Evaluation of Tailings Dams Subjected to Large Earthquakes

Évaluation des barrages de rejets miniers soumis à de grands séismes

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ABSTRACT: Acceleration records obtained during the Illapel Earthquake, Mw = 8.3, in two instrumented large tailings sand dams are analyzed; the natural periods were computed evaluating the transfer functions. The Chilean experience suggests that tailings sand dams designed and constructed using the downstream method have an excellent seismic behavior. However, numerical models normally predict relatively significant seismic displacements. If an apparent cohesion of 20 kPa due to suction is adopted in the unsaturated tailings, the dynamic numerical analyses show a significant reduction in the permanent displacements.

RÉSUMÉ : Les registres d'accélération obtenus au cours du séisme d'Illapel Mw = 8,3 dans deux grands barrages à rejets de sable instrumentés sont analysés ; les périodes naturelles ont été calculées en évaluant les fonctions de transfert. L'expérience chilienne suggère que les barrages à rejets de sable conçus et construits en utilisant la méthode en aval ont un excellent comportement sismique. Cependant, les modèles numériques prévoient normalement des déplacements sismiques relativement importants. Les résultats des analyses dynamiques montrent une réduction significative des déplacements permanents lors de la considération d'une cohésion apparente de 20 kPa, due à la succion capillaire dans les sables partiellement saturés.

KEYWORDS: Tailings dams, seismic deformations, dynamic stability analysis, earthquake geotechnical engineering.

1 INTRODUCTION

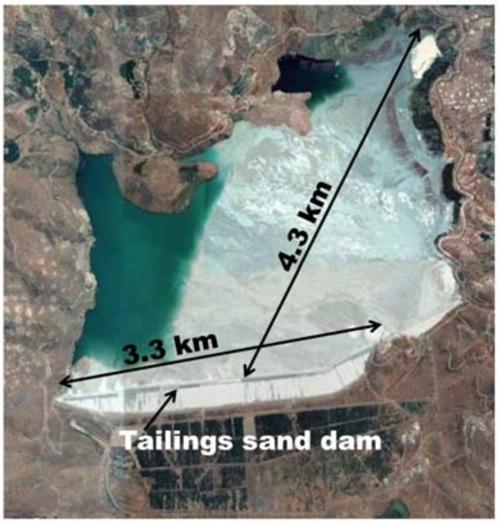
The production of minerals is necessarily associated with the generation of a significant amount of residues, normally called tailings, that the mining operations have to manage and place efficiently in reservoirs confined by dams. These geo-structures raise challenges related to the design and construction of stable and cost-efficient disposal facilities. Different types of tailings disposals can be constructed depending upon how the tailings are processed, transported, discharged, and stored. The most common tailings disposals are: Conventional tailings disposals in reservoirs, most frequently with sand tailings dams; Filtered tailings disposals, and Thickened tailings disposals with some low confinement structures.

The largest tailings deposits are constructed as conventional reservoirs, being one of the main reasons that there is no restriction in the amount and rate of tailings that can be deposited at any time. As an example of these geo-structures, Fig. 1 shows the reservoir and the tailings sand dam of Ovejeria, which is planned with a final height close to 130 m, with a capacity of storing 1.3 millions of cubic meters of tailings.

The experience learned from large earthquakes indicates that tailings sand dams are sensitive to seismic excitations, undergoing large and catastrophic deformations when the liquefaction phenomenon has occurred. To avoid a failure due to liquefaction, the tailings sand dams are constructed in Chile, one of the most seismically active country, according to the downstream or center-line methods (Troncoso et al, 2017). Additionally, the cycloned tailings sands are compacted, in general, to a relative density greater than 60% and its fines content is restricted to a maximum value of 20%.

Considering that tailings dams must remain physically stable well beyond after the mine has ended its operation, it is necessary to evaluate the seismic stability for the so-called abandon period. In high seismic regions, as the case of Chile, the resulting Maximum Credible Earthquake associated with the abandon period is extremely demanding. Therefore, it is necessary to study in detail the geotechnical properties of the tailings sands used in the dam to verify their adequacy or to avoid overdesign.

Figure 1. General view of Ovejeria tailings sand dam (Chile)



An important consideration is related to the effect of aging on the liquefaction resistance of tailings sands (Troncoso et al, 1988). When the tailings dam has been in operation for several years, it is possible to retrieve samples at different depths, which are associated with different years of deposition. Testing these undisturbed samples, it is possible to establish the improvement of the cyclic strength with the age of deposition, which allows an estimation of the gained cyclic resistance with time.

Another factor that is important to consider is the actual unsaturated condition of the tailings sands that constitute the dam body. Normally, sand materials are denominated "cohesionless soils", which obviously means that they shear strength is basically controlled only by both interlocking and friction between grains. However, it is a well-known fact that sandy soils with some water content (below saturation), develop an apparent cohesion that can be explained by means of the suction generated by the unsaturated soil condition.

This article presents empirical and numerical evidence that could explain the importance of the apparent cohesion in the seismic stability of tailings sand dams.

2 OBSERVED SEISMIC BEHAVIOR

Recently, the Illapel Earthquake of Magnitude, Mw = 8.3, hit the Central-North region of Chile. The peak accelerations recorded by the stations of the National Seismological Center are presented in Fig. 2, where a maximum value of 0.83g is observed. Two tailings sand dams located in the affected area have reported the acceleration records obtained on the crest of these dams as well as in the nearby rock outcrops. These tailings sand dams are El Torito with 83 m in height and West-Tortolas, with 30 m in height (for location see Fig. 2).

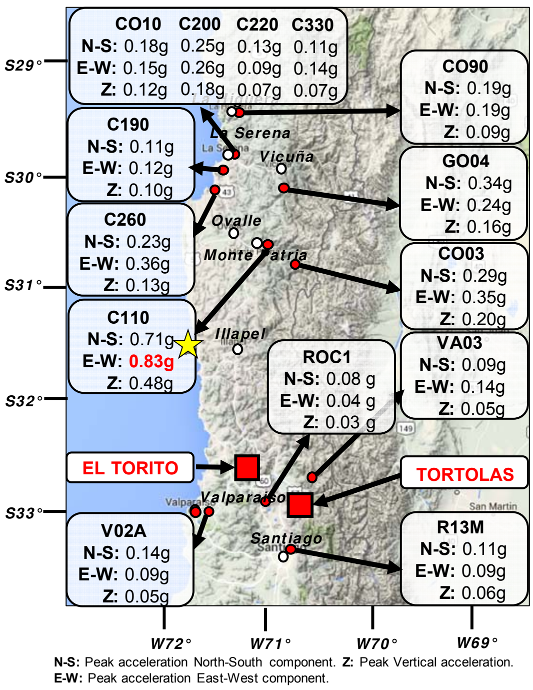


Figure 2. Peak ground acceleration recorded during the Illapel Earthquake. Location of El Torito and Tortolas tailings sand dams.

The recorded acceleration histories and the associated Fourier Spectra of West-Tortolas and El Torito are presented in Figs. 3 and 4, respectively. The peak horizontal accelerations of the transversal components are resumed in Table 1. It can be observed that the peak accelerations recorded on the outcrops are amplified by a factor of 3.7 and 1.7 in the crest of El Torito and West-Tortolas dams, respectively.

The transfer functions (expressed as ratio crest - outcrops) of each tailings sand dam computed from these available records (transversal component) are presented in Fig. 5. Additionally, the theoretical fundamental period of an idealized triangular elastic dam (2,61Vs/H) was evaluated considering a representative constant value of the shear wave velocity, Vs, of the tailings sands (data reported by Verdugo 2016 were used). Assuming a relative density of 60% and a level of confining pressure associated with one third of the dam heights, shear wave velocities of 320 and 250 m/s were established as representative of El Torito and West-Tortolas dams, respectively. Accordingly, theoretical fundamental periods of 0.68 and 0.31 s were obtained for El Torito and West-Tortolas dams, respectively. It can be observed that there is a good match between the predominant periods obtained empirically and by the simplified theoretical expression.

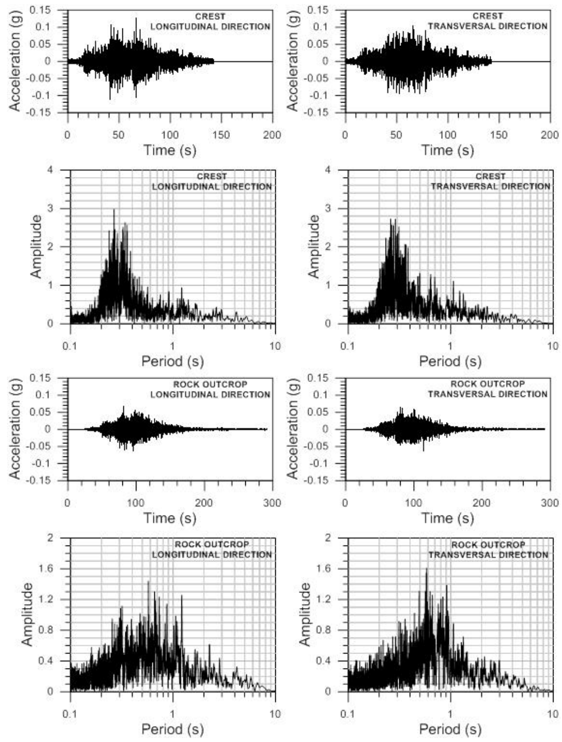


Figure 3. Acceleration records and Fourier Spectra (Tortolas).

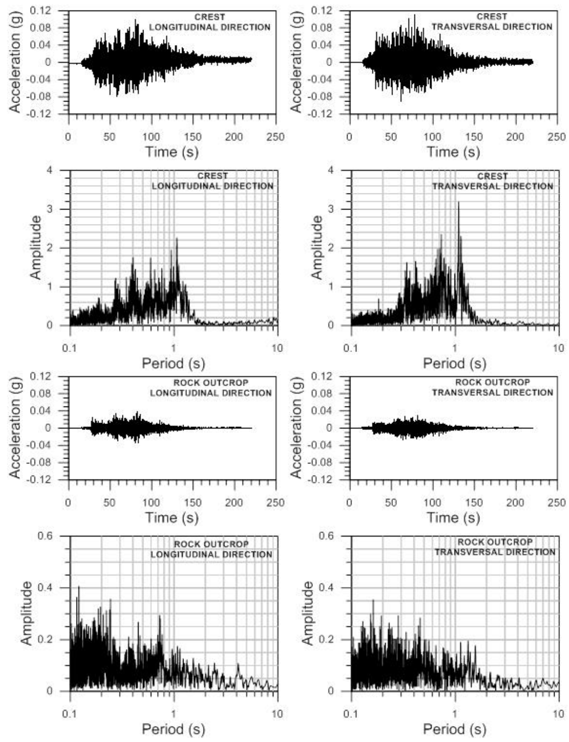


Figure 4. Acceleration records and Fourier Spectra (El Torito).

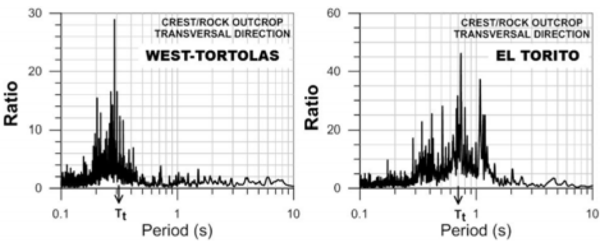


Figure 5. Empirical Transfer Functions (as ratio crest-outcrop): West-Tortolas & El Torito

It is important to mention that just after the Illapel Earthquake hit the area both dams were visited and inspected by professionals in charge of the operation. As a result no damages, no settlements and no visible fissures, were reported. Indeed the seismic behavior of both dams was excellent. Similar results have been reported in tailings sand dams constructed by means of the downstream method when subjected to strong shaking (Valenzuela 2015). However, numerical analyses usually predict a not negligible amount of deformation. The authors hypothesize that an important factor could be associated with the fact that, except by the lower part of the dam usually saturated, the main body of the tailings sand dams is always wet (unsaturated), which generates suction and therefore, an apparent cohesion is developed, increasing the strength of the tailings sands. This idea is evaluated below.

Table 1. Peak horizontal accelerations recorded at El Torito and West-Tortolas dams during the Illapel Earthquake (transversal component).

	El Torito	West-Tortolas
Peak horizontal acceleration at crest	0.11g	0.10g
Peak horizontal acceleration at rock outcrop	0.03g	0.06g
Amplification Ratio	3.7	1.7

3 DYNAMIC NUMERICAL ANALYSIS

The dynamic analysis of a tailings sand dam of 100 m in height was carried out in order to figure out the effect of suction (cohesion greater than zero) in the seismic dam response. A simplified elasto-plastic model was adopted, with the elastic stiffness as function of pressure. The Mohr-Coulomb failure criterion was used. The parameters are summarized in Table 2.

Table 2. Geotechnical parameters used in the analysis.

	Stored slimes	Dam sand tailings	Saturated bottom tailings	Foundation
Unit Weight [Ton/m^3]	1.7	2.0	2.1	2.1
Cohesion [Ton/m^2]	$0.06\sigma`_v$	0	0	0.5
Friction Angle [º]	0	35	35	40
Poisson Ratio	0.33	0.33	0.33	0.25
V_s [m/s]	180	$190\sigma`_0^{0.25}$	$190\sigma`_0^{0.25}$	$450\sigma`_0^{0.26}$
E_{Static} [Ton/m^2]	$E_0/10$	$E_0/10$	$E_0/10$	$E_0/10$
$E_{Dynamic}$ [Ton/m^2]	$E_0/10$	$E_0/5$	$E_0/7$	$E_0/5$

* Calculations in undrained conditions: $c = S_u$ and $\phi = 0º$

**Calculations consider a constant Rayleigh Damping of 2%

***Eo represents the maximum Modulus of Deformation associated with to Go, obtained from shear wave velocity.

On the other hand, the effect of suction has been represented by means of an apparent cohesion. There are reported data suggesting that the friction angle is also affected, but the increment is rather negligible (Gallage and Uchimura 2010). The water content measured in different tailings dams is presented in Fig. 6 (Bard 2017).

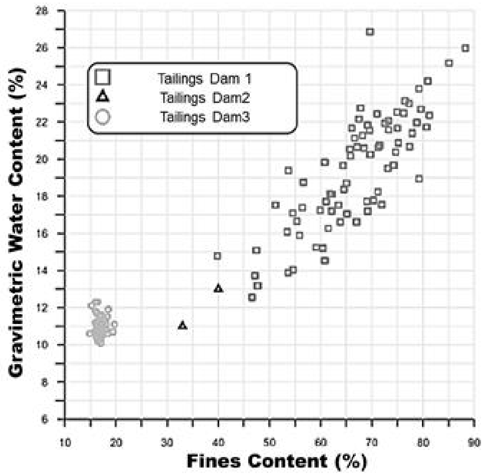


Figure 6. Gravimetric water content measured on Chilean tailings disposals (Bard 2017).

Considering a fines content of the order of 20%, a gravimetric residual moisture of 11% is obtained. This value can be associated with an apparent cohesion greater than 60 kPa (Masekanya 2008). Accordingly, the seismic responses have been numerically evaluated considering apparent cohesions of 20 and 40 kPa, which are values on the safe side.

The dynamic analyses were performed using the commercial computer code FLAC2D. The dimensions and materials considered in the model are shown in Fig. 7. Downstrean and upstream slopes of 4:1 (H:V) and 2:1 (H/V) were used. A fully saturated zone at the bottom of the tailings sand dam with a thickness of 3 m was considered. In practice this layer is well compacted, so it was modeled with drained parameters. The slimes stored in the pond were considered liquefied from the beginning of the seismic disturbance and modeled with its undrained residual resistance (post-liquefaction strength). The mesh was defined small enough to propagate adequately the band of frequencies of the shear waves of the input motion (Kuhlemeyer and Lysmer 1973). The horizontal input motion at the base of the model was selected to reach a PGA close to 0.7g at the free surface of the model, which represents what has been recorded in the recent large earthquakes occurred in Chile.

Figure 7. Model of tailings sand dam of 100 m in height.

The results of the model considering apparent cohesions of zero, 20 and 40 kPa, are shown in Fig. 8 in terms of permanent displacements. The resulting permanent displacements computed at the crest of the dam are summarized in Table 3 for the different adopted values of the apparent cohesion of the unsaturated tailings of the dam body. When no cohesion is used, the model predicts permanent displacements along the surface of the downstream slope, which compromise half of the crest of the dam. The maximum permanent displacements at the crest take place in the downstream corner, reaching almost 80 cm in horizontal direction and 21 cm of settlement. These permanents displacements are drastically reduced when an apparent cohesion of 20 kPa is considered in the unsaturated tailings sand that constitutes that main dam body. When an apparent cohesion of 40 kPa is adopted, the resulting permanent displacements are negligible, which is compatible with empirical observations.

It is important to mention that the toe of the analyzed dam undergoes permanent deformations that are associated with the saturated condition assumed for this zone, that in fact it is not present if an effective drainage is provided at the bottom of the dam. This pessimist assumption was adopted because it represents the worst possible scenario.

Table 3. Effect of apparent cohesion in the computed permanent displacements at the dam crest

Cohesion (kPa)	*Maximum permanent displacement at the dam crest (m)*	
	Vertical	*Horizontal*
0	0.21	0.77
20	0.09	0.14
40	0.001	0.11

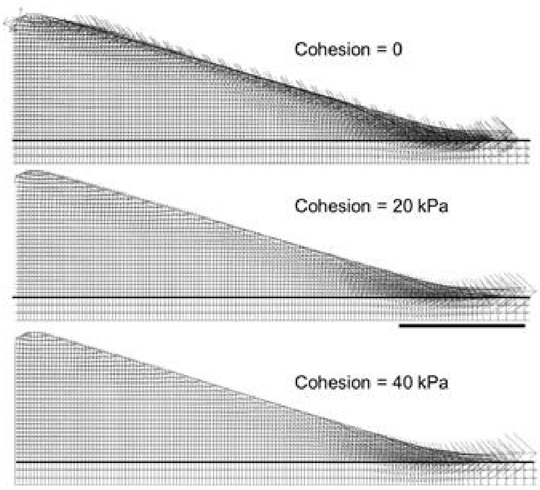


Figure 8. Computed permanent deformation of tailings sand dam considering different values of apparent cohesion due to suction

4 CONCLUDING REMARKS

Acceleration records obtained in two instrumented tailings sand dams are analyzed. These records were obtained during the Illapel Earthquake, Mw = 8.3, that hit the Central-North part of Chile in 2015. An excellent seismic behavior of these two dams was reported by the professional in charge of their operations. A similar behavior was observed in other sand tailings dams such as in the 200 m high Quillayes dam, located around 140 km from the epicenter of Illapel earthquake.

The predominant periods of these dams were empirical evaluated through the transfer functions computed from the records obtained at the crest and nearby rock outcrop. The resulting values were in good agreement with the ones obtained by the simplified expression of an elastic triangle excited by one dimensional shear wave propagation.

The Chilean experience left by large earthquakes indicates that tailings sand dams designed and constructed using the downstream method have an excellent seismic behavior. However, numerical models normally predict non negligible displacements. An explanation of this difference could be the actual higher strength of the unsaturated tailings sand, which develops an apparent cohesion due to suction.

Unsaturated tailings sands with fines content less than 20 % may have residual gravimetric water content around 11%, which reasonably may be associated with an apparent cohesion greater than 60 kPa.

Dynamic numerical analyses considering apparent cohesion of zero, 20 and 40 kPa were performed. When no cohesion is used, the model predicts permanent displacements along the surface of the downstream slope, which compromise half of the crest of the dam, reaching almost 80 cm in horizontal direction and 21 cm of settlement. These permanents displacements are drastically reduced when an apparent cohesion of 20 kPa is considered. When an apparent cohesion of 40 kPa is adopted, the resulting permanent displacements are negligible, which is compatible with empirical observations.

The authors strongly recommend the mining and geotechnical communities to share the seismic registers obtained in their dams together with the deformations and damages suffered after medium to strong earthquakes. This information would contribute to improve design and numerical analysis of dam seismic behavior.

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