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Wave propagation in tailings dams by the Finite Element Method. Numerical simulation of real seismic data using a linear elastic model

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ABSTRACT: The effects of seismic events on natural and anthropogenic structures are well-documented, and the consequences depend on the characteristics of the seismic action and the structural response capacity. Among engineered structures, dams—constructed from concrete or natural materials—require meticulous analysis of their seismic response due to the potentially severe consequences of failure, including loss of life, significant economic losses, and extensive environmental damage. This study focuses on modelling seismic wave propagation in mining tailings storage facilities, commonly known as tailings dams, which are designed to contain waste material from mining operations. The numerical analysis is based on acceleration time histories recorded during one minor earthquake in 2018 at an unconventional tailings storage facility at the Neves-Corvo mine (Alentejo, Portugal). With the facility equipped with two triaxial accelerometers (one installed at the base and another at the crest of the containment embankment), it was possible to conduct a back-analysis of wave propagation within the structure. The calculations use a bidimensional finite element code under a time-step integration scheme, using a linear elastic approach that is compatible with the strain level imposed by the earthquake, which causes no significant stiffness degradation nor damping increase in the materials. Particular attention is given to the constitutive models adopted and the calibration of dynamic properties through the analysis of accelerometric data and the frequency content of the calculated response. The results contribute to enhancing our current understanding of the propagation of seismic waves on tailings dams.

KEYWORDS: Tailings facilities, Wave propagation, Finite Element Method, Elastic linear model, Dynamic back analysis.

1 INTRODUCTION

1.1 *Importance of the dynamic analysis of tailings dams*

Tailings dams are geotechnical structures built to retain mining residues—often loose, saturated, and poorly characterised materials—posing unique challenges to their long-term stability. In seismically active regions, these structures may be particularly vulnerable to failure, with potentially catastrophic consequences for human life, the environment, and surrounding infrastructure.

Despite their critical importance, seismic assessment in practice often relies on simplified methods (e.g., pseudo-static approaches) that aim at replacing dynamic loads with equivalent static forces. While convenient, these methods can misrepresent the true response, especially where wave propagation, geometric effects, and material nonlinearity are significant.

Understanding the dynamic behaviour of tailings dams requires detailed analysis of seismic wave propagation through the dam body. This involves accounting for the geometry of the structure, the stiffness and damping characteristics of the materials, and the level of seismic excitation. In particular, small-to-moderate earthquakes—which induce low strain levels—offer a unique opportunity to evaluate the adequacy of linear or equivalent linear models under realistic field conditions.

1.2 *Modelling of wave propagation in tailings dams*

1.2.1 *Earthquake magnitude and induced strain levels*

The propagation of seismic waves through a dam depends on the interplay between input motion characteristics, induced strain levels, soil behaviour, and the geometry of the structure. Advanced numerical methods, such as the Finite Element Method (FEM), allow the representation of these coupled effects, provided that the material model and boundary conditions are carefully chosen.

For low-magnitude events, shear strains often remain below thresholds for substantial modulus degradation and hysteretic damping. Under such conditions, linear elastic or equivalent-linear formulations are generally sufficient, provided the assumption is verified against field data to ensure consistency between computed and observed behaviour.

1.2.2 *Material models and geotechnical parameters*

Tailings materials exhibit highly variable properties, often compounded by limited site investigation data. For dynamic modelling, the small-strain shear modulus (G_{max}) and damping ratio (ξ) are critical inputs, both of which depend on confining stress, void ratio, and plasticity. In equivalent linear models, these parameters are iteratively adjusted based on the computed strain level using empirical degradation and damping curves. Accurate representation of the materials' behaviour is thus

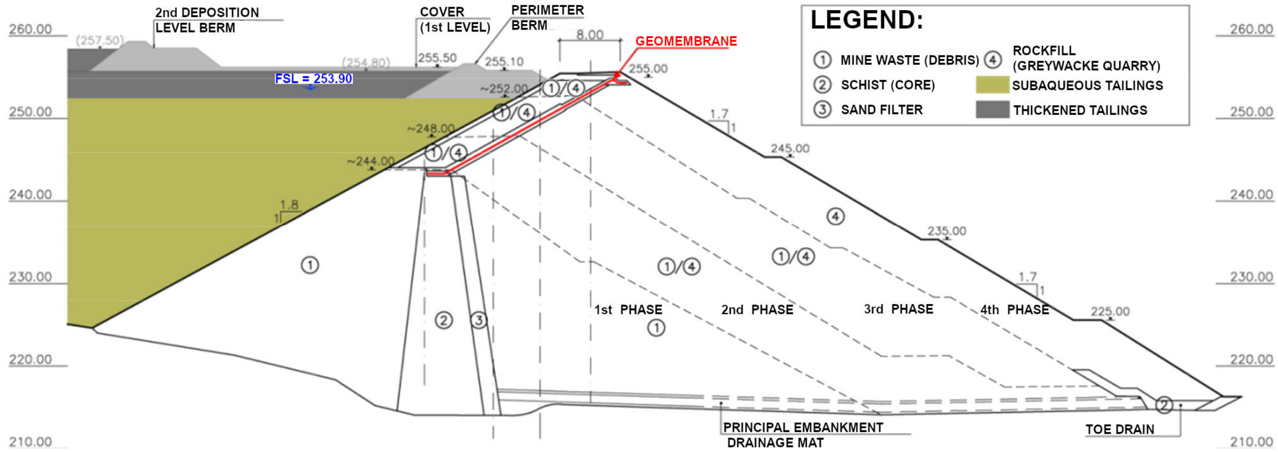

Figure 1. Cross-section of the IRCL main embankment (Ferreira et al., 2018).

essential to capturing the seismic response of the dam realistically.

1.2.3 *Bidimensional character of the problem*

The geometry of tailings dams introduces effects such as wave trapping, multiple reflections, and topographic amplification that 1D models cannot capture. Although one-dimensional models can incorporate more or less advanced constitutive laws for stress-strain behavior, their application to a structure with such complex geometry as the present one is unsuitable. Two-dimensional analyses are therefore required—particularly for embankments with inclined faces, zoned materials, and lateral heterogeneity—to obtain realistic internal stress distributions and crest accelerations. On the other hand, considering the geometry of the IRCL main embankment, a 3D analysis is unnecessarily complex

2 CASE STUDY

2.1 *Cerro do Lobo Tailings Storage Facility (IRCL)*

The structure under analysis is located at the Neves-Corvo mine complex, in the Alentejo region of Portugal (Ferreira et al., 2018 and Tavares et al., 2012). The mining–industrial activity at Neves-Corvo generates two types of mine waste: waste rock, originating from ore extraction, and tailings, resulting from the ore concentration process. Both wastes are managed internally by the company and stored at the Neves-Corvo waste facilities. Waste management techniques at Neves-Corvo have evolved over the years, the most significant change being the shift in the deposition method at the Cerro do Lobo Tailings Storage Facility (IRCL) from subaqueous deposition of slurry tailings to subaerial deposition of thickened tailings together with waste rock, using vertical stacking, which allowed vertical expansion of the deposit. The IRCL is currently licensed to accommodate up to 91.3 Mt / 50 Mm^3 of waste, within a facility geometrically bounded by five rockfill embankments. In one of these embankments, referred to as the Main Embankment, the two accelerometers used in this study were installed—one at the crest of the Main Embankment and the other in the foundation, downstream of it.

The tailings storage facility presented herein can be described as an unconventional tailings dam, as it is designed as a rockfill dam built to retain tailings. A cross-section of the Main Embankment, discretised into the tailings, body, transition zones and foundation soil, is shown in Figure 1.

2.2 *Instrumentation setup for seismic observations*

As part of a pilot project conducted by LNEC and IST, the dam was equipped with two triaxial accelerometers. The first sensor (Sensor A) was installed near the base of the dam, embedded in the foundation bedrock. The second sensor (Sensor B) was placed near the dam crest. Both sensors were installed at the surface but ensuring coupling to the surrounding material.

Their spatial positioning allows for the observation of seismic wave propagation within the embankment, particularly in the vertical direction.

To analyse the recorded data, the sensor local reference systems were transformed into a global coordinate system aligned with the dam geometry. This transformation was necessary to ensure consistency in the comparison of time histories between the two sensors.

2.3 *The Arraiolos (2018) Earthquake*

On January 15, 2018, a shallow crustal earthquake occurred near Arraiolos (central Alentejo), with magnitude ML 3.5 and epicentral distance of approximately 55 km from the Neves-Corvo site. Despite its moderate magnitude, the event produced clear seismic signals on both sensors, with distinguishable S-wave arrivals and sufficient signal-to-noise ratio for analysis.

The recorded accelerations were processed using baseline correction and reorientation into the global frame. Both horizontal components (longitudinal and transverse) and the vertical component were retained for analysis. The crest sensor exhibited higher amplitudes and longer durations, consistent with wave amplification effects within the dam.

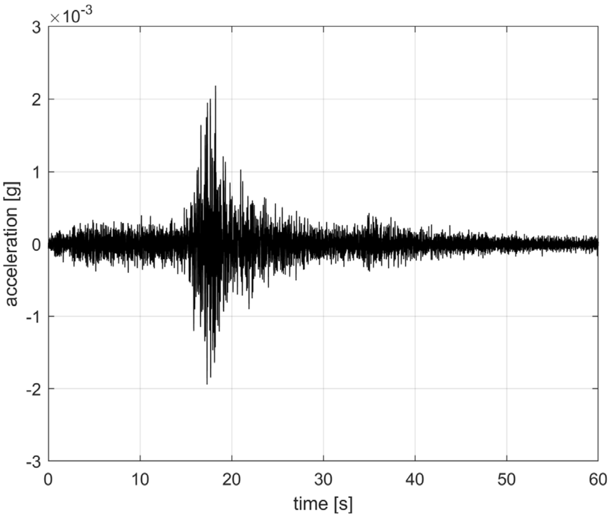

Figure 2. Acceleration time histories recorded during the Arraiolos earthquake at base sensors.

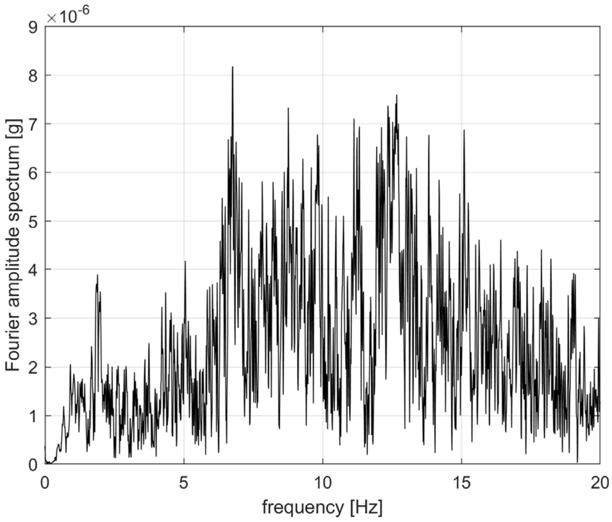

Figure 3. Frequency content (FFT) for the Arraiolos earthquake time history presented in Figure 2.

This event was selected as the target motion for the numerical back-analysis developed in the following sections, given its quality and representativeness within the range of small-strain seismic loading.

Figure 2 shows the acceleration time history recorded during the Arraiolos earthquake at base sensors, with the direction parallel to the cross section. The peak ground registered values are 0.0022 g, 4.0x10^{-4} m/s and 7.6x10^{-3} m for PGA, PGV and PGD respectively. Figure 3 shows the amplitude spectrum after the FFT computation. The amplitude spectrum (|FFT|) shows broadband content up to 20 Hz, with dominant energy concentrated between about 9–12 Hz where |FFT| peaks near 0.12–0.13. Energy is small below ~3 Hz and decays gradually beyond ~15 Hz.

3 NUMERICAL MODELLING OF THE BEHAVIOUR OF THE OBSERVED TAILINGS DAM

3.1 *Material modelling*

The structure was modelled with constitutive laws consistent with the geotechnical information available for the IRCL site. Since the earthquake-induced shear strains were below 10^{-6}, the use of linear viscoelastic models was justified (even though modulus-reduction and damping curves were adopted for the initial run, they were ultimately discarded).

Table 1. Parameters adopted for the stress-strain analyses.

Material	γ [kN/m^3]	υ [.]	G$_{max}$ [MPa]	ξ [.]
Thickened tailings	22.0	0.1	Figure 4	0.06
Slurry tailings	22.0	0.1	Figure 4	0.06
Schist (core)	21.5	0.3	Figure 4	0.03
Mine waste / Rockfill	21.5	0.3	Figure 4	0.05
Rock foundation	26.0	0.2	10000	0.02

The adopted parameters (namely unit weight (γ), Poisson's ratio (ν), elastic shear modulus (G$_{max}$) and viscous damping ratio (ξ)) for the stress-strain analyses (for initial stress state generation and for dynamic computation) are presented in Table 1.

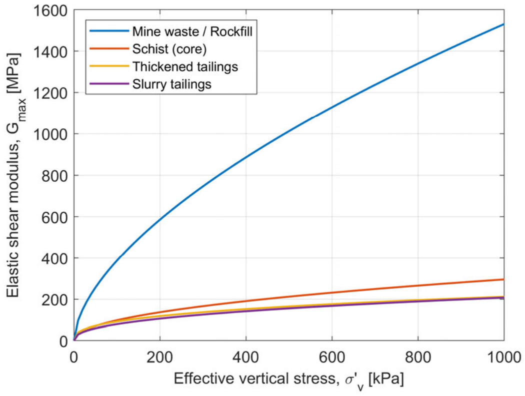

Figure 4. Elastic shear modulus as a function of vertical effective stress, for representative materials adopted in the model calibration.

The curves presented in Figure 4 follow the relationship $G_{max} = \alpha\sqrt{\sigma'_m}$, where the coefficient α was initially estimated based on values reported in the literature (e.g. Kramer, 1996) and subsequently calibrated through a parametric performance analysis. This calibration aimed to achieve good agreement between measured and computed responses, both in terms of acceleration amplitudes and frequency content. The damping ratio, ξ, also derived from this calibration procedure. The parametric analyses, which are too extensive to be fully presented in this paper, are documented in Santos (2024).

The Quake/W dynamic analyses were performed in the time domain using the equivalent linear approach, in which the entire acceleration time history is analysed repeatedly in successive iterations. Initially, each soil layer is assigned small-strain shear modulus and damping values. A full time-history analysis is then carried out, from which shear strain time histories are obtained throughout the model. Based on the resulting effective shear strain levels, updated strain-compatible shear modulus reduction and damping ratios are determined for each material. These updated properties are subsequently used in a new full time-history calculation, and the process is repeated until convergence is reached, i.e., until changes in stiffness and damping between consecutive iterations become negligible.

3.2 *FE discretization*

The structure was modelled in the FEM software Quake/W, from GeoStudio Suite (Seequent, 2022). The finite-element mesh was sized to balance wave-propagation fidelity and runtime. The target element size followed the wavelength criterion:

$$h_{max} \le \frac{\lambda_{min}}{8} = \frac{v_s}{8 \cdot f_{max}} \tag{1}$$

with f$_{max}$=12.5 Hz as the target frequency for this case. A graded mesh was used: 1.0 m elements in stiffer zones (foundation rock mass, greywacke rockfill, clay core, mine waste rock) and refined elements in the tailings where lower stiffness implies lower v$_s$: 0.45 m (thickened tailings) and 0.70 m (slurry tailings). Figure 5 shows the adopted mesh.

The base accelerogram recorded during the Arraiolos 2018 event was applied at the model base. The 2D section was aligned with the transverse component (in-plane motion). To reduce runtime without loss of relevant content, the low-energy coda at the end of the record was trimmed.

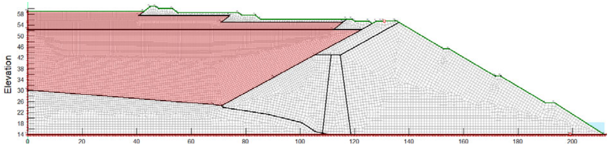

Figure 5. Finite-element mesh with graded discretisation (1.0 m in stiff materials; 0.45–0.70 m in tailings).

3.3 *Results obtained and comparative analysis*

The computed response shows small cyclic shear strains throughout the embankment, confirming a small-strain regime consistent with the viscoelastic-linear assumption, with all shear strains below 4.5×10^{-7} (Figure 6).

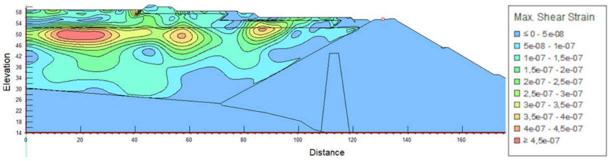

Figure 6. Contours of maximum shear strain, showing very-small strain response.

Time-domain comparisons between recorded and computed accelerations at the crest show close agreement in phase and envelope for the main shaking window, with peak values within the observed range (Figure 7). The positive and negative measured PGAs at the crest were 5.4×10^{-3} and -6.0×10^{-3} g, while the computed values where 7.9×10^{-3} and -7.4×10^{-3} g.

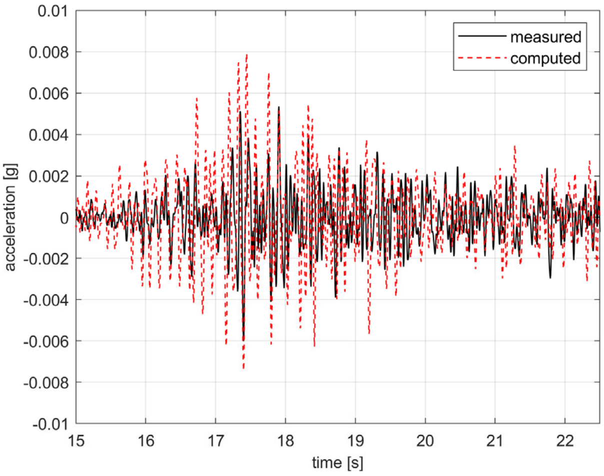

Figure 7. Comparison between measured and computed acceleration time histories ate the structure's crest

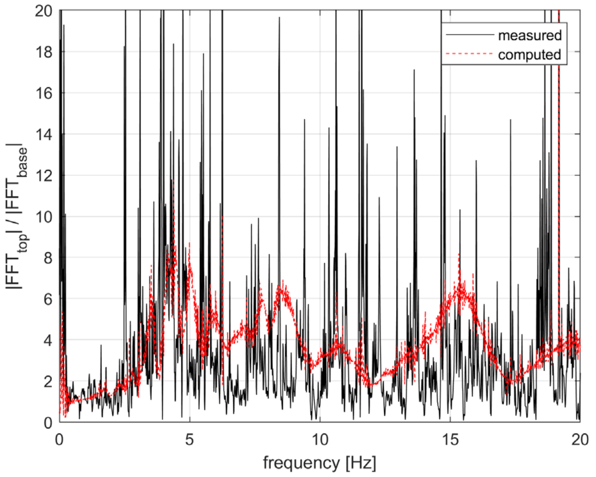

Figure 8. Comparison between measured and computed transfer function between base and top

In the frequency domain, the transfer function (crest/base Fourier amplitude ratio) reproduces the first resonant peak and the overall spectral shape of the measurements, although some measured peaks are not captured by the model (Figure 8). Taken together, these findings confirm that the dam behaved in a small-strain regime under this excitation and that a linear formulation captures the salient features of the response.

4 CONCLUSIONS

A two-dimensional finite-element model, constrained by site-specific stiffness profiles and records from the IRCL instrumentation, reproduced the observed small-strain response to the 2018 Arraiolos earthquake. Maximum cyclic shear strains remained below 4.5×10^{-7}, no plastic yielding was mobilised, supporting the adequacy of a viscoelastic linear formulation for this excitation level. The base-to-crest transfer characteristics—including the position of the first resonance around 6–7 Hz—were captured with good fidelity.

These results indicate that, for weak-to-moderate motions of similar spectral content, equivalent-linear analyses calibrated with site data provide a reliable tool for assessing crest amplification and internal demand at IRCL-type sections. Extrapolation to stronger shaking should consider explicit nonlinear and cyclic-degradation behaviour of tailings and rockfill, and potential pore-pressure generation.

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