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Feasibility Evaluation of Converting a Conventional Tailings Disposal in a Thickened Tailings Deposit

R. Verdugo *CMGI Ltda., Chile*

J. Echevarría *Codelco, Chile*

G. Peters *CMGI Ltda., Chile*

G. Caro *Codelco, Chile*

Abstract

The feasibility evaluation of thickened tailings conversion at one brownfield project is presented from a geotechnical point of view. The lack of space and the need of water have pushed the owner (Codelco – Chile) to analyse this option of depositing thickened tailings on top of existing conventional tailings ponds. The conducted study attempts to provide technical support proving that thickened tailings can be deposited on top of conventional tailings in a stable condition even under strong seismic disturbances. Therefore, the paper is focused on the stability evaluation of the whole system, underlying slurry materials as well as the thickened tailings. Because conventional tailings have shown to be susceptible to undergo liquefaction, this phenomenon actually controls the global seismic stability. Therefore, the geotechnical characterization of both tailings impoundments and thickened tailings was carried out based on a comprehensive series of laboratory tests (thickened tailings) and a field investigation consisted on boreholes with SPT, CPT-U and shear wave velocity measurements. The field investigation was complemented with laboratory tests on "undisturbed" specimens that were retrieved using Shelby tubes. The geotechnical characterization and testing methodologies are discussed and the stability analysis of the global system (thickened over conventional tailings) is presented.

1 Introduction

Chile is among the countries that have developed an important mining industry; accordingly, together with the ore production, it generates significant quantities of waste material (tailings) that has to be properly stored. The resulting tailings disposals impose challenges to the design and construction to ensure stable as well as economically feasible disposals. However, stability is an issue that generally affects the costs and therefore for accomplishing an economically affordable tailings deposit, a high level of geotechnical engineering is required. Although stability is already a relevant issue, in the near future it will be even more due to the increasing strict environmental regulations that have to be peremptorily satisfied.

Additionally to the common stability requirements to be fulfilled by tailings disposals, because Chile is located in a region of high seismicity, disturbances induced by strong motions have to be incorporated and analysed. Unfortunately, the past experience has shown several cases of catastrophic seismic failures of tailings dams due to the occurrence of liquefaction. This phenomenon is associated with a sudden drop of the strength of saturated loose sandy soils to a residual value, commonly called post-liquefaction strength or undrained strength. It is important to mention that during the last years, the designs of the tailings deposits in Chile have been developed with high standards, avoiding the construction of upstream tailings dams.

In summary, the high seismic activity of Chile requires that the geotechnical design of tailings deposits guarantees their seismic stability, being the liquefaction analysis one of the main factors to be considered.

On the other hand, during the last decades the lack of water resources is definitely affecting the long term sustainability of the mining operations. In this context, the use of thickened tailings instead of conventional ones constitutes a very attractive method because it permits an important water recovery. In addition to these tremendous environmental and economic accomplishments, the total storage capacity is significantly increased by the conversion of a conventional tailings disposal in a thickened tailings deposit. Accordingly, the technical feasibility of converting one of the largest conventional tailings disposals existing in Chile, Talabre, by depositing thickened tailings above the existing tailings has been analysed.

Considering the high seismicity of Chile, the focus of this paper is associated with the seismic stability evaluation of the whole system, i.e. both the underlying slurry materials (existing conventional tailings) as well as the thickened tailings deposited above the existing ones. In a more general sense, this paper can be seen as the technical feasibility of “upgrading” a conventional tailing disposal by converting it into a thickened tailing deposit.

2 Description of the current Talabre tailings disposal

Chuquicamata mine is presently the biggest open pit copper mine worldwide. It is located 15 km north of Calama City and about 245 km northeast of Antofagasta City. Mining processes began in 1915 and since 1971 (Codelco Chile) Chuquicamata have had a remarkable growth throughout time, involving a large generation of wastes that have been safely stored in the tailings deposit named Talabre, which is located 15 km northeast of Calama City (Figure 1). Talabre is currently one the world's largest conventional tailings disposal in terms of area, reaching more than 50 km^2.

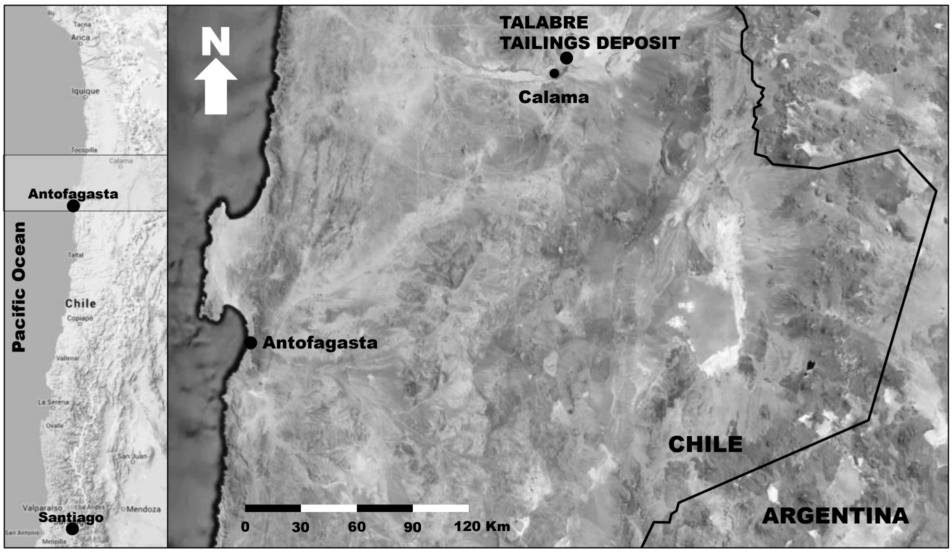

Figure 1 Location of Talabre tailings deposit

Talabre tailings deposit mainly consists of three resistant dams called North, South and West Dams (Figure 2). These three dams have a total length of 11 km and a maximum height of 45 m (2490 m.a.s.l.).

Initially the dams were constructed using the Downstream Method, compacting cycloned tailings up to elevation 2485 m.a.s.l. Later on, the construction of these dams was modified by the Center Line Method, using compacted waste rock material obtained from the open pit. A cross section of the West Dam is shown in Figure 3. Both upstream and downstream slopes, in the part made of cycloned tailings, are 3:1 (H:V).

Conventional tailings are currently being deposited at a rate of 182,000 tons per day (dry means), having an average solids content of 57%, which will increases in the near future to a rate of 225,000 tons per day.

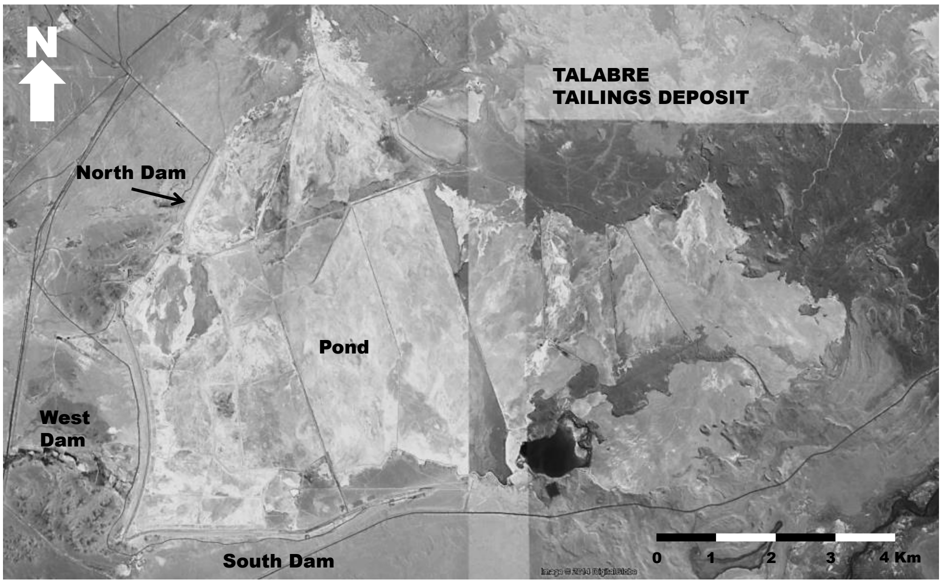

Figure 2 Satellite image of Talabre tailings deposit

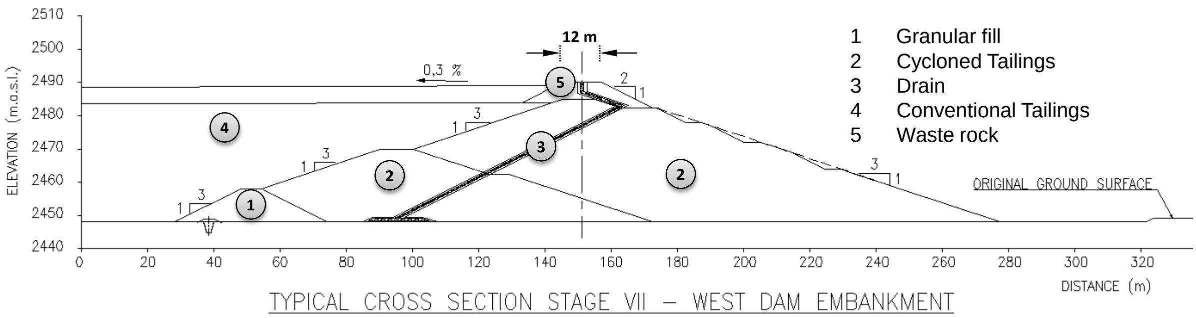

Figure 3 Cross section of West Dam

3 Project of converting Talabre in a thickened tailings facility

The project considers the operational continuity in the long term, by transforming Talabre from conventional to thickened tailings. The new scenario is for a treatment rate of approximately 400,000 tons per day, reaching a total surface over 90 km^2 in 35 years (Figure 4). Currently, this is the world's biggest project of thickened tailings disposal, with tremendous technical, economic, environmental and social challenges and benefits associated. The conversion from conventional to thickened tailings involves a huge amount of studies and considerations that give much to the knowledge of the art of thickened tailings and paste disposal in brownfield projects.

Conversion of Talabre from conventional into thickened, has a number of technical challenges and complexities that must be evaluated. Within these, the geotechnical evaluation of materials, to establish the technical feasibility of this transformation is crucial. Due to the high seismicity in Chile, it is very important to know very well the expected properties of the materials involved, among which are the thickened tailings and conventional tailings that make up the foundation soil. Thus, it is possible to be sure of the evaluation of the seismic response of the deposit against a great seismic event.

The prefeasibility studies of the project shows that the key issues, in terms of stability, should focus on underlying conventional tailings, since thickened tailings have better geotechnical conditions and can be controlled in the operation, according to design specifications. The investigations that are being developed in this line, achieve a greater understanding of the phenomenon of geotechnical resistance in brownfield projects that intend to develop changes in their tailings disposal technology.

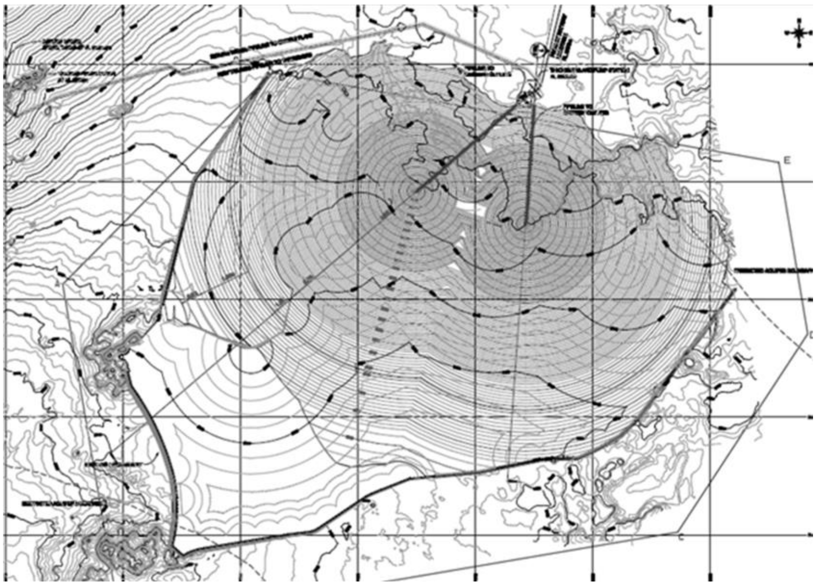

Figure 4 General geometry of the thickened tailings project

4 Geotechnical characterization of the tailings

4.1 Thickened tailings

The conversion of Talabre also involves an increase in the rate of tailings deposition from the current 200,000 tons per day generated by concentrator of Chuquicamata and Ministro Hales, to about 400,000 tons per day when entering into operation as thickened. This increase in rate is because the concentrator of Radomiro Tomic Division will start operating; whose generated tailings will be added to the current ones to Talabre. Therefore, the project has had develop a deep and comprehensive study of the tailings generated by these three concentrators.

The Chuquicamata mine has over 100 years of operation and still has reserves for the next 40 years and beyond. Radomiro Tomic mine has been operating for approximately 10 years, but treatment of sulphide ore will begin in 2018. Finally, the Ministro Hales mine is the newest of the three and started operating in January 2014, treating sulphide ores and generating tailings. Chuquicamata tailings have very low clay content, unlike the other two, so its geotechnical and rheological properties are quite different. The variability of these tailings, from the rheological point of view, is not addressed in this study, but focuses on the geotechnical point of view. At a pilot level, samples of tailings that will be produced in the future by each concentrator were generated, according to their treatment protocols. Thus, the project studied three possible mixtures of tailings, according with alternatives proportions being considered in the long term.

The tailings produced by the concentrators will be at 57%-60% solids, and the project considers the thickening of these to a nominal level of 67% solids.

The following table summarizes some samples, which were considered in this analysis.

Table 1 Summary of future tailings samples studied

Sample / Mix	D80 [μm]	<#200 [%]	Specific Gravity [t/m^3]	Shrinkage limit density [t/m^3]
Mix 1 (Chuqui 48%, RT 32%, MH 20%)	336.5	36	2.68	1.70
Mix 2 (Chuqui 47%, RT 26%, MH 27%)	269.9	44	2.69	1.72
Mix 3 (Chuqui 64%, MH 36%)	212.6	54	2.71	1.75

4.2 Conventional tailings deposited in Talabre

A comprehensive field investigation was carried out by means of a series of bore-holes with SPT measurements and “undisturbed” sample retrieve using Shelby tube, in order to establish the geotechnical characterization of conventional tailings disposed in Talabre.

Complementarily, a series of CPTU with shear wave velocity measurements was performed. The locations of both bore-holes (SPT) and CPTU inside the pond of Talabre are shown in Figure 5, where it is possible to visualize that the site investigation covered the existing tailings stored in the pond. The depths of each bore-hole and CPTU are indicated in Tables 2 and 3.

Samples from Shelby tubes were extracted and transported to the laboratory for characterization and triaxial testing. The average of the samples showed that the material varies from sand with 20% fines to fine soil with 15% sand. The average specific gravity of the samples was 2.67 t/m^3.

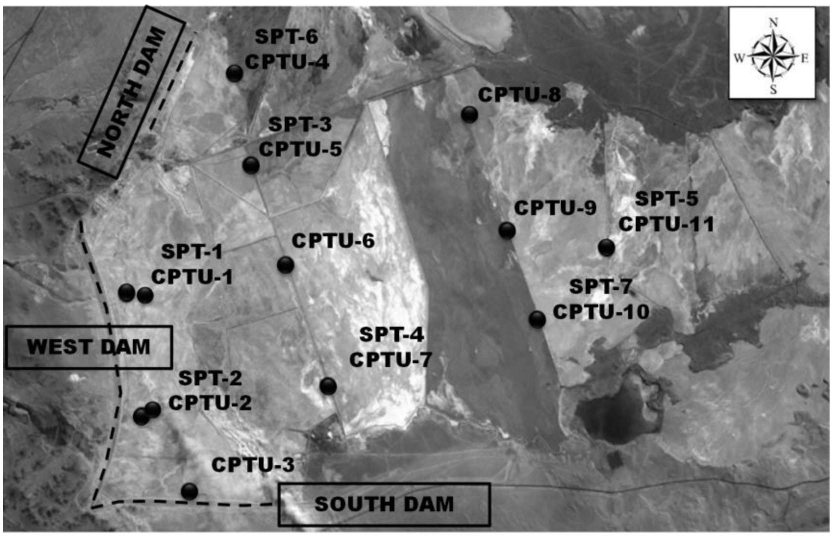

Figure 5 Site investigations on the existing tailings

Table 2 Depth of cone penetration tests

Cone penetration test	Depth (m)
CPTU-1	26.0
CPTU-2	28.7
CPTU-3	10.6
CPTU-4	24.2
CPTU-5	33.6
CPTU-6	35.0
CPTU-7	34.5
CPTU-8	10.1
CPTU-9	32.0
CPTU-10	39.5
CPTU-11	35.1

Table 3 Depth of bore-hole where SPT were performed

Borehole	Depth (m)
SPT-1	27.5
SPT-2	28.0
SPT-3	27.0
SPT-4	27.0
SPT-5	34.5
SPT-6	23.0
SPT-7	35.0

5 Liquefaction analysis

5.1 Liquefaction phenomenon background

The term liquefaction was coined by Hazen (1920) to describe the failure of the hydraulic fill sand of Calaveras Dam on March 24th, 1918. In this failure, the upstream toe of the under construction Calaveras dam, located near San Francisco in California, suddenly failed "flowing" approximately 700,000 m^3 of material for around 90 m. Apparently, at the time of the failure, none special disturbance was noticed, indicating that this phenomenon can occur in the absence of earthquakes.

Since that failure, the term liquefaction has been used in a broad sense for describing two different phenomena that may occur in saturated cohesionless soils, as tailings. These phenomena have in common a significant pore pressure build-up and large deformations of the ground. Nevertheless, to understand the actual soil behaviour, it is of a great importance to distinguish between the so-called flow failure, where a sudden loss of strength takes place (Castro 1969), and the term cyclic mobility that is essentially associated with a progressive strain softening without any loss of strength. The term true liquefaction (flow failure) was proposed by Casagrande (1975) for the phenomenon where a sudden loss in strength to a residual value takes place in a loose cohesionless soil. When the existing driving forces, or permanent forces, are larger than the mobilized residual strength, the failure is triggered and the soil mass deforms and flows resembling a viscous fluid. After failure has occurred, the soil mass involved in the collapse tends to reach very gentle slopes. Typically, flat angles of 1° to 8° have been observed. This failure can be triggered not only by earthquakes, but also by disturbances that are fast enough to induce an undrained response of the initially loose soil mass.

True liquefaction or flow failure is the phenomenon that has been observed in the catastrophic failures of tailings dams, causing adverse scenarios with a significant amount of soil mass flowing hundreds of meters in a few minutes. Consequently, seismic analysis of tailings dams must include the evaluation of the eventual occurrence of flow failure. The condition of flow failure generates a large level of deformation where the steady state or ultimate state of the soil is reached, so the use of this concept in the evaluation of a potential flow failure is suitable.

The ultimate response of the specimen has been referred to as the steady state of deformation (Poulos, 1981). Experimental results of undrained triaxial tests performed on specimens at different effective confining pressure and at the same void ratio after consolidation, are shown in Figure 6 (Verdugo, 1992; Ishihara, 1993; Verdugo et al, 1996). It can be seen that, regardless the initial level of confining pressures, the same undrained strength or steady state strength is achieved. Additionally, the effect of the stress history is shown in Figure 7, in terms of stress-strain curves on loose specimens loaded monotonically and cyclically (Verdugo, 1992). As it is observed, the ultimate condition or steady state strength achieved at large deformations is independent of the previous cyclic loading, indicating that the stress history does not affect the strength developed at large deformations (Verdugo, 1992).

These experimental results suggest that the steady state strength is mainly a function of the void ratio. Therefore, the analysis of a flow failure basically needs to establish the level of static shear stresses and the undrained strength, which would be only dependent on the void ratio of the soil mass. The seismic action has to be seen as a trigger of the undrained strength.

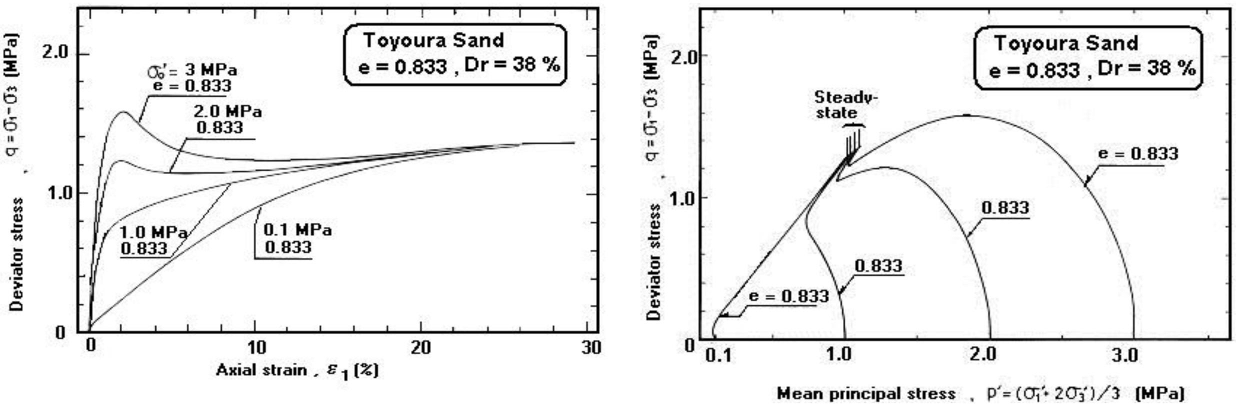

Figure 6 Undrained strength at large deformations or steady state strength (Ishihara, 1993)

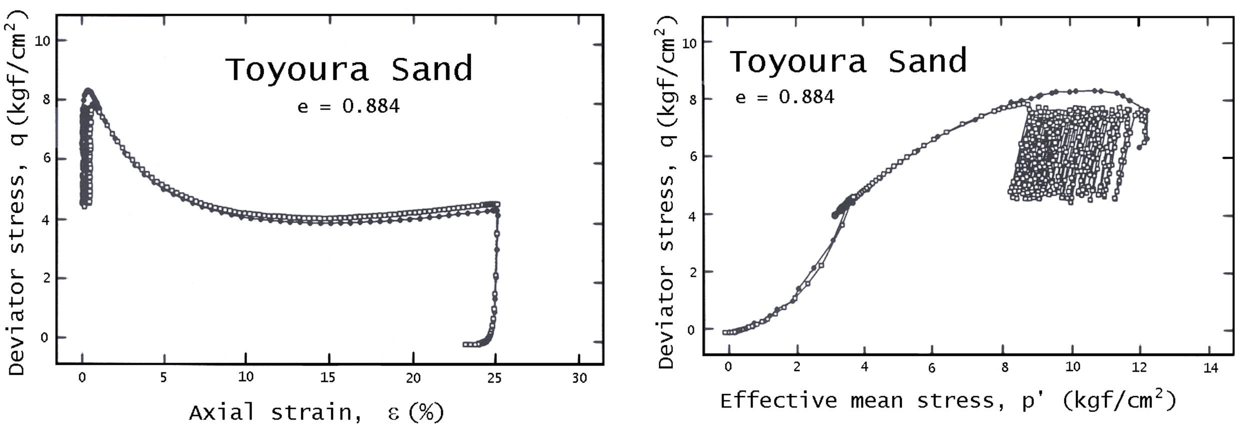

Figure 7 Effect of stress history on loose sand (Verdugo, 1992)

5.2 Undrained strength of thickened tailings

In the case of thickened tailings disposal system, the main goal is to create a self-supporting tailings mass, so confining dikes can be eliminated or at least minimized. To accomplish this, the water content of the initial tailings slurry is reduced as much as possible, prior to discharge, by means of high-density thickeners, resulting in a tailings deposit of a gently-sloping conical shape, with typical angles between 2 to 6 percent. The concept of thickened tailings was introduced by Eli Robinsky in the late 60´s and actually used since the beginning of the 90´s (Robinsky, 2000).

The project conducted a laboratory testing program, using five different tailings batches of different grain size, which covers the different materials that are expected to be stored as thickened tailings. Series of triaxial tests were performed on compacted specimens, using the moist tamping sample preparation procedure at a target dry density of 1.38 t/m^3. The specimens were anisotropically consolidated and sheared in undrained condition. The test results indicated a normalized undrained strength, S_u/σ_1, in the range of 0.07 – 0.36, adopting the following project value:

$$S_u/\sigma_1 = 0.09$$

Where, σ_1 represents the mayor principal stress.

This result indicates that the thickened tailings reach a higher undrained strength. Therefore, the stability of the whole system is controlled by the existing tailings stored in the pond.

5.3 Liquefaction resistance of existing tailings

The Chilean high seismicity has shown that conventional tailings disposals are susceptible to fail due to the occurrence of liquefaction, so this phenomenon actually controls the global stability of the conventional–thickened tailings deposit. Therefore, the assessment of the geotechnical properties of the existing tailings, i.e. post-liquefaction resistance, is one of the main goals associated with the study of the seismic stability of the combined deposit.

Liquefaction resistance from existing tailings was studied in different ways, depending on the tests performed. For this, the test results of CPTU and triaxial were considered.

From triaxial tests, the relation between undrained strength and effective initial confinement pressure is shown in Figure 8. From these results, the minimum normalized undrained resistance, is the following:

$$S_u/\sigma'_0 = 0.20$$

Where, σ'_0 represents the initial effective stress.

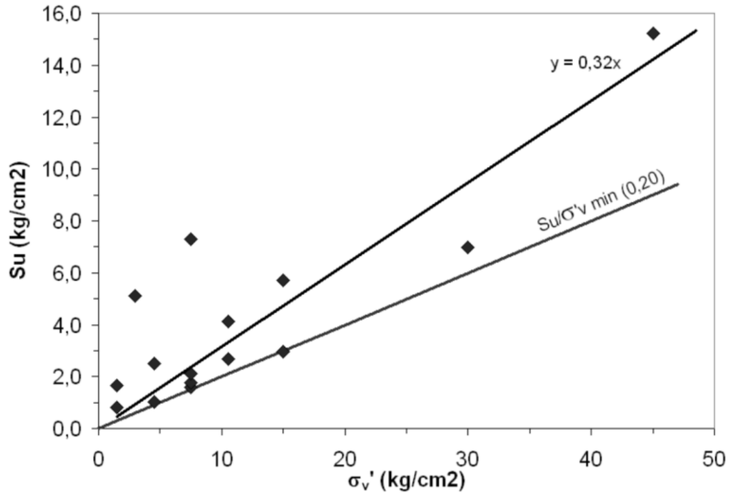

Figure 8 Undrained resistance vs. initial effective confinement pressure

From CPTU, the peak undrained strength is considered to correlate with the tip resistance, while the sleeve resistance can be interpreted directly as the undrained residual strength or undrained strength at large deformations (Robertson, 2009). Therefore, the sleeve resistance obtained from the CPTU was analysed in order to establish the undrained strength (post-liquefaction strength) of the present stored tailings.

Typical results of sleeve resistance obtained from the CPTU are shown in Figure 9. As can be observed, there is an important variation of the sleeve resistance, suggesting that the stored tailings are highly stratified and constituted by thin layers of sandy and silty materials.

The selection criterion to determine the representative normalized undrained shear strength of the conventional tailings corresponds to the value that is exceeded by 80% of the measurements. As shown in Figure 10, the inferred value is:

$$S_u/\sigma_v' = 0.06$$

Where, σ_v' represents the vertical effective stress.

Considering that triaxial test results are affected by sample retrieving, transportation and laboratory handling, the results obtained from CPTU were considered representative of the normalized undrained strength.

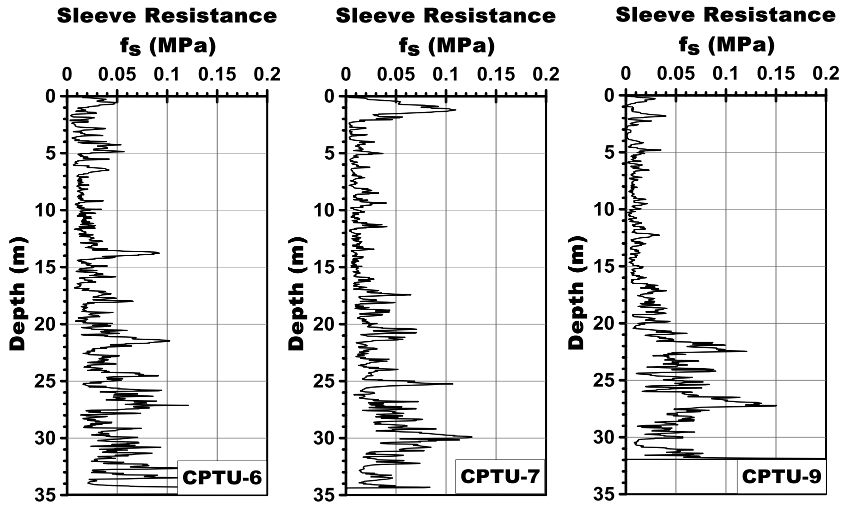

Figure 9 Typical values of sleeve resistance

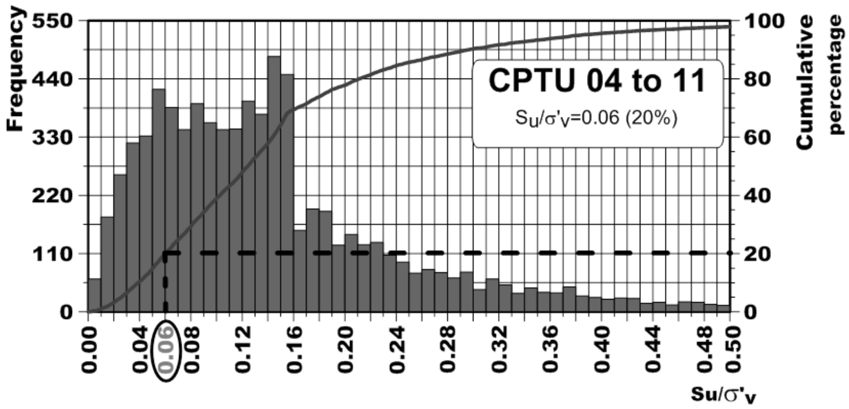

Figure 10 Normalized undrained strength obtained from sleeve resistance

6 Seismic analysis of the conventional - thickened tailings deposit

A 2D seismic stability analysis using commercial software was carried out in order to estimate the global behavior of the deposit and the magnitude of deformations of thickened tailings deposited on top of conventional tailings. Materials were defined having a Mohr-Coulomb constitutive model, and properly incorporating the dependency of overburden pressure and Modulus of Deformation. For the analysis, it has been conservatively estimated that both conventional and thickened tailings will fully undergo liquefaction from the beginning of the motion; hence their resistance is defined by means of the undrained strength.

The summary of the geotechnical parameters of the involved materials is detailed in Table 4. The dam was simplified as a single material of cycloned tailings sand.

Table 4 Summary of geotechnical parameters of materials

Parameters	Unit	Foundation materials		Existent conventional tailings	Cycloned tailings (Dam)	Thickened tailings
		Granular	Claystone			
In-situ density, γ	t/m^3	1.8	2.0	1.78	1.65	1.36
Cohesion, c	t/m^2	0.1	10	$0.06\sigma_v'$	0	$0.09\sigma_v'$
Internal friction angle, ϕ	°	37	40	0	40	0
Deformation Modulus, E_s	Kg/cm^2	2.0×10^3	2.0×10^4	122	5.0×10^4	$245 \cdot (\sigma_3')^{0.55}$
Seismic Deformation Modulus, E_d	Kg/cm^2	1.0×10^4	2.0×10^4	$6 \cdot (\sigma_3')^{0.76}$	5.0×10^5	$245 \cdot (\sigma_3')^{0.55}$
Poisson's Ratio, ν_s	-	0.33	0.25	0.33 / 0.49	0.30	0.30 / 0.49

The section of analysis was selected considering both the height of the tailings deposit and the relative distance between the thickened tailings and the North Dam. At the last stage of construction, it is estimated that the thickened tailings deposit will reach a maximum height of 118 m (relative to the existent pond level) and a total length of about 8 km, having a static concave slope between 0.5% up to 3%. Chosen section is shown in Figure 11, where the height of the Dam is 20 m (the highest section of the West Dam is about 52 m) and the thickened deposit presents the shortest distance to the dam, of about 105 m.

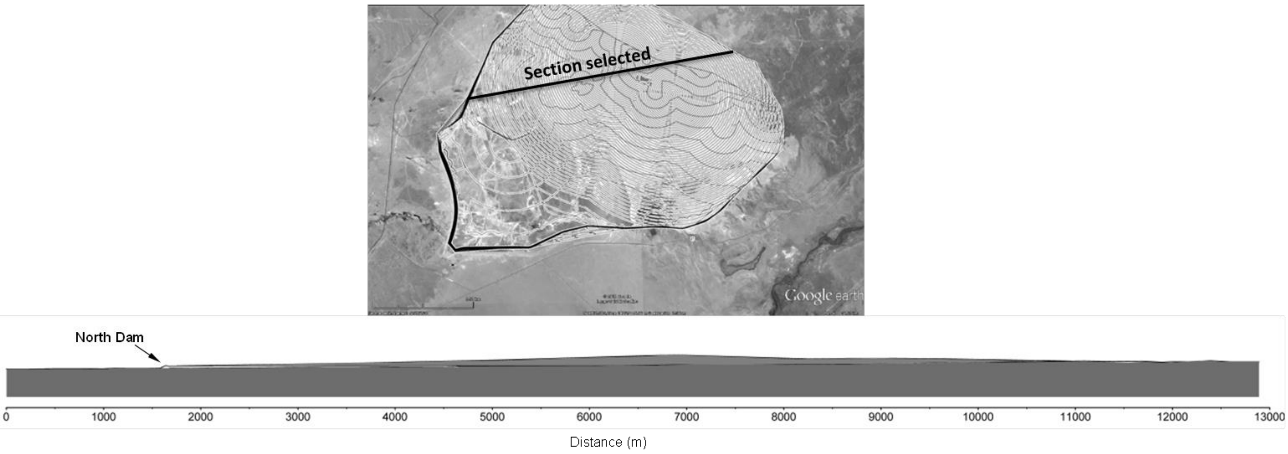

Figure 11 Section analysed (above) and Geometric and Stratigraphical Model (below)

The 2D model (Figure 12) was limited to a total extension of 5 km, which is considered to be adequate for the purposes of evaluating the global stability of the deposit. Foundation soil has a mean depth of 70 m thus the location of the soil-rock interface is defined; the existent pond (conventional tailings) presents heights varying from 0 to 20 m and the thickened tailings disposal has a maximum height of 80 m above the level of the pond. The mesh of the model has a serious limitation due to the size of the model, so the better possible mesh was adopted, attempting to transmit the main frequencies of the input motion.

The Seismic Hazard study specified a design earthquake associated with the Maximum Credible Earthquake (MCE) event, characterized by an intraplate mechanism of an intermediate depth of 60 km, a focal distance of 160 km from the site of the project and a Richter magnitude of Ms=8.0. As it is shown in Figure 13, the MCE acceleration time history has a total duration of about 65 s and a peak acceleration of 0.803g, which was scaled to consider that the input motion is actually applied at the base of the model.

The computed dynamic response was monitored in several locations of the slope of the thickened tailings deposit and at the crest of the Dam, in terms of both deformations and accelerations during earthquake (Figure 14). It is worth to mention that acceleration was barely registered at the surface of the tailings due to liquefaction state during the earthquake.

As a result of the dynamic analysis, remnant magnitude of deformation of the thickened tailings deposit is shown in Figure 15. It is observed that deformations are mainly concentrated towards the center of the thickened deposit with deformations of up to 8 m, which is believed to be compatible with both the applied MC earthquake and the extension of the deposit. It is also noticed that in the surroundings of the Dam and at the Dam itself, experienced seismic deformations were rather low, being significantly lesser than 1 m. Deformations at the highest part of the thickened disposal are also low.

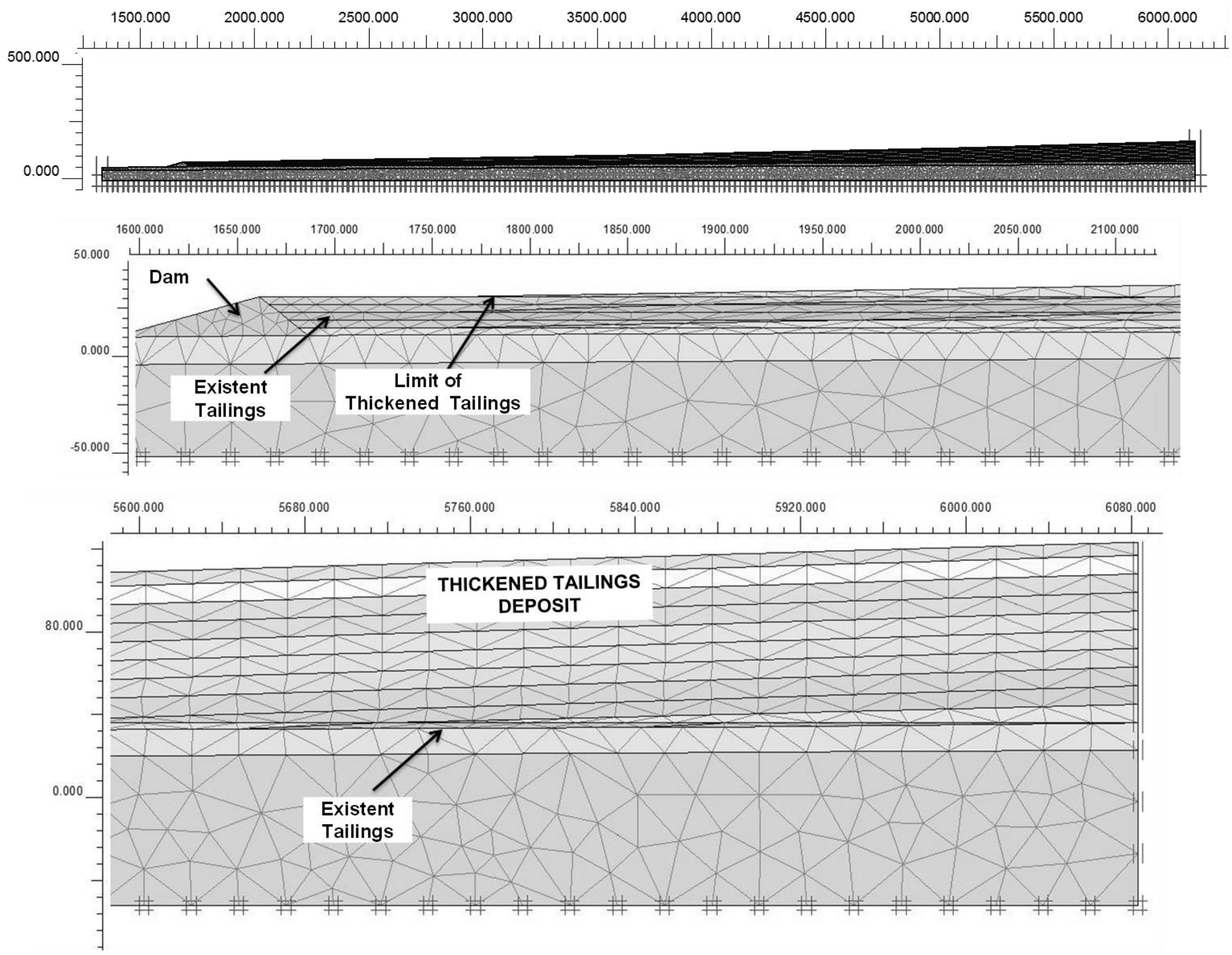

Figure 12 General view of the model (above); Dam's nearby zone (middle); and maximum thickened tailings height modelled (below)

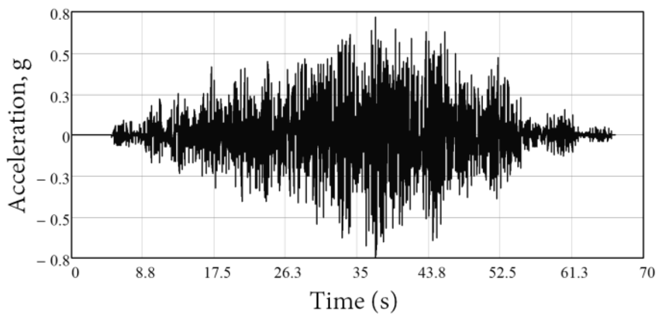

Figure 13 MCE design earthquake

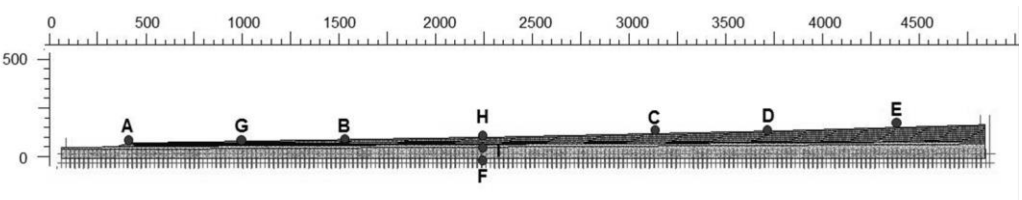

Figure 14 Points of computed accelerations and deformations

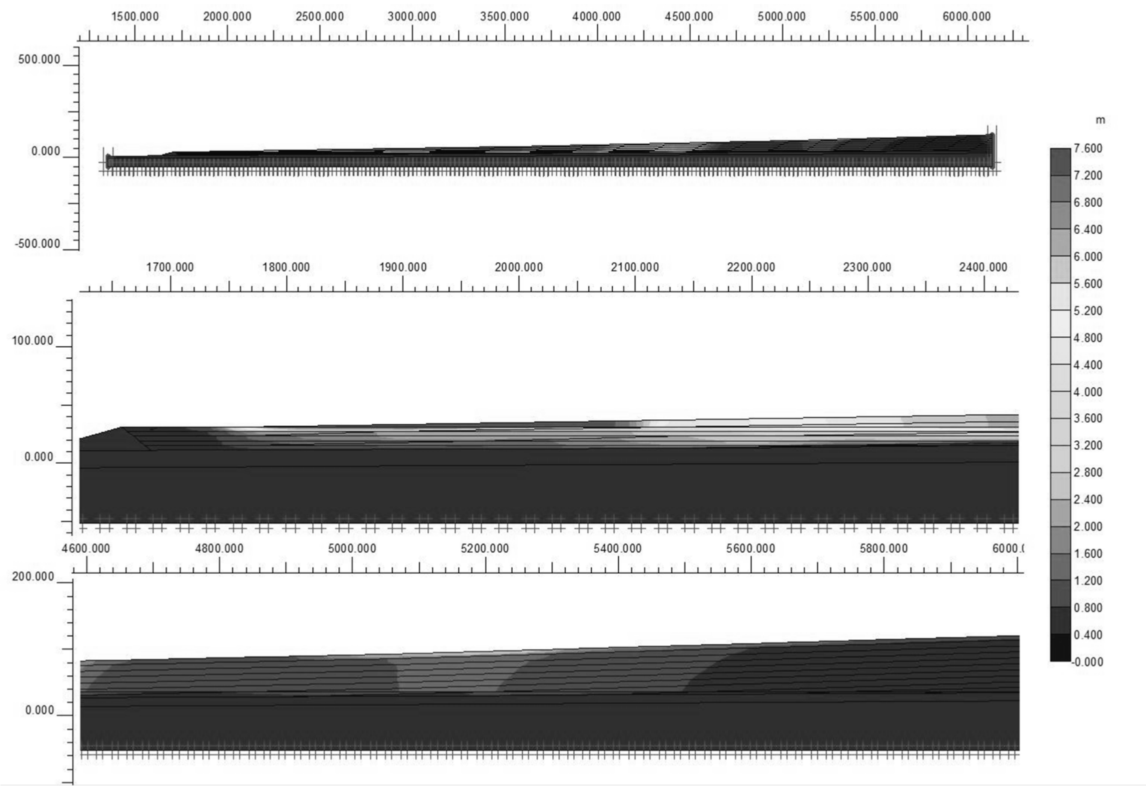

Figure 15 Post earthquake remnant deformation field (maximum magnitude)

In order to understand the pattern of deformations in depth, seismic deformation profiles of four sections of the model are presented in Figure 16. As it is observed, the first chart shows total deformations are rather negligible (less than 3 cm). Profiles G and H practically show that the whole height of the thickened tailings experienced mayor deformations, showing a “rigid body” response of the deposit. Nonetheless, the area affected by such magnitudes is limited to the third central part of the thickened tailings deposit.

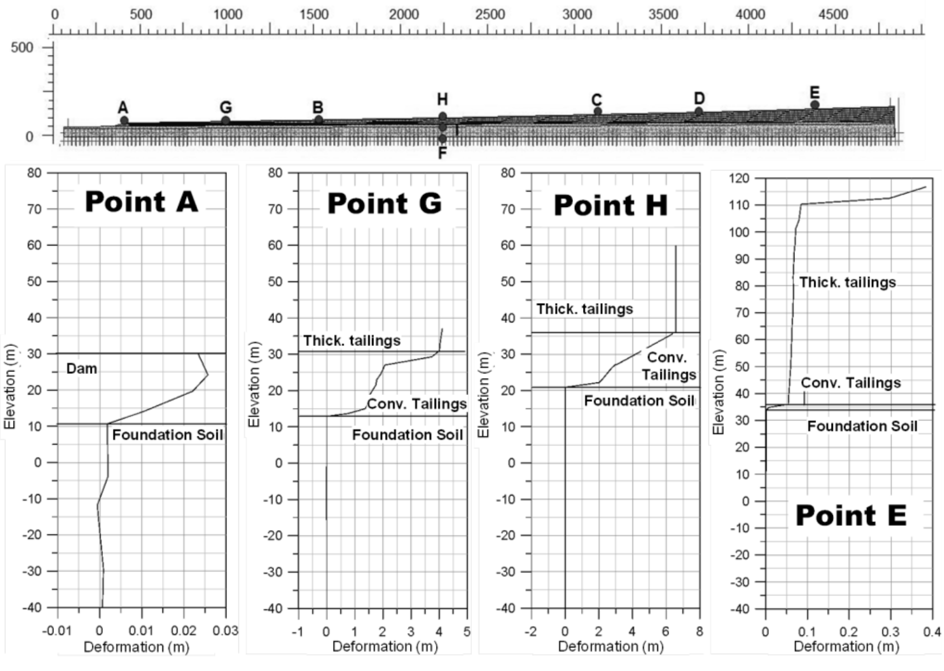

Figure 16 Remnant deformation profiles of four sections (maximum magnitude)

7 Conclusions

During the last years, the characteristics of Chilean copper mining, along with new environmental and social policies, have demonstrated the need for changes in the management of tailings deposits. Production rates of large mining entail high water consumption and, in the case of tailings management, the design of major works with extensive use of space. This is a reality in the country, where new projects are currently considering new alternatives, such as high density thickening and filtering, as well. Thus utilization surfaces deposits are minimized and the use of water in the process is optimized. This is not alien to current operations and which have long-term projections for its continuity. This is the case of Codelco, the largest mining company of the country and one of the largest cooper producers in the world, which is studying these aspects in its 6 Operational Divisions throughout the country.

Currently Talabre is the tailings deposit of Chuquicamata and Ministro Hales Divisions, and from 2018 it will be also for Radomiro Tomic Division. It is a strategic work for this Codelco mining district, so its transformation from conventional operation to thickened one has been accompanied by a series of studies and research.

From geotechnical point of view, a comprehensive site investigation was carried out on the existing stored tailings that permitted the evaluation of their undrained strength or post-liquefaction strength. A laboratory testing program on the thickened tailings was accomplished, that also resulted in an estimation of its undrained strength. These parameters are considered the key variables that control the seismic stability of the whole system, underlying slurry materials as well as the thickened tailings.

A 2D dynamic analysis in the time domain was performed, applying the Maximum Credible Earthquake provided by the seismic risk study of the site. The worst scenario of liquefied tailings from the beginning of the shaking was considered.

The computed results indicate that total displacements of the thickened tailings are limited to less than 10 m, which means that the proposed storing solution (thickened over conventional tailings) remains within the pond, showing that global system is seismically stable.

The aspects that this research attempts to explain are related to those of a brownfield project, from a geotechnical point of view, where not only must study the conditions of future tailings, but also of the current tailings that will form the foundation of the project surface. These are issues that all brownfield projects of operational transformation from conventional to thickened, will have to assess.

Acknowledgements

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