Foreword

These proceedings document the single-day Risk Assessment Short Course, delivered as part of ICOLD's 91st Annual Meeting at Gothenburg, Sweden on 11 June 2023. These proceedings are meant to serve as a lasting compendium of the short course for the attendees and as a testimony of the contemporary state of risk assessment and its challenges for those who, though absent from the event, maintain a vested interest in this topic.

Many owners, consultants, and researchers have struggled with the enigmatic domain of tailings dams risk assessment for an extended period, and this struggle only intensified after the importance of risk assessment was pointed out and the acronym "ALARP" was included in the Global Industry Standard on Tailings Management (GISTM), released in 2020. ICOLD Bulletin 194, released as a preprint in 2022, partially addressed this issue by offering an overview of a typical risk assessment process, while making reference to other ICOLD and national committee guidelines, which were primarily designed for water storage dams. The members of the ICOLD Committee on Tailings Dams and Waste Lagoons have committed to a series of initiatives aimed at assisting professionals involved in tailings dams to develop appropriate approaches to risk. This short course was part of that broader initiative.

The common framework of risk, as a measure of probabilities and consequences, finds its origins in the games of chance, wherein both the likelihoods and consequences of repetitive events unveil themselves predictably. However, tailings dams failures are one-off events, and the a priori likelihoods and consequences of such events are estimated by tailings practitioners and subject matter experts. These estimates, by their very nature, are subjective to the perspectives of those who proffer them based on limited inputs and imperfect techniques used in absence of phenomenological models of dam failures. Consequently, the level or magnitude of risk of a tailings dam failure is not an objective attribute intrinsic to the dam itself but rather a measure of belief in the proposition of the dam failure and the potential consequences. This concept of risk holds, irrespective of the type of tailings dam risk assessment, and the tools and level of sophistication adopted, and is consistent with the definition of risk provided in ICOLD Bulletin 130. Unfortunately, comprehending the essence and the magnitude of risk of a tailings dam failure does not inherently elucidate whether the risk is being maintained as low as reasonably practicable (ALARP) or necessitate further risk reduction actions.

I accepted the convenor's role with the mission to convey the key messages from David Bowles, Desmond Hartford and Malcolm Barker who, amongst others, introduced the concept of risk assessment to the dams' profession in the 1990's and have been dedicated to this discipline for decades. Their collective knowledge holds paramount significance for the tailings profession for three principal reasons. Firstly, the tailings industry can learn invaluable lessons from the successes and pitfalls encountered in the application of risk assessment primarily for water dams, thereby accelerating the progress in the realm of tailings dams. Secondly, the speakers were involved in developing leading industry guidance, including the ICOLD Bulletins 130 and 154 and ANCOLD Guidelines on Risk Assessment, which tailings practitioners rely upon and interpret. Finally, their independence from mining organisations liberates them from corporate or industry mandates, rendering them more amenable to candid discussions.

As most tailings dam owners have only recently embarked on the course of risk-informed dam safety management, they may find it useful to learn the perspective of an organisation that has been on this journey for a much longer time. Dom Galic from the US Department of Interior Bureau of

Reclamation (Reclamation) kindly accepted the challenge and presented the Reclamation's risk assessment and dam safety management practices, which now spans over three decades.

Finally, recognising that the legal considerations for tailings dams and risk assessment are often underappreciated and misunderstood, I invited Joel Mårtensson to present the legal considerations for tailings dams and risk assessment within the host country, Sweden.

Notwithstanding the very different backgrounds and area of practices, it was intriguing to observe that the presenters converged on the following pivotal facets of risk assessment:

- What is reasonably practicable refers to risk control actions not the risk magnitude or risk level, and ALARP ought to be understood as a state at which all reasonably practicable risk controls are in place. A good practice is to identify all practicable risk controls and if not all of them are implemented, justify the reasons for not implementing them.
- Discerning reasonably practicable risk controls goes beyond cost-benefit analyses and is intertwined with current industry practice and standard of care.
- Risk tolerability frameworks were constructed for specific contexts and objectives. Hence, their application should remain circumscribed to their intended purview. Adopting risk tolerability criteria as the sole basis for decision making may not be legally and morally defensible after a failure occurred and lives were lost.
- Risk assessment is meant to provide inputs into a wider decision-making process, which factors in the nuances of ethics, perception, legal and regulatory imperatives, politics, culture and other intangible aspects of making a decision affecting the lives of others.

As part of the short course, the attendees identified and analysed a potential failure mode (PFM) based on the information provided from a real tailings dam and experienced the difficulties of estimating the probability of the dam failure by this PFM. The activities, undertaken in small groups, were intended to provide participants an insight into the process, the role of personal judgement and the difficulties of having incomplete data, which is common for tailings dams.

The short course concluded with two panel discussions adeptly moderated by Paul Ridlen, wherein the discourse revolved around compliance with GISTM requirements, difficulties in assessing risks of static liquefaction and the meaning of ALARP in different jurisdictions. The benefits of having presenters with no direct affiliation to mining entities were fully manifested in the high-quality discussions, which did not avoid deliberations upon attainability of the GISTM requirements and the ultimate goal of zero-harm.

I extend my gratitude to all presenters, moderators and all attendees of the short course for their generous contribution, unwavering support and active engagement.

Jiri Herza, Short Course Convenor

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1 Motivation

The members of the ICOLD Committee L – Tailings Dams and Waste Lagoons recognised that there was no specific guideline available for risk assessment for tailings dams, although risk assessment was made mandatory in many jurisdictions and the Global Industry Standard on Tailings Management (GISTM) required risks presented by tailings facilities to be reduced to as low as reasonably practicable.

ICOLD Bulletin 194 (2022) partly addressed the issue by providing an overview of the typical risk assessment process. However, for further details the reader was referred to applicable ICOLD and national guidelines, which were primarily developed for water storage dams. Therefore, the members of Committee L explored how ICOLD could assist tailings practitioners in developing risk assessments of tailings dams and this short course formed part of that process.

2 Background

This short course was built upon a risk assessment short course held as part of the Tailings and Mine Waste (TMW) Conference in November 2022.

The main objective of the TMW short course was to provide an overview of risk assessment for tailings storage facilities that included lessons learned from water dam risk assessment, legal perspectives, approaches by different mining companies, quantitative risk assessment, and the ALARP concept.

The TMW short course was attended by over 100 practitioners from the mining industry.

3 Course objectives and scope

The ICOLD short course objective was to present the current state of practice of risk assessment for tailings dams, building upon the principles outlined in Bulletin 194, with the view to improve the safety of tailings operations across the world.

The course covered the following aspects of risk assessment:

- Importance of understanding risk assessment objectives
- Key steps in the risk assessment process
- Clarification of risk tolerability concepts
- Identification of risk control measures and their verification
- Evaluation of what is reasonably practicable
- Integration of risk assessment into tailings management systems

Group activities provided an opportunity for the attendees to engage in the key risk assessment activities including hazard and failure mode identification, risk analysis, probability calculations, evaluation of the risk magnitude and consideration of reasonably practicable measures to address risks.

The short course was intended for dam owners, regulators, authorities, designers and consultants, contractors and NGOs.

4 Presenters

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5 Content and Program

No.	Item	Start	Duration (min)
	Introduction	08:00	
	Workshop opening, Wider program of risk-related ICOLD activities, purpose of workshop, agenda review	08:10	10
Part 1	**Risk Assessment Overview**	08:10	
1.1	Why we conduct RA, objectives and methods	08:10	15
1.2	What is Risk - a measure of uncertainty, measure of consequence and probability	08:25	15
1.3	Question of Probability - Classical, Relative frequency, Bayesian theorem	08:40	15
1.4	Triplets of scenario, probability, consequences, representative failure scenarios	08:55	15
1.5	Risk tolerability questions - is a line on F-N plot defendable and does it meet the equity criteria?	09:10	25
1.6	Steps in risk assessment and what is and is not covered in B130, B194 and ANCOLD 2022	09:35	15
	Morning Tea	09:50	20
Part 2	**Prepared example - Risk Identification**	10:10	
2.1	Dam description and definition of problem - potential piping through the dam body	10:10	15
2.2	Piping assessment - owner's practice	10:25	45
2.3	Group activity 1 - Development of piping failure mode - event tree, fault tree, bowtie	11:10	45
2.4	Identification of risk controls	11:55	20
	Lunch	*12:15*	*40*
Part 3	**Prepared example - Risk analysis**	12:55	
3.1	Estimation of system responses	12:55	25
3.2	Estimation of probability of occurrence	13:20	25
3.3	Group activity 2 - Estimate of failure probability of embankment piping	13:45	45
	Afternoon Tea	14:30	20
Part 4	**Prepared example - Risk Evaluation**	14:50	
4.1	Defensible decision making - basic requirements	14:50	20
4.2	Assessment of risk controls to assist in decision making (what is ALARP)	15:10	30
4.3	Group activity 3 - selection of control measures to be implemented to mitigate the risk of piping	15:40	20
4.4	Societal confidence in dam risk assessments	16:00	20
4.5	Architecture of Dam Safety Management Systems	16:20	10
	Panel discussion	16:30	30

Appendix A. Short Course Presentations

Appendix B. Panel discussion transcripts

The panel discussions were audio recorded and minor edits of the transcripts were made for clarity.

Panel Discussion No. 1

On ALARP

Paul Ridlen

The term ALARP is found throughout the Global Industry Standard for Tailings Management and has become the subject of much discussion in the mining industry. How well do you think ALARP is understood among the tailings practice, do you think it is an appropriate standard, and what do you think should be done to fill any current gaps in knowledge and regulation?

Des Hartford

Now there's one of my slides, which shows the difference between the ends of spectrum of what constitutes ALARP. In your notes you'll see a page that shows the spectrum of ALARP applications from at one end of the spectrum, which is general industry, health and safety at work, reducing risk, protecting people, which is the most commonly used version of tolerability risk and ALARP in the dams industry. Today, it has been in place for 20 odd years. According to John Remington who wrote the whole thing in the first place and formulated ALARP, it's not invalid for dams, but it's not directly applicable. One of the unwritten statements around ALARP, is that there is an underlying assumption that industry is malleable. What you mean by malleable is that you can continue to improve it over life, as technology advances. You know, science improves the new methods that arrived. This works for industrial plants doesn't work for dams because they're heavy civil infrastructure, because they are not malleable. So, the whole thing about ALARP is that rather than being a state, which is what's actually commonly used in the industry, that you've read a lot about, ALARP is a lever, mechanism used by government in these malleable industries to continually keep pressure on the owner, the creator of the risk to drive risk down. So, John Remington's advice in relation to the application of tolerability, risk and ALARP is that when you're building your dam, it doesn't matter whether it's a tailing dams or water dam and because they're not readily improved over time, once they are built, that you make them as safe as you can when you get the chance and you prevent a deterioration in the risk position. BC Hydro has taken John Remington's advice. We have worked with him for 20 years. Taking this advice and applied it to dams problem will be explained together with how we make decisions in the tolerability risk and on our framework on Tuesday afternoon 16:05. I'm not going to talk about it now, but the idea of ALARP as a downward thrust on the risk is central to how certainly John Remington explained to me. So, he says there's a spectrum. General industry reducing risk protecting people. The other end of the spectrum, you've got dams, rigid fixed infrastructures, not readily improved. And in the intermediate position you've got nuclear power stations, some which are fixed and some parts of which can be made safer and safer over time as technology advances. So, it's a completely different interpretation of a lot as applied to them.

Paul Ridlen

So maybe if I could rephrase the question, it was a three-part question. And I'm going to skip the one about whether it's understood or appreciated in the mining industry. The second one would be maybe more applicable is,

"Is that an appropriate standard?"

And again, I use it in a different term perhaps than what we conventionally think of, but is ALARP appropriate to be applied to tailings dams?

Des Hartford

It depends on how you're applying it, how you're interpreting it. If you're interpreting tailing dam as if it's a …Now, during construction you can continue and modify it. Once you've built it, it's done and by the way, it's there forever. So, what's this end state going to be is where your real target is. Sure, you don't want it to fail along the way, but at the end state, you want to close it out and walk away. Which means that you know the idea of reinvesting or decommissioning the tailing storage facility is really not on the table. And the whole question about decommissioning, you know, the large water dams is basically not on the table either. Very difficult to do in many cases. Sometimes it's impossible. So, you're still faced with these forever infrastructures. When you get the chance, make them as safe as you can because it's a one-shot deal.

Paul Ridlen

David, it looks like he wants to go next.

David Bowles

I'm not sure I've got anything really profound to add. However, it struck me as a little bit odd when I first went through the GISTM and saw ALARP, because I'm used to seeing it in the common law (originating in the in the UK) context; and to see it in a global standard I thought, well, that's interesting. I wonder how it got there and maybe some of you can answer that question. But it seems to me as long as it's there, and as long as there is a willingness by the industry to work towards that, there really is a need to better define what ALARP means for tailings dams, right? The things that I can offer, and that I think Des can offer are from our experience, which goes back to the roots that Des has described. But you're looking for something that applies across the globe. It seems to me that actually is in part a legal matter with a lot of different legal contexts around the world. I would think it's got to somehow mesh or connect to the legal context in different parts of the world. The mining industry needs to better define ALARP, so the industry can apply it. But that's not a simple thing to do and it's going to take some consultation with legal minds around the world, I would think.

Jiri Herza

I fully agree with David, and I don't think it is possible to define what ALARP means for all jurisdictions around the world in a single document. ALARP, in the Commonwealth world, refers to reasonably practicable controls rather than risk position. If you have a capital FN plot, you might not say what area is ALARP, or you might say it, but it would be wrong. ALARP is a temporal state at which you can objectively demonstrate that all reasonably practicable risk controls are in place, and they are managed using reasonable processes, that include verifications of the controls being effective. This may be a very basic definition of ALARP applicable in certain jurisdictions and if you want to apply it somewhere else, be aware that it (ALARP) is a temporal and circumstantial state applicable to a specific environment, in which the dams are operated. It's a very difficult quest to define what ALARP is for all dams in the world and I don't think it is going to work.

Attendee

But just sorry, I think it's like a continuous process. So basically, probably that's the reason it is not very clear and identified across the world what ALARP means. Because it should be continuous process at the end of the day.

Jiri Herza

The risk assessment and the verification, as David put in one of the slides (Slide 56) is the external loop and if something happens then you go into an internal loop before you return outside again. So, it (ALARP) is an ongoing process of improvements and reduction of risk. But being able to define ALARP is A, B, C, D, E and F? I don't think it (a globally applicable definition) is possible for the whole world.

Malcolm Barker

I guess I'm going to ask Des, is that the fact that you do improve the dam's facilities as you see a problem mean that they are malleable. In that sense, they are fixing them, they are improving them as they go along. And is that not part of the ALARP process?

Des Hartford

Well, you could construe it to be that if you wanted to, but it's no different to any construction project, like when we're building anything, you know you're applying the observational method. You're always modifying things as you go. So, there is the whole idea of the dynamic situation during construction as opposed to once you get to closure. It's when you get to closure that you've really got to be clear about what you're doing now. But the whole question about ALARP take out the R and think about it ALAP. So, in other words, have all the practicable things being done? Take a list of all practicable things and then justify why you haven't done some of them, if you haven't done them all. So, there's a reverse way into it: everything is practicable, and then justify why you haven't done everything practicable…and there will be justifications.

Paul Ridlen

So, what you're saying is, I think, is don't throw the baby out with the bathwater. It may be that there's an adapted approach that's needed for the industry that is distinct from other industries that have applied to ALARP.

Des Hartford

I would think so. And there's also the issue that never gets discussed and that is living with legacy risk. You're stuck with what you've got. And it's more dangerous to do anything than not do anything. So, there you're basically between a rock and a hard place. That's reality.

David Bowles

Des, the process that you described there of coming up with every practicable option is one that we recently went through on a portfolio of about 40 dams in Australia though they were water dams; but nevertheless that that's the process we went through. And then, the next step was to make the argument about why you wouldn't do everything on that list.

Paul Ridlen

Any anyone else, any comment for you?

Joel Mårtensson

Well, just two notes. One of course, having something that can be applied to all jurisdictions sounds like pretty much impossible. But this process of not going after what's reasonable first, but instead first defining what is possible to do, i.e., what it's practicable, and then saying whether or not it's reasonable, this pretty well resonates with the Swedish environmental code. There you start by looking at what technologies are the best possible, and also available, and then try which technology is reasonable to use. That is, I will say, a good way of thinking about it.

Paul Ridlen

Anything to add Dom?

Dom Galic

Our situation is different. I can talk about it but I'm not sure how relevant it is to anyone in this room though. As far as I know, there's no expectation of ALARP in the US legal system. Most liability for a dam owner is going to be based on negligence, I believe, at least private dam owners. If somebody is being taken to court over a failure that's (ALARP) probably not even going to come up. Rather, they're going to focus on how they were negligent. All the different parties that could have a part of that negligence and so on. Reclamation has adopted the practice voluntarily. Voluntarily, again because there's nobody above us that's saying you have to do this or demonstrate this. The way that we use it now is a little bit different than others use it because we have the flexibility to see what is appearing to be working and to adapt the process. It's just another example of how it's (ALARP) really different for everybody.

David Bowles

There's at least one case of ALARP in the US, that Des may know some details about as well. It was a class action suit against the Ford Motor Company a few decades ago because the Ford Pinto was having a problem. The gasoline tank (petrol tank) was in the back of the car and when it got hit from behind it would explode and people lost their lives or they got seriously injured from the resulting fire. It turned out that when they (Ford) did the design of the Ford Pinto, they identified this issue before it went to market. And they did calculations - they did them on a chalkboard. And the discount calculations where they said OK, this is what it would cost to provide extra protection that would significantly reduce the risk of that (the explosion) happening. And I think it was less than $40 a car at that time. But it would have taken that vehicle over the $2,000 mark, which was kind of a niche in the market that they were aiming for. That was one thing that made them hesitate. The other thing was they did some calculations where they looked at statistics of this kind of an accident, and they made some calculations about what their liability would be on a case-by-case basis. They did the sums, and they essentially got to a balancing point where the additional revenue they expected to get by going to market at under $2,000, they thought was justification in their minds for being prepared to compensate people who were harmed. It turned out that somebody wrote that information down from the chalkboard and it went into the file and it was discovered during the class action lawsuit. And they (Ford) lost that lawsuit and I'm not giving you the right legal details here, but the gist of it was because they were at that …, essentially at a balance point, they weren't prepared to invest in a disproportionate way to save lives even if it meant hurting their market share. So, you know there's an example where ALARP principle seem to be applied in the US.

Dom Galic

But that was also probably more of an emotional appeal. I don't know if it was a jury trial or not, but again, I don't think that's set up legal precedent for ALARP in the United States. It's an example of how it can be used in a trial, but if you can convince the jury that they should be outraged, doesn't really matter what the reason for that is. That's going to determine liability.

David Bowles

So, another interesting thing is that Kip Viscusi[1] looked at product liability cases in the US and he also got some information on what U.S. companies were prepared to invest to avoid a product liability lawsuit - in terms of making things safer than maybe they needed to do. So, he came out with, an on average, about a 10:1 disproportionality, which again isn't a legal thing, but it's an interesting example of what people are prepared to do, or a company is prepared to do to avoid getting into that (liability) situation.

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[1] Viscusi, W.K. 1998. Rational Risk Policy: The 1996 Arne Ryde Memorial Lectures. Oxford University Press, Inc. May.

Paul Ridlen

I'm a moderator but I would like to comment. Even though there is not a strict expectation of ALARP in U.S. law, we are held to a standard of care, which is typically a reasonable main type of principle, so the principle would still apply, even though it's not strictly stated, as ALARP, I think that's what you're saying.

Dom Galic

One thing that could be interesting is, again, FERC requires its licensees to demonstrate if they are ALARP. I don't know if they really understand what that means, but it's in there, it's in their guidance. So if a FERC regulated dam under the new guidance fails and it goes to trial, it's quite possible that that concept will come up, unless it's simply easier for the parties to, again, focus on the emotional arguments and skip all that.

David Bowles

I suspect, just as you pointed out that after the fact that (ALARP) probably won't really matter; but FERC has resisted providing any guidance on disproportionality and they basically say that's a matter for the owner.

Dom Galic

It makes it hard to demonstrate ALARP as an owner. If nobody's telling you what to do or use.

David Bowles

They (FERC) have laid out some ALARP guidance, but they've just said they haven't provided guidance on disproportionality.

On static liquefaction

Paul Ridlen

If you have a static liquefaction failure mode, should you not do a risk assessment without considering the mitigation measure in place? Or without considering the mitigation measure?

Malcolm Barker

So, should you do one considering the mitigation? Is there a double negative?

Paul Ridlen

If you have a static liquefaction failure mode, should you do a risk assessment without considering the mitigation measure?

David Bowles

The challenge there is how you're going to characterise a full range of triggers, right? That's the challenge and I don't know that there's a way to do that. So, to me, if it's really a viable failure mechanism, a viable process, then you need to prevent it to the degree that you can. That's the highest point on the hierarchy of controls, right?

Jiri Herza

We attempted to address that question (of static liquefaction) in Appendix A and B of the ICOLD Bulletin 194 and I think we provided some answers in there. After many months of negotiations, we hope we developed something practical for people to follow and it was reviewed by David Reid, who led the short course on static liquefaction yesterday. The conclusion we came to is basically that we don't have the knowledge to be able to predict when static liquefaction happens. We don't even have names for all the triggering mechanisms, and we would be kidding ourselves if we put numbers to them. So, our rule no. 1 is: don't allow conditions at a tailings dam to result in a situation where liquefaction can occur. If that situation exists, don't look for the trigger, because the trigger may not be visible to you, and we believe you should take action.

Attendee

The reason I would maybe take issue with that approach is, you know, we have to show compliance to GISTM and how can we define whether or not static liquefaction or dynamic liquefaction, you know is credible. I mean we have to make a judgement on what is credible. And I know I'm getting into all the definitions, but that's required of us by the GISTM. And so, at some point you have to make a judgement call. Now, I agree with everything that you've said on that. If you have these issues, then you need to mitigate those issues. But if you don't have those issues and you've documented that. You know how are you able to meet their criteria for the GISTM that we have to complete risk assessment? And because I guess sorry the going back to the original concept for me is I would not go in front of an independent technical review board with a risk assessment without having considered static liquefaction. So, that's the first thing that I wouldn't do and my company wouldn't allow that. And so, we have to, you know, put static liquefaction into our risk assessment. And somehow, we have to make a judgement call now in, in our case, we do a lot of SQRA. And so you know, we make qualitative estimates on some of these things. But, anyway, it would be impossible for us not to include something about static liquefaction.

Jiri Herza

I agree with you and we are not suggesting that you should say "I do not look into static liquefaction, or any other failure". Static liquefaction is one failure mode that might or might not occur. You might recall about two hours ago we opened the piping toolbox. The screening tool which was there provided conditions at which the mechanism (piping) could not take place. Take static liquefaction, if you have a dry stack with no phreatic line and no saturation whatsoever, you may say I'm excluding this failure mode from happening because I don't have the conditions which are required for static liquefaction to occur. Or I might have, for example, materials compacted to a level that I can't get static liquefaction for any foreseeable loading conditions because I'm so outside of the zone (referring to a state at which contraction is possible). So, you might have conditions at your dam you can provide documented evidence of, that will not allow static liquefaction to occur because we know what susceptibility to static liquefaction is. We can't predict when it happens, but we know the circumstances at which it might happen. So, if you can demonstrate that you don't have those conditions at your site then you don't have to even go into probability to estimate.

Attendee

Then maybe, perhaps change the statement that was said that that a quantitative estimate of the likelihood of static liquefaction is difficult, possible beyond our certain capabilities. Is that a more fair statement to say?

David Bowles

That's my understanding and if I was in your situation then I think the option is to say, when you present your risk assessment, "This is credible, but it's indeterminate." We just can't put a number on it, but we've got to address it. And then it becomes the baseline for looking at the additional or residual risk beyond that and making your ALARP arguments beyond that, because you've already dealt with that particular credible failure mode.

Paul Ridlen

And that's what we're saying, what Jiri is saying and what is in the ICOLD bulletin. If static liquefaction is possible, if it's technically justified, then you just consider that it will occur rather than trying to assign a probability of occurrence, you assume a probability of 100%, of 1, which is pretty much what Morgenstern said in his 2018 paper. Now he did limit in his statement to preliminary design. But what he said is in his practice for preliminary design, if liquefaction can occur, I assume that it will and design for it. I think that's really where the current kind of standard of care is that you can actually have a static liquefaction to occur. And again, Jiri had described two ways that you can eliminate it, if the structural zone is compacted sufficiently so that it cannot occur under all reasonably anticipated loading conditions, or if it's unsaturated or saturated to such a low degree under all loading scenarios that that it can't be triggered as well, those would be the two kinds of primary exclusions that you could justify eliminating static liquefaction as a possibility.

Attendee

Or you have very plastic soil? You have a very plastic soil, so maybe, you're working in the very plastic domain and you're not having cohesionless soil. But you may have undrained conditions.

Paul Ridlen

Potentially, yes, potentially that there's enough plasticity or some other behaviour or you have, actual cement, right? So maybe, you add cement and you have a concrete dam in essence, so concrete dams typically are not considered to be liquefiable.

Attendee

Thank you for clarification.

Jiri Herza

Thank you all very much.

Panel Discussion No. 2

On duration of comprehensive risk analysis

Paul Ridlen

This one is for Dom. How long would it take to complete that (risk) review process on the example project that you presented?

Dom Galic

It depends on when you start the clock, but there is a formal milestone involving the physical exam of the dam, and then there's three months between then and when the results are presented. However, the review, the tabletop review can begin before the physical exam, so from the first time the team meets to when the work is completed could be on the order of 6 months. They usually end up being 500, 600 page documents, so they're pretty comprehensive.

On GISTM

Paul Ridlen

How do you, to the panel, correlate the ALARP requirement versus the GISTM's goal of zero harm to people and the environment, risks identified in the broadly acceptable zone versus acceptable loss of life. This is a risk, as it could wrongly suggest, that any additional preventative measures shall be implemented? ALARP does not mean necessarily safe TSF operation or safe closure. Does that make sense, or do I need to repeat?

Malcolm Barker

I think, Des once said, there's no such thing as a safe dam. There is always a probability that a dam could fail. ALARP is just trying to address what you can do to bring it down as far as the risk is concerned. It's not saying, "It's going to be safe." It's just you're trying to bring down your safety margin.

Paul Ridlen

So, in other words, it isn't totally consistent with having a zero-harm goal but requiring ALARP to be met.

Jiri Herza

I believe that zero harm is an aspiration rather than objective. The only way you achieve zero harm associated with any asset is not to have that asset. But then it brings the burden to society of not having any benefits from the asset. You have one thing being an aspiration and another (thing) being a goal that you can actually achieve. I don't see that there is any disagreement and I see zero harm as the aspiration and we manage the dam towards this aspiration although it is not something that we may physically achieve.

Des Hartford

Can I make an observation? I was very surprised when the GISTM came out the way it did. Not only the way it did, but it didn't come out in interim form. Because if it came out in interim form it would be possible to test drive and work out all the bugs, over the five or a 10-year period and then revise it. So, is there a mechanism to go and get the GISTM into some type of, revision, evolving, updating basis? Because if it is not going to evolve, it will not be relevant in what is an evolving policy world anyway. So, in my view, there's a need to essentially take the step of getting to an updatable document where a lot of these wrinkles can be ironed out. The simplified matter is that we take these risks in the interests of societal progress. That's reality. We cannot come up with zero risk. It's impossible. And the rest is this is a balancing act. In my view, there's too much of government running away from it, dealing with its position as to what should be in relation to the public interest. If they were a little bit clearer there, then policy scientists would be able to work with it. COVID did expose, in governments all over the place, total inadequacy to deal with these types of tough issues. 40 years ago in the UK, Health and Safety Executive is only a shadow of its former self. They had a huge amount of capability in those days. They've lost a huge amount of it for political reasons. So, the whole question about the role of government, the role of regulations, the interpretation and where the owners sit relative to that, is something that is going to evolve. Who actually is the authority that produced GISTM?

Paul Ridlen

It was a temporary committee convened by three groups.

Des Hartford

Well, and now, look at what people have to deal with on the ground. Something that doesn't fit together.

Jiri Herza

Unfortunately, there is no one to complain because the offices are closed, and there is no one to receive feedback.

Des Hartford

Well, the offices might be closed, but the initiators, like one of them was in Sweden there was the Church of England, so the initiators are still around. It doesn't mean to say," It's closed." You can find these groups and then, once use of this approach and we have the experience, then we can go back to the same groups as the pension funds aren't going to disappear.

On failure modes

Paul Ridlen

OK, I'm going to try to get through these (questions) so we get as much as we can. The next one I think is pretty practical. Is there any list or generic list of failure modes and associated controls that are being developed for companies to use as a checklist or a starting point for identifying failure modes on TSF? Anybody aware of any? Papers or documents in progress.

Jiri Herza

There is one you might be aware of it. It's ANCOLD guideline on geotechnical investigation for dams that lists typical failure mechanisms and controls. It's not exhaustive and it just refers to failure mechanism associated with foundations including tailings dams. I'm not aware of any exhaustive list of potential failure modes and what you should do (referring to controls).

Paul Ridlen

There is a list of failure modes in the ICOLD Bulletin 194. It's not comprehensive and its very high level, but that is a place to start.

Des Hartford

Could I make an observation on this line because the question about failure modes is a difficult one. And again, all dams are unique. But every component in the dam has a functional mode. And you can invert the functional mode to get the failure mode directly. Loss of function gives you a failure mode, so if you know the functional mode, if you know how your dam your tailings dam works (you also know the failure mode). Now you've got these long structures, so you're going to have differences in foundation condition. You'll have to discretise your structure to be able to say everything in this section is pretty well the same. All the components work the same way. They're all under the same state of stress or whatever. But if you understand the functional modes, you can then invert them to get your failure modes unique to your structure and the way it works.

Jiri Herza

And vice versa, if you are able to express the narrative of failure, you are able to express the narrative of controls.

Malcolm Barker

I think just going out with that, every failure mode you define when you start to work through your process of the failure mechanism. To have a generic thing is sometimes dangerous. But you've got to think about your own dam and say well, what are the failure mechanisms, what other failures, what other components, what other functions, etc. To force you to think carefully about your dam, your tailings dam.

Paul Ridlen

I'm the moderator, but if I could just say that was the purpose of the exercise with the tool for piping. It was really more to walk through the process of thinking through and it's a well-documented process which has its value not to determine the actual calculation precisely. What the risk is, but of really informing the process so you follow the same process for other types of modes. They're identified through your understanding of how it functions.

Malcolm Barker

I know that the risk assessment guidelines at ANCOLD have a very small bit on tailings dams and basically say, you've got to look into tailings dams where the process is similar, but the failure modes are different, and you need to look carefully at the failure modes. They don't go through a list of exhaustively …, there's nothing of that.

On evolving nature of tailings dams

Paul Ridlen

This one should be quick. TSFs are structures that are continuously evolving over time. So what should you consider in the analysis? In the risk analysis? Do you evaluate the current condition or do you evaluate ultimate or final conditions?

David Bowles

I think there's some stages in between as well and you look at essentially critical stages all the way.

Malcolm Barker

I think you got to be very, very careful in saying this is what it's going to look like in 10 years time. You have no idea as it might change. You look at it right now, this is what it is now. And if you think it's going to change, you can try and do that. We've been asked to do all the time. What about in 10 years' time you say? Well, hang on, the population's going to change. They are going to put something over there, forget about the dam itself, the whole. downstream consequences will change. You don't know, so I think it's dangerous to try and say, yeah, I can evaluate it for 20 years time. Forget it. But closure is a different beast. If you said I'm going to have to close this, I have to reduce, I have to eliminate this, as Des says you walk away. I don't think any dam owner walks away. Actually mines, all the mining guys I know of, they still have to go there and do their operation and maintenance on a closed dam because they realise I cannot walk away from this beast, it has things that are happening.

Des Hartford

If the company still exists.

Malcolm Barker

Some don't exist and the government had to take over, right? And it's a nightmare for them.

Jiri Herza

I believe that, especially for tailings dams and especially for those that are raised upstream, you have to understand the future conditions. We discussed risk informed decision making during the design earlier, when, as Des explained, the situation is malleable, and we can modify design and reduce the risk. If you build upstream, what you are doing now will one day form a structural zone underneath the dam shoulder. You must therefore consider the future conditions and make risk informed decisions. For example, you have to compact say a 150 m long strip (of tailings) along the perimeter embankment in preparation for future raises and you have only one opportunity to do so, as now. In the future, you can't go back, remove the upstream raises and recompact (the tailings). You're right Malcolm, you never know what you're going to have, but you have to have in mind the foreseeable loading conditions.

Paul Ridlen

I guess my thought would be you, you have to evaluate the future conditions based on your current state of knowledge. So you don't know everything about the future, but you have a current state of knowledge and you use that to evaluate future conditions to the best of your knowledge. But I don't think you could stop just now because of the way that loading changes over time.

Ryan Singh

When you talk about risk assessment also depends the form, the tools you use. So something like the piping toolbox requires an understanding of your current performance, which you can't have for future facilities. It doesn't exist so you can't measure the performance, but you can use a risk informed design. The future actions, so it depends on what you mean by risk assessment as well.

Jiri Herza

The risk profile of water dams is changing as well. In Western Australia, we have a growing population and in Denver you have a growing population too Dom, right? So, you might have a dam, which had zero consequences of failure in terms of potential fatalities (when it was built) but as the population (downstream) has since grown and the consequences and risks have increased.

Malcolm Barker

To finalise that, as far as I'm concerned, when you're designing your facility you have to plan for the closure. That's part of your original plan, right? How many times have you had a closure plan that's changed? I guarantee your closure plan changes. Every single dam I've worked on has changed from the original. So you're struggling to actually say I'm going to be there in 10 - 20 years time. You really struggle. You can only do your best. And as things change, exactly like the population downstream, you got to fiddle around and that's where I'm coming from. You got to be very careful in saying, I can predict the future, you can't predict.

On risk informed design process

Paul Ridlen

I think there is one more important question and I think we've covered most of it, Dr. Morgenstern and others has advocated for the application of risk in the design process. The performance based, safe or performance based risk informed safe design? Do you think these concepts of risk assessment are applicable to design and is there adequate guidance in the literature to actually implement that? Ask Dom to start.

Dom Galic

Obviously, we've talked about this, but we are a little bit sceptical of risk for design at Reclamation simply because we don't want to be put in a corner. We don't want somebody to say to us, hey, look, if we do this, you're below guidelines, therefore it's OK. The guidelines are not a design tool. Designers should be making design decisions based on good practices and I can elaborate on that, but I won't. What I will say is there are some situations where there's really no existing design guidance. One example would be Teton Dam, like I mentioned earlier, Reclamation's only catastrophic failure to date. The reason the dam failed was because they decided, during the design process, that they could save money by creating these trenches in the fractured rock at either abutment. Once they did that, they could backfill those trenches with soil and basically be grouting from a lower elevation to save on grouting costs. There was no existing design standard at the time saying not to do that. And really the threats associated with that kind of design decision I don't think could have been appreciated at the time without really looking at it from a PFM perspective. I think if we had encountered that scenario today, we would be able to convince ourselves that it probably wasn't a good idea regardless of what the design standard said. So I think there's a place for it but we also have to be cautious about how it's going to potentially be used against you to put you in a place where you don't want to be, which is not what we should be doing.

David Bowles

I think the process of, as you go through your design, identifying failure modes, identifying controls and then making choices on what are reasonable controls to implement, that's a very good discipline to go through in the design.

Jiri Herza

And as engineers we do it although not explicitly expressed as a risk informed design process.

David Bowles

Yes, it's the thought process.

Malcolm Barker

We have to do safety in design. It's a requirement to do a safety in design evaluation, which is a living document that starts from when you can go from conceptual right through to the final construction. That's a risk basis in the sense of you're looking at safety. How you can do all your construction safely? Are you posing a risk by doing A, B or C or whatever else you can take it right down to component level or building a concrete beam that has to go across in a tunnel. Is it safe? Well, how do you put it in there? And what are the risks associated with this thing collapsing on somebody, et cetera. So I think it's quite appropriate to use risk informed design in that sense.

Des Hartford

Having tried on numerous occasions to understand precisely what Professor Morgenstern was saying, I failed on every occasion, but there is not sufficient guidance as to what is meant and how it might be applied, and across a broad spectrum of situations. What might be used in relation to risk informed design? Good practise risk assessment to plug the holes in good practise. Can't do much better than that, but basically you're meeting your deterministic criteria and your probabilistic criteria. Because the whole thing about these big structures that are there forever, as I mentioned earlier, they are a one-shot deal and you can't do cost benefit analysis on future generations. Just doesn't make sense.

Paul Ridlen

So it seems like the consensus is, again for the sake of closing things out, is that there is an application of these risk principles in design, but there's inadequate guidance currently on how to actually do that. I think we agree on that.

Dom Galic

And we could probably also agree that plotting below guidelines, whatever that means, does not mean the dam won't fail. It's an arbitrary bar. We said that we want to be below, but it doesn't mean anything in that sense.

Malcolm Barker

I think Des made the very good point that when a dam fails they're going to check you out. They're going to say “did you identify that failure mode and all of the things you did?” and if you say, “oh I didn't see that” you're in trouble. At the same time, when you're doing your design, what else you've got to find, you have to dig into. My ex-boss in Zimbabwe, he said there's a whole lot of work they're doing on Kariba Dam that is a complete waste of time on the plunge pool. I don't know if you know all about that now, doing this huge excavation, millions of dollars going into this. He disagreed with that whole failure mechanism in there and considered that rubbish. But it's been postulated, therefore, they've done something about it. If it failed and they hadn't done something about it, they'd be in serious trouble. Even though you might think it's a waste of time, it's not. It is a plausible failure mechanism, it can happen and you need to address it in some way, if it is really going to be serious.

On responsibility

Attendee

What's the responsibility? I mean, how does it work for a closed facility with very small consequences because there was nobody living downstream. Then, the government decides to build a town downstream and your consequences and your ALARP is out. So who's responsible and accountable for that?

Malcolm Barker and Jiri Herza

The government.

Des Hartford

Well, they (the government) should be responsible but they will do their best to pass it on.

Jiri Herza

The government should be (responsible), but in reality is not. They (the government) would grant the permit for those to build a house and it's up to you to make sure that they are not killed I'm afraid. That would be the case.

Paul Ridlen

I think it would depend on the location where you're at, so in theory it should be. The government is the one that imposed the risk because they're the one that imposed the consequence. But I think it depends on the location.

Des Hartford

But they (the government) also permitted the dam in the first place. So they've got it from all angles. It's just a difficult political decision for people who've got a short four-year mindset.

Dom Galic

You could also be a different government that granted the permit like in the United States, could be a local government, that permits the land use, whereas somebody else granted the permits for the dam.

Jiri Herza

And the circumstance may have changed. The pressure then was to build a dam for, let's say, agriculture. Now the pressure is to create more room for people to live in and it might be that the inundation zone below the dam break is the best zone for people to live in.

Dom Galic

Or the only area left to build it.

Des Hartford

I do agree, because I've had situations where chief executive would come to me and say, here's the one we're stuck on, come up with something and come up with basically a justification to take risk at a particular level. After doing everything that we could reasonably do to minimise the risk. I have got the dubious privilege of actually writing these things for them and it does actually force you to really think hard and going way beyond. You do an awful lot of things that are uneconomical to get yourself out of a political bind.

Jiri Herza

This is the last request for today. Can you all try to use this QR code and provide feedback for us to get better?

Appendix C. Material for group activities

Example dam – TSF1

Summary of facility statistics

Operational details

Type of information	Data
Name of facility	TSF1
Country	Australia
Region	Pilbara
Site/Operation	Undisclosed
Mineral	Iron Ore
Climate	Arid with hot dry summers and mild winters
Ore process	Crushing and screening

Facility details – Current arrangement

Component	Type of information	Data
Facility details	Facility-type	Single cell storage with one cross-valley embankment (Main Embankment) and two saddle embankments.
	Status of facility	Active
	Years active	30
Storage areas	Facility impoundment area (present) (m^2)	800,000
	Facility catchment area (m^2)	900 ,000
	Storage capacity (Mm^3)	18
	External catchment description	Catchment area sparsely covered with shrub and spinifex grass.
	External runoff coefficient	Not specified
Freeboard	Beach freeboard allowance	< 0.5 m
	Operational freeboard allowance	> 1.5 m

Component	Type of information	Data
	Wet season allowance	None
Flood handling	Flood handling capacity	PMF, estimated to be 1:1,000,000 AEP
	Flood management	Flood managed through flood freeboard and spillway.
Seismic design	Operating Basis Earthquake (ANCOLD)	1 in 475 AEP, PGA 0.0359g to 1 in 1000 AEP, PGA 0.0580g
Spillway	Location	Excavated into natural ground (rock). Located approx. 500 m away from the confining embankment. Arranged such that flows are directed away from the confining embankment.
	Type of spillway crest	Broad crested
	Type of spillway chute	Over natural ground (rock)
	Type of energy dissipating structure	N/A
	Sill level (RL m)	765
	Depth (m)	1.0
	Width (m)	35
	Capacity (m^3/s)	48

Facility details – Current arrangement (cont.)

Component	Type of information	Data
Tailings deposition system	Stored material delivery method	Delivery pipeline
	Deposition arrangement	Perimeter discharge, multiple spigots
	Sub-aerial / sub-aqueous?	Sub aerial
	Pipeline details (process plant to TSF)	DN 300 PE lined steel pipeline
	Pipeline details (at TSF)	DN355 HDPE PE100 PN10
	Spigot details	DN225 HDPE PN10 slotted pipe

Component	Type of information	Data
	Spigot spacing (m)	50
Return water system	Decant arrangement	Skid mounted diesel pump with floating suction line and screen
	Pump details	No details
	Pipeline details	DN250 PN10 HDPE
	Suction line details	DN315 HDPE PN10 open end pipe
	Decant return rate (m^3/hr)	200
Decant causeway	Details	Earth fill access ramp with a series of pads for the decant ramp to be located. Access ramp is located approx. 500 m upstream of the embankment, along the storage rim.
	Crest level (RL m)	Ramp down from RL 766 m to RL 759 m
	Raise details	N/A

TSF1 Main Embankment details – Summary

Component	Type of information	Data
General	Function	Confining embankment of TSF1
	Crest level (RL m)	766
	Max. dam height above ground level (m)	24
	Facility crest length (present) (m)	300
	Dam crest width (m)	6
	Average upstream slope (1v to ??H)	2
	Average downstream slope (1v to ??H)	2.75
	Depth of foundation cut-off (m)	2

Component	Type of information	Data
	Chimney filter present?	Yes
	Blanket filter present?	Yes
	Liner details	None
	Number of raises	1
Foundation	Foundation type	Soil foundation
	Foundation geology	Alluvial (soil)
PAR / PLL	Population at Risk (Flood Failure (FF))	10
	Population at Risk (Sunny Day Failure (SDF))	5
	Incremental Potential Loss of Life (FF)	5
	Incremental Potential Loss of Life (SDF)	0
ANCOLD consequence category	ANCOLD Flood Consequence Category (CC)	High B
	ANCOLD SDF CC	High C
	ANCOLD Environmental Spill CC	Low
Underdrainage	Type	None
	Drainage details	N/A
	Outlet details	N/A

Component	Type of information	Data
Starter embankment	Type	Cross valley embankment
	Crest level (RL m)	762
	Construction date	1989
	Construction material	Zoned earth fill: Compacted clay core with compacted earth fill shoulders with filter blanket and chimney filter
Raise 1	Type	Modified centreline raise

Component	Type of information	Data
	Crest level (RL m)	766
	Height	4 m raise
	Construction date	2015
	Construction material	Homogenous earth fill

History of TSF1

The original TSF1 was designed by a reputable design consultant (Consultant A) with a demonstrated history in the design and construction of water and tailings. The construction for the original TSF was carried out between June to October 1989 and the facility was commissioned in 1990. The TSF1 storage area was formed by the construction of one Main Embankment built across a valley in a historical watercourse that featured seasonal flows prior to the facility being built.

The Main Embankment was constructed to a reference level of RL 762 m. The Main Embankment was originally 20 m high and designed as a water retaining structure. A steel decant tower was constructed upstream of the Main Embankment with buried decant outflow pipes leading to a lined return water sump located downstream of the Main Embankment. The original tailings deposition formed a decant pond against the embankment to allow for decant water to be transferred via the decant tower to the return water sump. From there the return water was pumped back to the process plant.

A Pre-Feasibility Study (PFS) completed by another design consultant (Consultant B) in 2008 recommended that the next stages for TSF1 include staged upstream raising to a final height of RL 790 m to provide storage for then planned Life of Mine. To facilitate this, a change in the deposition practice occurred in approximately 2009 to move the decant pond away from the Main Embankment to allow for potential upstream raises. The decant tower was decommissioned and an alternative decant location was developed upstream in the storage area with ground-mounted pumps.

The buried outlet conduit was sealed and decommissioned during this time, however, there are limited design and construction records for this project.

The required deposition change was not implemented in sufficient time to develop adequate tailings conditions to allow an upstream raise of the Main Embankment. As a result, the strategy to upstream raise TSF1 was abandoned.

Instead, a mined-out pit was used for tailings storage between 2010 and 2015.

Additional TSF1 storage was created in 2014 by raising the Main Embankment by 4 m raise to RL 766 m. The raise was designed by a third design consultant (Consultant C), and construction was completed in February 2014. The condition of the tailings beach upstream of the Main Embankment had improved during the inactive period and the raise was completed using the centreline method. The raise also included the construction of two homogeneous earthfill saddle embankments.

Main Embankment details

Length: 300 m

Height: 24 m.

Cross section from original design report by Consultant A details embankment with zoning and filters. Internal clay core and chimney filter constructed to 757 m with starter embankment to RL 762 m, however, during the centreline raising of the embankment to RL 766 m, the filter and clay core were not extended.

Downstream face of 1V:2.5H.

Nominal 2 m depth cut-off shown in the As-Constructed Drawings. The photos of the keyway in the Construction Report suggest the cut-off was slightly deeper at the south abutment.

Has been raised 1 time using centreline raise technique.

Foundation details:

Original geotechnical investigation report for the facility stated that the ground conditions was identified to comprise variable thicknesses of clay and gravel overlying variably weathered banded iron formation rock types. The selected location for TSF1 was located across a narrow steeply sided valley. The abutments and downstream section of the valley were identified to comprise slightly weathered, dipping and jointed hard ridges and near vertical cliffs. Additionally, relatively thin scree slopes of gravels and clays were present at the bases of these ridges.

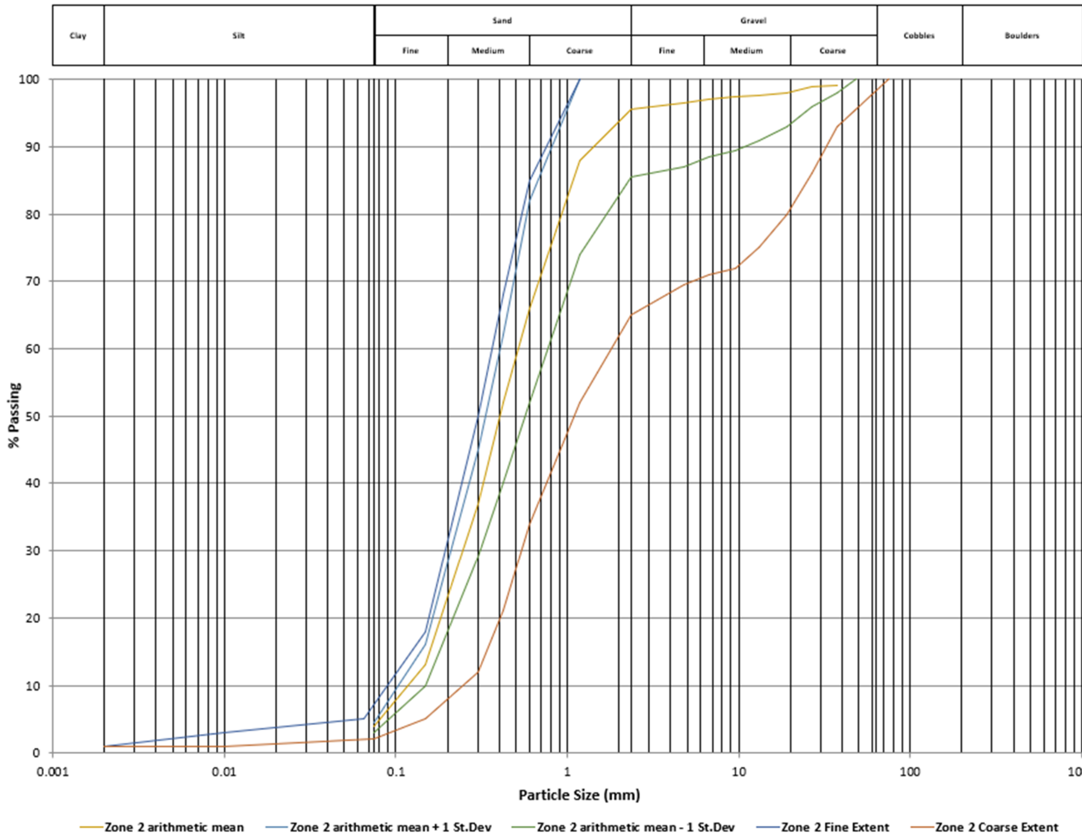
In the valley floor and towards the upstream section of the proposed embankment footprint, the ground conditions typically comprised clays and gravelly clays overlying variably weathered dipping and jointed shales and cherts. The report also documented that the abutment slopes were gentle to steep and covered by variable thickness of scree material. Identified rock outcrops generally coincided with the steeper sections of the slope near the contact with the banded iron rock.

A fourth consultant (Consultant D) completed a 2019 geotechnical investigation which included drilling of 3 boreholes in the Main Embankment crest, one in the middle, and one at either abutment, as well as a borehole at the downstream toe. The borehole logs indicate the foundations are soil, inferred to be alluvial.

Chimney and blanket filters:

The design of the filter zones in the Main Embankment was not clearly documented in the documentation made available for review. Additionally, there were no Quality Control or Quality Assurance certificates available, however, a Particle Size Distribution was found in available construction records which provide the bounds of the filter material.

These were later digitised as part of the raise design, in addition to the particle size distribution mean and standard deviations.



Tailings delivery arrangement:

HDPE delivery pipe running along crest of embankment and perimeter roads of the storage, with a series of spigots along the crest and perimeter roads. No structural assessment of the HDPE pipe is available, though it has been in operation for more than 6 years.

Supernatant pond details:

Decant pond has been located away from the Main Embankment for some time, with a stated minimum beach length of 200 m to be maintained. The beach length has typically been maintained at more than 400 m. These beach lengths correlate to a current pond elevations of RL 764.20 m and RL 763.20 m.

Extreme rainfall management:

The detailed design report for the raise to RL 766 m included flood routing which confirmed that the spillway at TSF1 will have sufficient capacity to convey the PMF flood, with the maximum water level as a result of the PMF being estimated to just be below the embankment crest level. Other rare and extreme flows were routed through the facility as part of the design, with the reported maximum water level, assuming a maximum operating pond for the facility at RL 764.5 m.

Event	Maximum water level (RL m)
PMF (1:1,000,000 AEP event)	765.94
1:10,000 AEP event	765.15 m
1:100 AEP, 72 hour event	764.6 m

Operational details and practices:

Based on available documentation, TSF1 has been operated as intended and has performed within expected limits.

Key inspection and performance note

Cracking – Transverse cracking on the crest of the Main Embankment has been noted periodically throughout the life of the facility. Typically, these cracks have formed all along the crest and does not appear to be located preferentially at any point on the crest. The majority of reported cracks have been in the order of 3 mm wide, however, there have been four reported instances of cracks being up to 20 mm wide at the crest. For these four instances, the crest was locally excavated up to 0.5 m deep, and material was replaced. An effort was made to see whether the cracks extended beyond the excavations, however, the earthworks resulted in the embankment conditions being obscured.

Seepage – There have been no reported instances of seepage from the Main Embankment, including during Stage 1 of the facility, when water was stored against the Main Embankment.

Stability assessments

A single section on the Main Embankment was analysed for stability in the raise to RL 766 m as presented in the design report. No discussion is provided in the report regarding the process of selecting and locating the sections.

A subsequent review in 2022 identified that the stability analyses presented in the design report for raise to RL 766 m does not meet current state of practice standards. This was due to the reviewer identifying that not all applicable scenarios or loading conditions were assessed. Additionally, pseudo-static analyses was carried out and at the time of the review it was deemed as an inappropriate technique for seismic stability assessments of TSFs.

Assessed Factors of Safety in the design raise report were:

- Drained – 1.6
- Undrained – 1.6
- Post-Seismic – 1.6

The outputs from the stability assessments completed in the raise design report are presented on the following pages.

Available documentation

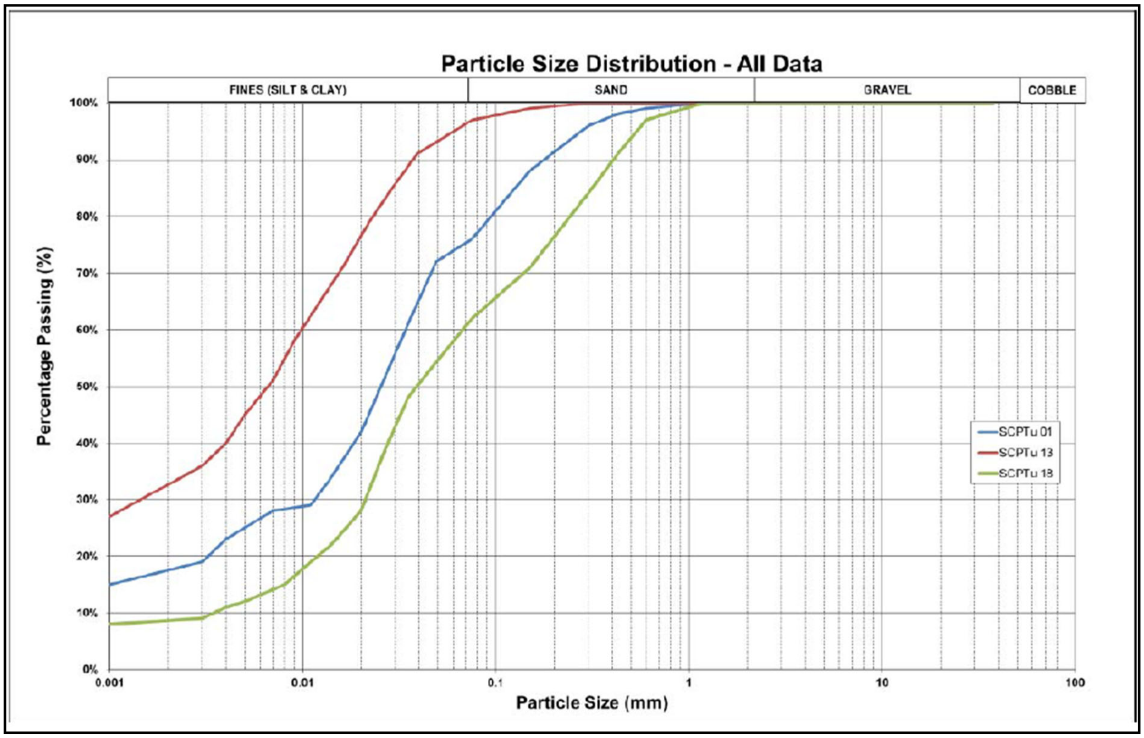
Geotechnical investigation reports and data

A significant number of native files related for the factual and interpretive geotechnical information from the original and raise projects was not available for this assessment.

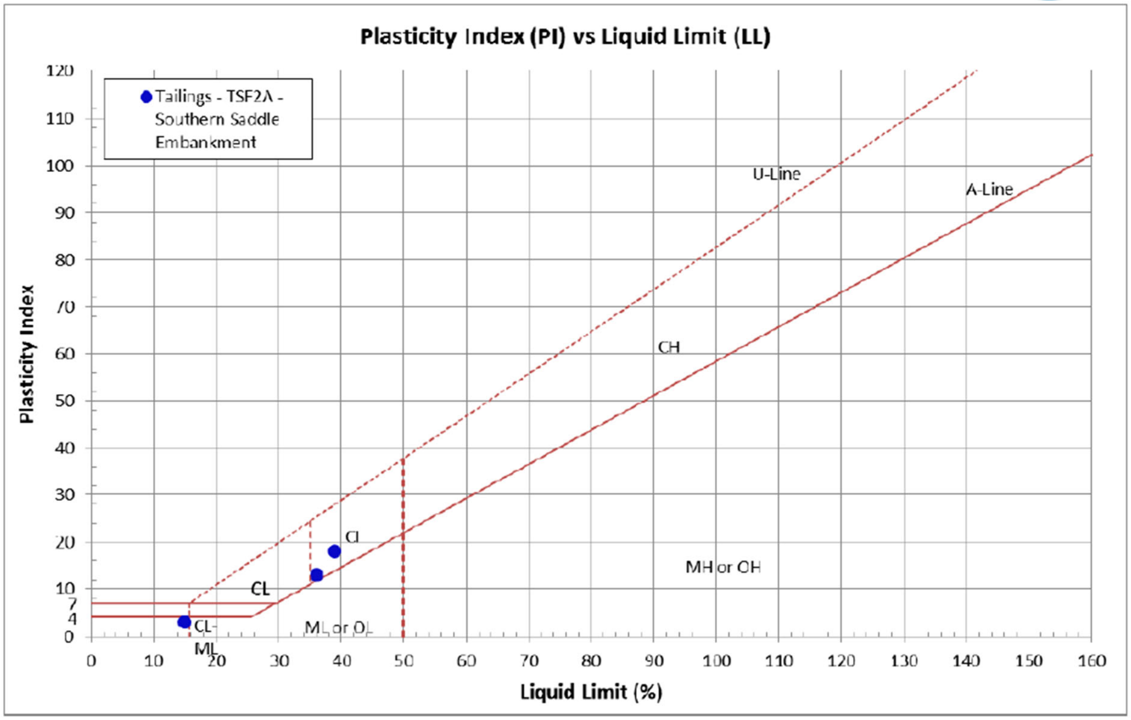
Select information, with notes, is presented below.

Tailings geotechnical data and interpretation

PSDs (locations of testing unknown, though understood to be from within 20 m of starter embankment)



Atterberg Limits – Tailings (locations of testing unknown, though understood to be from within 20 m of starter embankment)



Tailings particle density (locations of testing unknown)

Particle density tests completed for tailings sampled within 20 m of the starter embankment estimated a range of specific gravity between 3.42 and 4.20.

Tailings in situ moisture content

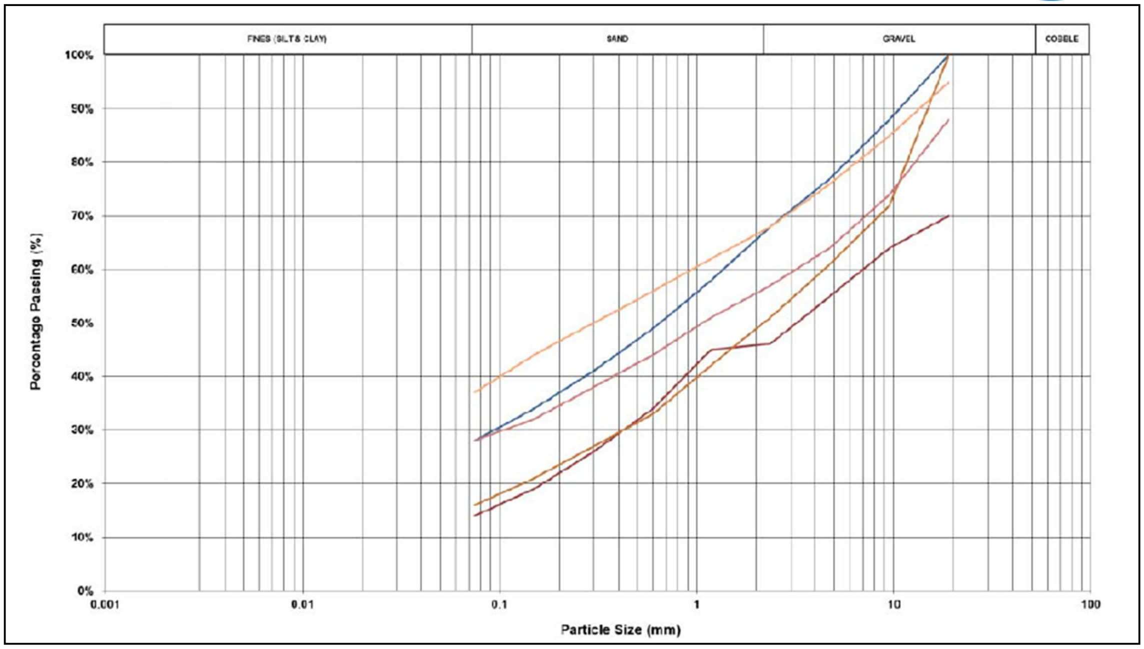
The moisture content of several tailings samples obtained from the tailings beach surface was measured by oven drying and the results ranged from 2.2% to 40.0 %

Tailings in situ density

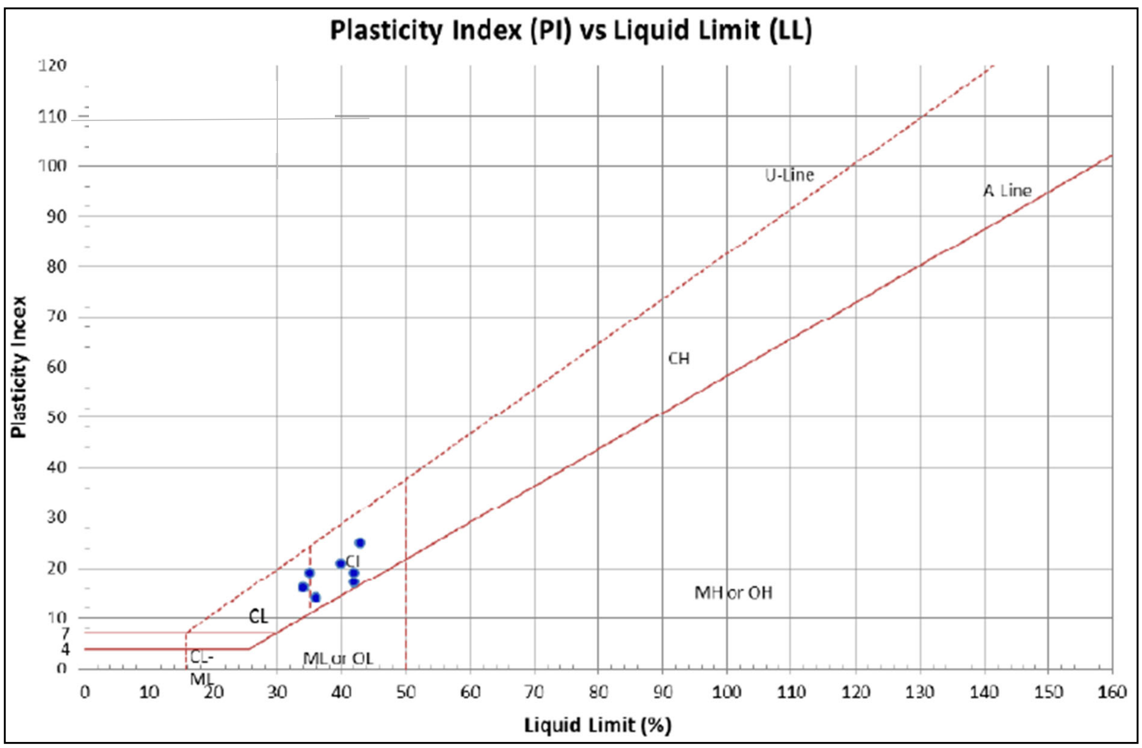
The in situ unit weight of the tailings was estimated from CPTs along the tailings beach of the starter embankment during the TSF1 raise project. The bulk unit weights shown in the table below were adopted for the embankment design stability analyses.

Embankment geotechnical data and interpretation

PSDs - Embankment core material (depths and locations unknown)



Atterberg Limits – Embankment core material (depths and locations unknown)



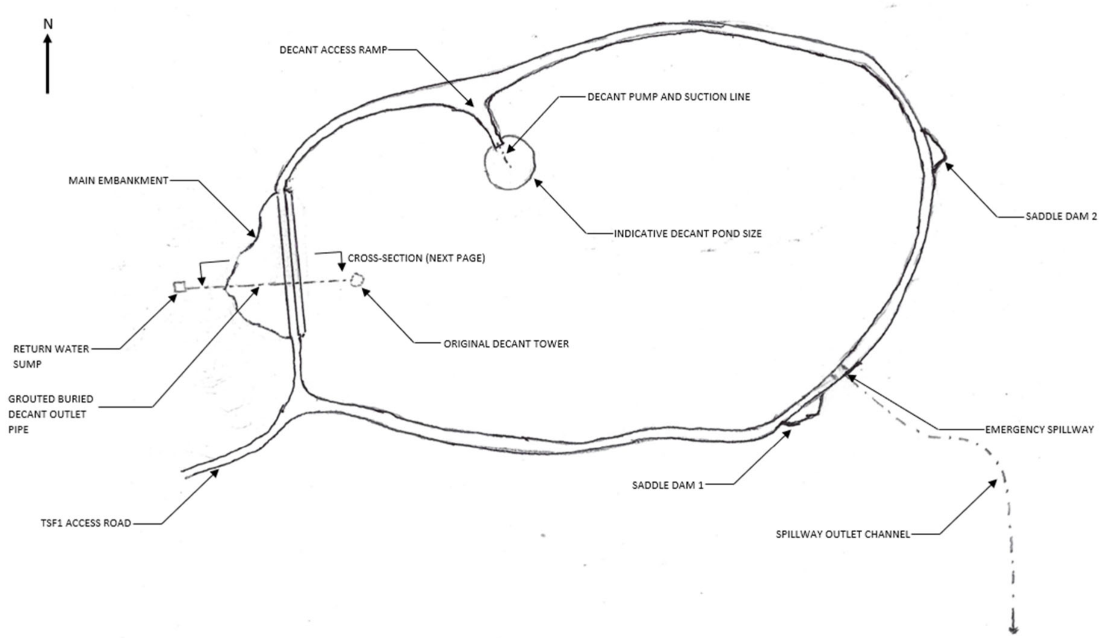
Embankment material moisture content and in situ density

For the TSF1 raise design, the dry density and moisture content of the embankment fill was estimated using lab certificates reporting the dry density of samples obtained from geotechnical investigations completed in 2010.

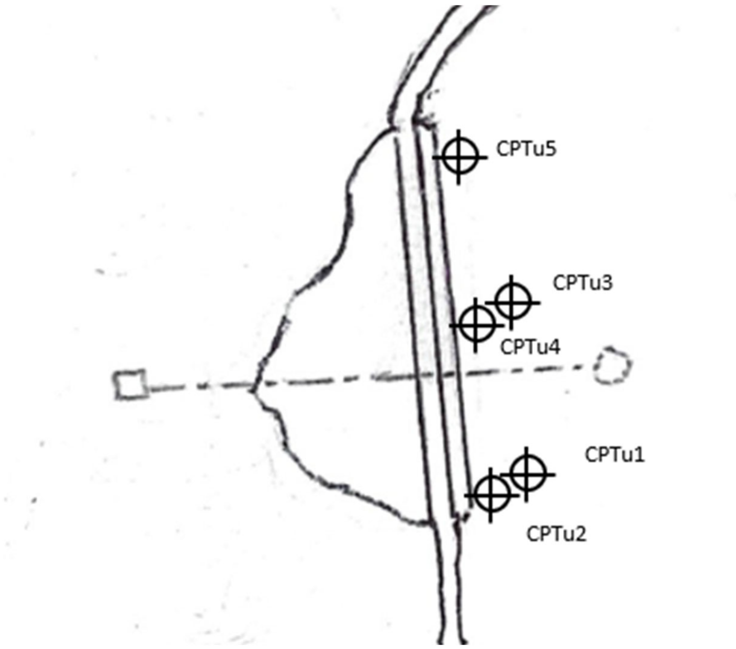
The results showed that the material moisture content was generally between 10% and 20% with a dry density of 1.75 t/m^3 to 2.15 t/m^3. This corresponded to a bulk density of 2.06 t/m^3 to 2.43 t/m^3. The average of these values corresponds well with the bulk density stated to be adopted in the design for the starter embankment. The raise design adopted a bulk density for the Zone A and Zone B embankment fill material for the Main Embankment of 21.5 kN/m^3 and 22.0 kN/m^3 respectively.

Additional figures

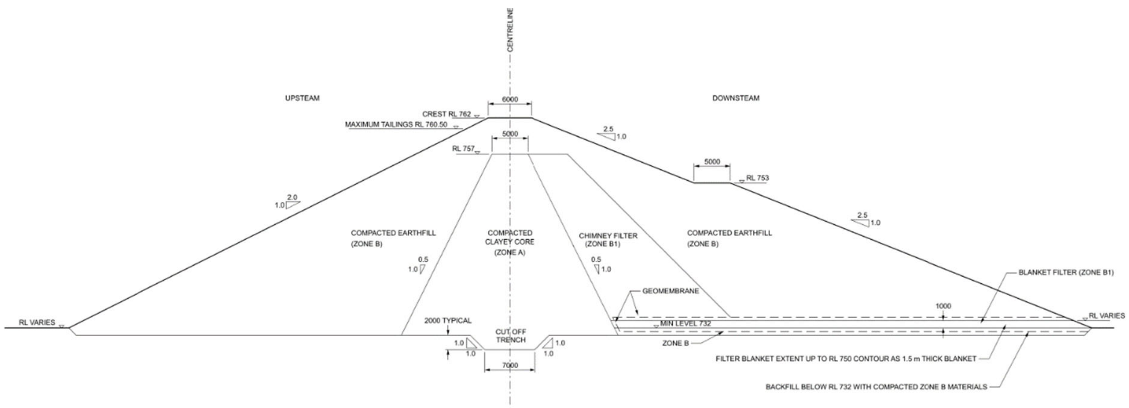
Hand-drawn plan of TSF1, indicating layout of key infrastructure (not to scale)

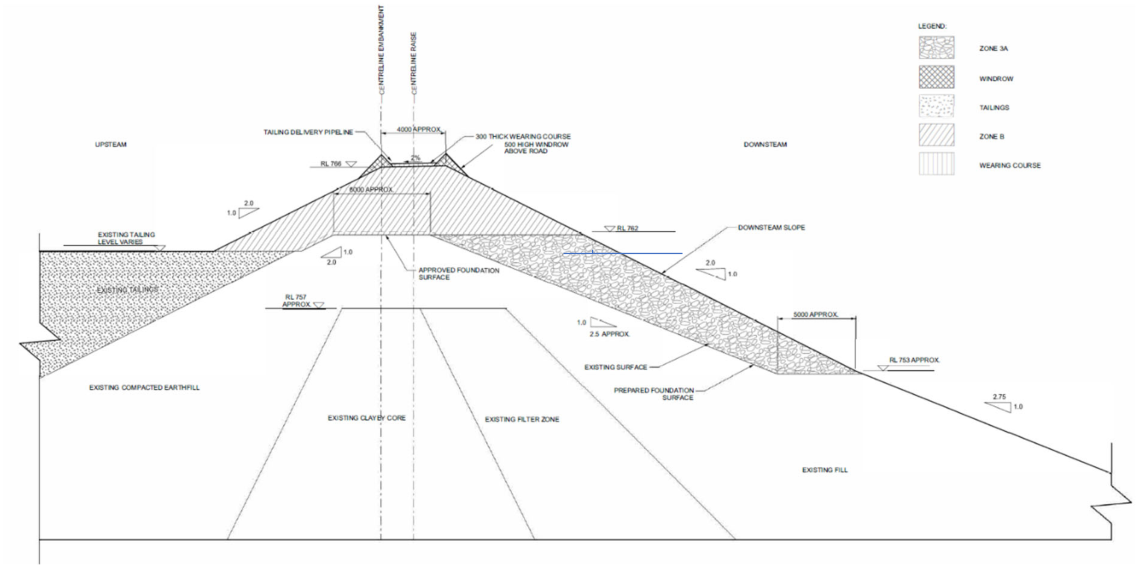


Hand-drawn plan of Main Embankment, indicating nominal locations of CPTu tailings investigation

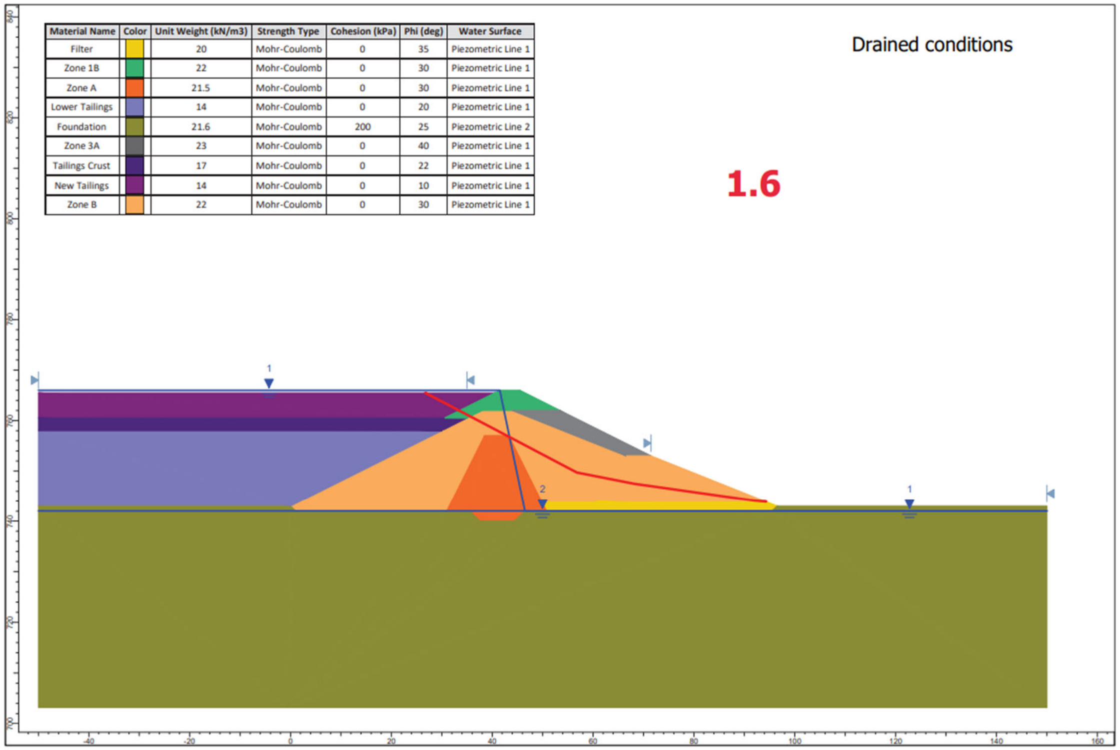


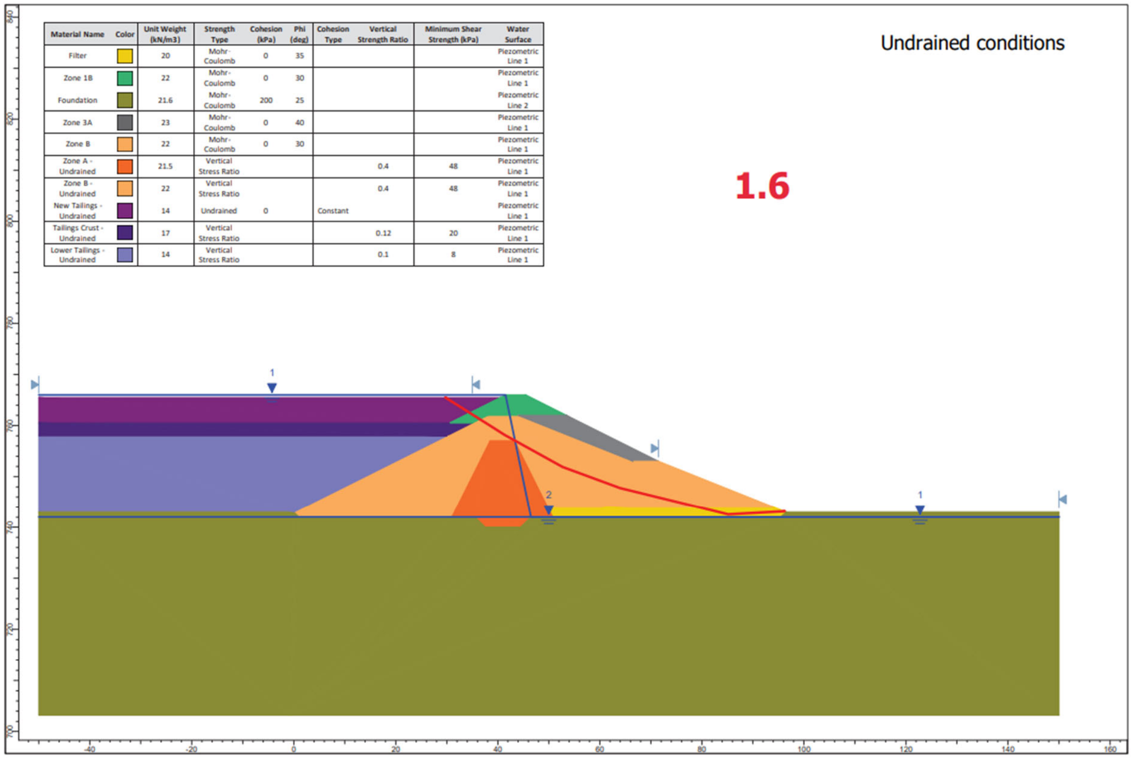
Typical section of Main Embankment – Starter Embankment



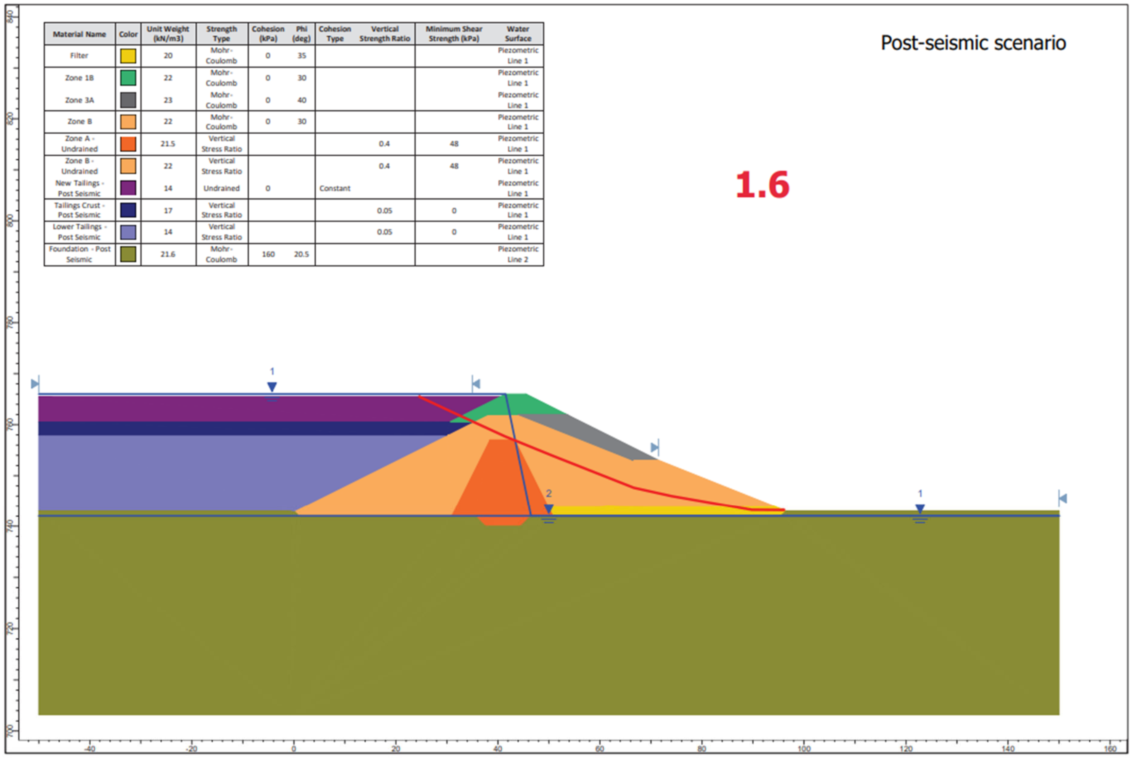

CENTRELINE EMBANKMENT
CENTRELINE RAISE
UPSTEAM
DOWNSTEAM
TAILING DELIVERY PIPELINE
4000 APPROX.
300 THICK WEARING COURSE
500 HIGH WINDROW
ABOVE ROAD
RL 766
2%
6000 APPROX.
2.0
1.0
EXISTING TAILING
LEVEL VARIES
EXISTING TAILINGS
1.0
2.0
APPROVED FOUNDATION
SURFACE
RL 757
APPROX.
RL 762
DOWNSTEAM SLOPE
2.0
1.0
1.0
2.5 APPROX.
5000 APPROX.
RL 753 APPROX.
EXISTING SURFACE
PREPARED FOUNDATION
SURFACE
2.75
1.0
EXISTING COMPACTED EARTHFILL
EXISTING CLAYEY CORE
EXISTING FILTER ZONE
EXISTING FILL
LEGEND:
ZONE 3A
WINDROW
TAILINGS
ZONE B
WEARING COURSE

Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface
Filter		20	Mohr-Coulomb	0	35	Piezometric Line 1
Zone 1B		22	Mohr-Coulomb	0	30	Piezometric Line 1
Zone A		21.5	Mohr-Coulomb	0	30	Piezometric Line 1
Lower Tailings		14	Mohr-Coulomb	0	20	Piezometric Line 1
Foundation		21.6	Mohr-Coulomb	200	25	Piezometric Line 2
Zone 3A		23	Mohr-Coulomb	0	40	Piezometric Line 1
Tailings Crust		17	Mohr-Coulomb	0	22	Piezometric Line 1
New Tailings		14	Mohr-Coulomb	0	10	Piezometric Line 1
Zone B		22	Mohr-Coulomb	0	30	Piezometric Line 1





Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Cohesion Type	Vertical Strength Ratio	Minimum Shear Strength (kPa)	Water Surface
Filter		20	Mohr-Coulomb	0	35				Piezometric Line 1
Zone 1B		22	Mohr-Coulomb	0	30				Piezometric Line 1
Foundation		21.6	Mohr-Coulomb	200	25				Piezometric Line 2
Zone 3A		23	Mohr-Coulomb	0	40				Piezometric Line 1
Zone B		22	Mohr-Coulomb	0	30				Piezometric Line 1
Zone A - Undrained		21.5	Vertical Stress Ratio				0.4	48	Piezometric Line 1
Zone B - Undrained		22	Vertical Stress Ratio				0.4	48	Piezometric Line 1
New Tailings - Undrained		14	Undrained	0		Constant			Piezometric Line 1
Tailings Crust - Undrained		17	Vertical Stress Ratio				0.12	20	Piezometric Line 1
Lower Tailings - Undrained		14	Vertical Stress Ratio				0.1	8	Piezometric Line 1



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Cohesion Type	Vertical Strength Ratio	Minimum Shear Strength (kPa)	Water Surface
Filter		20	Mohr-Coulomb	0	35				Piezometric Line 1
Zone 1B		22	Mohr-Coulomb	0	30				Piezometric Line 1
Zone 3A		23	Mohr-Coulomb	0	40				Piezometric Line 1
Zone B		22	Mohr-Coulomb	0	30				Piezometric Line 1
Zone A - Undrained		21.5	Vertical Stress Ratio				0.4	48	Piezometric Line 1
Zone B - Undrained		22	Vertical Stress Ratio				0.4	48	Piezometric Line 1
New Tailings - Post Seismic		14	Undrained	0		Constant			Piezometric Line 1
Tailings Crust - Post Seismic		17	Vertical Stress Ratio				0.05	0	Piezometric Line 1
Lower Tailings - Post Seismic		14	Vertical Stress Ratio				0.05	0	Piezometric Line 1
Foundation - Post Seismic		21.6	Mohr-Coulomb	160	20.5				Piezometric Line 2

Group Activity 1

Potential Failure Mode Analysis for piping failure mode

Produce a Potential Failure Mode Analysis using suitable tools, such as event trees, fault trees or bow-ties for an embankment piping failure mode.

The Potential Failure Mode Analysis should include the cause and steps to the development of uncontrolled release of stored material.

Note: It may help to first define the system and sub-system of the TSF relevant to this failure mode.

Group Activity 2

Quantification of probability of embankment piping

Estimate the probability of piping through the embankment due to a poorly compacted layer in the embankment clay core.

Please refer to the calculation spreadsheet which will be provided on the day.