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How long is 'long-term'? Carrying seismic risk through the post-operational period

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Abstract

Recent trends in industry have led to triggers for static liquefaction being assumed in the absence of evidence to the contrary for tailings prone to liquefaction. However, for seismic liquefaction, the risk is often accepted provided that a target Factor of Safety (FoS) is achieved for the earthquake design event stipulated in standards and codes. In the post-operational period, the triggers associated with static liquefaction can be modelled and, in many cases, ruled out. However, for the assessment of 'long-term' conditions following the end of operations (i.e. post-closure), the earthquake design event under consideration is often greater. Rather than installing additional risk mitigation measures, the 'long-term' performance discussion is often focused on the time period during which sufficient drain down will occur such that the post-seismic FoS is acceptable. This raises the question: 'How long is 'long-term'?' Or, 'How long will the owner carry the post-seismic risk after operations cease?'

In many cases, mitigation measures such as buttresses are put in place to maintain compliance under static conditions during the operational period. As the tailings storage facility (TSF) drains down, the potential for failure under static conditions is often reduced. This provides an opportunity to reconsider the extent of mitigation measures required to maintain geotechnical stability over time. For sites that are material constrained there is the potential to consider reusing material that was previously in place to manage the static stability risk without adversely affecting the stability of the facility.

This paper presents two case studies related to the drain down of the phreatic surface in the post-operational period for two TSFs located in semi-arid climates but with contrasting tailings behaviour — a hard rock sand-like tailings versus a finer, clay-like residue — with the difference in hydraulic conductivity relative to the foundation playing a key role in the drain down period. The paper explores the drain down periods in the context of the time frame over which the post-seismic FoS would become compliant under an elevated design earthquake event. The potential to reuse the buttress material for other TSFs is also explored, noting that removal of the buttress material can have a positive influence on the stress state of the foundation, mimicking a pre-loading arrangement.

Keywords: *tailings, failure mode, seismicity, stability*

1 Introduction

Recent trends in industry have led to triggers for static liquefaction being assumed in the absence of evidence to the contrary. For seismic liquefaction, the risk is often accepted provided that the minimum Factor of Safety (FoS) is achieved for the earthquake design event stipulated in standards and codes. However, the earthquake design event can be much less in the operational period when compared to the earthquake design event recommended for a closed tailings storage facility (TSF). Rather than installing additional risk mitigation measures, the 'long-term' performance discussion is often focused on the time period during

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which sufficient drain down will occur such that the post-seismic FoS is acceptable. This raises the question: 'How long is 'long-term'?' Or, 'How long will the owner carry the seismic risk after operations cease?'

It is noted that in some cases the potential for static liquefaction triggers to occur may be more likely than the seismic trigger. Assessment of static liquefaction triggers are outside the context of this paper but should be undertaken as part of any design process.

2 Seismic risk framework

The seismic event that is required to be managed to achieve compliance with industry guidelines is based on the consequence category for the facility in question. The standards typically indicate a maximum design earthquake or safety evaluation earthquake varying from a one in 1,000-year return period event for High C (Australian National Committee on Large Dams [ANCOLD 2019]) and High (Canadian Dam Association [CDA] 2013; Global Tailings Review 2020) consequence categories, increasing to one in 5,000-year and one in 10,000-year return period events for High B/Very High and High A/Extreme, respectively. After the operational period is complete, all three standards indicate that the one in 10,000-year return period event needs to be considered.

For High or Very High consequence categories, a facility can therefore be designed to manage the lower events and still be compliant. In many cases, this would then be a significant change to the loading conditions after operations. At this point, the question arises about the approach to be adopted.

As noted above, the owner often carries the seismic risk through the post-operational period, and this paper reflects this position. However, for completeness, it is noted that there are two other pathways that can be adopted:

- implement measures such that the design can manage the larger design earthquake (e.g. construct a buttress)
- adopt a risk-informed framework. Provided the results from a detailed quantitative risk assessment indicate a tolerable position, the seismic risk may be tolerable. The owner would still need to demonstrate that the risk is as low as reasonably practicable (ALARP) under this framework (see ANCOLD 2022) and the time frame for carrying the seismic risk would be an important consideration in the ALARP process. It should be noted that changes in the potential loss of life over the post-operational period need to be carefully evaluated under this pathway.

3 Case study

3.1 Context

This paper presents two case studies related to the drain down (lowering) of the phreatic surface in the post-operational period for two TSFs located in semi-arid climates but with contrasting tailings behaviour — a hard rock, sand-like tailings versus a finer, clay-like residue — with the difference in hydraulic conductivity playing a key role in the drain down period. The paper explores the drain down periods in the context of the time frame over which the post-seismic FoS would become compliant under an elevated design earthquake event.

3.2 Methodology

For both TSFs, the stratigraphy of the facility was developed based on geotechnical investigation data (for the foundation) and as-constructed drawing records (for the TSFs). Both TSFs have been investigated during the operational phase via cone penetration testing with pore pressure measurement (CPTu), and vibrating wire piezometers (VWPs) are installed to monitor pore pressure changes over time. The CPTu data were used to assign the strength parameters for the material, and a combination of the CPTu data and VWP data was used to estimate the phreatic surface for the models.

The stability models were developed taking into account the knowledge base available, including the physical characteristics of the tailings discussed in the following section.

3.3 Physical characteristics

Both TSFs are perimeter discharge, upstream raised on a foundation that is slightly more permeable than the tailings and are in semi-arid settings. The tailings were deposited at a solids concentration associated with conventional thickened, resulting in a material that displays a slightly positive state parameter and hence is subject to seismic liquefaction when saturated.

The relevant physical characteristics for the two tailings types are summarised in Table 1. The characteristics are based on laboratory testing and CPTu investigation data.

Table 1 Relevant physical characteristics

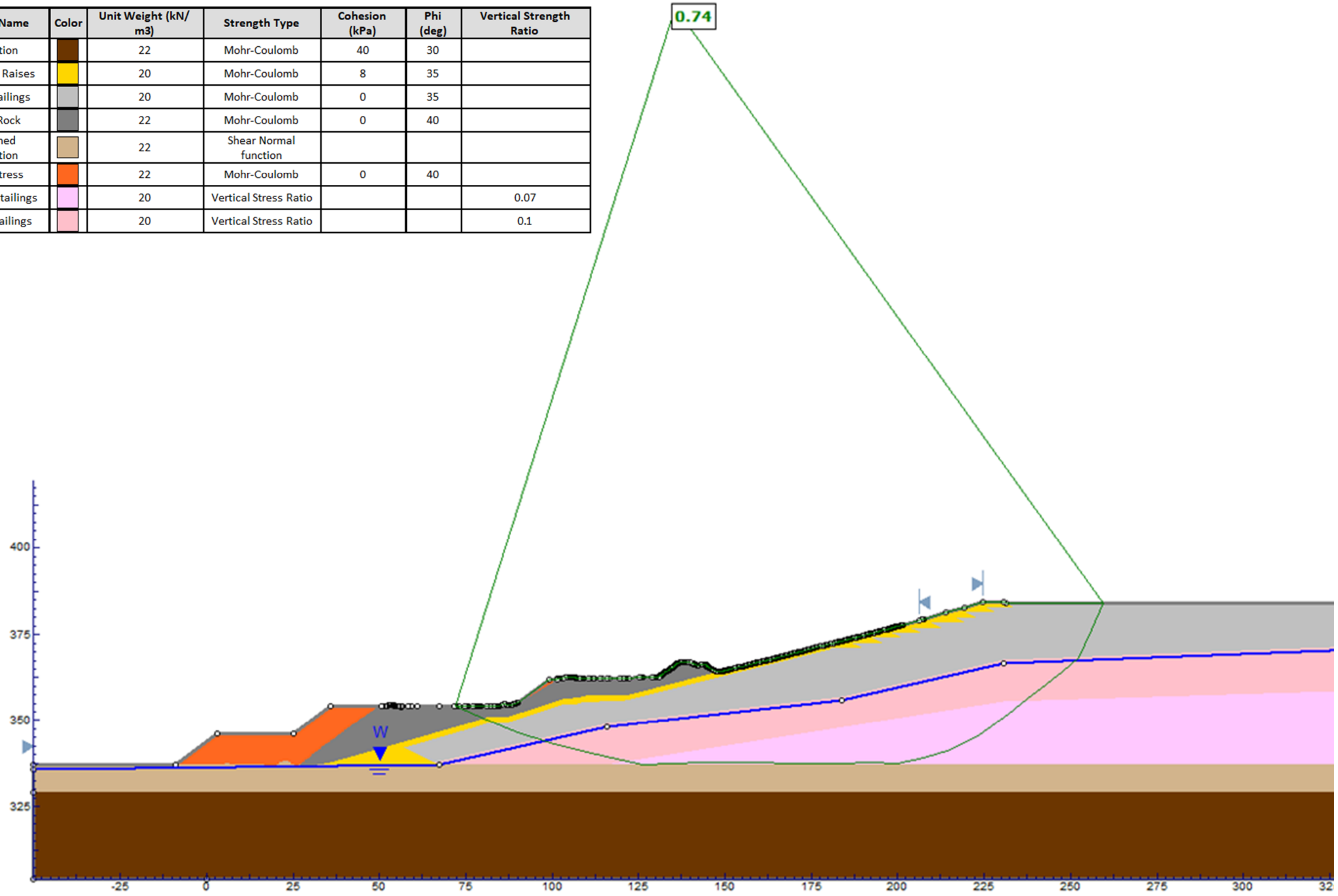
Material characteristic	Unit	TSF 1	TSF 2
Particle size distribution	% passing 75 mm	55–85	80–97
Plasticity	%	Non-plastic	3–9
Particle density	Specific gravity	2.9	3.1
Dry density	t/m^3	~1.6	~1.8
Consolidation	cv (m^2/year)	50 to 2,500	10 to 50
Hydraulic conductivity	kv (m/s)	$\sim 1 \times 10^{-8}$	$\sim 1 \times 10^{-9}$
	kh (m/s)	$\sim 1 \times 10^{-7}$	$\sim 1 \times 10^{-8}$
Characteristic state parameter	–	0.1	0.08

In both cases the TSF has been assigned a Very High consequence category and hence carries the same design loading condition.

3.4 Drain down periods and implications for stability

For both TSFs the stability condition at the end of operations is:

- a static FoS of ~1.5 under static conditions by virtue of the construction of buttresses
- a post-peak FoS less than unity, acknowledging that the increased earthquake design loading associated with the one in 10,000-year return period event (the closure design earthquake) results in liquefaction of the saturated and near-saturated contractive tailings. The FoS for TSF 1 under this scenario is presented in Figure 1, along with the parameters applied in the model.



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Vertical Strength Ratio
Foundation		22	Mohr-Coulomb	40	30	
Starter and Raises		20	Mohr-Coulomb	8	35	
Drained Tailings		20	Mohr-Coulomb	0	35	
Waste Rock		22	Mohr-Coulomb	0	40	
Undrained Foundation		22	Shear Normal function			
Trial Buttress		22	Mohr-Coulomb	0	40	
V.Loose PP tailings		20	Vertical Stress Ratio			0.07
Loose PP tailings		20	Vertical Stress Ratio			0.1

Figure 1 The post-peak Factor of Safety for tailings storage facility 1 at the end of operations, assuming the tailings liquefy under the closure design earthquake

As noted earlier, at this point, there are two broad options for the owner: (1) increase the buttress size to maintain a satisfactory FoS for post-peak conditions or adopt a risk-informed framework or (2) carry the seismic risk until the phreatic surface drains down sufficiently to reach a satisfactory FoS (noting that there is potential for undrained conditions to be realised in the near-saturated zone directly above the phreatic surface).

In the context of option 2, the subject of this paper, there are two drain down points that have been considered in the case studies:

- the phreatic level that corresponds with a post-peak FoS of 1.1 — at this point, the seismic risk is managed (as well as static liquefaction risks)
- the phreatic level at which the facility has substantially drained down such that the buttress is no longer required.

Figures 2 and 3 indicate the post-peak and peak FoS values for drain down point 1, respectively, for TSF 1. The modelling indicates that a drain down of about 10 m is required to reach a post-peak FoS > 1.1 (Figure 2), which corresponds to a peak FoS of near 2.0 (Figure 3).

Figure 4 shows the phreatic condition corresponding with drain down point 2, where the buttress is no longer required. A further 10 m reduction in phreatic level beneath the crest (20 m total) would be required to reach this condition.

The time frame for achieving these points for TSF 1 is presented in Figure 5: about 7.5 years for drain down point 1 and 35 years for drain down point 2.

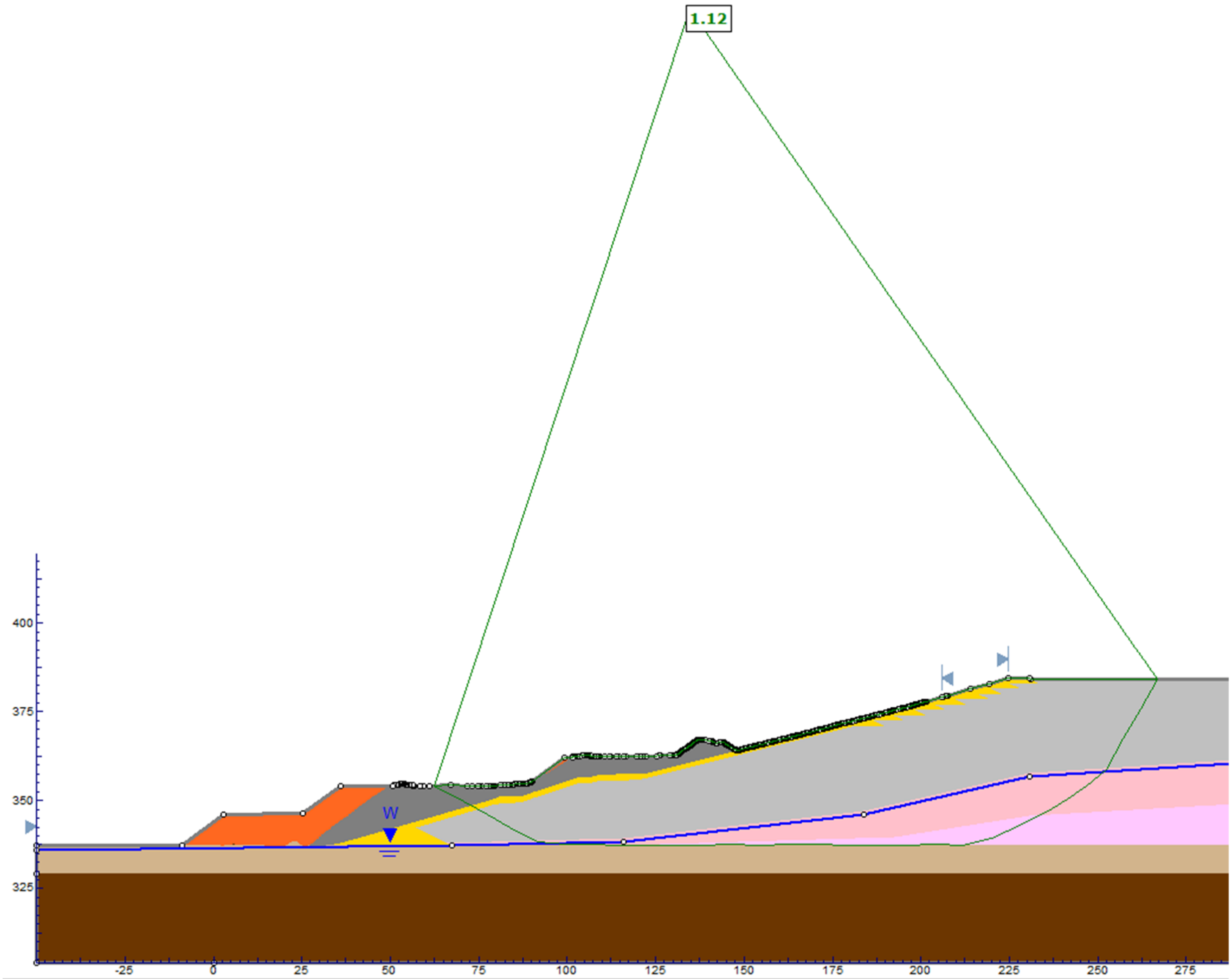


Figure 2 Drain down point 1: post-peak Factor of Safety > 1.1 for tailings storage facility 1 — 10 m reduction in the phreatic surface below the crest

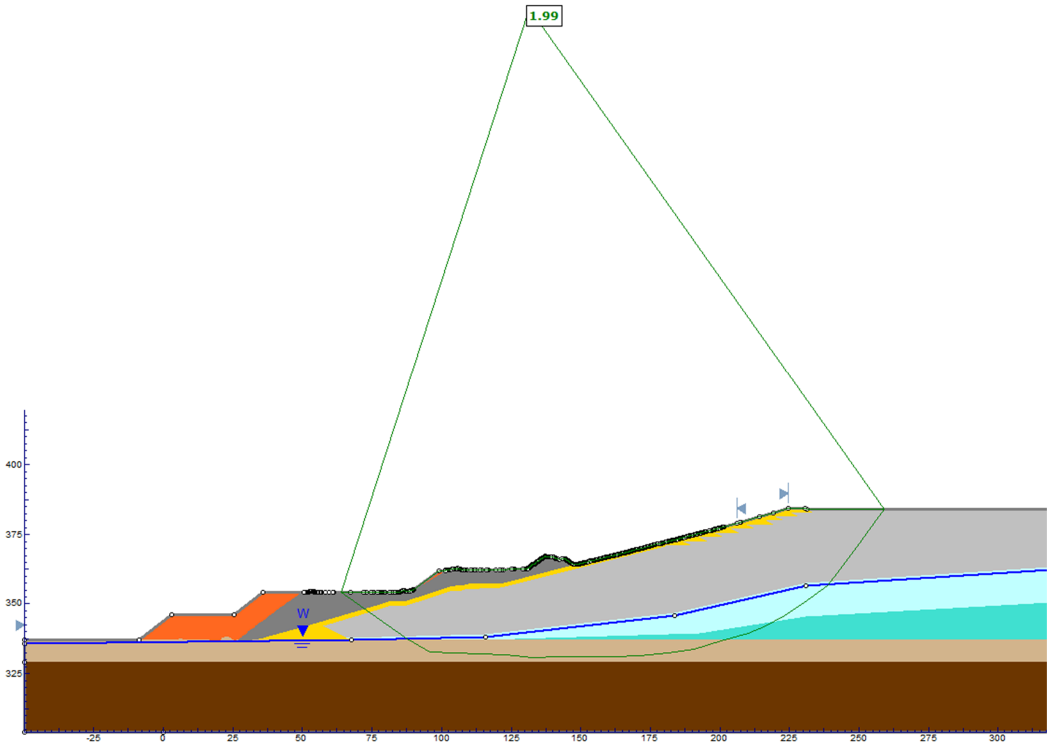


Figure 3 **Peak Factor of Safety for tailings storage facility 1 at drain down point 1 — 10 m reduction in the phreatic surface**

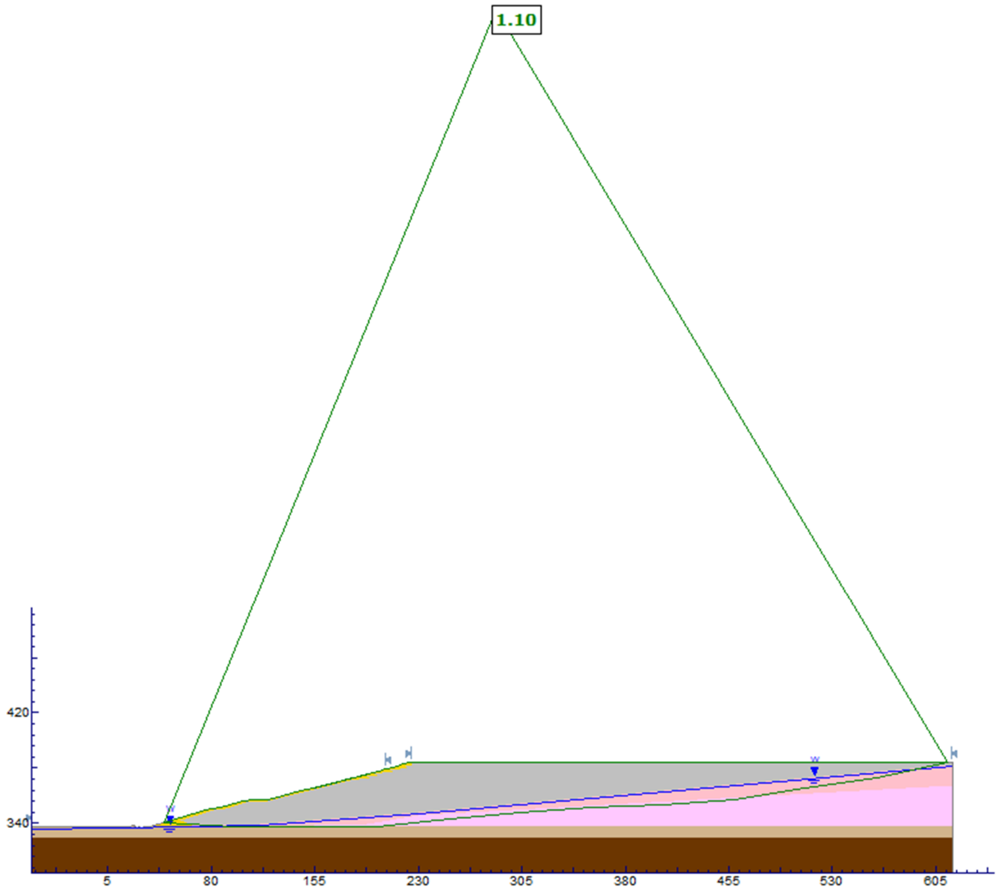


Figure 4 **Drain down point 2: post-peak Factor of Safety > 1.1 for tailings storage facility 1 with no buttress — a further 10 m reduction in the phreatic surface (20 m total)**

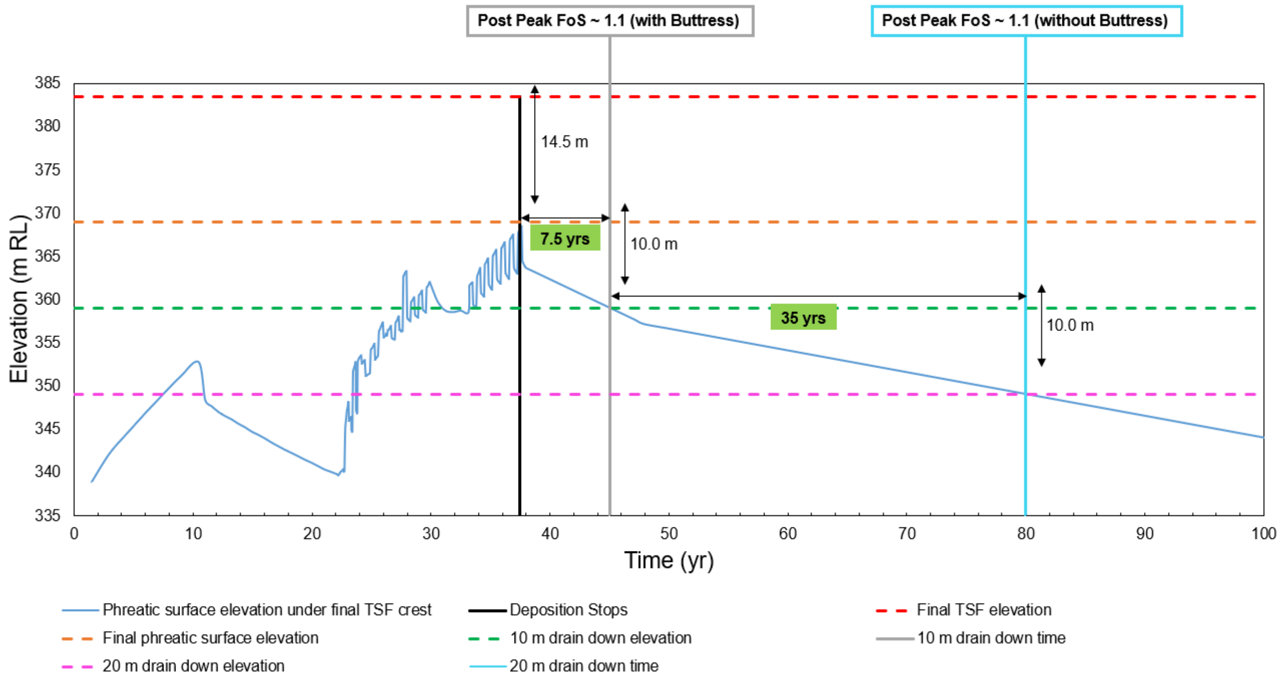


Figure 5 Time frame for drain down — tailings storage facility 1

A similar exercise was completed for TSF 2, noting that the hydraulic conductivity of TSF 2 is slightly lower than that for TSF 1. The results for TSF 2 are compared to TSF 1 in Table 2.

Table 2 Summary

Drain down point	Aspect	TSF 1	TSF 2
1 — Seismic risk is managed (post-peak FoS > 1.1)	Reduction in phreatic surface	10 m	16 m
	Time frame	~7.5 years	~30 years
2 — Buttress is no longer needed	Reduction in phreatic surface	Additional 10 m	Additional 10 m
	Time frame	~35 years	~100 years

Clearly the hydraulic conductivity has a significant influence on the time frame that the seismic risk needs to be carried for. Regarding the question of how long 'long-term' is, which is equivalent to drain down point 1, the outcomes of the assessment suggest that the time frame for TSF 2 is well beyond what is typically adopted for the post-operation monitoring period (typically 10 to 20 years). While the seismic risk is a credible failure mode by virtue of a FoS less than unity should the tailings liquefy, the governance and monitoring processes would need to remain in place and hence the facility could not be considered as reaching safe closure.

4 Concept of removable buttresses

In many cases, mitigation measures such as buttresses are put in place primarily to maintain compliance under static conditions during the operational period. As the TSF drains down, the potential for failure under static conditions is often reduced. This provides an opportunity to reconsider the extent of mitigation measures required to maintain geotechnical stability over time. For sites that are material constrained there is the potential to consider reusing material that was previously in place to manage the static stability risk without adversely affecting the stability of the facility.

The general approach to construction of buttresses is to incorporate them into the final closure landform, with progressive rehabilitation often occurring during the operational stage. However, on material-constrained sites, the cost of the material can be significant.

As demonstrated in the case studies presented in Section 3, there is the potential to recover some or all of the placed buttress material for use elsewhere once the phreatic surface has drained down sufficiently to manage the instability risk (i.e. beyond drain down point 1). In some cases an older, inactive TSF that may have been buttressed will drain down in the operational life of the active TSF at the site. This presents an opportunity for 'removable buttresses' to be implemented.

If TSF 1 is considered, there is the potential to harvest material from the buttress in campaigns between drain down points 1 and 2 over a period of 20 years. During this time satisfactory stability would be maintained by ongoing reduction in the phreatic surface, and material shortages that may be present could be addressed. While this would delay rehabilitation of the slopes of the inactive TSF, it may provide the opportunity to more effectively shape the slope to manage long-term erosion risks, leaving a component of the more durable material in place.

For TSF 2, the time frame for reaching drain down point 1 is much longer, which reduces the opportunity for this process to be implemented unless the mine has a sufficiently long life.

The authors note that if the approach to construct a buttress to meet a post-peak FoS of 1.1 under the closure design earthquake loading is adopted, then removable buttresses are an option at a time frame commensurate with the drain down time frame. Furthermore, in all cases there is potential for removal of the buttress material so as to have a positive influence on the stress state of the foundation, mimicking a pre-loading arrangement.

5 Conclusion

TSFs are often designed to manage the design earthquake event associated with the consequence category during the operational stage. For High or Very High consequence categories, a facility can therefore be designed to manage the lower events than required at closure and still be compliant. This would then be a significant change to the loading conditions after operations. As operations near completion there are two broad options for the owner: (1) increase the buttress size to maintain a satisfactory FoS for post-peak conditions or adopt a risk-informed framework, or (2) carry the seismic risk until the phreatic surface drains down sufficiently to reach a satisfactory FoS.

The outcomes of the assessment presented in this paper demonstrate that, depending on the hydraulic conductivity of the tailings, the drain down may be within a reasonable post-operational monitoring period (TSF 1) or well beyond it (TSF 2). With this knowledge, the 'long-term' condition could be considered the time frame under which the owner is willing to apply active governance and monitoring.

The concept of removable buttresses is also presented. As the TSF drains down, the potential for failure under static conditions is often reduced. This then provides an opportunity to reconsider the extent of mitigation measures required to maintain geotechnical stability over time. For sites that are material constrained, the owner could consider removing part of the buttress and reusing material without adversely affecting the stability of the facility.

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