Parametric and Sensitivity Analysis for a Proposed Filtered Tailings Storage Facility in Challenging Topography

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ABSTRACT: Parametric and sensitivity analyses were performed for a proposed filtered tailings storage facility in challenging topography from the Southern Peru region. The purpose was to identify elements which are likely to dictate performance and stability, and to understand the risk profile for the facility. The analyses were performed varying: foundation material physical and hydraulic properties, tailings physical and hydraulic properties, foundation configuration, seismicity, and staged construction. The physical properties of the foundation material were varied by changing the Mohr-Coulomb strength parameters c' and ϕ', whereas the hydraulic properties were varied by moving the groundwater table upwards or saturating a larger amount of the foundation material. A similar approach was adopted in order to vary the physical and hydraulic properties of the tailings. The foundation configuration was varied by hypothetically moving the starter buttress closer to the edge of steep slopes further downhill from the facility. Staged construction stability analyses were simulated by analyzing filtered tailings fill configurations, which followed the overall design slope but varied in height. All analyses presented herein were conducted for the most critical failure mode for each scenario. The results from these parametric analyses showed that the design of the facility was highly sensitive to tailings potential saturation. In the simulation scenarios, saturation of the tailings caused instability in both static and seismic conditions. This sensitivity to moisture conditions highlighted the importance of properly defining the unsaturated filtered tailings parameters and simulating water infiltration processes through the vadose zone.

1 INTRODUCTION

Topographic conditions, as well as archeologically sensitive areas, can cause significant challenges for the location of mining infrastructure in the Peruvian Andes. In this type of setting, many times filtered tailings can be an appropriate form of tailings storage since they can be placed, spread and compacted to form an unsaturated, dense and stable tailings stack or "dry stack", which requires no dam for water or slurried tailings retention (Davies & Rice, 2001).

The Ollachea gold mine project is located in the Puno Region of southern Peru. The project consists of an underground mine to exploit an orogenic or mesothermal-style gold deposit hosted in Devonian-aged carbonaceous metasediments on the eastern flank of the Cordillera Oriental of the Peruvian Andes. The ore deposit will be mined from underground using long-hole-open-stoping (LHOS) with paste fill. Topography is highly irregular with elevations ranging from about 2,500 to 3,100 m above mean sea level within the main facilities.

Previous studies (AMEC, 2011) identified filtered tailings as the preferred tailings management alternative for this project. A tailings storage facility (TSF) was designed to accommodate storage of 5.85 Mt of filtered tailings with overall ultimate slopes of 2.5H:1V and an ultimate height of approximately 145 m as measured from the toe of the starter buttress to the crest. The

TSF site is located just west of the Ollachea River (where topographic relief is about 150 m) and north of the Curcunchaca River, approximately 2 km north of the process plant and the mine lower portal access tunnel (see Figure 1).

Given the potentially active geomorphology of the area, two inclinometers were installed downslope of the design TSF footprint to monitor global stability of the TSF site. Additionally, parametric and sensitivity analyses were carried out for the filtered TSF to identify the material properties and other design parameters that likely dictate the performance and physical stability of the structure.

These parametric and sensitivity analyses focused on the following: (a) foundation material physical and hydraulic properties; (b) tailings physical and hydraulic properties; (c) foundation configuration; (d) seismicity; and (e) staged construction.

This paper presents the results of these parametric analyses and highlights the importance of properly defining the unsaturated filtered tailings parameters and simulating water infiltration processes through the vadose zone.

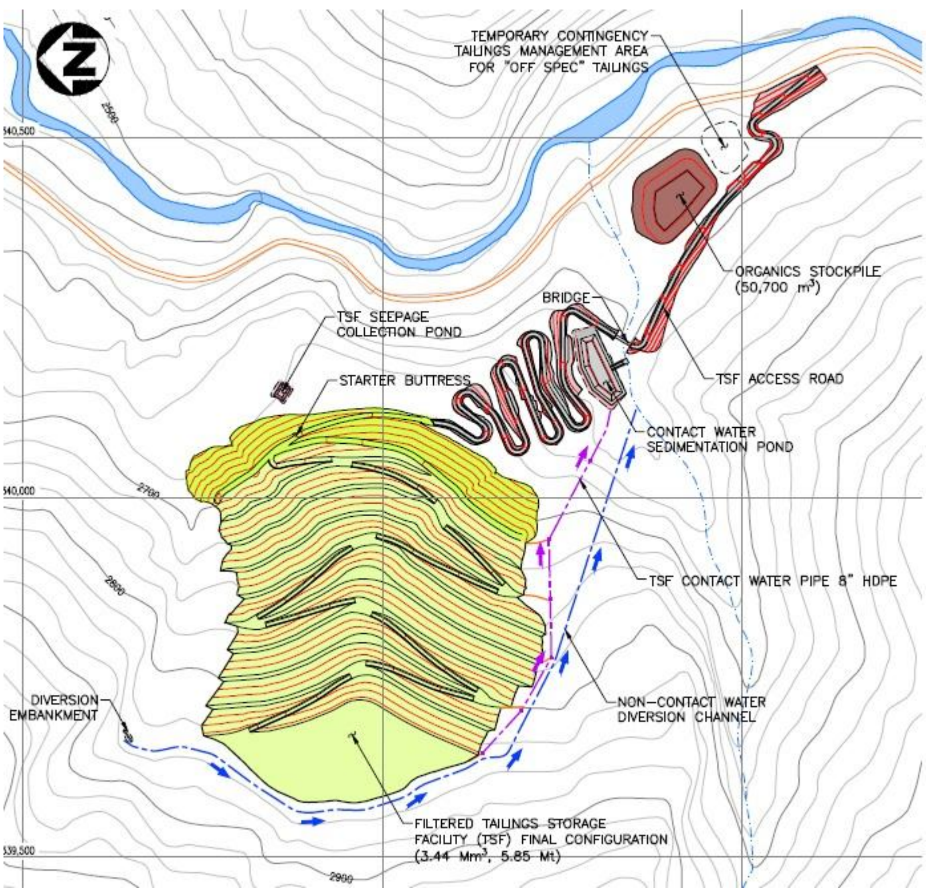

Figure 1. General Arrangement of the Filtered Tailings Storage Facility.

2 GEOTECHNICAL CHARACTERIZATION OF MATERIALS

The TSF site consists of Quaternary sandy gravel and cobble deposits with estimated thickness of 50 to 150 m overlying lightly metamorphosed sandstone. The TSF will be set back from the crest of steep valley slopes between the TSF and the Ollachea River. A geotechnical site investigation program was carried out at the TSF site, including 10 boreholes and 10 test pits. Groundwater was observed at depths of 38 to 47 m in piezometers installed in selected boreholes.

The TSF design includes a starter buttress at the toe of the TSF constructed from locally sourced granular soils. Tailings will be hauled to the TSF by truck and be compacted according to design specifications. Two tailings zones with different compaction requirements have been specified to provide operational flexibility while maintaining stability of the TSF. A nominally compacted zone (90% of maximum dry density -MDD) in the interior of the tailings stacking and a “full spec” compacted zone (95% of MDD) in the exterior of the staking to confine the tailings fill. An erosion protection layer will be progressively placed on the exterior slope of the TSF during operations. Figure 2 shows a typical cross section of the TSF along the E-W direction, and the materials that composed the sections analyzed.

The following materials were considered for the analyses: (1) compacted tailings, (2) nominally compacted tailings, (3) starter buttress material, (4) foundation soil; and (5) bedrock. The material properties used in the parametric analyses are described below and summarized in Table 1.

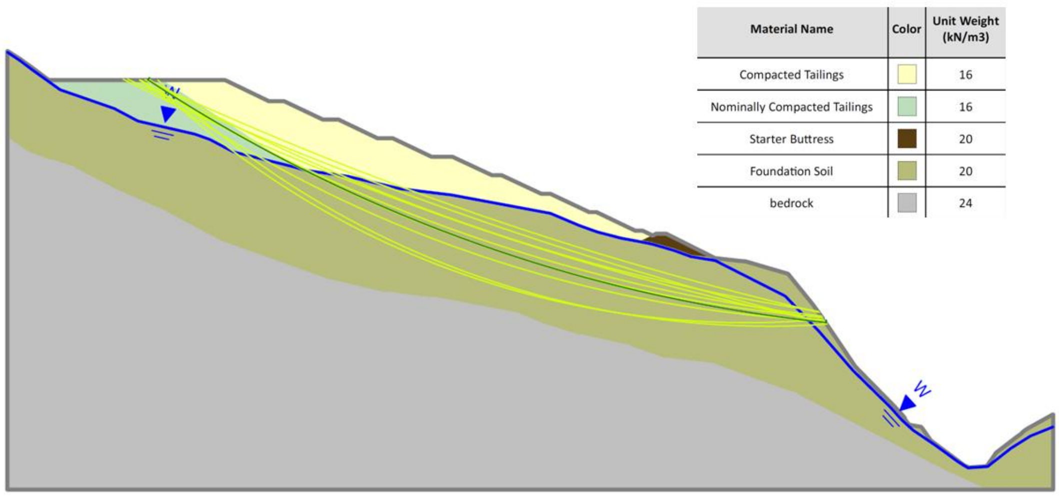

Figure 2. Critical Section of the TSF showing the Materials considered for the Analyses

2.1 *Filtered tailings*

Tailings material was classified as non-plastic sandy silt with clay trace (ML) according to the UCSC. This material has approximately 70% (by weight) finer than 75 microns and a P80 of 114 microns. The estimated specific gravity is 2.83.

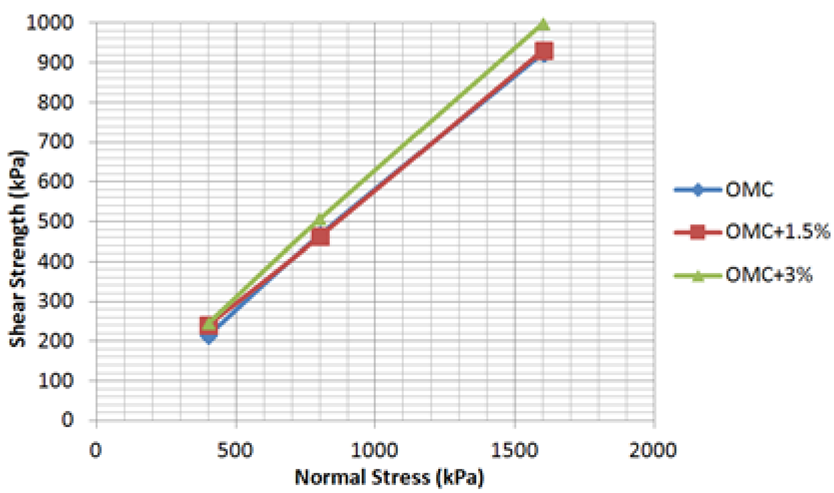

Figure 3. Direct Shear Test Results for Filtered Tailings.

Based on the standard proctor compaction test, the tailings had a MDD of 1.806 kg/m^3 with optimum moisture content (OMC) of 16.9%. The tailings had an estimated void ratio of 0.65 and 74% saturation at 95%compaction of MDD.

The tailings shear strength properties were obtained from direct shear tests, which were conducted on tailings compacted to 95% of MDD. Three direct shear tests were conducted, at the optimum moisture content (OMC), at 1.5% above OMC, and at 3% above OMC. The three tests yielded effective friction angles ranging from 30° to 32° with null cohesion (Figure 3).

Tests results demonstrated no loss of strength for tailings compacted at moisture content slightly higher than OMC compared to those compacted at OMC. Nonetheless, a strength reduction was applied to the nominal compacted tailings.

Two permeability tests in a constant head permeameter at 95% of MDD yielded average saturated hydraulic conductivity of 2E-9 m/s. The soil water characteristic curve was obtained to know the unsaturated seepage behavior. The moisture retention curves were obtained from suction and soil water content measurements with a Tempe cell. The model proposed by van Genuchten (1980) was fitted to the experimental measurements to determine the water retention curve. The Brooks and Corey model (1964) was used to estimate unsaturated hydraulic conductivity from the saturated hydraulic conductivity (AMEC, 2012a).

2.2 *Starter buttress material*

The material proposed for the starter buttress consisted of locally sourced granular soil (colluvial soil from the TSF foundation preparation and grading removal) compacted at 95% of MDD of standard proctor. Geotechnical investigations at the TSF indicate that the colluvial soils are typically well-graded sandy gravel (GW) with cobbles and trace silt. Shear strength properties for this material were assumed conservatively to have null cohesion and a ϕ'= 35°, based on experience with similar materials.

2.3 *Foundation Soils*

Similar to the starter buttress material, foundation soils consisted of medium dense to very dense, sandy gravel and cobbles with silt, lightly to moderately cemented. Shear strength parameters were obtained based on SPT and LPT values (Large Penetration Tests) from the site investigations. The values obtained from N_{SPT} correlations for ϕ' ranged across the soil profile from 35° to 42°. Given the type of material composing the foundation soils, cohesion due to cementation was difficult to estimate from conventional laboratory tests. Back-analyses for exposed steep slopes of similar material returned “cohesion” values of up to 30 kPa.

For design purposes, values for cohesion of 0 kPa, internal friction angle of 40°, and unit weight of 20 kN/m^3 were initially considered.

2.4 *Bedrock*

Bedrock was encountered at 56 m depth, approximately. Bedrock mostly consists of slate encountered at depths between 56 and 67 m, and lightly metamorphosed sandstone encountered between 67 and 85 m. Field logging characterized the slate as moderately fractured, high hardness (R4), with basic rock mass rating (RMR) between 40 and 57, and classified as “fair” rock according to RMR’89 (Bieniawski, 1989). The meta-sandstone is moderately fractured, low to high hardness (R2-R4), and classifies mostly as “poor” to “good” rock according to its RMR’89.

Table 1. Materials Shear Strength Properties Considered for Analysis.

Material Type	Unit Weight (kN/m^3)	Effective Friction Angle (°)	Effective Cohesion (kPa)
Compacted Tailings	16	30	0
Nominally Compacted Tailings	16	28	0
Starter Buttress Material	20	35	0
Foundation Soil	20	40	0
Bedrock	24	40	1000

Considering the RMR values and the characteristic of theses rocks, the values of cohesion of 1000 kPa, internal friction angle of 40°; and unit weight of 24 kN/m3 were assumed.

3 PHREATIC SURFACE

Standpipe piezometers installed in five boreholes showed that water table ranged from approximately 38 to 47 m depth. For sensitivity purposes, two different conditions for the water table depth were analyzed:

- Water table at 40 m below the native foundation ground surface.
- Water table at the foundation ground surface.

4 CONSIDERATIONS ON SEISMICITY

The pseudo-static coefficients for stability analyses were based on a site specific probabilistic seismic hazard study developed for the project (AMEC, 2012a). Peak ground accelerations (PGA) for return periods of 2475, 5000 and 10000 years were determined to be 0.29g, 0.34g, and 0.41g, respectively. Pseudo-static coefficients equal to one-half of the PGA were used for seismic stability analyses as suggested by Hynes and Franklin (1984) and Seed (1982).

5 GEOTECHNICAL ANALYSIS

5.1 *Methods of analyses*

All analyses presented herein were conducted for the most critical failure mode for each scenario. The parametric and sensitivity stability analyses were done using Spencer´s method for limit equilibrium in the SLIDE 6.0 software (Rocsience, 2012; Spencer, 1967). The minimum factors of safety (FS) used for the project consisted of 1.5 for static long-term condition, 1.3 for static short term condition and 1.0 for pseudo-static or seismic conditions.

5.2 *Parametric and sensitivity analyses*

Parametric and sensitivity analyses were performed based on evaluation of stability of the TSF under static and seismic (pseudo-static) conditions considering different scenarios and varying material parameters that could affect the stability of both the foundation and the tailings facility. The scenarios considered and the results are detailed as follow:

5.2.1 *Physical and hydraulic properties of foundation material*

The analyses were performed on foundation materials by varying the original strength properties (effective cohesion c' and effective friction angle ϕ'), and developed considering different scenarios:

- Varying the cohesion parameter to 0 kPa, 15 kPa and 30 kPa in order to obtain FS for different ϕ' values in both static and pseudo-static conditions.
- Varying the cohesion factor to different intervals 0 kPa, 15 kPa and 30 kPa in order to obtain a minimum effective friction angle ϕ' needed to achieve the minimum FS for both static and pseudo-static conditions.
- Two water table conditions were also considered: design conditions (40 m depth approximately) and shallow surface groundwater conditions.

The values obtained from sensitivity analyses were compared with the friction angle ϕ' values obtained from the site investigation.

Table 2 presents the FS´s obtained by varying cohesion and friction angle parameters for static and pseudo-static conditions and considering two water table scenarios for the critical section

analyzed (Figure 2). For the pseudo-static analyses, a value of 1/2 of the PGA (0.145g) was used, which corresponds to a return period of 2475 years.
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Table 2. Factors of Safety Varying c and ϕ’ of the Foundation Material– Critical Section

Cohesion, c (kPa)	Foundation soil unit weight γ (kN/m³)	Friction angle, ϕ’ (°)	Design water table condition FS		Shallow water table condition FS	
			Static	Pseudo-static	Static	Pseudo-static
0	20	25	1.4	0.9	1.1	0.7
		30	1.6	1.1	1.2	0.8
		35	1.9	1.2	1.5	1.0
		40	2.0	1.3	1.7	1.2
15	20	25	1.4	1.0	1.1	0.7
		30	1.7	1.1	1.3	0.9
		35	1.9	1.3	1.5	1.0
		40	2.1	1.4	1.8	1.2
30	20	25	1.5	1.0	1.1	0.7
		30	1.7	1.2	1.3	0.9
		35	2.0	1.4	1.6	1.1
		40	2.2	1.5	1.8	1.3

Table 3 presents the minimum ϕ’ values for the foundation material obtained from parametric and sensitivity analyses on the critical section, required to reach the minimum FS´s for static and pseudo-static conditions under two water table scenarios.

Table 3. Friction Angles required in the Foundation Material to reach Minimum FS.

Cohesion, c (kPa)	Foundation soil unit weight, γ (kN/m³)	Minimum friction angle ϕ’ (°) for foundation soils: Design water table condition		Shallow water table condition	
		Static	Pseudo-static	Static	Pseudo-static
0	20	28.0	27.6	35.2	32.6
15	20	26.6	24.8	34.5	34.8
30	20	25.1	25.0	33.7	35.1

5.2.2 *Physical and hydraulic properties of tailings*

The critical section was analyzed considering a variation in tailings parameters (mechanical and hydraulic) under the geometrical configuration of original design. This analysis was performed considering that all failure surfaces involve only the tailings stack. Two cases were analyzed:

- Case 1: Sensitivity analysis considering a variation of friction angle for the tailings under static and seismic conditions (2475 years of return period).
- Case 2: Sensitivity analysis considering a variation of Ru parameter (hydraulic pore pressure) under static and seismic conditions.

Tables 4 and 5 show the critical strength and hydraulic parameters required to reach the minimum specified factors of safety.

Table 4. Critical Strength Parameters for Tailings required to reach Minimum FS.

Case	Type of Analysis	FS c'=0 kPa			Critical Friction Angle ϕ' (°)
		Φ'_{min}=25°	Φ'_{max}=35°	Minimum	
1	Static	1.2	1.9	1.5	29.7
	Pseudo-static	0.9	1.4	1.0	26.5

Table 5. Critical Hydraulic Parameters of Tailings required to reach Minimum FS.

Case	Seismic Coefficient (g)	FS c'=0 kPa, ϕ'=30°			Critical Ru
		Ru_{max}=0.5	Ru_{min}=0	Minimum	
2	0	0.7	1.5	1.5	0.01
	0.145	0.5	1.1	1.0	0.11

The Ru parameter, simplistically represents the hydraulic head within the tailings material (water pore pressure). The value of Ru equal to 0.5 means that the soil is completely saturated; a null value represents an unsaturated soil.

5.2.3 *Foundation configuration*

A sensitivity analysis for the foundation configuration was performed on the critical section of the TSF. As Figure 4 shows, three configurations were developed:

- Case 1: Original study design conditions.
- Case 2: The slope of natural ground was moved to a mid-point between the current natural ground and the location of the starter buttress, assuming erosion of the downhill slopes closer to the starter buttress.
- Case 3: The slopes downhill were placed right at the toe of the starter buttress.

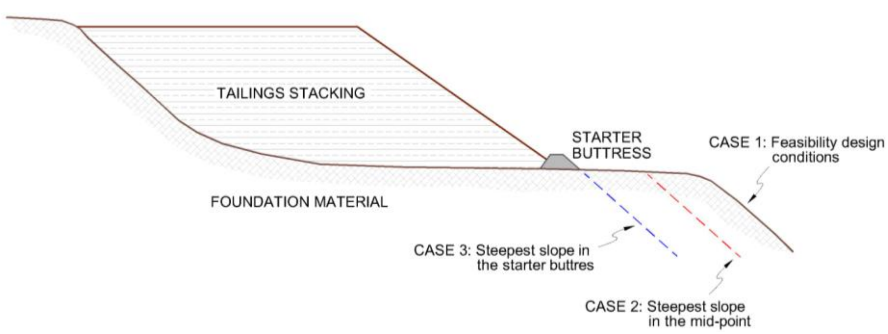

Figure 4. Foundation Configurations considered for Sensitivity Purposes.

The three configurations were analyzed under static and pseudo-static conditions and the results are summarized in Table 6.

Table 6. Sensitivity Analyses Results due to Different Foundation Configurations

Condition	FS		
	Case 1	Case 2	Case 3
Static	2.2	2.1	2.1
Pseudo-static	1.4	1.4	1.4

5.2.4 *Seismicity*

Stability sensitivity analyses for different return periods were conducted on the critical section of the final TSF configuration (maximum height and storage volume). The FS´s obtained from the analyses are shown in Table 7.

Table 7. Factors of Safety for Different Seismic Conditions

FS		
2475 year (k=0.145g)	5000 years (k=0.170g)	10,000 years (k=0.205g)
1.4	1.4	1.3

5.2.5 *Staged construction TSF*

Sensitivity analyses were performed considering 4 stages of construction for the TSF (tailings stacking of: 30, 60, 90 and 120 m high (Figure 5). These analyses were conducted under static and pseudo-static conditions.

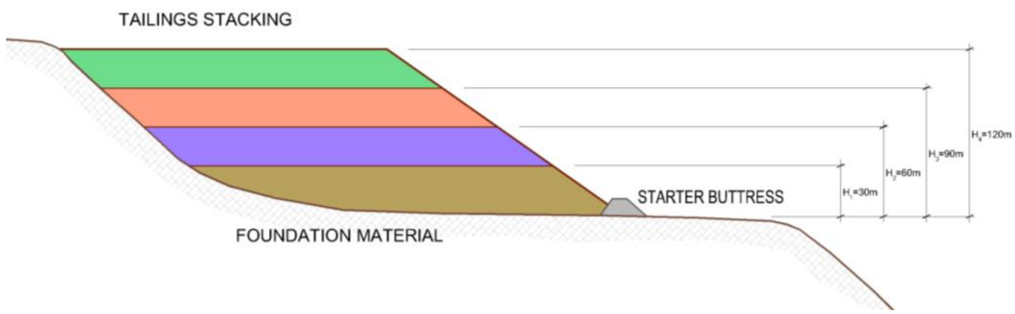

Figure 5. Conceptual Staged Construction Analysis.

Table 8 shows the values of critical factors of safety for each analysis conducted and their respective minimum FS.

Table 8. Factors of Safety for different construction stages

H (m)	FS			
	Static		Pseudo-Static (0.145g)	
	Computed	Minimum	Computed	Minimum
30	1.5	1.3	1.0	1.0
60	2.0	1.3	1.3	1.0
90	1.8	1.3	1.2	1.0
120	1.5	1.5	1.1	1.0

6 DISCUSSION ON SENSITIVITY STABILITY ANALYSES

The foundation materials showed more sensitivity in the stability analyses to ϕ’than c. The hydraulic conditions of the foundation materials had a significant impact on the factor of safety. These conditions had a more pronounced effect on the tailings stacking as this material depends exclusively on its shear strength properties and pore water pressure conditions.

Based on the stability analyses, the foundation configuration in theory appeared not to have a significant effect on the resulting FS. However, it was recognized that a situation where either local slope failure or erosion progressed right to the limits of the foundation would be highly undesirable.

The TSF design showed low sensitivity to PGA`s corresponding to different return periods, covering both operational and long-term physical stability conditions. Staged construction and its corresponding overburden stress showed a varying effect on the resulting FS, which peaked midway through construction of the tailings staking and had its lowest values at one third and at the proposed final height.

7 RELEVANCE OF UNSATURATED TAILINGS BEHAVIOR

Sensitivity stability analyses showed a high vulnerability of the TSF design to potential saturation of the tailings stacking. The applicability of this sensitivity results to the TSF highly depended on the actual hydraulic performance of the unsaturated tailings material, i.e whether or not the tailings stack could saturate and be susceptible to significant increase in pore water pressures under static or seismic loads.

The moisture retention curves were obtained from suction and soil water content measurements with a Tempe cell AMEC´s laboratories in Hamilton, Ontario (Figure 6). The model proposed by van Genuchten (1980) was fitted to the experimental measurements to determine the water retention curve. The Brooks and Corey model (1964) was used to estimate unsaturated hydraulic conductivity from the saturated hydraulic conductivity. Characteristic curves were fitted to data of the filtered tailings and foundation soil to generate suction curves (Van Genuchten Model), and unsaturated hydraulic conductivity curves (Brooks and Corey Model).

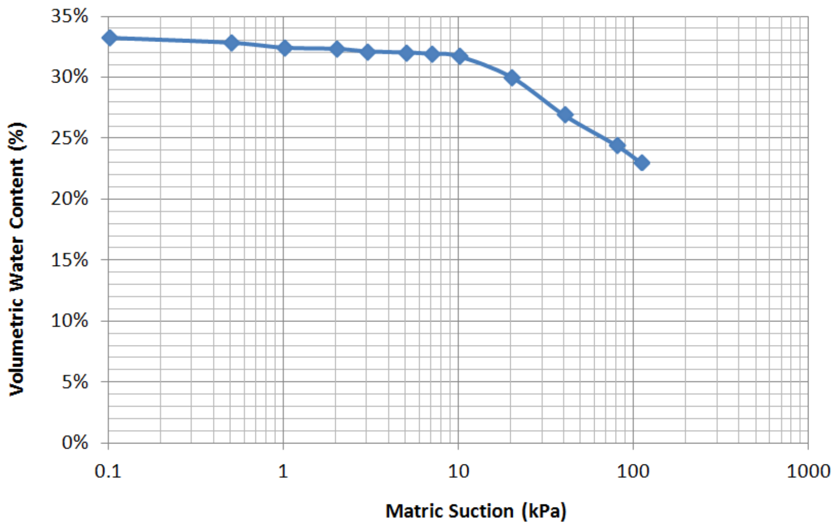

Figure 6. Suction-water content characteristic curve for tailings (AMEC, 2012b).

Based on the hydrological information and the TSF design configuration, a conceptual model was developed, which took account of the balance of the volume flow control of the tailings storage facility. This conceptual model was developed to determine an appropriate discretization in time and space (AMEC, 2012c).

A seepage numerical model was developed to estimate the volume and rate of seepage from the filtered tailings storage facility. This seepage was calculated by steady-state and transient flux water models using the finite-difference groundwater simulation code, MODFLOW-SURFACT, which included saturated and unsaturated flow, recharge, and fracture flow capabilities, and analysis of contaminant transport (Panday and Huyakorn, 2008). Based on this modeling approach, it was determined that the seepage flows were mainly a result of the low saturated permeability of filtered tailings, and thus the surface of the tailings stack becomes saturated very quickly and does not allow the passage of water at deeper levels. Therefore, precipitation rates in excess of the tailings infiltration capacity will run-off the TSF, making it very improbable to be sensitive to saturation.

8 CONCLUSIONS

Parametric and sensitivity analyses were performed for a proposed filtered tailings storage facility in challenging topography from the Southern Peru region. The analyses were performed varying: foundation material physical and hydraulic properties, tailings physical and hydraulic properties, foundation configuration, seismicity, and staged construction. Results indicated that the design of the facility was highly sensitive to the tailings moisture conditions. In the simulation scenarios, saturation of the tailings caused instability in both static and seismic conditions.

These parametric and sensitivity analyses stressed the importance of properly characterizing the hydraulic behavior of the tailings stacking to determine whether saturation of the tailings was a probable scenario. Based on tailings material unsaturated testing and numerical modeling, it was determined that despite the relatively wet site conditions, tailings were very unlikely to saturate and hence that the potential sensitivity to this condition would not likely materialize as long as construction and operation followed the design criteria and design assumptions of the facility.

A proper geological and geohazard assessment has to be coupled with any parametric and sensitivity analyses. The analyses presented here followed a comprehensive assessment of multiple potential tailings sitting options that was conducted in previous studies. However, further data will need to be collected to conduct additional probabilistic sensitivity analyses, which will extend beyond a factor of safety based approach. It is anticipated that additional foundation material characterization (through large scale laboratory testing or further in-situ testing), as well as more instrumentation will be required to monitor the adequate performance of the proposed facility.

Given the specific conditions presented for the project site, it has been shown that filtered tailings can be a feasible waste storage option in challenging topography and wet climatic conditions. Additionally, with proper surface and subsurface water management measures, filtered tailings can help mitigate potential risks for groundwater contamination due to their low tendency to saturate and allow solute transport.

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