Proceedings 10th NUMGE 2023
10th European Conference on Numerical Methods in Geotechnical Engineering
Zdravkovic L, Kontoe S, Taborda DMG, Tsiampousi A (eds)

https://doi.org/10.53243/NUMGE2023-307

Impact of foundation layer characteristics on the seismic response of a tailings dam

D. Solans[1], S. Kontoe[2,1], L. Zdravković[1]

[1]*Department of Civil and Environmental Engineering, Imperial College London, London, UK*
[2]*University of Patras, Patras, Greece*

ABSTRACT: The foundation layer thickness and stiffness impact the site response by influencing the fundamental frequencies and vibration modes in soil structure interaction (SSI) problems. From a practical perspective, the geotechnical characterisation of earthfill dams is typically focused on the borrow materials comprising the dam, while the foundation materials are often under-characterised, with the depth to the bedrock commonly only approximately estimated. In the seismic response of dams, these unknowns may also impact the deformation patterns affecting the overall stability of the dam. A back-analysis of seismic recorded data for an existing tailings sand dam is performed, to determine the thickness and stiffness of the soil foundation layer by finite element analysis. A cyclic non-linear model (CNL) is employed in the Finite Element analyses which consider different depths to bedrock and soil stiffness profiles. The results suggest satisfactory agreement with the recorded data in terms of acceleration response spectra and amplification ratios and highlight the impact of the foundation layer characteristics on the overall dam response.

Keywords: seismic response; tailings dams

1 INTRODUCTION

The occurrence of several failures of tailings storage facilities (TSFs) during the last decade (Jefferies et al., 2019; Morgenstern et al., 2015, 2016; Robertson et al., 2019) has spotlighted the need for further understanding of this type of man-made structures. In active seismic environments, their seismic response adds to the complexity of the problem and can significantly impact the overall stability of TSFs.

In TSFs projects, the site investigation (SI) is mainly focused on the characterisation of the dam body, typically constructed with borrow materials or the coarse fraction of the tailings (tailings sands). In contrast, the foundation materials are often under-characterised and are only explored to shallow depths. Hence, the stiffness and thickness of the foundation soils are commonly crudely estimated due to their better hydro-mechanical characteristics, especially in terms of shear strength and permeability, as in most of the cases.

The stiffness and thickness of the foundation materials play a key role in the seismic response of the overall tailings dam – foundation system, affecting the amplitude and frequency content of the acceleration response, as well as the deformation patterns which control the overall seismic stability.

This article aims to highlight the impact of the foundation layer on the dam response through a finite element (FE) back-analysis of an existing TSF located in a highly seismic environment.

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) are used to construct the dam or a series of dams, whereas the remaining fine fraction (i.e. fine tailings or slimes) are stored in areas constrained by these dams. The dam started its operation in 1993 and during its lifetime has suffered several earthquakes to date. One recent event corresponds to the Illapel Earthquake (M_w= 8.3) on 16th September 2015 (Barrientos, 2015; Ruiz et al., 2016), in which the epicentre was located 100 km away from the El Torito site. The seismic performance of the dam during this earthquake was satisfactory, with negligible observed damage (Verdugo et al., 2017).

The local geology of the El Torito tailings dam site is characterised by sedimentary deposits, primarily alluvial to colluvial sediments mainly transported by the El Cobre stream in a hilly local environment (AngloAmerican, 2018; Chilean National Committee on Large Dams, 1996; Rivano et al., 1993). Based on the limited reported data, the thickness of these sediments is unclear, with maximum values varying between 80 m and 160 m. The sediments are compatible with the local surrounding hills, reducing their layer thickness as they approach the sound rocks.

The "on-going" nature of the construction and operation of TSFs makes the geometric features change

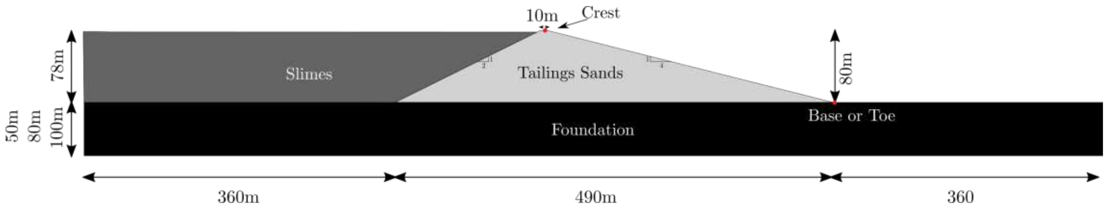

Figure 1. Model dimensions for the tailings sand dam

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. Recent data reported in Consejo Minero (2021) indicates the current geometry conditions of the dam correspond to 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 METHODOLOGY

3.1 Model description

Two-dimensional plane strain time domain FE analyses were performed, considering a tailings sands dam – foundation system overlying a rigid bedrock. The FE model is presented in Figure 1, indicating the model's main dimensions and points of interest, such as the base or toe of the dam. For simplicity, the adopted crest width was 10 m, while the upstream and downstream slopes were 2:1 (H:V) and 4:1 (H:V), respectively. The dam height was estimated at 80 m by the time of the 2015 Illapel earthquake, and a freeboard of 2 m is considered. The materials forming the TSF are simplified to tailings sands, slimes and the soil foundation.

The study was carried out using the Imperial College Finite Element Program ICFEP (Potts & Zdravković, 1999), 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 lateral boundaries. The dynamic stage of the analysis considered the same BCs at the bottom boundary due to the rigid bedrock assumption, while normal and tangential dashpots are used on the lateral boundaries for the upper material (slimes) and tied degrees of freedom (TDOF) for the lateral faces of the foundation.

The spatial discretisation of the mesh follows the recommendations by Bathe (2014) for 8-noded elements, where the element dimension, Δl, was considered as $\Delta l \leq V_{s,min}/4 \cdot f_{max}$, where $V_{s,min}$ and f_{max} correspond to the minimum shear wave velocity for each material in the analysis and the maximum frequency of the input motion, respectively. 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 Figure 2)

Table 1. Shear wave velocities, V_s, and element dimensions

Material	Unit weight, γ [kN/m³]	V_s [m/s]	Δl [m] adopted
Tailings sands	18	240	2
Slimes	17	130	2 to 4
Foundation	20	600(*)	5 to 10

(*) adopted for mesh discretisation

The input motion corresponds to the outcrop-recorded component at the El Torito tailings dam during the 2015 Illapel Earthquake. The seismic record and acceleration response spectra (PSA) are plotted in Figure 2, where the maximum acceleration value is 0.03 g. The figure also includes the recorded data at the base or toe of the dam, which is used for the comparison with the numerical predictions in the following section. The input motion (outcrop) was incrementally applied at the bottom model boundary as a horizontal acceleration time-history, assuming a perfectly rigid bedrock at the model's base.

3.2 Examined soil profiles

Three depths and five soil stiffness profiles are examined herein. The depths considered are 50 m, 80 m and 100 m. The stiffness profiles analysed are: (i) a constant stiffness profile, $G_{constant}$; (ii) three stiffness profiles varying with depth following an exponential law, G_{var-1}, G_{var-2} and G_{var-3}; and (iii) a randomised stiffness profile based on Toro's model through statistical approach mainly by Monte Carlo simulations (Toro, 1995), $G_{var-random}$. The maximum shear modulus expressions, G_0, for each profile are as follows, considering a p'_{ref}= 100 kPa:

$$G_{constant};\, G_0 = 840.000 \text{ kPa} \quad (1)$$

$$G_{var-1};\, G_0 = 490.000\left(p'/p'_{ref}\right)^{0.5} \text{ kPa} \quad (2)$$

$$G_{var-2};\, G_0 = 700.000\left(p'/p'_{ref}\right)^{0.25} \text{ kPa} \quad (3)$$

$$G_{var-3};\, G_0 = 740.000\left(p'/p'_{ref}\right)^{0.1} \text{ kPa} \quad (4)$$

$$G_{\text{var-random}};$$

$$G_0 = \begin{cases} 740.000 \text{ kPa}, \; z < 20 \text{ m} \\ 675.000\left(p'/p'_{ref}\right)^{0.11} \text{ kPa}, z \geq 20 \text{ m} \end{cases} \quad (5)$$

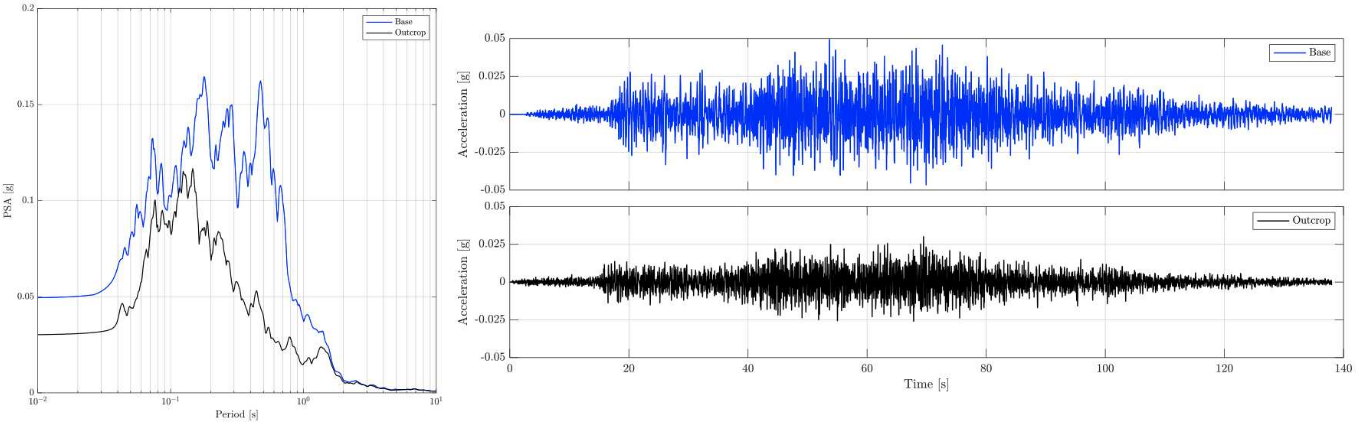

Figure 2. Acceleration time histories and response spectra (5% damping) for the recorded data at the El Torito dam during the 2015 Illapel Earthquake

The soil stiffness profiles were chosen based on seismic design codes for granular soils (Eurocode 8, ASCE 7-10 and DS61 Chilean standard). Since the soil foundation corresponds to alluvial to colluvial deposits, mainly transported by streams in a hilly environment, the presence of stiff gravels in a sandy to clayey matrix is expected. For this soil type, V_{s30} values between 500 m/s to 800 m/s (Type B for Eurocode 8 and DS 61, and Type C for ASCE 7-10) are typically observed in soil profiles where V_s increases with depth. This approach disregards the presence of any soft soil layer, which could affect the vibration modes of the soil foundation.

The Toro's profile ($G_{var\text{-}random}$) is determined using 100 randomised profiles employing STRATA (Kottke & Rathje, 2009), and then their median is represented by the $G_{var\text{-}random}$ profile proposed (see Figure 3). Figure 4 plots the maximum shear modulus, G_0, and the shear wave velocity, V_s, profiles considered in the analyses for a maximum depth of 80 m. The 50 m and 100 m depths follow a similar distribution.

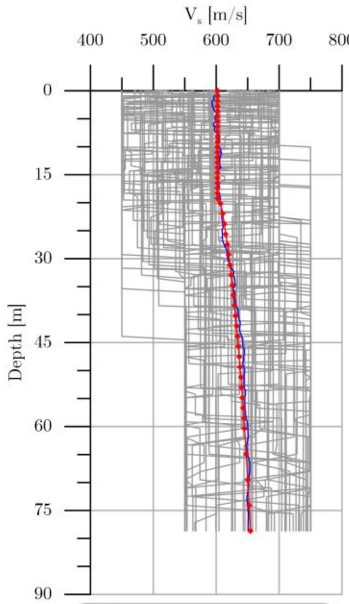

Figure 3. Vs randomised profiles obtained from Toro (1995)

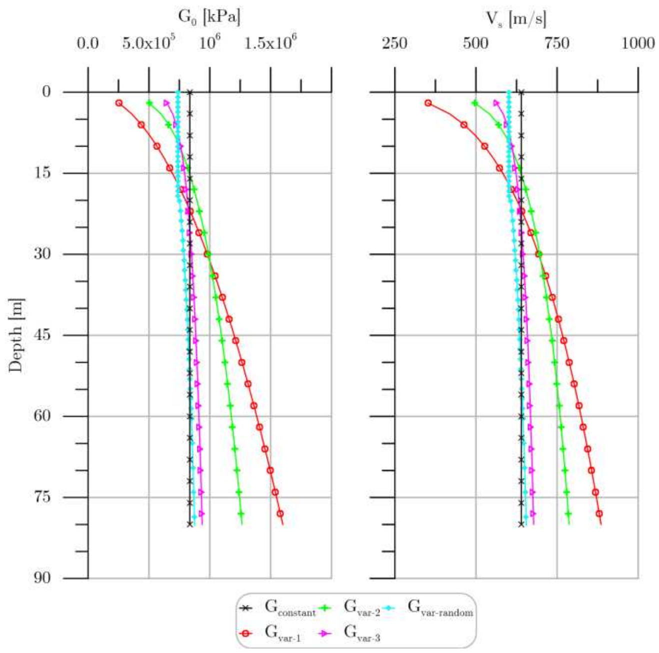

Figure 4. G_0 and V_s for the profiles studied

3.3 Constitutive models

ICFEP is equipped with a cyclic non-linear (CNL) elastic model in the form of the Imperial College Generalised Small-Strain Stiffness (ICG3S), which can reproduce some of the fundamental aspects of soil dynamics such as the unloading/reloading behaviour and essential aspects of energy dissipation through soil hysteresis. A detailed description of the formulation can be found in Taborda & Zdravković (2012). The CNL model is adopted for the soil foundation, while for the other materials, tailings sands and slimes, visco-elastic behaviour with the use of Rayleigh damping is assumed for the purpose of this study. A more elaborate analysis, focusing on the deformation patterns of the dam body (tailings sands) and slimes employing an advanced bounding surface plasticity model can be found in Solans (2023)

The calibration of the CNL model is typically conducted by simulating the stiffness degradation and damping curves with the available data. In the absence of experimental data for the foundation soil, the curves for gravels given by Rollins et al. (1998) were chosen. A lower limit curve suggested by Taborda & Zdravković (2012) was used in the calibration, as it introduces higher damping at very small strain levels (see Figure 5). The damping ratio curve agreement is prioritised due to the better response for a broader range of strains, confirmed in simulations by Han et al. (2017) for the Kik-net downhole array.

For the calibration process, a constant Poisson's ratio, ν, was adopted, which means that the bulk modulus degrades in the same manner as the shear modulus. Additionally, the cyclic reversal behaviour has been considered decoupled between the deviatoric and volumetric behaviour, which means that any reversal detected in one of the mechanisms does not affect the other. The model parameters are summarised in Table 2, where the stiffness at small strains is previously defined in Equations (1) to (5) for each profile. Poisson's ratio is considered 0.25 in all the soil profile cases. A Mohr-Coulomb strength envelope is coupled with the CNL considering cohesion, c'= 10 kPa, friction angle, ϕ'= 40°, and dilation angle, ν= 20°.

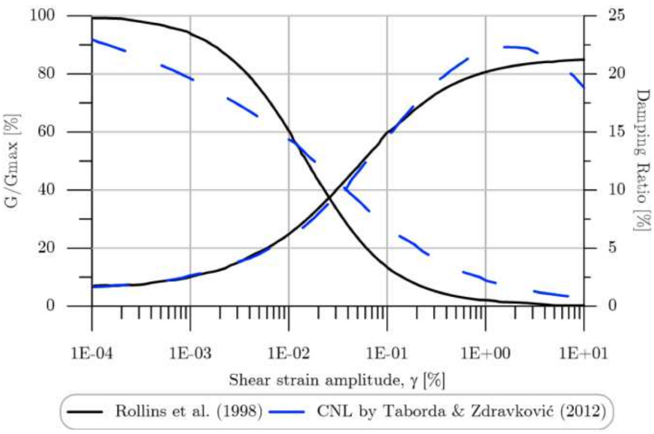

Figure 5. CNL model compared with empirical curves proposed by Rollins et al, (1998). Modified from Taborda & Zdravković (2012).

Table 2. Summary of CNL parameters for the soil foundation

Component	Model parameters
Shear stiffness degradation	
	a_0= 5.904e-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

Model parameters detailed in Taborda & Zdravković (2012)

The linear elastic properties for the tailings sands and slimes are shown in Table 3. For the dynamic analyses, the target damping ratio, ξ, 3% for slimes and 5% for tailings sands, is achieved by calibrating the Rayleigh damping parameters to the predominant frequency of the input motion and the fundamental period of the soil foundation – tailings dam system. The fundamental period was computed based on a simplified 1D column along the axes of the dam-foundation. A sensitivity analysis for the Rayleigh damping parameters was carried out, obtaining a satisfactory agreement for the wide range of frequencies covered by the motion examined in this study.

Table 3. Linear elastic parameters for tailings materials

Material	Young Modulus, E [kPa]	Poisson's ratio, ν [-]
Tailings sands	272800	0.30
Slimes	80000	0.35

4 RESULTS

The results are presented in Figure 6 in terms of acceleration response spectra (PSA) at the base or toe of the dam for each soil stiffness profile and are plotted for different foundation layer depths. The computed response is compared with the recorded data (Base recorded), suggesting good agreement, in terms of PGA (PSA at T= 0.01 s) and spectral acceleration, for the stiffness profiles (G_{var-3} and $G_{var-random}$) close to the uniform stiffness profile ($G_{constant}$). The stiffness profiles with a marked increment with depth (G_{var-1} and G_{var-2}) indicate higher PGA values and spectral acceleration peaks which are not observed in the recorded data. On the other hand, the effect of the thickness of the foundation layer is evident in the plots. The spectral response for the 50 m depth analyses is shifted towards low periods, while the corresponding 100 m depth trend is shifted towards high periods. The 80 m depth response suggests a better agreement on the overall range of periods, where the response for the profiles $G_{constant}$, G_{var-3} and $G_{var-random}$ is similar to the recorded data.

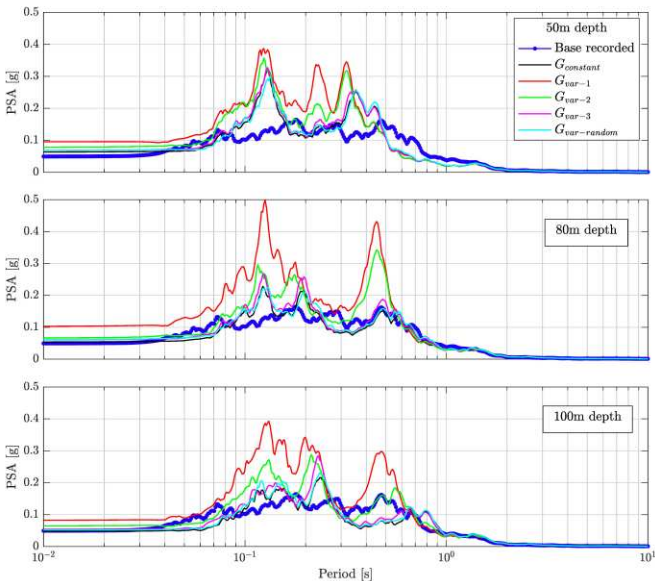

Figure 6. Acceleration response spectra at dam's toe for 50 m, 80 m and 100 m depth with stiffness profiles studied.

Complementing these results, Figure 7 plots the spectral ratio or response amplification spectra (RAS) for Base / Outcrop for each soil profile and depth. This normalisation helps to determine the fundamental periods of the model and to isolate the soil response from the input motion. The results confirm that 80 m depth is the most suitable depth for the modelling purpose of the soil foundation. Additionally, the stiffness profiles $G_{constant}$, G_{var-3} and $G_{var-random}$ are confirmed to resemble the broad range of periods of the recorded data with accuracy at different peak values.

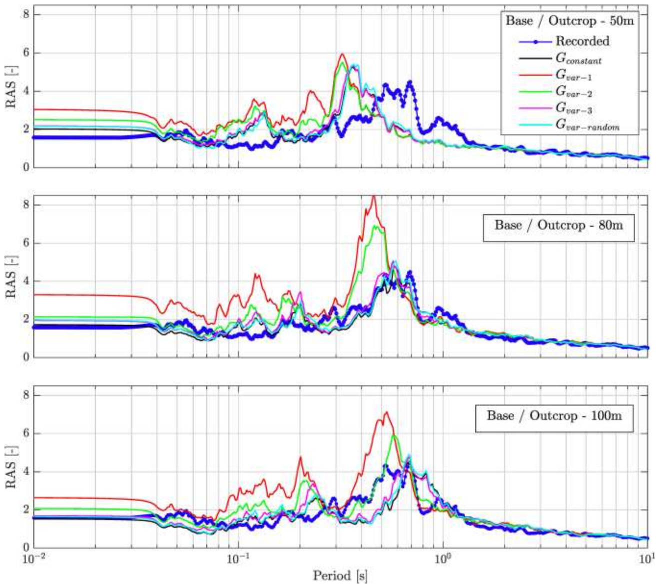

Figure 7. Response amplification spectra at the dam's toe for 50 m, 80 m and 100 m depth with stiffness profiles studied.

It is important to highlight that the soil profiles with a marked stiffness increment with depth (G_{var-1} and G_{var-2}) do not resemble the recorded response because the low stiffness in the shallow layers amplifies the soil response for a low period range (0.1 – 0.5 sec), and consequently the high frequency corresponding to the upper layers appears in the response. For the examined case, the uniform stiffness profiles better agree with the recorded seismic response. Hence, the profiles $G_{constant}$, G_{var-3} and $G_{var-random}$ are deemed suitable for the numerical modelling of the El Torito TSF. Based on the analysis results, the presence of soft-soil layers in depth would eventually enhance the seismic response for the G_{var-1} and G_{var-2} profiles, by attenuating the peaks observed. However, there is no evidence to justify the presence of any of these soft soils.

Complementary to this, the response of the dam is examined in terms of horizontal acceleration response spectra with a monitoring point located at the crest of the dam. The results are plotted in Figure 8 for the three foundation depths examined. It is important to highlight that the constitutive model employed for the tailings sands materials is linear elastic coupled with Rayleigh damping. Hence, the comparisons at this level are mainly a preliminary exercise for further advanced simulations. The results suggest that the foundation depth and stiffness do not severely impact the PGA recorded at the crest of the dam. The effect of the thickness of the foundation layer is consistent with the previous foundation analysis results, the range of periods with high peak values is shifted toward high periods as the depth is increased, clearly observed for G_{var-1} and G_{var-2} profiles. The peak amplitudes for $G_{constant}$, G_{var-3} and $G_{var-random}$ profiles are considerably lower than the other two profiles, making the interaction between the dam and the superficial soil foundations layer relevant in the vibration modes.

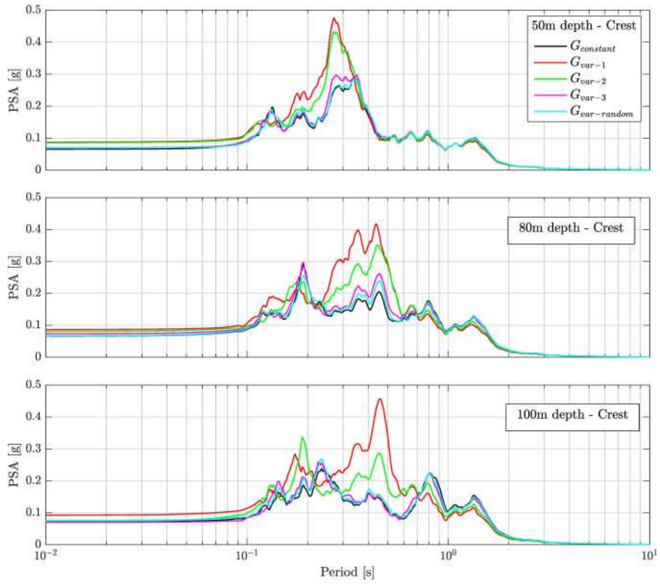

Figure 8. Acceleration response spectra at the dam's crest for 50 m, 80 m and 100 m depth with stiffness profiles studied.

5 CONCLUSIONS

This article presents the results of numerical back-analyses to determine the foundation layer stiffness and thickness of an existing TSF in a highly seismic environment. The numerical results were contrasted with the seismic recorded data at the El Torito tailings dam during the 2015 Illapel Earthquake.

Due to the lack of information on the foundation soil, five soil stiffness profiles, based on seismic design codes, were examined for three different depth conditions. The results are presented in terms of acceleration response spectra, and spectral ratio or response amplification spectra (RAS) for Base / Outcrop for each soil profile and depth examined.

The numerical simulations suggested that 80 m is the most suitable thickness of the foundation for modelling purposes, since the range of periods simulated matched the recorded ones. The examined soil stiffness profiles indicated that the $G_{constant}$, G_{var-3} and $G_{var-random}$ cases resembled the overall recorded seismic response with good agreement, especially in PGA and the different PSA peak values.

The results from simulations obtained at the crest of the dam suggest the effect of the foundation characteristics in the seismic response of the dam, affecting the amplitude of the acceleration spectra and position of the peaks in terms of periods.

Finally, regardless of the heterogeneity expected for the alluvial to colluvial deposits which form the foundation soil of the El Torito tailings dam, the modelling approach employed is capable of reproducing most of the aspects of the seismic recorded data at the toe of the dam.

6 ACKNOWLEDGEMENTS

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

7 REFERENCES

AngloAmerican. (2018). *4541 Adenda "Estudio Impacto Ambiental Continuidad Operativa Tranque de Relaves El Torito Operacion El Soldado" (in Spanish). "Environmental Impact Assessment for Continuing Operation El Torito Tailings Dams El Soldado Mining Operation" report by ARCADIS*. https://seia.sea.gob.cl/documentos/documento.php?idDocumento=2141826792

Barrientos, S. (2015). Informe Técnico Terremoto Illapel 16 Septiembre 2015. (In Spanish). In *Centro Sismológico Nacional*. http://www.csn.uchile.cl/

Bathe, K.-J. (2014). *Finite Element Procedures* (Second). Prentice-Hall, Pearson Education, Inc.

Chilean National Committee on Large Dams. (1996). *Large Dams in Chile* (Chilean National Committee on Large Dams - CIGB ICOLD, Ed.).

Consejo Minero. (2021). *Plataforma de Relaves - Anglo American. El Torito*. https://consejominero.cl/comunicaciones/plataforma-de-relaves/anglo-american/

Han, B., Zdravkovic, L., Kontoe, S., & Taborda, D. M. G. (2017). Numerical investigation of multi-directional site response based on KiK-net downhole array monitoring data. *Computers and Geotechnics*, *89*, 55–70. https://doi.org/10.1016/j.compgeo.2017.04.008

Jefferies, M., Morgenstern, N. R., Van Zyl, D. J. A., & Wates, J. (2019). *Report on the NTSF embankment failure, Cadia Valley Operations for Ashurst Australia*.

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. https://doi.org/10.1016/j.compgeo.2007.05.001

Kottke, A., & Rathje, E. M. (2009). *Technical manual for Strata*. Pacific Earthquake Engineering Research Center.

Morgenstern, N. R., Vick, S. G., & Van Zyl, D. (2015). *Report on Mount Polley Tailings Storage Facility Breach. Independent Expert Engineering Investigation and Review Panel*.

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.*

Potts, D. M., & Zdravković, L. (1999). *Finite element analysis in geotechnical engineering: Theory*. Thomas Telford. https://doi.org/10.1680/feaiget.27534

Rivano, S., Sepúlveda, P., Boric, R., & Espiñeira, D. (1993). Hojas Quillota y Portillo, V Región. N°73. *Servicio Nacional de Geología y Minería, Carta Geológica de Chile*.

Robertson, P. K., De Melo, L., Williams, D. J., & Wilson, G. W. (2019). *Report of the Expert Panel on the Technical Causes of the Failure of Feijão Dam I Expert Panel :*

Rollins, K., Evans, M., Diehl, N., & Daily, W. (1998). Shear modulus and damping relationships for gravels. *Journal of Geotechnical and Geoenvironmental Engineering*, *124*(5), 396–405.

Ruiz, S., Klein, E., Del Campo, F., Rivera, E., Poli, P., Metois, M., Christophe, V., Baez, J. C., Vargas, G., Leyton, F., Madariaga, R., & Fleitout, L. (2016). The seismic sequence of the 16 September 2015 Mw 8.3 Illapel, Chile, Earthquake. *Seismological Research Letters*, *87*(4), 789–799. https://doi.org/10.1785/0220150281

Solans, D. (2023). *Seismic performance of tailings sand dams* [PhD Thesis]. Imperial College London.

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. https://doi.org/10.1016/j.compgeo.2012.02.001

Toro, G. R. (1995). *Probabilistic models of site velocity profiles for generic and site-specific ground-motion amplification studies*. Technical Report 779574.

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*.