate or ban upstreaming is not justified in regions with low seismicity. Provided that the ten rules for upstreaming are applied, there is no reason why future upstream raised facilities cannot be designed and constructed to be as safe as centreline and downstream facilities.

Eliminating upstreaming in Southern Africa is not justified by the record of failures of upstream facilities in the region. The cost of shutting down and replacing existing facilities associated with operating mines would be ruinous for most mines, while the risk has been shown by the record to be reasonably low.

The continued use of existing upstream raised facilities can be motivated, provided there is strong engineering backing and comprehensive assessment of the probability of the development of abnormal trigger mechanisms that could induce undrained behaviour. The motivation for continued use of facilities that do not comply with the minimum factors of safety, but with demonstrated acceptable margins of safety, must be underpinned by a comprehensive ALARP process that provides a defensible argument for the mitigation that is implemented.

Obsession with the assumption that static liquefaction is the most significant risk for upstream tailings facilities introduces additional risk, since this distraction could lead to the key mechanisms being overlooked. It is critical to point out that a design can be flawed (perhaps even fatally) if important, plausible failure mechanisms are not considered and that factors of safety cannot fully account for gross omissions in design and analysis. Designers and Engineers of Record should not be distracted by focusing blindly on meeting the standards.

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