Seismic response of a tailings sand dam

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ABSTRACT

This article investigates the seismic performance of the El Torito tailings dam, located in central Chile, during the 2015 Illapel Earthquake. Two-dimensional plane strain time domain finite element (FE) analyses were performed to simulate the construction, operation, and seismic response of the tailings storage facility (TSF). The hydro-mechanical (HM) coupled consolidation formulation implemented in the Imperial College Finite Element Program (ICFEP) is employed in the simulations. Firstly, a state parameter-based bounding surface plasticity model (BSPM) is calibrated against the laboratory and field data of the tailings materials, highlighting the challenges of the process. Then, the construction and operation of the El Torito tailings dam is simulated, following the detailed construction sequence of the TSF prior to the application of any seismic loading. Finally, the seismic response of the 2015 Illapel Earthquake is examined, where the results are compared with the recorded data at the crest and toe of the dam. The computed results suggest satisfactory agreement with the monitoring data, predicting similar acceleration response spectra for a wide range of periods.

Keywords: Numerical modelling, tailings dams, bounding surface plasticity model

1 INTRODUCTION

The recent failure events in tailings storage facilities (TSFs) (e.g. Fundão in 2015 (Morgenstern et al., 2016)) have highlighted the need for further understanding of these man-made structures. Their extensive use in highly seismic regions adds complexity to the problem, which can significantly impact the overall stability of the TSF. Furthermore, the wide range of tailings gradations and the high degree of saturation typically observed make these materials highly susceptible to developing liquefaction-type phenomena.

In TSF design projects, the use of advanced constitutive models depends on the availability of data from site-specific field campaigns focused on characterising tailings with extensive laboratory and in-situ tests. The models' calibration process is highly challenging due to the inherent heterogeneity of tailings materials and their complex storage mechanisms. Despite the extensive database of tailings characterisation, only a few well-documented case histories are available to validate numerical simulations, mostly based on the failure events under static conditions (e.g. Fundão in 2015). Unfortunately, for seismic-related cases, the available information is even more restricted.

This paper examines the seismic performance of the El Torito tailings dam under the 2015 Illapel Earthquake (M_w= 8.3) through finite element (FE) simulations with a state parameter-based BSPM.

2 TAILINGS DAM BACKGROUND

The TSF studied is the El Torito tailings dam located in central Chile. This TSF is a conventional tailings sands dam constructed using the downstream method, where the coarse fraction of the tailings (i.e. tailing sands) is used to construct the dam or a series of dams, whereas the fine fraction (i.e. slimes) is stored in areas constrained by these dams. The dam started its operation in 1993 and, during its lifetime to date, has been exposed to several earthquakes. The Illapel Earthquake (M_w= 8.3) on 16th September 2015, with its epicentre 100 km away from the El Torito site, is examined herein.

The geology of the El Torito tailings dam site is characterised by sedimentary deposits, primarily alluvial to colluvial sediments mainly transported by a local stream in a hilly local environment (AngloAmerican, 2018). Based on the limited reported data, the thickness of the foundation layer is unclear, with maximum values varying between 80 m and 160 m, depending on the elevations of the sound rock encountered in the surrounding hills.

Due to the "on-going" nature of the construction and operation of TSFs, the geometric features change during their lifetime according to the storage capacity and environmental requirements. The dam was initially designed to a maximum height of 62 m, width a crest width of 8 m and upstream and downstream slopes of 2.5:1 (H:V) and 4.5:1 (H:V), respectively. The current

https://doi.org/10.3208/jgssp.v10.OS-22-01

geometry conditions, reported in Consejo Minero (2021), indicate a crest width of 13 m, upstream and downstream slopes of 2:1 (H:V) and 3.7:1 (H:V), respectively; the current height is 94.5 m, and the projected final height by 2027 is 107 m. The operational freeboard is a minimum of 3 m and 4 m for abandonment conditions.

3 NUMERICAL MODELLING

3.1 Model description

2D plane strain time-domain FE analyses were performed to simulate the response under static and dynamic conditions of the El Torito tailings dam. A sketch of the FE model is presented in Fig 1, indicating the materials simulated, dimensions and control monitoring points. For modelling purposes, the adopted crest width was 10 m, with upstream and downstream slopes as 2:1 (H:V) and 4:1 (H:V), respectively. By the time of the 2015 earthquake, the dam height was estimated at 80 m, with a freeboard of 2 m considered.

The study is carried out employing the Imperial College Finite Element Program (ICFEP) (Potts & Zdravković, 1999), where hydro-mechanically (HM) coupled consolidation formulation is adopted for the static (the construction stages and operation prior to the earthquake event) and the dynamic conditions. The dynamic stage is simulated in the time domain employing the generalised-α time integration scheme (Kontoe et al., 2008). In terms of boundary conditions (BCs), for the static stage of the analysis, the horizontal and vertical displacements are equal to zero at the bottom boundary of the mesh, while the horizontal displacements are set at zero along the vertical lateral boundaries. The dynamic stage considered the same BCs at the bottom boundary due to the rigid bedrock assumption, while cone BCs (Kellezi, 2000) are used on the lateral boundaries for the slimes and tied degrees of freedom (TDOF) for the lateral faces of the foundation.

The presence of the decant pond during the construction and operation of the TSF is simulated by hydraulic BCs. Pore pressure (PP) BCs are imposed on the lateral boundary and over the part of the horizontal surface of the slimes to simulate the water pond. For the former, a nodal linear PP distribution is employed, while for the latter, a zero nodal PP is imposed along the impoundment area, maintaining a 200 m free top surface of the slimes as a beach for each of the construction stages. Additionally, the precipitation BC at the toe of the dam is employed to simulate the unconfined seepage and the resultant phreatic surface, which is estimated to be about 6 m above the ground level in the axis of the crest of the dam.

The FE mesh consists of 5358 8-noded elements, where the spatial discretisation followed the Bathe (2014) recommendations, with element dimensions, Δl, chosen to be smaller than 1/5 ~ 1/4 of the smallest wavelength (minimum shear wave velocity over the maximum frequency of the input motion $V_{s,min}/f_{max}$). Table 1 summarises the adopted values for Δl employed in the analyses. The f_{max} values are in the order of 10 to 20 Hz (period T from 0.05 s to 0.1 s) (see Fig 6)

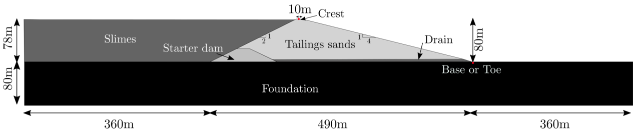

Fig 1. Model materials and dimensions for the tailings sand

Table 1 – Shear wave velocities and element dimensions

Material	Unit weight, γ (kN/m^3)	V_s (m/s)	Δl adopted (m)
Tailings sands	18	240	2
Slimes	17	130	2 to 4
Drains	18	350	2
Starter dam	18	350	2
Foundation	20	600	5 to 10

3.2 Constitutive models

Two different constitutive models are employed in modelling the response of the El Torito tailings dam. ICFEP is equipped with a bounding surface plasticity model (BSPM) (Taborda et al., 2014) and with a cyclic non-linear (CNL) model in the form of the Imperial College Generalised Small-Strain Stiffness model (ICG3S) (Taborda & Zdravković, 2012). Both constitutive models are briefly introduced herein, indicating the original references for further details.

A state parameter-based bounding surface plasticity model (BSPM, Taborda et al., 2014) is employed for modelling the tailings sand and the slimes stored in the impoundment. The cyclic behaviour of the soil is simulated by means of a fabric variable influencing the hardening modulus, as well as by modifications introduced by Tsaparli (2017) to the spherical part of the flow rule and the fabric tensor, aiming to improve the prediction of the cyclic strength. The calibration process of the El Torito tailings sand is detailed in Solans (2023), where an extensive database was employed in the calibration process of this tailings material. Table 2 summarises the model parameters for the tailings sand and includes those for the slimes, detailed later in the article.

Fig 2 plots the simulations obtained for a set of undrained triaxial tests on the El Torito tailings (Solans, 2010), showing good agreement with test data and reproduction of characteristic features (e.g. phase transformation). The selected tests cover a wide range of mean effective stresses (p' from 98 kPa to 4.9MPa) and void ratios (e from 0.613 to 0.805).

Undrained cyclic triaxial tests are employed in the calibration of the cyclic response of the tailings sands. The experimental data and simulations of these tests are summarised in Fig 3, in terms of cyclic strength curves. The calibration reproduces the cyclic curves that agree reasonably with test data at around 10 to 15 cycles and reproduce the effect of p' on the response, commonly referred to as K_{σ}. The calibration process, detailed in the cited references, is not included here for brevity.

Table 2. Model parameters for El Torito tailings sand and slimes

Component	El Torito tailings sand	Slimes
Critical State	p'_{ref}= 100 kPa; $e_{o,ref}$= 1.105; λ= 0.2395; ξ=0.205	p'_{ref}= 100 kPa; $e_{o,ref}$= 1.0; λ= 0.1325; ξ=0.135
Small-strain parameters	B= 458; n_g= 0.55; ν= 0.15	B= 350; n_g= 0.10; ν= 0.25
Surface parameters	M^c_{cs}=1.50; M^e_{cs}= 1.05; k^b_c= 2.0; k^d_c = 4.0 A_o= 0.80; $A_{o,min}$= 0.0; b_d= 0.10; d_1= 3.83861; d_2= 0.00538; d_3=0.0	M^c_{cs}=0.983; M^e_{cs}= 0.741; k^b_c= 2.0; k^d_c = 4.0 A_o= 2.5; $A_{o,min}$= 0.0; b_d= 0.10; d_1= 0.0528; d_2= 0.01308; d_3=0.0
Hardening modulus	h_o= 0.13; ν= -0.10; α= 1.0; β=-0.5; γ= 0.92	h_o= 0.10; ν= 0.40; α= 1.0; β= 0.0; γ= 1.10
Fabric Tensor	H_o= 15000; ζ= 0.0; C_f= 75	H_o= 0.0; ζ= 0.0; C_f= 75

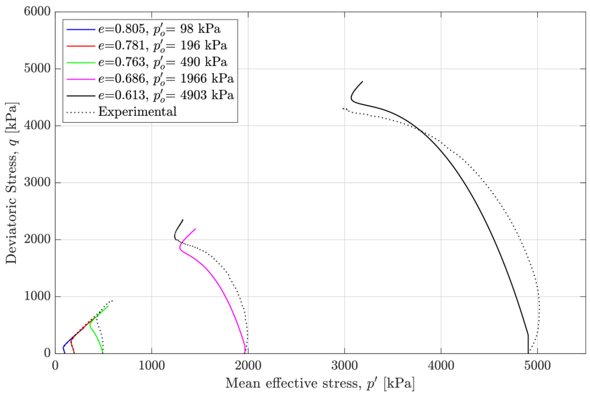

Fig 2. El Torito tailings sand. Simulation compared with experiments in undrained triaxial tests based on Solans (2010).

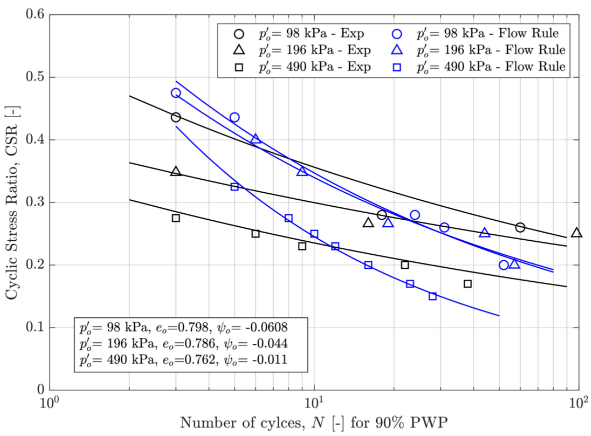

Fig 3. Cyclic strength curves and simulations for the El Torito tailings sand (based on Solans, 2010)

In the case of slimes, due to the high heterogeneity observed in-situ (resulting from the manner of storage deposition) and the lack of data, the calibration is focused on a practical approach to reproduce the following key aspects of their behaviour: (i) low undrained strength, S_u; (ii) strain softening, and (iii) low cyclic resistance.

The value of S_u is governed by the void ratio, e, which is particularly variable in the case of slimes. Reported values from in-situ tests (Castro & Troncoso, 1989) and back-analyses of tailings dam failures (Jefferies & Been, 2016) suggest normalised undrained strength S_u/σ'_{v0} in the range of 0.06 to 0.16. For modelling purposes, a target $S_u/\sigma'_{v0} = 0.1$ is assumed, depending on the impoundment's void ratio distribution. Further assumptions of the critical state line (CSL) are based on the tailings sands' CSL, following the experimental observations of Li & Coop (2019) over the different tailings gradations. The remaining parameters adopted for the slimes are: (i) very low maximum shear stiffness (G_{max}= 35000 kPa, $V_s \approx$ 140 m/s); (ii) stiffness distribution almost uniform with depth; (iii) low strength envelope parameters; (iv) bounding and dilatancy surfaces similar to the tailings sands; and (v) high dilatancy constant A_o. The last point allows the generation of large plastic deviatoric strains and enables the development of highly strain-softening response.

Despite the high heterogeneity observed in-situ in slimes deposits, their cyclic resistance is considered in the model. Ishihara et al. (1980) reported a compelling set of undrained cyclic triaxial tests on copper tailings materials, where one of the materials was from an abandoned deposit in the proximity of the El Torito tailings dam (Cobre No. 4). These experimental results (p'= 98 kPa and e= 0.902 in Fig 4) are compared with simulations at different p' and e values to evaluate the K_{σ} effect on the slimes. The results in Fig 4 show $K_{\sigma} \approx$ 0.5 for p' values over 200 kPa (measured at 10 cycles).

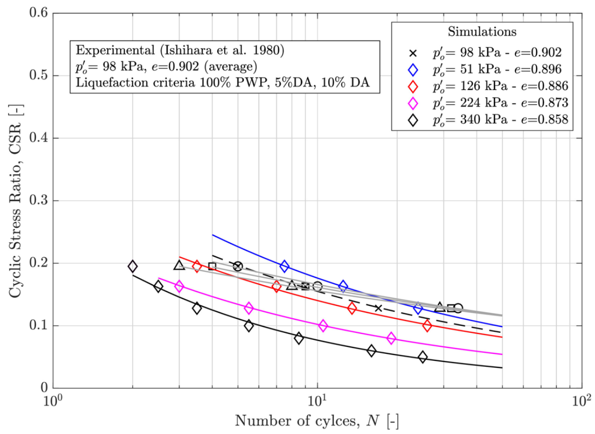

Fig 4. BSPM performance for slimes under undraied cyclic triaxial conditions

The foundation soil, starter dam and drains are modelled with the CNL model (Taborda & Zdravković, 2012) introduced earlier. The calibration of the CNL model typically involves evaluation of the stiffness and damping variation with strain level using available data. Due to the lack of experimental data for the above materials, curves reported in the literature have been chosen; specifically, the results of Rollins et al. (1998) for gravels are adopted. The lower limit curve suggested by Taborda & Zdravković (2012) is adopted, as it introduces higher damping at very small strain levels. The thickness and stiffness of the foundation layer were carefully examined with a parametric study detailed in Solans et al. (2023).

The CNL model parameters for each material are summarised in Table 3. Coupled with it is a Mohr-Coulomb strength envelope, adopting cohesion, c'= 10, 10 and 5 kPa, friction angle, φ'= 40°, 45° and 38°, and dilation angle, ν= 20°, 25° and 16°, for the foundation, starter dam and drains, respectively.

Table 3 – Summary of CNL parameters for the started dam, drain and foundation.

Component	Starter dam / drain	Soil foundation
Stiffness	G_0=300000 kPa; m_G= 0.25	G_0=840000 kPa; m_G= 0.001
	p'_{ref}= 100 kPa; ν= 0.25	
Shear stiffness degradation	a_0= 5.904x10^{-5}, a_1= 0.0, a_2= 0.0, b_0= 1.180, $R_{G,min}$ = 0.03, G_{min}= 10000 kPa	
Varying scaling factor	$d'_{1,G}$= 454.64, $d''_{1,G}$= 0.0, $d_{2,G}$= 0.168, $d_{3,G}$= 4437.21, $d_{4,G}$= 0.520	

To establish the seepage conditions, a permeability model is necessary in the HM coupled formulation adopted. A variable permeability model (Potts & Zdravković, 1999), which reduces the permeability when the soil sustains a tensile value of pore fluid pressure in zones above the phreatic surface, is employed for the tailings materials. Due to the lack of data, values reported in the literature are adopted (Valenzuela, 2015) considering an isotropic permeability. Further details can be found in Solans (2023).

4 CONSTRUCTION AND OPERATION OF TSF

The HM coupled numerical model of the El Torito tailings dam aims to reproduce the timeline of the downstream construction process and the associated evolution of stresses and seepage conditions in the TSF, prior to applying the earthquake motion. This is achieved by firstly initiating the ground conditions in the foundation soil, which is considered fully drained due to its alluvial and colluvial sediments. All other materials are fully HM coupled. The construction process starts with the starter dam, followed by an alternate construction of a slimes layer, in the decant part of the TSF in Fig 1, and the dam layer, on the downstream side of the starter dam, maintaining a freeboard of 2 m until reaching 80 m dam height and 78 m height of the slimes. The evolution of the pond is simulated with appropriate hydraulic boundary conditions described in the previous section.

For brevity, and due to the paper's focus on the dynamic response of this TSF, the results of the construction stage are limited to Fig. 5, which compares the profile of the computed state parameter, ψ (Been & Jefferies, 1985), along the vertical axis of the dam through the crest, with that interpreted from CPTu tests. The correlations proposed by Been et al., (1986) (also known as Plewes' method), Robertson (2010) and Shuttle & Jefferies (2016) are employed in the interpretation of three CPTu tests performed along the crest of the dam in 2018 and reported in AngloAmerican (2018). It should be noted that the CPTu tests were performed approximately one year after the earthquake. The model simulation resembles favourably the field CPTu ψ values along the dam's height.

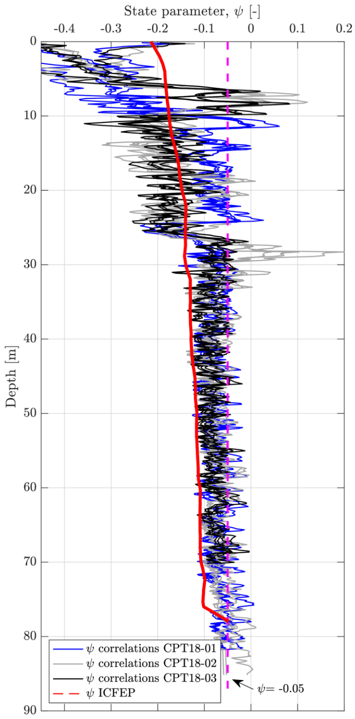

Fig 5. ψ computed profile compared with empirical correlations obtained from different authors, along the axis of the dam

5 SEISMIC RESPONSE

5.1 Seismic record and input motion

The accelerometers located at the crest, base (toe) and an outcrop rock recorded the 2015 Illapel Earthquake at the El Torito TSF. The records are shown in Fig 6 in terms of acceleration response spectra for the Longitudinal and Transversal components. The recorded motion at the outcrop rock (Transversal component) is employed as the input motion for the numerical model, and the computed results are compared against recorded data at the crest and toe of the dam. The record was baseline-corrected and frequencies over 25 Hz were filtered.

5.2 Results

The El Torito tailings dam's seismic response is examined in terms of displacements, excess PWP and deviatoric plastic strain, E_d, at the end of the motion (see Fig 7), resulting solely from the applied motion. E_d corresponds to the generalised deviatoric strain defined as follows:

$$E_d = \frac{2}{6}\sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_1 - \varepsilon_3)^2} \quad (1)$$

where the sub-indexes 1, 2 and 3 are related to the principal strains, ε.

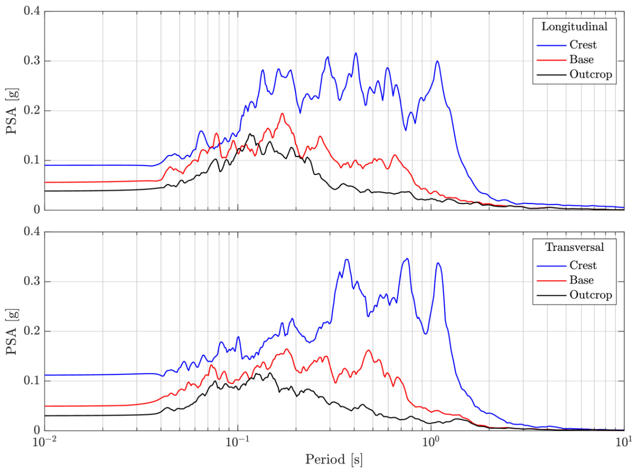

Fig 6. Acceleration response spectra (a) Longitudinal and (b) Transversal components.

The resulting displacements indicate a maximum of 4.5 cm mobilised in the dam's downstream face, while only 2 to 3 cm are predicted in the impoundment area. The generated excess PWP (Fig 7.b) contours suggest maximum values of 50 kPa near the top surface of the impoundment and close to the contact between the slimes and the dam. Since the bottom part of the dam allows PWP build-up, there is a localised minor excess PWP near the toe of the dam, which is attributed to the low p' values near the dam's face. Likewise, the E_d contours in Fig 7.c indicate strain concentrations at shallow depths in the impoundment, with values close to 0.002 (0.2 %). The top part of the dam (last constructed stage) exhibits strain concentration, which is attributed to a combined effect of low p' and the more significant amplification near the dam's surface. As part of the impoundment region mobilises suctions during the construction and operation stages, given the 200 m length of beach, the plastic region in this area is limited.

The predicted displacements, excess PWP and E_d in the El Torito dam are of low-magnitude and mainly superficial at the dam's downstream face and certain zones of the slimes. The reported "eye-sight" evidence, just after the earthquake, indicated no damage, no permanent settlements and non-visible cracks, suggesting the excellent performance of the dam under the motion (Verdugo et al. 2017). Therefore, qualitatively, the numerical analysis results agree well with the reported observations in terms of displacements.

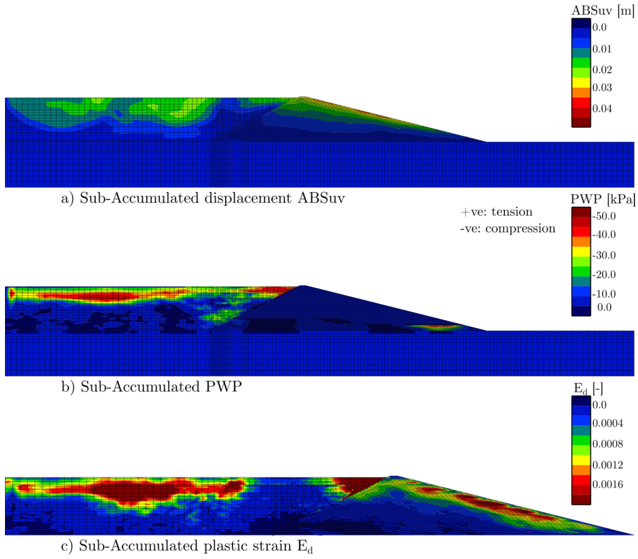

Fig 7. Sub-accumulated (a) resultant displacements (ABSuv), (b) excess PWP and (c) plastic strain E_d at the end of motion

The computed acceleration response spectra are compared in Fig 8 with the available monitoring data from Fig. 6. The results agree reasonably well at the base of the dam, where the predicted response captures the PGA and some of the peaks in the transversal direction. At the crest of the dam, the computed results underestimate the PGA and partly reproducing the transversal response spectrum (solid line), while being in better agreement with the longitudinal record (dashed line), capturing a wider range of periods and reproducing the PGA and several peaks accurately. Due to the construction of the El Torito TSF, where the crest elevation is permanently shifting, it is possible that the measuring instruments were swapped shortly before the 2015 earthquake, such that the longitudinal sensor corresponds to the transversal direction and vice versa. This possibility was examined through theoretical and empirical approaches with no definitive conclusion, hence, the comparison here is only a numerical exercise.

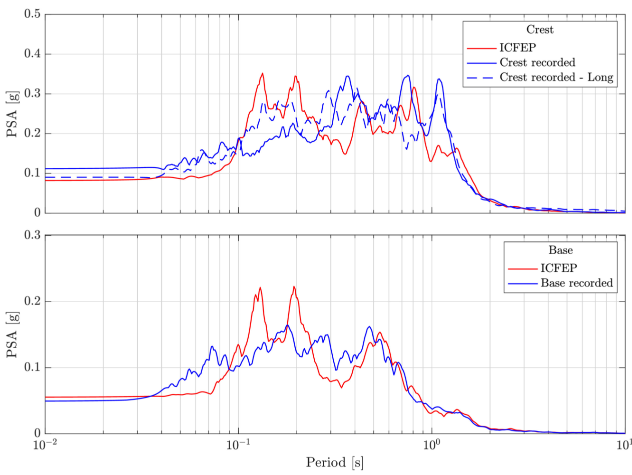

Fig 8. Acceleration response spectra results and recorded data (upper) crest and (bottom) base of the dam.

6 CONCLUSIONS

This paper examined the seismic performance of the El Torito tailings dam during the 2015 Illapel Earthquake (M_w = 8.3) using a state parameter-based BSPM. The numerical results were contrasted with the monitoring data captured during the motion.

The tailings materials (tailings sand and slimes) were modelled with a BSPM, calibrated against available experimental data comprising an extensive database of monotonic and cyclic tests for the tailings sands. The simulated monotonic tests compared well with the experimental data in a wide range of p' examined and reasonable simulations were obtained for the cyclic tests. In the case of the slimes, due their high heterogeneity and the lack of experimental data, the calibration used a practical approach of reproducing the key relevant aspects in the behaviour of this material.

The simulated timeline of the construction and operation of the TSF reproduced a satisfactory distribution of the state parameter, ψ, along the vertical axis of the dam, being in agreement with ψ interpretations from in-situ CPTu tests using different correlations. The predicted seismic response of the dam showed and overall good agreement with the recorded data at the toe and the crest of the dam in terms of the acceleration response spectra.

Despite the complexity of the examined boundary value problem, the employed advanced constitutive model such as BSPM and the overall numerical modelling approach enabled the prediction of the seismic response of the dam with satisfactory accuracy, thus contributing the El Torito TSF case study to better understanding of the seismic stability of tailings dams.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to ANID Chile (grant number: 72180052) and Dixon Scholarship from Imperial College London, for the funding of the PhD studies of the first author during which this work was developed.

REFERENCES

1) AngloAmerican. (2018): *4541 Adenda 'Estudio Impacto Ambiental Continuidad Operativa Tranque de Relaves El Torito Operacion El Soldado' (in Spanish). 'Environ. Impact Assessment for Continuing Operation El Torito Tailings Dams El Soldado Mining Operation' report by ARCADIS.*
2) Bathe, K. J (2014): *Finite Element Procedures* (Second Ed.) Prentice-Hall, Pearson Education, Inc.
3) Been, K., Crooks, J. H. A., Becker, D. E., & Jefferies, M. G. (1986): The cone penetration test in sands: Part I, state parameter interpretation. *Geotechnique*, *36*(2), 239–249.
4) Been, K., & Jefferies, M. G. (1985): A state parameter for sands. *Géotechnique*, *35*(2), 99–112.
5) Castro, G., & Troncoso, J. H. (1989): Effects of 1985 Chilean Earthquake on three tailings dams. *5as Jornadas Chilenas de Sismologia e Ingenieria Antisismica*, 71–92.
6) Consejo Minero. (2021): *Plataforma de Relaves - Anglo American. El Torito*.
7) Ishihara, K., Troncoso, J., Kawase, Y., & Takahashi, Y. (1980): Cyclic strength characteristics of tailings materials. *Soils and Foundations*, *20*(4), 127–142.
8) Jefferies, M., & Been, K. (2016): *Soil Liquefaction: A Critical state Approach* (2nd ed.). CRC Press.
9) Kellezi, L. (2000): Local transmitting boundaries for transient elastic analysis. *Soil Dynamics and Earthquake Engineering*, 19(7), 533–547.
10) Kontoe, S., Zdravković, L., & Potts, D. M. (2008): An assessment of time integration schemes for dynamic geotechnical problems. *Computers and Geotechnics*, *35*(2), 253–264.
11) Li, W., & Coop, M. R. (2019): Mechanical behaviour of panzhihua iron tailings. *Canadian Geotechnical Journal*, *56*(3), 420–435.
12) Morgenstern, N. R., Vick, S. G., Viotti, C. B., & Watts, B. D. (2016): *Fundão Tailings Dam Review Panel. Report on the Inmediate Causes of the Failure of the Fundão Dam.*
13) Potts, D. M., & Zdravković, L. (1999): *Finite element analysis in geotechnical engineering: Theory*. Thomas Telford.
14) Robertson, P. K. (2010): Estimating in-situ state parameter and friction angle in sandy soils from CPT. *2nd International Symposium on Cone Penetration Testing*.
15) Rollins, K., Evans, M., Diehl, N., & Daily, W. (1998): Shear modulus and damping relationships for gravels. *Journal of Geotechnical and Geoenviron. Engineering*, *124*(5), 396–405.
16) Shuttle, D., & Jefferies, M. (2016): Determining silt state from CPTu. *Geotechnical Research*, *3*(3), 90–118.
17) Solans, D. (2010): *Equipo Triaxial Monótono y Cíclico de Altas Presiones y su Aplicación en Arenas de Relaves (in Spanish)*. (MSc Thesis) University of Chile.
18) Solans, D. (2023): *Seismic performance of tailings sand dams* (PhD Thesis). Imperial College London.
19) Solans, D., Kontoe, S., & Zdravković, L. (2023): Impact of foundation layer characteristic on the seismic response of a tailings dam. In L. Zdravković, S. Kontoe, D. M. G. Taborda, & A. Tsiampousi (Eds.), *10th European Conference on Numerical Methods in Geotechnical Engineering (NUMGE)*.
20) Taborda, D. M. G., & Zdravković, L. (2012): Application of a Hill-Climbing technique to the formulation of a new cyclic nonlinear elastic constitutive model. *Computers and Geotechnics*, *43*, 80–91.
21) Taborda, D. M. G., Zdravković, L., Kontoe, S., & Potts, D. M. (2014): Computational study on the modification of a bounding surface plasticity model for sands. *Computers and Geotechnics*, *59*, 145–160.
22) Tsaparli, V. (2017): *Numerical modelling of earthquake-induced liquefaction under irregular and multi-directional loading.* (PhD Thesis). Imperial College London.
23) Valenzuela, L. (2015): Tailings Dams and Hydraulic Fills. The 2015 Casagrande Lecture. *Geotechnical Synergy in Buenos Aires 2015: Invited Lectures of the 15th Pan-American Conference on Soil Mechanics and Geotechnical Engineering and the 8th South American Congress on Rock Mechanics, 15--18 November 2015, Buenos Aires, Argentina*, *5*, 5.
24) Verdugo, R., Peters, G., Valenzuela, L., Campaña, J., & Bard, E. (2017): Evaluation of Tailings Dams Subjected to Large Earthquakes. *19th International Conference on Soil Mechanics and Geotechnical Engineering, ICSMGE 2017*.