Case Study: Approach to Determining the Risk Mitigation Priority of a Historic TSF in North America

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Abstract

Following an exploratory site investigation campaign consisting of more than twenty sections on a series of historic tailings dams, it was clear that many, if not all, of the historic cells would require some type of risk mitigation. Over the facility's long history, the tailings basin had been divided into cells, some of which were partially closed while others were receiving new tailings. All the cells had been constructed using the upstream method, with some cells showing interbedded layers of potentially contractive material.

A series of buttresses were proposed for the site; however, the buttressing project was extensive enough that it required annual construction for up to five years. Furthermore, portions of the historic dam were located directly adjacent to other infrastructure – so close, in fact, that a buttress in those areas was considered unfeasible. As such, a combination of tailings reprocessing, dam deconstruction, and buttressing was proposed to mitigate the risks on site.

These mitigations were proposed in phases, beginning with the highest risk facility. The highest risk facility was determined based on a series of seven parameters. Six of these were geotechnical parameters, and the seventh was a parameter to measure the unknowns remaining in the site investigation at the time. The geotechnical parameters were the Average Cyclic Resistance Ratio (CRR), the Normalized Shear Wave Velocity (Vs1), the Average State Parameters, the geometric design parameters (called the Geometric Product), the Undrained Factor of Safety at Residual Strength, and the Presence of a Pond of Fresh Tailings in the Impoundment. These factors, along with a two-day risk assessment workshop, were used to prioritize the risk mitigation campaign and target areas for further investigation. This case study will show the approach to prioritizing and mitigating these risks.

Introduction

This case study focuses on the risk mitigation prioritization of a series of historic upstream tailings dams located in North America. These dams were constructed in a relatively flat basin as a series of approximately 15 cells. Each new cell would be constructed against a portion of previous cell(s) such that at least one of the perimeter edges of a previous cell would be effectively buttressed by newly deposited tailings (herein referred to as "internal dam[s]"). Some of the cells were subdivided later in their life for operational reasons (also referred to as "internal dam[s]"). Several cells appear to have been sub-divided (such that the dividing/internal dam is founded on tailings) and then raised up to 15 meters above the originally constructed cell. In other cases, external dams (either starter embankment or subsequent upstream raises) had been placed, and years of erosion and operations in the area had exposed hydraulically deposited tailings on the external face of the facility. However, since the project history is more than 100 years, it was unclear in many cases how the dam cells were constructed, divided, and operated; historic photography, interviews with staff, and in-situ investigation were required to approximately re-create the facility history.

The long history meant that the construction materials and methods, facility geometries, deposition history, and level of background information varied widely across the complex. Due to this variability, few universal assumptions could be applied in the analyses. Therefore, despite the dam complex being interconnected, each cell was analyzed separately to better understand the risk associated with the facility.

Given that extremely limited geotechnical data were available for the site, twelve external dams were selected for the initial site investigation (later increased to over 20 sections) and associated engineering analyses. The initial site investigation and lab testing confirmed a high level of variability across the site and the need for supplemental investigation(s). However, a series of sensitivity analyses revealed that the critical sections analyzed resulted in estimated factors of safety below current international standards regarding potential undrained behaviour and would require remediation. It should be noted that many of these structures were designed, built, operated, and, in some instances, closed before current international or local standards were established.

A series of remediations were designed for the complex, which included a series of buttresses along much of external perimeter with additional tailings excavations to reduce the geotechnical stability risks in areas where buttress construction was not feasible. Due to the extensive remediation plan, construction is anticipated to take approximately five years to complete.

As the facilities are estimated to produce extreme consequences associated with a hypothetical failure and the extended project timeframe, it was decided that although remediations should commence immediately, a staged remediation plan would be developed to selectively target the areas with the highest geotechnical risks (the product of likelihood and consequence) for remediation. Although the factor of safety (FOS) had been estimated for the various critical sections across the site based on the limited initial site investigation, the presence of additional complicating factors, as well as numerous remaining unknowns (e.g., geometry, material variability, and in-situ pore pressure conditions), meant that the factor of safety alone was not adequate to measure the geotechnical risks across site.

To accommodate a broader geotechnical risk profile, given the limited available data, a total of six metrics were analyzed for each section:

1. Average Cyclic Resistance Ratio (CRR)
2. Average Normalized Shear Wave Velocity (V_{s1})
3. Average State Parameter
4. Geometric Product (Slope Height × Slope Angle × Saturated Height / Slope Height)
5. Undrained Factor of Safety at Residual Strength
6. Presence of a Pond or Fresh Tailings in the Impoundment

These metrics were compiled into a matrix for each section, weighted, and then used to prioritize the remediation plan. After completing the ranking scheme, the results were reviewed with the client, consultant, and Independent Third-Party Review Panel (ITRP) to confirm the results were consistent with expectations. The following sections describe these metrics and how they were used to dictate an overall risk profile for each section.

Metric methodology

Average Cyclic Resistance Ratio (CRR)

The Average Cyclic Resistance Ratio (CRR) provides a measure of resistance to liquefaction due to cyclic loading. The CRR is derived from correlations to Cone Penetration Tests (CPTs) using the methods developed by Peter Robertson (Robertson, 2009). This method was used to determine the normalized cone resistance (Q_{tn}) corrected for a silty to clean sand ($Q_{tn,cs}$), which was used to calculate the CRR.

This approach indicates which sections may require "more energy" to liquefy relative to each another upon occurrence of a design earthquake that is considered a viable trigger for this project site. At the time of this analysis, the site-specific seismic hazard assessment (SHA) was not complete, and a site response model was not available to estimate the factor of safety against cyclic liquefaction. Therefore, a quantitative weighting could not be applied, and a best estimate was made regarding risk scaling, with 1 being the lowest risk for liquefaction and 10 being the highest. Uncertainty was also taken into account and is discussed later in the results section. Table 1 presents the Average CRR results from the analyzed sections.

Table 1: Average CRR

Profile	Average CRR (Robertson 2009 $Q_{tn,cs}$)	Std Dev. CRR	Uncertainty metric (avg – std dev.)	Ranking	Scaling by best estimate	Scaling by uncertainty
1	0.099	0.004	0.095	2	3.3	8.5
2	0.106	0.010	0.096	12	10.0	10.0
3	0.102	0.008	0.094	8	6.2	7.0
4	0.097	0.002	0.095	1	1.0	7.9
5	0.101	0.007	0.094	5	5.4	7.3
6	0.101	0.008	0.093	6	5.6	6.1
7	0.102	0.009	0.093	8	6.2	5.5
8	0.106	0.015	0.092	12	10.0	3.3
9	0.104	0.014	0.090	9	8.1	1.0
10	0.100	0.005	0.095	3	4.3	8.5
11	0.101	0.009	0.092	4	5.2	4.0
12	0.105	0.010	0.095	10	9.0	8.5

Average Normalized Shear Wave Velocity (V_{s1})

The Average Normalized Shear Wave Velocity (V_{s1}) provides additional information on small strain behaviour of materials and may also identify aging effects of old tailings (Andrus and Stokoe, 2000). This metric was also estimated from CPT probes that took measurements approximately every meter of advancement. The values taken in the foundation, in the upper crust, and in compacted raises were removed from the average because this metric was intended to evaluate the tailings only.

The scaling was given a value of 1 to 10, with 1 being lowest average V_{s1} value obtained (163 m/s) and 10 being a V_{s1} of 200-225 m/s, considered as a rule of thumb above which liquefaction is not anticipated. The Normalized Shear Wave Velocity did not provide a highly valuable metric because the values proved to be too similar to make meaningful distinctions between profiles. Table 2 shows the range of values for V_{s1}. Uncertainty was also taken into account and is discussed in the results section.

Table 2: Average Normalized Shear Wave Velocity

Profile	Avg. Normalized Shear Wave Velocity (V_{s1}) (m/s)	Std deviation V_{s1} (m/s)	Uncertainty metric (avg – std dev.)	Ranking	Scaling by best estimate	Scaling by uncertainty
1	174.4	25.4	149.0	3	4.9	3.9
2	187.3	19.3	168.0	11	9.5	8.0
3	179.5	13.7	165.8	5	6.7	7.5
4	175.5	28.5	147.0	4	5.3	3.5
5	188.7	14.2	174.5	12	10.0	9.4
6	163.4	27.8	135.5	1	1.0	1.0
7	182.3	11.3	171.0	8	7.7	8.6
8	180.9	28.6	152.3	7	7.2	4.6
9	180.9	14.2	166.6	7	7.2	7.7
10	171.7	14.8	156.9	2	3.9	5.6
11	186.1	8.7	177.4	9	9.1	10.0
12	186.8	20.3	166.5	10	9.3	7.7

Average State Parameter

The Average State Parameter provides an indication of how much of the material encountered at a given profile may be susceptible to contractive behaviour or liquefaction. As in the last data sets, the standard deviation was calculated for each profile to quantify the variability. The scaling was based on a value from 1 to 10, with 1 being the highest state parameter value (0.06) and 10 being a state parameter of -0.05, below which contractive behaviour is not anticipated. Again, data pertaining to the foundation materials, upper desiccated zones within the tailings mass, and embankment fills were removed. As a matter of interest, the percentage of data points that plotted in the potentially contractive zone were also estimated within the probed tailings. Table 3 shows the range of values for the Average State Parameter. Uncertainty was also taken into account and is discussed in the results section.

Table 3: Average State Parameter

Profile	Avg. state parameter	Std dev.	% of Probes used	Uncertainty metric (avg + std dev.)	Ranking	Scaling by best estimate	Scaling by uncertainty	% of Values > -0.05
1	0.05	0.01	60%	0.06	4	2.3	3.7	100%
2	0.06	0.03	89%	0.09	2	1.0	1.0	99%
3	0.00	0.04	89%	0.04	10	8.0	6.2	97%
4	0.06	0.03	38%	0.09	1	1.0	1.6	100%
5	0.01	0.02	56%	0.03	8	6.6	6.6	98%
6	-0.02	0.02	37%	0.00	12	10.0	10.0	98%
7	-0.01	0.04	84%	0.03	11	8.8	6.7	96%
8	0.01	0.04	86%	0.05	9	6.9	5.1	93%
9	0.04	0.03	66%	0.07	5	3.3	2.9	98%
10	0.05	0.02	83%	0.07	3	2.2	3.0	100%
11	0.03	0.04	81%	0.07	7	4.4	3.4	96%
12	0.04	0.02	61%	0.06	6	3.5	4.0	99%

Geometric product

Determining the geometric product was a recommendation developed from the ITRB and oversight committee and aimed to provide a geometric comparison of the profiles to relatively rank the major contributors to slope (in)stability.

The selected geometric product was as follows:

$$Geometric\ Product = Slope\ Height * Slope\ Angle * \frac{Saturated\ Height}{Total\ Slope\ Height}$$

These values were estimated using topographic data and pore pressure dissipation test data taken from CPT probes and piezometers in each profile. This metric is a straightforward approach to qualitatively evaluating the risk present at each profile.

The scaling was set again for 1 to 10, with 1 being the lowest and 10 being the highest relative value. Table 4 shows the range of values for the Geometric Product. Note that uncertainty was not included here because this value was a straight metric of verified conditions.

Table 4: Geometric product

Profile	Geometric product	Ranking	Scaling by best estimate	Straight rank
1	12.4	5	5.6	6
2	13.2	4	6.1	4
3	18.8	2	8.9	3
4	3.2	12	1.0	10
5	5.3	10	2.1	11
6	4.9	11	1.9	7
7	10.7	7	4.8	9
8	8.8	9	3.8	12
9	11.0	6	5.0	8
10	18.0	3	8.5	2
11	21.1	1	10.0	1
12	10.5	8	4.7	5

Undrained Factor of Safety at Residual Strength

The Undrained Factor of Safety at Residual Strength was calculated to provide a direct metric of the factor of safety for the estimated geometry and material stratigraphy in a post-liquefaction condition for materials that may be subject to liquefaction (cyclic or static) based on the results of CPT testing. This analysis was repeated using yield and drained strengths for sensitivity, and similar rankings were found. These factors of safety were further calculated under non-conservative assumptions because these data were reflective of an early stage of investigation. In this calculation, "nonconservative" referred to an assumed desaturation and non-liquefaction of un-characterized materials approaching the facility's downstream extents. It was found that under both conditions, many of the profiles were below industry guidelines (CDA, 2019).

Scaling was done from 1 to 10, with 1 being the lowest FOS and 10 being an FOS of 1.2 (the minimum FOS recommended by the CDA for post-liquefaction conditions). Table 5 shows the range of values for the Undrained Factor of Safety at Residual Strength.

Table 5: Factor of safety at residual strength

Profile	Factor of Safety	Uncertainty metric (nonconservative FOS)	Uncertainty parameter	Ranking	Scaling by best estimate	Scaling by uncertainty
1	0.26	0.54	0.337	2	1.3	1.8
2	0.24	0.8	0.675	1	1.0	4.2
3	0.24	0.46	0.265	1	1.0	1.0
4	0.59	1.42	1.000	9	7.1	10.0
5	0.56	0.81	0.301	8	6.5	4.3
6	0.76	0.92	0.193	11	10.0	5.3
7	0.32	0.5	0.217	4	2.9	1.4
8	0.32	0.68	0.434	4	2.9	3.1
9	0.52	0.72	0.241	6	7.8	3.4
10	0.61	0.74	0.157	10	10.0	3.6
11	0.42	0.54	0.145	5	6.6	1.8
12	0.53	0.65	0.145	7	10.0	2.8

Presence of a pond or fresh tailings in the impoundment

The presence of a pond or fresh tailings in the impoundment metric was a way of quantifying the potential geotechnical stability risk posed by the presence of an ongoing source of saturation in the profile and an increase to the consequence of failure if a failure were to occur. A simple "low"=1, "medium"=2, and "high"=3 value was applied to each section, with high being the ongoing presence of impounded water above the profile, medium being recent deposition or water storage, and low being a decommissioned cell with no water storage in the past several years. Uncertainty was not considered because this metric was directly observable. Table 6 shows the range of values for the Presence of a Pond or Fresh Tailings in the Impoundment.

Table 6: Presence of water

Prof.	Water/ recent deposition	Ranking	Scaling by best estimate	Prof.	Water/ recent deposition	Ranking	Scaling by best estimate
1	2	5	5.5	7	3	1	1
2	2	5	5.5	8	1	10	10
3	3	1	1	9	1	10	10
4	2	5	5.5	10	2	5	5.5
5	2	5	5.5	11	1	10	10
6	2	5	5.5	12	1	10	10

Weighting factors

Since these criteria cannot be meaningfully combined into a single profile, each metric used a scaling, and then, a final weighting was applied to the metrics. The final weighting is intended to sum to a value of 10 to provide a normalized contribution. The major contributors to the risk profile were the Factor of Safety and the Liquefaction Potential. Since the first three metrics were all related to the liquefaction potential, metrics 2 and 3 were lowered so that those metrics were not over-emphasized.

Table 7: Weighting factors

#1 - Avg. CRR	2.2
#2 - Avg. Shear Wave Vel.	0.6
#3 - Avg. State Parameter	0.6
#4 – Geometric Product	1.1
#5 - FOS residual	3.3
#6 - Water at Crest/Recent Deposition	2.2

Results and limitations

Combined rankings

Table 8 shows the combined rankings that were calculated with and without weighting factors to show the general risk profile of each section. The highest rank indicates the lowest priority for mitigation, while the lowest rank indicates the highest mitigation priority. However, the mitigation priority did not necessarily consider which areas could be mitigated the most readily and which could not.

Table 8: Combined rankings

	No weighting factors		*With weighting factors*	
Profile	**Scaling rank sum**	**Scaling overall rank**	**Scaling weighted rank sum**	**Scaling weighted rank**
1	23.96	2	34.30	1
2	34.13	5	50.41	5
3	32.78	4	37.67	2
4	21.87	1	42.48	4
5	37.14	8	57.81	6
6	34.96	6	66.06	8
7	32.40	3	40.66	3
8	41.87	9	66.40	9
9	42.34	10	77.31	12
10	35.33	7	67.44	10
11	43.64	12	65.58	7
12	43.30	11	73.69	11

Uncertainty

Due to lack of information in the complex, uncertainty was a key factor for measuring the validity of each metric and providing an uncertainty-corrected value. Uncertainty was calculated using the standard deviation of each given metric, and the normalized standard deviation was applied across scaling to provide both a standard scaling and an uncertainty scaling. Table 9 shows the uncertainty ranking that was used as an indicator of where to target additional site investigation and engineering analyses. The uncertainty ranking aims to identify areas where additional work may have a greater impact on reducing uncertainty and may reduce remediation efforts. The highest rank indicates the lowest opportunity provided by uncertainty reduction, while the lowest rank indicates the highest opportunity provided by uncertainty reduction.

Table 9: Uncertainty factors

	No weighting factors		*With weighting factors*	
Profile	**Uncertainty rank sum**	**Uncertainty overall rank**	**Uncertainty weighted rank sum**	**Uncertainty weighted overall rank**
1	17.84	3	29.03	6
2	23.18	11	41.21	11
3	21.73	6	26.94	5
4	23.00	10	53.44	12
5	27.61	12	39.81	10
6	22.41	8	37.55	9
7	22.20	7	25.84	4
8	15.97	2	23.05	3
9	15.03	1	19.90	1
10	20.73	5	35.82	8
11	19.14	4	22.61	2
12	22.98	9	34.90	7

To improve the process of targeted investigation, an additional sensitivity metric was prepared to show the potential change in the overall ranking with a change in the level of uncertainty. Table 10 shows that Profiles 8,9, and 11 were most sensitive to changes in uncertainty.

Table 10: Uncertainty sensitivity

	% Change with uncertainty		*Rank change with uncertainty*	
Profile	**Scaling rank sum**	**Scaling weighted rank sum**	**Scaling overall rank**	**Scaling weighted rank**
1	25.6%	15.4%	1	5
2	32.1%	18.2%	6	6
3	33.7%	28.5%	2	3
4	5.2%	25.8%	9	8
5	25.7%	31.1%	4	4
6	35.9%	43.2%	2	1
7	31.5%	36.5%	4	1
8	61.9%	65.3%	7	6
9	64.5%	74.3%	9	11
10	41.3%	46.9%	2	2
11	56.1%	65.5%	8	5
12	46.9%	52.6%	2	4

Final rankings

The final rankings for both the mitigation and the investigation priority were prepared. Following this analysis, the highest-ranking mitigation priorities were combined into construction phases for remediation. Each construction phase was scheduled for approximately one year. During this time, additional site investigations were also planned to begin the process of reducing uncertainties from the analyses.

Table 11: Final mitigation priority

Profile	Priority number
1	1
3	2
7	3
4	4
2	5
5	6
6	7
8	8
10	9
11	10
9	11
12	12

Table 12: Final investigation priority

Profile	Uncertainty rank
9	1
11	2
8	3
7	4
3	5
1	6
12	7
10	8
6	9
5	10
2	11
4	12

Conclusions

The methodology presented herein can be used to prioritize risk mitigation for a tailings storage facility where little information is available and where mitigation should begin in parallel with additional site investigation due to the potential consequences of a hypothetical failure scenario. The specific metrics and applications of this methodology may vary across sites based on site-specific risks that are identified by the engineer.

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