

# Selection criteria for two alternative thickened slurries to be deposited over conventional tailings: storage capacity and liquefaction

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This paper was first presented at Paste 2014, Vancouver, Canada, June 8-12, and published in Proceedings 17th International Seminar on Paste and Thickened Tailings (eds R.J. Jewell, A.B. Fourie, S. Wells and D. van Zyl), InfoMine Inc., Canada.

## Abstract

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Depositing thickened tailings over a conventional tailings deposit leads to a raft of considerations and risks relating to the interaction of the two tailings layers, and these must be identified and evaluated before making the significant financial investment involved in changing a disposal system.

As part of a selection process for a thickened tailings disposal strategy that involved placing thickened tailings over a conventional tailings deposit at an existing mine in Mexico, two alternative thickened tailings streams were characterised. One of these was a total tailings product, and the other was a fine product with coarse particles removed. Two issues were identified as key assessment criteria to enable an informed choice between thickening either the fine or total tailings: the evolution of density and pore pressures through self-weight consolidation and the potential for liquefaction of the composite tailings deposit. This paper discusses the considerations and methodology of assessing these two criteria.

The evaluation process involved a geotechnical laboratory test work program on both tailings materials. The test results provided inputs for a transient large-strain consolidation model and for stress-strain dynamic analyses. The consolidation model results were used to compare storage capacity estimation. These results provided critical inputs for a dynamic evaluation of both tailings composites. Liquefaction conditions were assessed through a dynamic analysis that compared the cyclic shear stress associated to dynamic loads with the mobilised cyclic shear strength of the tailings material. Associated plastic deformations were obtained for each scenario studied.

## 1. Introduction

Owners and designers of existing conventional tailings storage facilities (TSF) are moved by the many benefits of thickening to assess the feasibility of integrating thickened tailings into their current conventional disposal system. These benefits of thickened tailings include increased water recovery, reduction in the size of retaining embankments, improved facility safety, and reduced environmental impact.

The geotechnical behaviour of a proposed composite TSF, composed of thickened tailings over conventional tailings, was assessed for an existing mine in Mexico. The operation produces two tailings streams obtained from gravity separation at the plant: sand-size tailings (which can be stored separately at the waste rock dump) and a finer tailings fraction (fine tailings). The study considered a proposal to initially deposit tailings at a new TSF, which involves two years of conventional tailings deposition while the thickening plant is being commissioned, and then depositing thickened tailings up to completion of the life of the mine.

Combined coarse and fine tailings (total tailings) and the fine tailings were both characterised as part of the selection criteria to assist in deciding which stream to adopt for thickening for the tailings disposal strategy.

The evolution of density and pore pressures and the potential for liquefaction of the composite tailings deposit were identified as key criteria to enable an informed choice between thickening either the fine or total tailings. SRK commissioned a comprehensive geotechnical test work program to assist with assessing the likely behaviour of the tailings deposit under operational conditions.

One important outcome of this program is a reliable estimation of the evolution of the density profile and pore-pressure distribution with time for the dual-layer profile. This provides valuable information for estimating storage capacity, analysing stability, and assessing liquefaction at critical stages of the operation. The conventional tailings rate of rise was designed to be approximately 15 m/year; experience with this same tailings product indicates that this rate may be too high, and that pore pressures may not fully dissipate prior to the deposition of thickened tailings above.

The geotechnical testing provided inputs to an analysis for estimating the density and pore-pressure profiles for the whole tailings composite mass. The methodology used in this analysis involved a transient large-strain consolidation model, as it was necessary to obtain short- and long-term consolidation characteristics

such as void ratio and pore pressure under strains, and these exceed the limitations of conventional consolidation analysis methods. The model was set up to analyse the two tailings deposition phases – conventional slurry and thickened tailings – at the central discharge location. Scenarios run on these models provided justifiable storage capacity estimates, considering the transient consolidation of the tailings mass. The model also provided information on pore-pressure dissipation timing, aided in evaluating the tailings rate of rise, and ultimately was used to assign initial conditions of pore pressure and density distributions to a dynamic analysis.

The mine is located in an area of high seismicity in the Colima region of Mexico; the US Geological Survey's (USGS) *Seismic Hazard Map of Mexico* indicates that there is a one in 500-year probability of an event with a peak ground acceleration (PGA) of 0.5 g in this region. This suggests that, in addition to the probable initial excess pore pressures, there is a high potential for liquefaction of the composite tailings deposit. A simplified dynamic analysis to investigate the potential for liquefaction of the tailings mass was proposed in order to indicate which thickened tailings stream would lead to better performance of the composite profile during an earthquake.

This paper presents a methodology to study the behaviour of these alternative thickened tailings streams and discusses results of these comparative analyses. The assessment is focused on assisting the process of selecting one of the two tailings streams and is not intended for design purposes.

## 2 Model geometry

The final designed deposition stage of the TSF is illustrated in Figure 1, which shows the total conventional tailings initially deposited from the embankment followed by central thickened discharge of either the fine or total thickened slurry. The conventional tailings are deposited up to an elevation of 13 m below the crest, and the thickened tailings are deposited to an elevation 10 m above the conventional tailings adjacent to the embankment (including a 3 m freeboard allowance).

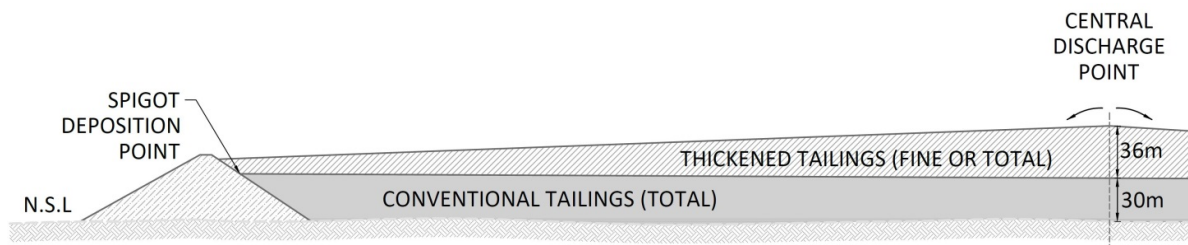


Figure 1 Selected TSF section used in analysis

## 3 Characterisation of the tailings streams

### 3.1 Laboratory testing program

A geotechnical laboratory test work program was undertaken on both streams of the thickened tailings slurry (total and fine), with the total thickened slurry also representative of the conventional tailings. Segregation of the conventional tailings has been considered as minimal, based on observation of the mine's existing TSF and the designed deposition strategy, which involves depositing from various points around the TSF to achieve a very flat, shallow beach. This could be investigated in more detail once the TSF is commissioned.

The laboratory tests included classification tests of characteristics such as specific gravity (SG), particle size distribution (PSD), and Atterberg limits, as well as the following tests:

- Rowe cell;
- consolidated undrained (CU) triaxial with pore pressure measurement;
- Bender elements; and
- cyclic triaxial.

The results obtained and interpreted from these tests were used for the consolidation and liquefaction assessments.

### 3.2 Classification of the tailings

The two tailings samples were classified according to the Unified Soil Classification System (USCS) as low plasticity sandy clay (CL). Figure 2 shows the PSD curves for the two tailings streams. From the PSD curve, it can be seen that 61% of the total tailings and 78% of the finer tailings is finer than 75  $\mu\text{m}$ . The Atterberg limits and SG are presented in Table 1. The class of the total tailings borders the line between sandy clay and clayey sand; according to Andrews and Martin's (2000) criteria, its liquid limit of 20 would make it

susceptible to liquefaction. The same criteria indicate that the fine tailings should be studied further to investigate their susceptibility to liquefaction.

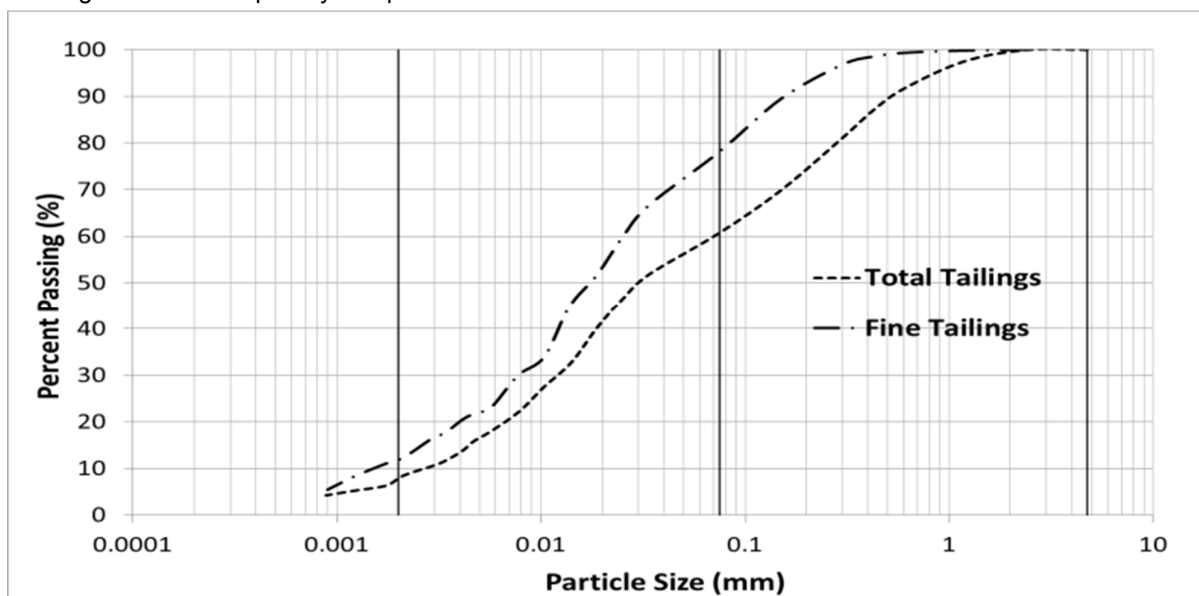


Figure 2 Tailings PSD

### 3.3 Consolidation characteristics

Settling tests were performed in the laboratory according to methodology provided by SRK. Three settling tests were performed: total tailings – conventional slurry, total tailings – thickened slurry, and fine tailings – thickened slurry. These involved preparing the dry tailings samples to the proposed deposition densities (see Table 1; densities are in  $t/m^3$ ). These samples were placed in a measurement cylinder at the deposition dry density ( $\gamma_d$ ) and void ratio ( $e$ ) and allowed to settle for 48 hours. As expected and shown in Table 1, the conventional tailings showed a large degree of settlement, and the thickened tailings showed very little settlement. These results do not yet account for self-weight consolidation.

Table 1 Tailings characteristics

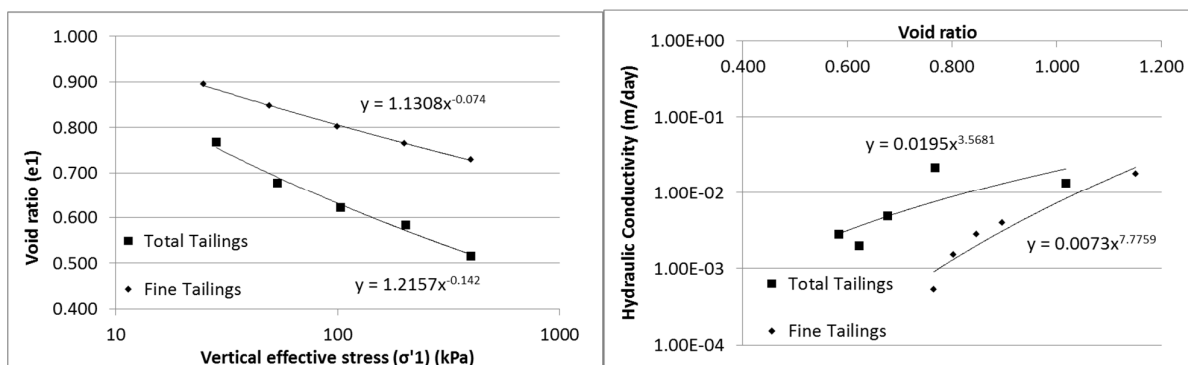
Tailings stream	SG	LL	PL	PI	$\gamma_d$ (deposition)	$\gamma_d$ (48 hr)	$e$ (deposition)	$e$ (48 hr)
Total conventional	3.06	20	13	7	0.61	1.18	4.02	1.59
Total thickened	3.06	20	13	7	1.52	1.61	1.01	0.90
Fine thickened	3.04	25	16	9	1.36	1.44	1.25	1.12

Rowe cell tests were performed on both of the tailings streams with the initial conditions determined from the thickened phase of each stream. The initial density was the 48-hour settled density as determined in the settling tests described above. The Rowe cell test applies specified loading stages to a prepared sample and measures the volumetric change in the sample. A five-stage loading test was selected to provide adequate points for defining the compressibility curve. The loading stages were determined as 25 kPa, 50 kPa, 100 kPa, 200 kPa, and 400 kPa to cover most stresses that will be applied to the tailings in the proposed TSF.

The stress and volumetric change data was analysed using the Terzaghi theory of consolidation to determine the relationship between void ratio and effective stress and the relationship between the void ratio and hydraulic conductivity. This analysis can provide a long-term dry-density profile for the tailings; in this case, these relationships are obtained and used as inputs for a transient consolidation model.

The permeability derived from this analysis was compared to the result of a constant-head permeability test. The results were of the same order of magnitude, indicating the relationship obtained was applicable. The summary results from the testing and analysis are presented below.

The equations derived for the relationships between void ratio and effective stress and between void ratio and hydraulic conductivity are key inputs into the large-strain consolidation models.



**Figure 3 Compressibility curves and variation of hydraulic conductivity with void ratio**

### 3.4 Geomechanical characterisation

The shear-strength properties of both the fine and total tailings samples were estimated using CU triaxial testing with pore-pressure measurement following the ASTM D4767 standard. Samples were prepared in a slurry state using dry-density/moisture content obtained from the 48-hour settled density test; the consolidation analysis on the total tailings sample indicated that the self-weight consolidation of the conventional tailings layer prior to deposition of the thickened tailings will vary from 1.59 at the top to 0.55 at the base, with an average of 0.66.

Samples were mixed with the required amount of water and preconsolidated under a 30 kPa load for 48 hours in the mould. This method provided a good consistency to the samples, to allow for handling during preparation and setup of the test. Test specimens were further consolidated to 50 kPa, 100 kPa, and 200 kPa respectively.

Both samples behaved contractively, with pore pressures initially rising and then dropping slightly after peak stress. The total tailings ( $\Phi' = 37^\circ$ ) showed higher shear-strength characteristics compared to the fine tailings ( $\Phi' = 34^\circ$ ); both samples were considered to have zero cohesion.

### 3.5 Dynamic characterisation

The purpose of the dynamic characterisation was to study the cyclic performance of both streams and obtain suitable geomechanical parameters to use in a dynamic analysis. A set of load-controlled cyclic triaxial tests were carried out on slurry-prepared specimens. The aim was to assess the cyclic stress ratio to induce liquefaction on the tailings samples at various confinement pressures and evaluate shear moduli.

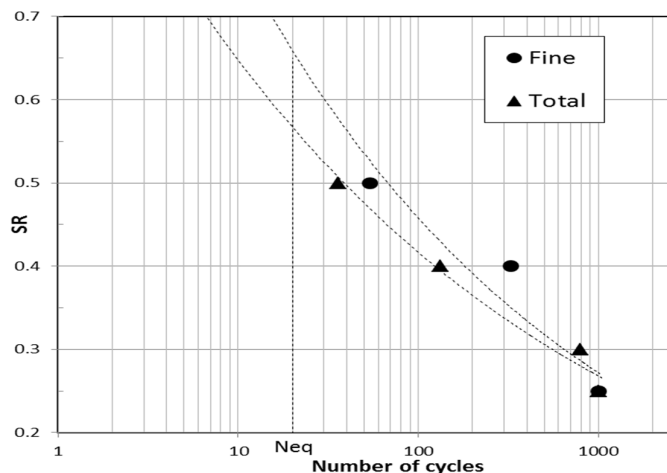
Remoulding of the samples was similar to that in the monotonic tests. The samples were then isotropically consolidated to 100, 200, and 400 kPa respectively. The initial void ratio and density of the samples was the same as detailed in Table 1. Samples were preconsolidated to 80% of their final isotropic consolidation load before being mounted in the testing apparatus. Table 2 presents the characteristics of the samples and the stress ratio (SR), defined as the deviatoric stress over twice the initial effective stress, applied to each test.

**Table 2 Cyclic triaxial tests**

Sample	Confining pressure (kPa)	Initial void ratio	SR
Fine tailings	100	1.15	0.075
	200	1.15	0.1, 0.4, 0.5
	400	1.15	0.15, 0.25
Total tailings	100	1.59	0.1
	200	1.59	0.15, 0.3, 0.4, 0.5
	400	1.59	0.25

The tests were conducted following the ASTM D5311-92 standard. The tests were stopped at axial-strain double amplitude ( $\square_{DA}$ ) of 2.5%, or when the number of cycles (N) exceeded 1,000, which were the criteria set for evaluating the susceptibility for liquefaction.

The tests indicated that for low SR ( $SR < 0.25$ ), both tailings streams exceeded the maximum N set out for initiation of liquefaction. The N required to initiate liquefaction (axial strain greater than 2.5 %) for each test was recorded and plotted in a single graph in terms of the applied SR, as presented in Figure 4.



**Figure 4** Number of cycles to liquefy ( $\varepsilon_{DA} = 2.5\%$ )

The number of equivalent ( $N_{eq}$ ) stress cycles for earthquakes of magnitudes 7.5 to 8.5 (which are noted as possible for the Colima region in which the mine is located) is 20 to 30, as recommended by the correlation done by Seed et al. (1975). The laboratory results presented in Figure 4 indicate that the fine and total tailings will initiate liquefaction at  $SR = 0.55$  to  $0.65$ . When correction factors to account for field conditions (0.9) and triaxial loading (0.72) are added, as suggested by Kramer (1996), the corrected resistance ratio ( $CSR_{Liq}$ ) range obtained is 0.35 to 0.42.

Bender elements tests were performed on both tailings streams to obtain the shear modulus for small strains. At strain levels less than about  $10^{-4}$ , the shear modulus in soils is considered constant and is generally called the small-strain shear modulus,  $G_{max}$ . The interpretation of the test in terms of effective confining pressure ( $\sigma'_3$ ) is based on Equations 1 and 2:

Total tailings (conventional and thickened):

$$G_{max} = -0.0068(\sigma'_3)^2 + 3.7888\sigma'_3 \quad (1)$$

Fine tailings:

$$G_{max} = -0.0052(\sigma'_3)^2 + 3.1904\sigma'_3 \quad (2)$$

These expressions were used as inputs for the numerical model for small strains ( $\varepsilon < 10^{-4}$ ).

## 4 Consolidation analysis

The analysis methodology is defined by a series of testing and analysis steps, with each step providing information required for the next step to progress.

These steps are outlined below:

1. Estimate deposition characteristics, including densities, rate of rise, and deposition intervals, to determine loading stresses.
2. Perform settling tests to determine settled densities.
3. Perform Rowe cell tests using settled densities and loading stresses as inputs.
4. Perform Rowe cell analysis to determine relationship between void ratio and effective stress.
5. Perform preliminary large-strain consolidation modelling using inputs from all of the above.
6. Perform secondary large-strain consolidation modelling scaled from preliminary model results.
7. Perform further iterations of the model as required.
8. Analyse and convert results to profiles within critical tailings deposition sections.

### 4.1 Deposition characteristics

The deposition characteristics for each of the tailings products are shown in Table 3. The deposition characteristics are used to determine the initial conditions for the settling tests, appropriate loading stages for the Rowe cell, and initial conditions for the consolidation model. An average dry density for each of the thickened tailings products was assumed prior to the preliminary analysis to estimate the rate of rise.

## 4.2 Large-strain consolidation modelling

Section 3.3 described the testing results obtained from the settling and Rowe cell tests, which were interpreted and adapted for use in the large-strain consolidation model.

One-dimensional (1D) transient large-strain consolidation modelling was performed in order to estimate the deposited tailings characteristics during the operational life of the TSF. Modelling was completed using the Somogyi consolidation application within the *SVOffice* software suite.

**Table 3 Deposition characteristics summary**

Sample	Value	Comment/Source
Total tailings conventional slurry		
Deposition slurry density	1.41 t/m <sup>3</sup>	Value provided
Maximum deposition depth	33 m	Value provided
Total deposition period (stage 1)	2 years	Value provided
Total tailings thickened paste		
Deposition solids content	75%	Calculated from rheological testing results corresponding to a yield stress of 100 Pa; yield stress limit provided
Maximum deposition depth	33 m	Value provided
Total deposition period (stage 3)	1.51 years	Calculated from provided production rate and volume versus elevation curve with an assumed average dry density of 1.7 t/m <sup>3</sup>
Fine tailings thickened paste		
Deposition solids content	71%	Calculated from rheological testing results corresponding to a yield stress of 100 Pa; yield stress limit provided
Maximum deposition depth	33 m	Value provided
Total deposition period (stage 3)	1.58 years	Calculated from provided production rate and volume versus elevation curve with an assumed average dry density of 1.6 t/m <sup>3</sup>

A preliminary consolidation analysis was completed using tailings parameters derived from the laboratory testing and a loading schedule based on the calculated rates of rise and deposition periods.

A second analysis was completed using adjusted rates of rise to compensate for the difference between the assumed final conditions used to calculate the rates of rise and the actual conditions, considering consolidation occurring during deposition. In this case, the rates of rise were increased for each material by a constant proportion to achieve a final depth of tailings solids equal to the depth assumed from the tailings deposition plan. The rate of rise was adjusted on the secondary model, rather than the deposition time, as for this project the deposition time was fixed due to operational constraints. In other situations, it may be more appropriate to adjust the deposition time to more accurately match the operational scenario.

The desired outcomes from the modelling are as follows:

- void ratio/dry density profiles with time;
- pore pressure/excess pore pressure profiles with time; and
- tailings depth with time.

## 4.3 Model descriptions and input data

Two models were completed, representing the two potential deposition scenarios (thickened total tailings or thickened fine tailings) at the deposition point illustrated in Figure 1. This location provides the thickest section of tailings and is used to develop density and pore-pressure profiles for a full two-dimensional (2D) section of the tailings mass.

The tailings input data is summarised in Table 4. The model-specific input data is summarised in Table 5.

**Table 4 Tailings material input data**

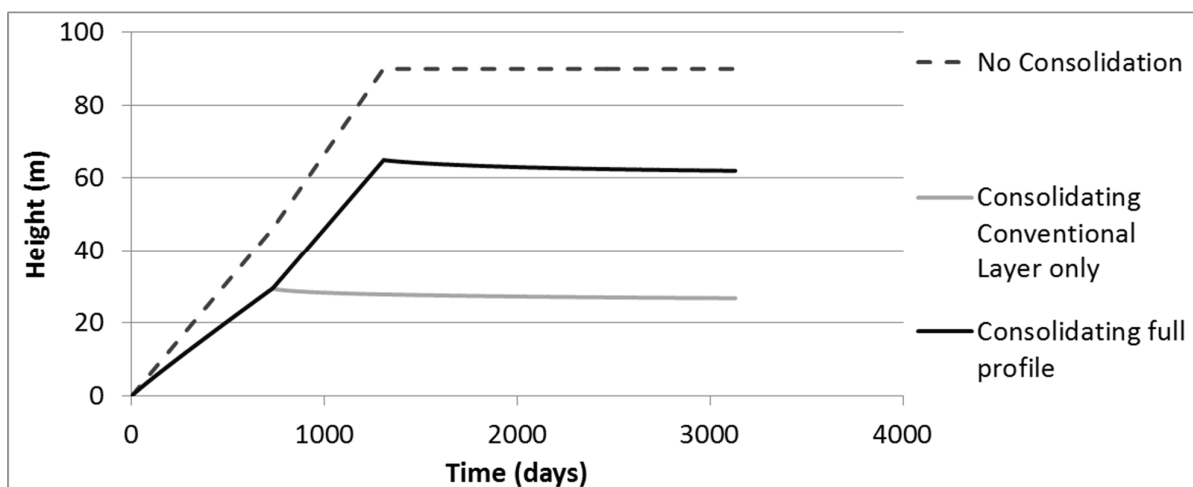
Input	Conventional tailings	total	Thickened total tailings	Thickened fine tailings
Void ratio ( $e_1$ ) versus effective stress ( $\sigma_1$ )	$e = 1.12157(\sigma_1)^{-0.142}$		$e = 1.12157(\sigma_1)^{-0.142}$	$e = 1.1308(\sigma_1)^{-0.074}$
Hydraulic conductivity (k) versus void ratio ( $e_1$ )	$k = 1.7052(e_1)^{0.1689}$		$k = 1.7052(e_1)^{0.1689}$	$k = 1.7746(e_1)^{0.1185}$
Discharge void ratio (e)	1.6		1.02	1.25
Specific gravity	3.06		3.06	3.06

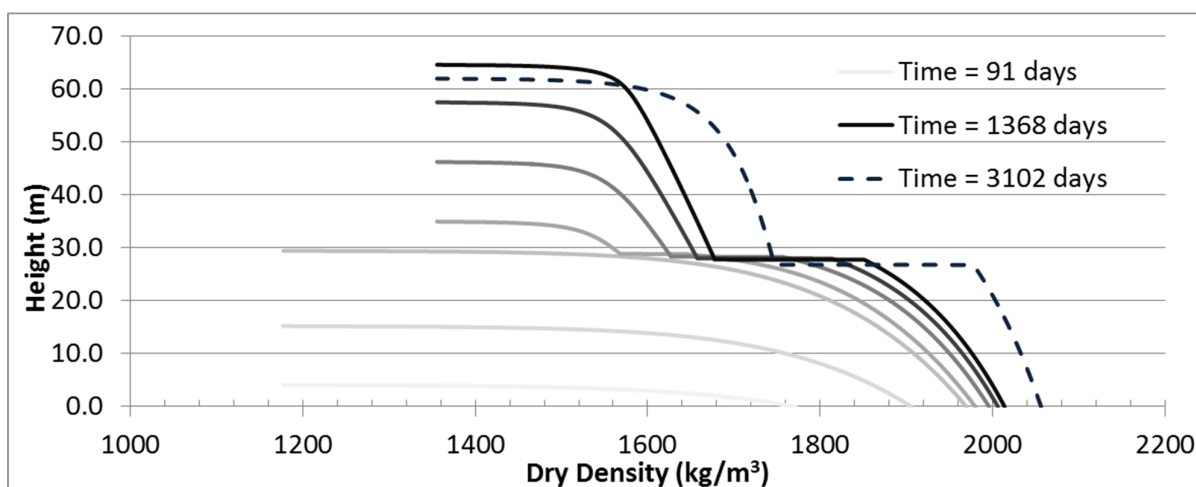
**Table 5 Model-specific input data**

Input	Total preliminary	Fine preliminary	Total secondary	Fine – secondary
Rate of rise (conventional tailings)	15.0 m/yr		23 m/yr	
Deposition period (conventional)	2 years			
Rate of rise (thickened)	23.84 m/yr	22.78 m/yr	29.13 m/yr	27.85 m/yr
Deposition period (thickened)	1.51 years	1.58 years	1.51 years	1.58 years
Quiescent period	5 years			
Lower boundary condition	Fixed, impervious			
Upper boundary condition	Free, pervious, zero surcharge			

#### 4.4 Results

The summarised results are provided as plots in Figures 5 through 7. These plots indicate the progression of the tailings properties over time. The dry density and excess pore water pressure plots have been produced with shading and dashes to indicate stages of the deposition. Lighter to darker shades indicate progression over time and dashed lines indicate that deposition has finished and excess pore-water pressure dissipation is occurring. Only the fine stream results are shown for conciseness.

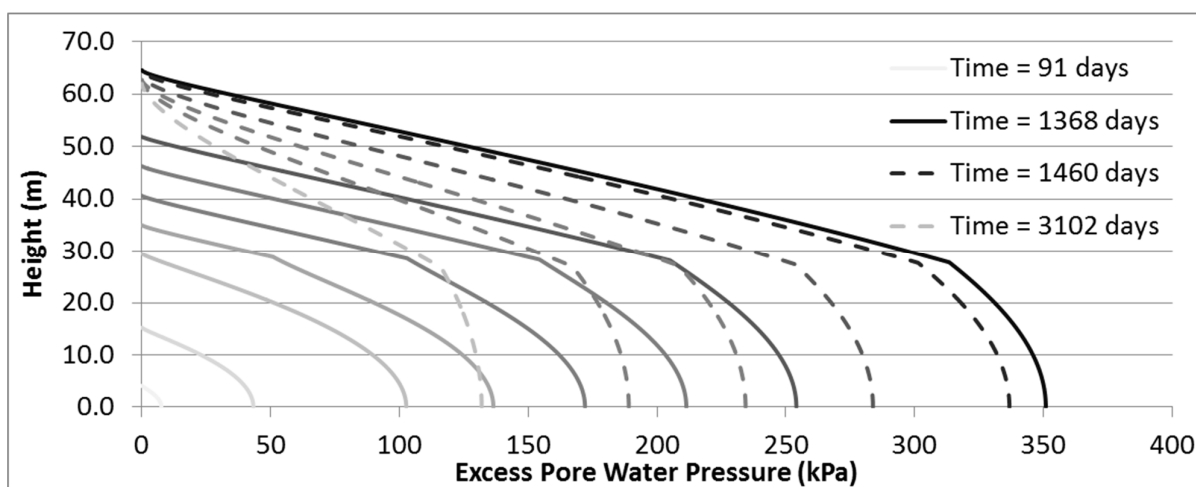
**Figure 5 Height versus time plot for thickened fine tailings scenario**



**Figure 6 Dry density versus height with time for thickened fine tailings scenario**

#### 4.5 Application

The model was set up to analyse the two tailings deposition phases at the deposition location (point of maximum tailings depth). The singular model was then used to analyse the full tailings' 2D profile. This was possible for this particular project as the base layer of the conventional tailings is of a relatively constant thickness: a linear beach slope is assumed and a minimal supernatant pond is expected. Additionally, the analysis considers the tailings profile at the time of reaching capacity and not following post-deposition consolidation. If these conditions are not met, then multiple models can be used to assess a variety of sections and relationships can be established to generate a 2D profile.



**Figure 7 Excess pore water pressure versus height with time for thickened fine tailings scenario**

The results from specific times, as the model progresses and the tailings height increases, are isolated. These isolated results were then applied to the corresponding thickness of the tailings section. Doing this in multiple locations allows researchers to analyse the full 2D tailings mass. The dry-density and pore-pressure profiles for the tailings mass were then developed and used as inputs for static and dynamic stability and deformation analyses.

The direct result obtained from this analysis is a justifiable estimate of the stage capacity, which takes into account transient consolidation. This is particularly important for tailings materials that are slow to consolidate, or in cases such as this, where the rate of rise is very high and life of the facility is short. This is also important in cases involving staged embankment construction. The difference between the long-term-calculated average dry density and the transient-calculated dry density at the time of reaching capacity can be very large. This difference is illustrated in the curves presented in Figure 8. The density profiles when the TSF reaches capacity are represented by the solid curve. This is noticeably lower for both scenarios than the dashed curve, which represents the long-term case.



In regard to performance and increasing storage capacity, Figure 8 shows that the total stream achieves a higher overall dry density. The average dry density for the full profile with thickened total tailings over conventional total tailings was 1.90 t/m<sup>3</sup>. The average dry density for the full profile with thickened fine tailings over conventional total tailings was 1.79 t/m<sup>3</sup>. This equates to 6% more tonnage stored in the TSF. This does not consider the coarse fraction, which must be stored separately in the fine stream scenario.

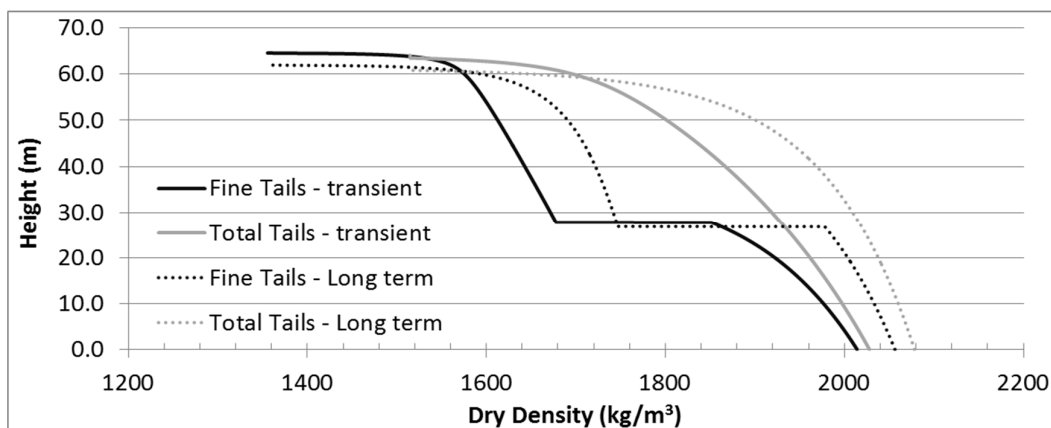


Figure 8 Dry density versus height comparison between streams and consolidation periods

## 5 Liquefaction assessment

In a high seismicity environment, the deposition of thickened tailings over existing conventional tailings poses a potential failure risk if the conventional tailings, which are regarded as having longer settling and consolidation timing, and/or the thickened tailings above this were to liquefy. The ability to mitigate the consequences of such an event is related to the level of deformation of the landform to a certain degree; excessive deformation could preclude the use of this deposition strategy. A comparative analysis has been conducted to evaluate which tailings stream would have better seismic performance or to aid in assessing whether this disposal strategy would be adequate for the site conditions.

The computer program *Fast Lagrangian Analysis of Continua* (FLAC 2D) was used to carry out the analyses, using the geotechnical parameters obtained from the laboratory. FLAC is an explicit finite difference program that simulates the behaviour of structures built of soil and rock. The model was built specifically for the project, to obtain the response of the tailings deposit system (foundation – embankment – conventional tailings – thickened tailings) to a specifically designed seismic input, and from there, to obtain a stress-strain history of the system elements. The stress pattern was evaluated throughout the model, and zones prone to liquefaction were identified by assessing the cyclic shear stress associated to the dynamic input compared with the mobilised cyclic shear strength of the tailings material. Details of the model will be discussed in the following sections.

The consequences of liquefaction depend on the level of tailings with respect to the crest of the embankment. As the tailings level gets closer to the crest, less freeboard is available to contain an eventual slurry rundown caused by liquefaction. Depositing thickened slurry over the conventional tailings creates a more critical scenario than a full conventional profile because the beach angle of the thickened product leads the tailings to stack upstream of the embankment. The further the central discharge point is located from the embankment, the more critical the scenario becomes, as the tailings will be positioned at a higher point above the embankment crest. The consequences of liquefaction include deformation of the tailings slopes, potentially mobilising large amounts of tailings down to the embankment face.

The vertical displacements obtained from FLAC were taken as an indirect assessment of the deformation of the landform due to liquefaction. Quantifying the flow that could be mobilised by liquefaction exceeds the complexity that can be afforded with the current level of investigation and is not the intention of this work.

### 5.1 Numerical model

A series of static/dynamic analyses of the TSF were conducted using FLAC 2D to obtain the stress-strain response of the TSF elements to a dynamic input. The sequence of this analysis was adapted from Palma and Verdugo (2007); it has been designed in FLAC code-based FISH language to obtain measurable parameters of the elements' mesh, which may enable the user to evaluate liquefaction by comparing the cyclic shear ratio to the maximum cyclic resistance ratio afforded by the elements. The TSF system is composed of three elements: the downstream embankment, the conventional tailings initially deposited, and the thickened tailings layer on top of the conventional tailings layer. The analysis sequence is discussed in Section 5.4.

## 5.2 Material properties

The tailings' geomechanical (static and dynamic) parameters used as inputs into the FLAC model were interpreted from the relevant test results. The materials properties used for the analysis are summarised in Table 6.

The empirical relationship between the dynamic and static Young's modulus has been adopted for this design, where  $E_{\text{Dynamic}} = 3 \times E_{\text{Static}}$ . The dynamic parameters were adjusted during modelling according to the strain levels experienced.

The undrained post-liquefaction strength was evaluated using the concept of liquefied strength ratio ( $S_u(\text{Liq})/\sigma'_{vo} = 0.05$ ) proposed by Olson and Stark (2002, 2003).

**Table 6 Materials properties for the analysis**

Material	Initial void ratio	c' (kPa)	$\phi'$ (°)	E <sub>Static</sub> (kPa)	v
Thickened total tailings	(*)	0	37	85 + 48.5 $\sigma_3$	0.35
Thickened fine tailings	(*)	0	35	218 + 42.6 $\sigma_3$	0.35
Conventional total tailings	(*)	0	37	85 + 48.5 $\sigma_3$	0.35
Foundation	2.5	200	36	400,000	0.3
Embankment fill	2	65	35	200,000	0.35

(\*) Total density was calculated from the large strain consolidation analysis and input as a profile.

Where:

- c' = cohesion.
- $\phi'$  = effective friction angle.
- E = Young's modulus.
- v = Poisson's ratio.

## 5.3 Seismic input

The dynamic input must be modelled considering the particular ground motion parameters in the project area. Databases such as those of the US Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), and Earthquake Engineering Research Institute (EERI) were consulted; these indicate that the largest seismic motions reported for the project site are within an epicentre distance of 50 to 150 km from the project site, originating from interaction of the Rivera and the Cocos plates.

The input motion was generated using the USGS seismic catalogue and typical maximum amplitude ratios ( $A/V = 1.25$ ,  $AD/V^2 = 0.35$ ) from earthquakes in western Mexico. The target motion spectrum was modulated using Newmark's recommendations (Kramer, 1996), considering a 5% damping.

The input motion thus obtained is representative of a magnitude 7.5 intraplate earthquake, with characteristics consistent with the regional seismicity. The motion was scaled to the project design criteria (PGA = 0.5 g), with maximum vertical acceleration of 2/3 PGA (Ambraseys, 2003) and duration of 20 seconds.

## 5.4 Sequence of the analysis

Two geotechnical models representing fine and total tailings were prepared using the various inputs discussed in previous sections. The FLAC analysis is a simplified evaluation of the liquefaction potential, including an estimation of post-liquefaction deformation (plastic flow considered), where seismic response is run at total stresses while the static runs are effective. The FLAC procedure was conducted using a predetermined sequence, as follows:

1. Perform static analysis of the embankment.
2. Perform static analysis of the full embankment/conventional tailings/thickened tailings to obtain the long-term tensional state of the deposit.
3. Perform seismic analysis to obtain cyclic stress ratio of the mesh.
4. Compare the cyclic stress ratio (CSR) with the cyclic resistance ratio obtained from the laboratory ( $CSR_{\text{Liq}}$ ) to identify the potentially liquefying zones.
5. Reduce the elastic/shear moduli and shear strength of the potentially liquefying zones from the previous step (post-liquefaction conditions).
6. Perform stress-strain analysis of the post liquefaction conditions.

The models were first analysed under static conditions to obtain initial conditions for the dynamic analysis. The dynamic run consisted of applying the scaled motion at the foundation level. FLAC was programmed to discriminate zones prone to liquefaction, using specific rules designed for that purpose. These identified potentially liquefying zones were assigned residual reduced elastic and strength parameters, and a further stress-strain analysis was conducted with this new set of parameters. The results of the latter were assessed by setting displacement monitoring points in the model along the top surface of the tailings, extending out to 120 m from the embankment crest.

The potential liquefying zones were identified using an algorithm that determined the maximum driving shear stress at every step based on the time-stress history for each cell during the dynamic run.

The CSR was calculated at each cell using Equation 3 and was compared to the  $CSR_{Liq}$ . Liquefaction condition for each cell was confirmed if  $CSR > CSR_{Liq}$ .

$$CSR = \frac{\tau_{cyc}}{\sigma'_{vo}} = \frac{\tau_{dynamic} - \tau_{initial}}{\sigma'_{vo}} \quad (3)$$

Where:

$\tau_{dynamic}$  = shear stress from time-stress history through dynamic analysis.

$\tau_{initial}$  = initial shear stress as obtained from the static analysis.

## 5.5 Results

Hydraulically deposited tailings consolidate over time; therefore, consolidation of the material is not immediate. Unconsolidated tailings are the most critical for geotechnical stability, particularly for dynamic stability and liquefaction. From the consolidation analysis, it was observed that pore pressures slowly dissipate over a period of five to 10 years after deposition. Therefore, the liquefaction analysis considers a short-term evaluation (zero to five years), where pore pressures are still dissipating and, as a result, effective stresses are lower than in the consolidated case (long term, or six to 10 years). As pore pressures dissipate, the tailings mass generally acquires higher effective shear strength and from there an enhanced dynamic resistance. These conditions were incorporated in the analyses to observe the short- and long-term effects.

### 5.5.1 Short-term conditions

In both cases, most of the tailings mass experienced liquefaction throughout the input seismic motion. It should be noted that the high pore pressure state induced by the high rate of rise translated into low effective stresses, which in turn led to low initial shear strength. This has a transient effect, as the pore pressure within the tailings mass starts stabilising with time. These models have been run considering peak pore pressures, representing short-term conditions.

Due to the reduction of strength and elastic properties of the material during liquefaction, the tailings settles, causing a reduction of the beach slope and resulting in an increase in the height of the material adjacent to the embankment as the tailings flow downstream.

The maximum vertical displacement adjacent to the embankment for the fine tailings is 6 – 7 m, approximately 50 m from the crest, while for the total tailings, it is 5 – 6 m, approximately 70 m from the crest. The vertical displacement typically decreased with distance from the embankment crest in both cases. The results indicate that both cases will experience significant deformation; there is a slight difference between them. Although more investigation would be necessary for a more accurate prediction of the tailings displacement in each case, it can be said that neither of the alternatives offers a major advantage over the other.

### 5.5.2 Long-term conditions

A similar dynamic analysis was conducted for the longer-term scenario, which assumes hydrostatic pore-pressure conditions when tailings are consolidated. This analysis was conducted to assess the impact of the reduction in excess pore pressure in the TSF.

The results of the analysis indicated that, in this case, displacement of the tailings due to liquefaction is limited to just shallow portions of the tailings body closer to the embankment. The maximum vertical displacement adjacent to the embankment is 1.5 – 2 m, approximately 50 m from the crest, for both the fine and total tailings. The vertical displacement typically decreased with distance from the embankment crest. Vertical displacements were reduced by approximately 70% compared to the short-term cases.

## 5.6 Discussion of the results

The results of the liquefaction analyses indicate that there is a high potential for liquefaction of the composite conventional/thickened tailings for both the fine and total tailings in the short term (zero to five years), when pore pressures induced by a rapid rise of the conventional tailings layer are still dissipating. Based on the consolidation analysis, the pore pressures of both the conventional and thickened tailings slowly dissipate over a period of five to 10 years after deposition. The fine-tailings profile takes longer to dissipate excess pore pressure than the total-tailings profile. After pore pressures in the conventional tailings layer are

stabilised with time, the potential for liquefaction appears to decline. In this case, liquefaction only developed at shallow depths (more freshly thickened tailings), and therefore consequences could be regarded as minimal, as any potential slurry rundown would be contained within the freeboard.

The high rate of rise of the tailings during conventional disposal translates into poorly consolidated tailings, and there is thus a high likelihood that the composite tailings deposit may liquefy during a large earthquake.

The actual consequences of liquefaction depend on the level of tailings with respect to the crest of the embankment. As the tailings level gets closer to the crest, less freeboard is available to contain an eventual slurry rundown caused by liquefaction. The further the central discharge point is located from the embankment, the more critical the scenario becomes, as the tailings will be sitting at a higher point above the embankment crest. The consequences of liquefaction may include deformation of the tailings slopes and mobilisation of large amounts of tailings down to the embankment face.

Quantifying the flow mobilised by liquefaction exceeds the complexity that can be afforded with the current level of investigation and is not the intention of this work. However, the analysis can be interpreted to suggest that the likelihood of a flow failure in the short term is high for both alternatives, given that the thickened tailings were placed over poorly consolidated conventional tailings. There is a small difference (approximately 20%) in vertical deformation of the top surface between the total and fine tailings, which indicates that the total thickened tailings experiences lower displacement compared to the fine tailings material and will therefore be subjected to a smaller effect if a trigger for liquefaction occurs.

The occurrence of liquefaction in the model means that it is necessary to implement strategies to aid pore-pressure dissipation in the field. Mitigation measures that could be explored in a further investigation may include the following:

- Revise the tailings disposal strategy, promoting wider spreading of the tailings and rotating discharge areas to allow for a slower rate of rise of the tailings (around 6 – 10 m/yr).
- Install drains to promote consolidation of critical areas of the tailings mass.
- Rotate the tailings discharge front around the basin frequently, allowing for drying of the beach.
- Ensure embankment freeboard (vertical distance between the crest of the embankment and the adjacent tailings level) is always maintained at 5 m or more.
- Provide additional freeboard until pore pressures have dissipated to a level such that the risk of liquefaction has diminished.
- Pump out any supernatant water that accumulates on top of the tailings.

## 6 Conclusion

Two geotechnical aspects of tailings disposal, consolidation and shear strength, have been evaluated to assess the implications of placing thickened tailings over recently disposed conventional tailings. Two alternative thickened slurry compositions were studied in order to assist with selecting the preferred stream for disposal. The effect of having an underlying conventional tailings layer deposited at a high rate of rise was incorporated into an analysis of the evolution of the density and dynamic behaviour of the composite tailings profile

The dual layer for both alternative thickened slurries will undergo significant settlement due to self-weight consolidation. The release of excess pore pressures will occur slowly and at a different rate for each of the streams. It was therefore necessary to use a large-strain consolidation model to assess the differences in storage capacity for each of the slurry streams. The difference in stored tonnage within the TSF obtained through the models was approximately 6%, with the total stream at a higher average dry density.

A dynamic analysis of the composite tailings was conducted for both alternatives to compare their behaviour during a representative strong motion. Short- and long-term conditions were set using the consolidation transient analysis to obtain initial void ratio and pore-pressure conditions for each case.

The results indicated that, for initial conditions representing the short term, both alternatives would reach liquefaction condition after a strong earthquake. Comparing their post-liquefaction deformation pattern, the total thickened tailings experienced slightly lower deformations of the beach (30% difference on average).

Both tailings composites exhibited an improved cyclic strength for the long term (six to 10 years) as the conventional tailings layer had time to dissipate pore pressures induced by the initial rapid rate of rise.

In conclusion, this study indicated that thickening the total tailings offers more advantages than the fine tailings from a storage capacity perspective and would result in lower seismic deformation. Nonetheless, the potential deformations could pose a serious hazard to the TSF operation; therefore, operators are suggested to further explore and implement mitigation measures prior to commissioning the TSF.

The results of the analysis were part of wider selection criteria and provided insight on the behaviour of a composite profile under static and dynamic conditions.

## Acknowledgements

The authors would like to acknowledge Daniel Prado of SRK Consulting for his significant contribution to the FLAC liquefaction modelling and William Gibson of SRK Consulting for his assistance with the seismicity inputs.

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