

Seismic Analysis for the Foundation of a Tailings Dam in Peru

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SUMMARY: The tailings dam studied in this paper is located in the department of Ayacucho, in Peru, a region of high seismic activity. The foundation consists of a surface layer of moraines and residual soil, followed by a layer of argillite material whose resistance increases with depth. The argillite stratum is deeper near the left abutment, and it is important to estimate its influence on the seismic response of the tailings dam. A simplified method consists in the selection of a representative profile characterized by the distribution of the shear wave velocity with depth. For the analysis of the dam behaviour, two models were used: a simple model for 1D seismic response based on the propagation of vertical shear wave through a layered viscoelastic medium and a 2D numerical model based on the finite element method and specific constitutive relationships for the different soil types. Results for 1D and 2D analyses are quite similar, although the 2D analysis permits a better accuracy because it includes topographical effects due to geometry of foundation site.

KEYWORDS: Seismic response, argillite, synthetic accelerogram, bi-dimensional analysis

1 INTRODUCTION

The design of tailings dams in Peru requires careful verification either by a pseudo-static slope stability analysis or by a full dynamic displacement analysis, depending on the importance of the project, since the country presents many areas of high seismic activity. The seismic response is strongly influenced by the soil properties and to quantify them it is required to carry out laboratory (cyclic triaxial) or field (geophysical) tests in order to estimate the values of shear modulus, Young's modulus, shear wave velocity, damping ratio, etc.

2 SITE OF THE TAILINGS DAM

The foundation of the tailings dam consists of a surface of moraines and residual soil followed by a layer of argillic material, whose strength increases with depth, and an andesitic

volcanic bedrock.

During the raising of the tailings dam to 4494 meters above sea level, it was found that, at the left abutment, this strength was much higher than the estimates made in previous studies, thus demanding additional geophysical tests to get a better characterization of the argillic material.

The geophysical tests consisted of 5 multichannel analysis of surface waves (MASW), 3 microtremor array measurements (MAM), 7 seismic refraction lines to estimate P- and S-wave velocity profiles (Fig. 1) and 5 electrical tomography tests, as indicated in Fig. 2 for a cross-section in the left abutment where the blue zones indicates presence of water. Although the strength of the argillite grows with depth, this material loses resistance significantly in contact with water.

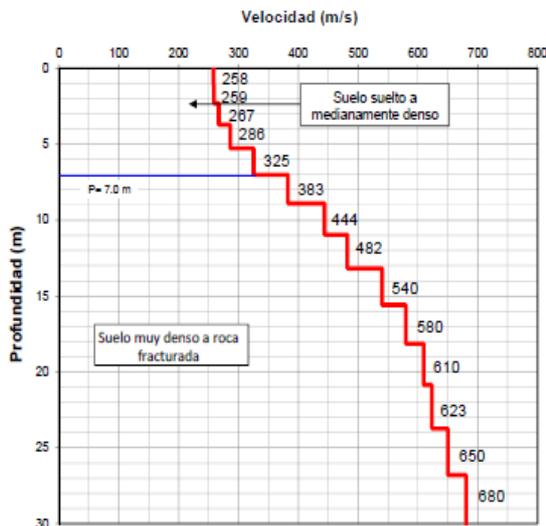


Figure 1 Shear velocity profile

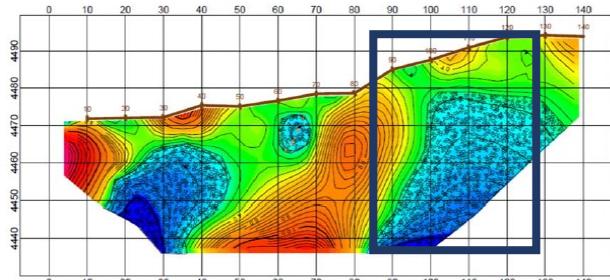


Figure 2 Electrical tomography for the cross section in the left abutment.

The geotechnical properties of the foundation soils are listed in Table 1 with the corresponding constitutive soil model used for numerical analysis, herein carried out with the finite element solver Geostudio (2012).

Table 1. Soil properties.

Soil	Constitutive model	E (kPa)	ν	γ (kN/m ³)	c' (kPa)	ϕ' (°)	
Moraines	Mohr-Coulomb	21 400	0,35	19,60	25,0	13,1°	
Residual soil	Mohr-Coulomb	20 000	0,30	21,00	30,0	24,0°	
Argillite	Soft clay	41 100	0,35	21,90	70,0	13,5°	OCR:1,5 $e_0=0,519$
Bedrock	Linear elastic	200 000	0,22	22,50	----	----	
Rockfill (drain)	Mohr-Coulomb	120 000	0,28	20,00	0	35,0°	

2.1 EQUIVALENT LINEAR METHOD

Soil behaviour under cyclic loading is not linear and depends on several factors, including the excitation amplitude, number of cycles and soil type.

In 1-D seismic analysis it is generally assumed that all viscous layers are horizontal and the dynamic response can be estimated solving the wave equation in the frequency domain considering vertical propagation of S waves throughout the soil mass. In the equivalent linear approach (Seed and Idriss, 1970) the nonlinear seismic responses are simulated by a shear modulus degradation curve and a viscous damping curve, both function of the cyclic shear strain level. Several other correlations have been suggested in the literature, for various types of soils, such as Darendelli (2001) as shown in fig. 3 for soils with different plasticity index PI.

Table 2 shows for each type of existing soil in the tailings dam foundation the corresponding linear equivalent model adopted in this research.

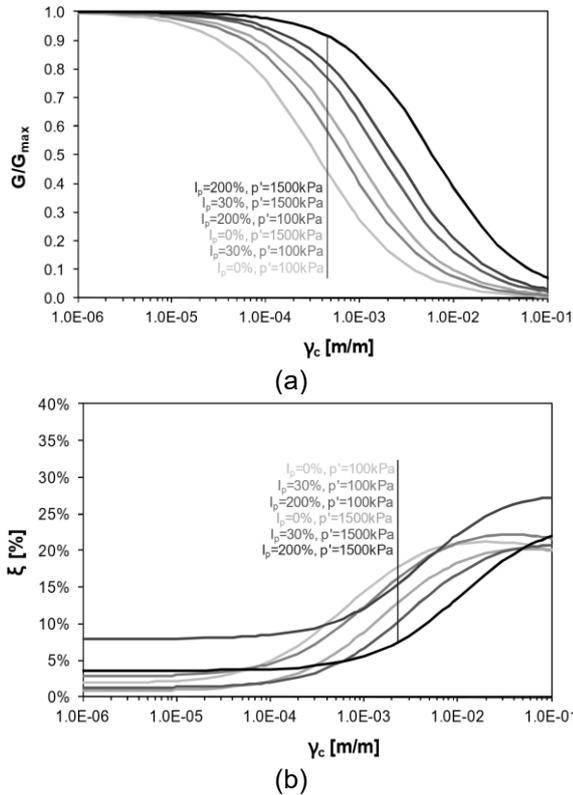


Figure 3 (a) Shear modulus degradation curve; (b) Damping ratio increase curve (Darendelli, 2001).

Table 2. Shear wave velocities and equivalent linear model

Type of soil	γ (kN/m ³)	Shear velocity (m/s)	P I	G degradation curve
Moraines	19,6	000-354	1	Darendelli, 2001
Residual soil	21,0	354-540	4	Darendelli, 2001
Argillite	21,9	540-680	8	Darendelli, 2001
Bedrock	22,5	680-750	-	-
Rockfill	20,0	250-350	-	Menq, 2003

Several computer programs have the linear equivalent model implemented, such as Shake2000 (2015) and Deepsoil v.6.1 (2016), the last one used in the present study. To perform a first nonlinear approximation, a backbone curve representing the material behaviour is selected; the program Deepsoil employs some variations of the hyperbolic model to represent the backbone curve obtained through MASW tests. (Hashash et al,

2010).

3 SEISMIC HAZARD ANALYSIS

A seismic hazard analysis considering a return period of 475 years was carried out at the tailings dam site (soil type B), as shown in fig. 4.

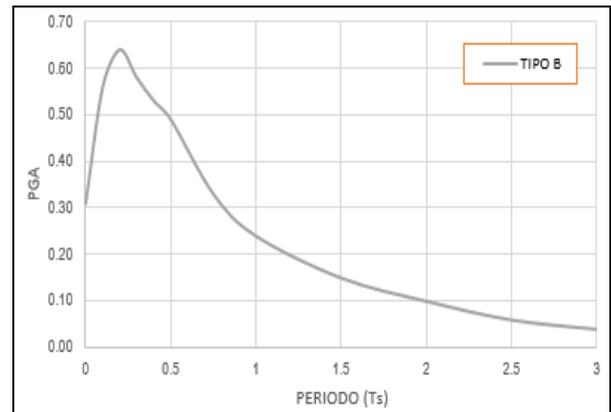


Figure 4 Seismic hazard analysis considering a return period of 475 years in soil type B.

Spectrum-compatible artificial accelerograms were generated for the design earthquake based on records of the Arequipa earthquake (2001) occurred near the tailings dam site. Such records were corrected according to a process (Boore, 2004) that included a baseline correlation and the filtering of high and low frequencies. The distortion of the baseline is more common in data recorded in analogy accelerometers.

Artificial accelerograms were generated with the software SeismoMatch (2016) with a peak acceleration of 0,31g for the design earthquake (Fig. 5).

4 1D SEISMIC RESPONSE

For a 1D response analysis the following steps are necessary:

- Soil profile definition with each layer characterized according to the wave velocities

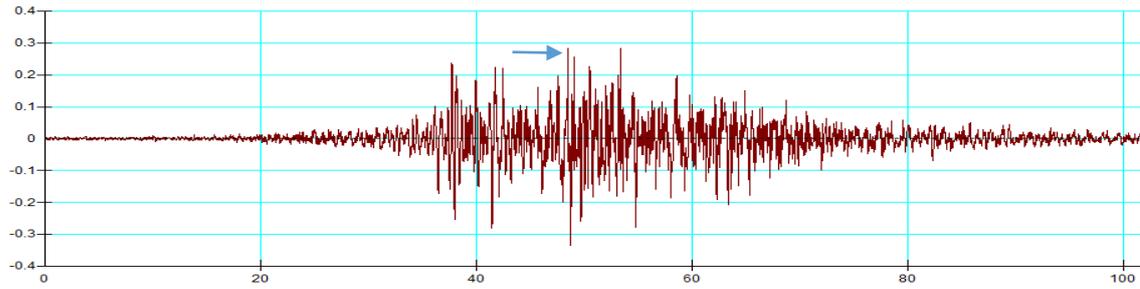


Figure 5 Artificial ground motion used in modelling - acceleration (g) vs. time (sec)

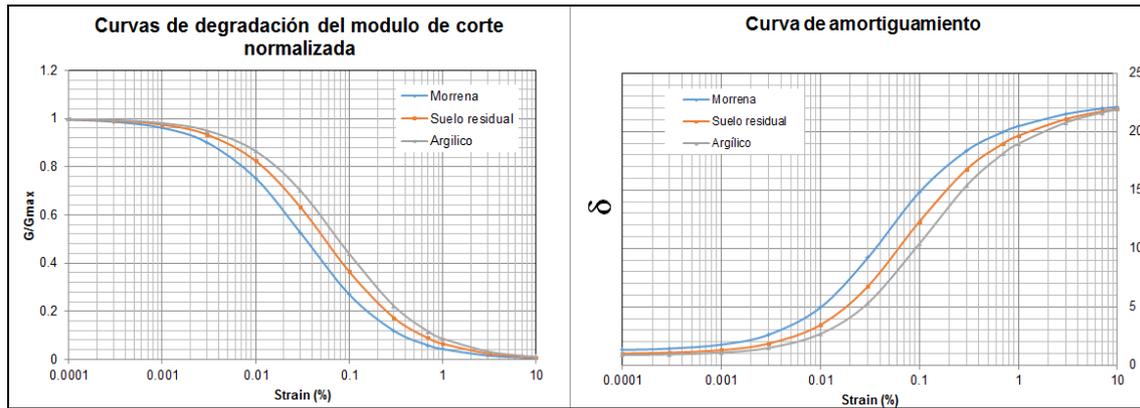


Figure 6 Degradation curves for the shear modulus (left) and increasing of the damping ratio (right).

- Depending of the soil type a variation of the shear modulus and damping ratio with effective shear deformation should be assigned to each soil layer (Fig. 6).

- The seismic response of the soil mass is obtained applying the design earthquake on the lower boundary of the model.

- Pseudo-static slope stability analysis considering the seismic coefficient equal to $k=2/3(a_{max})$ where a_{max} is the maximum acceleration obtained from the seismic response analysis (previous step).

Results computed in the 1D seismic analysis of the tailings dam indicated the following responses:

a) Soil amplification of the design earthquake through the soil layers, as shown by the acceleration curves in Fig. 7.

b) Small relative amplitude displacements, less than 1cm for all soil layers, as indicated in Fig. 8.

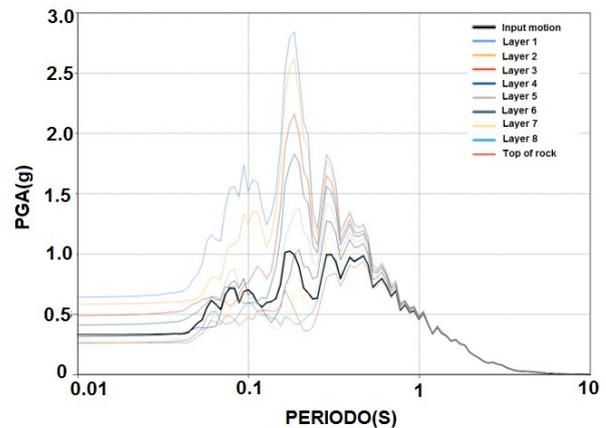


Figure 7 Response spectrum PGA(g)

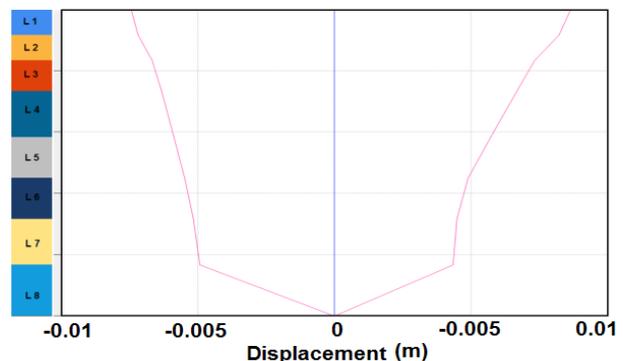


Figure 8 Relative displacements (m) obtained in 1D analysis.

5 2D SEISMIC RESPONSE

For a better understanding of the seismic response of the tailings dam, a two-dimensional finite element analysis of the left abutment was carried out using the software Geostudio (2012). For the dynamic analysis, the strongest 30sec of excitation was selected from the complete acceleration history (100s).

Fig. 9 shows the boundary conditions for

static analysis while Fig. 10 indicates the corresponding conditions for dynamic analysis with some control points select in order to display the final results.

The distribution of the initial vertical stresses (static condition) is illustrated in Fig. 11.

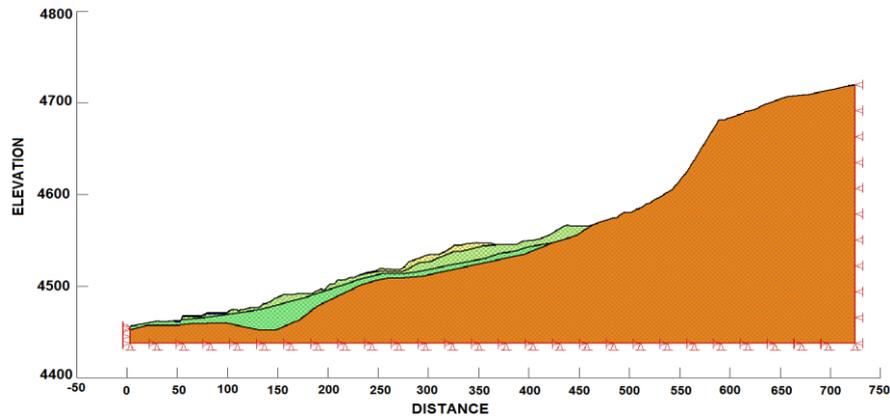


Figure 9 Geometry and boundary conditions of the left abutment for static analysis

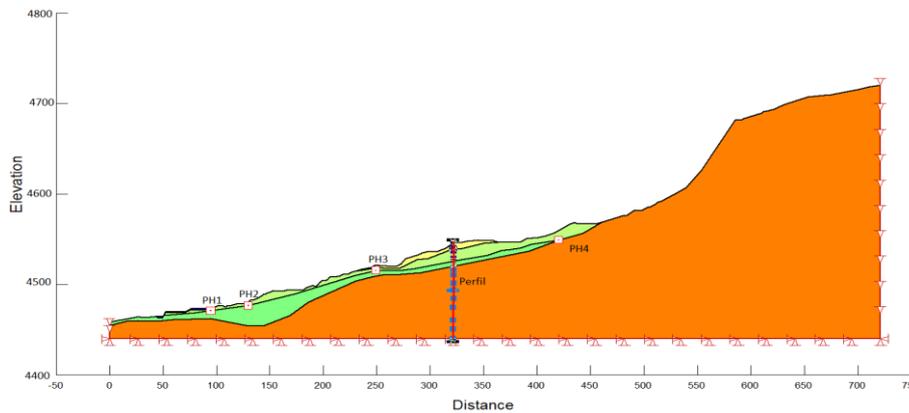


Figure 10 Boundary conditions to the dynamic analysis and the location of control points

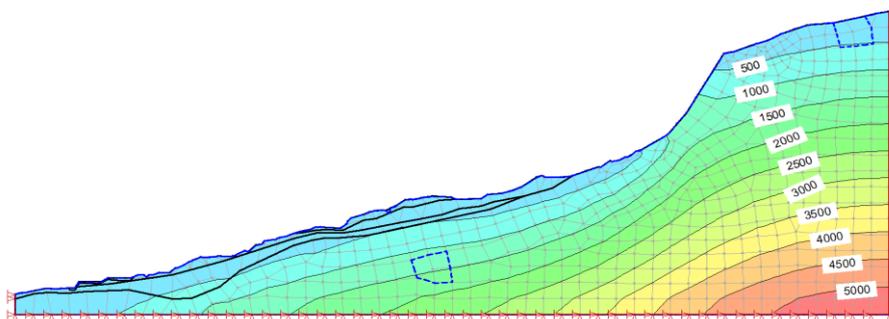


Figure 11 Initial vertical stress in the left abutment.

Figure 12 shows that for points on the soil surface the maximum horizontal acceleration occurred at time $t = 6,14\text{sec}$; $6,36\text{sec}$; $11,68\text{sec}$ and $11,88\text{sec}$, reaching values higher than $0,4g$. The maximum relative displacements computed at those instants mentioned before are shown in Fig. 13. They reach 15cm and occurred on the

soil surface between distances $450\text{m} - 600\text{m}$, where the slope is steepest. (Fig.14)

Results show a maximum surface displacement of $1,00\text{m}$. in Fig. 15 illustrates the permanent displacement field at the end of earthquake (30 sec).

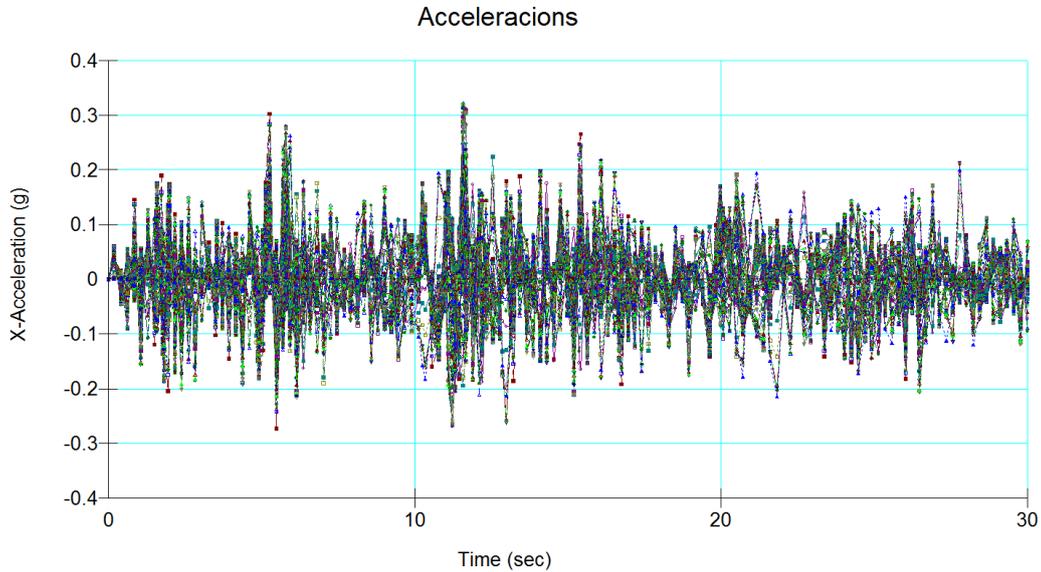


Figure 12 Acceleration versus time at points on the soil surface.

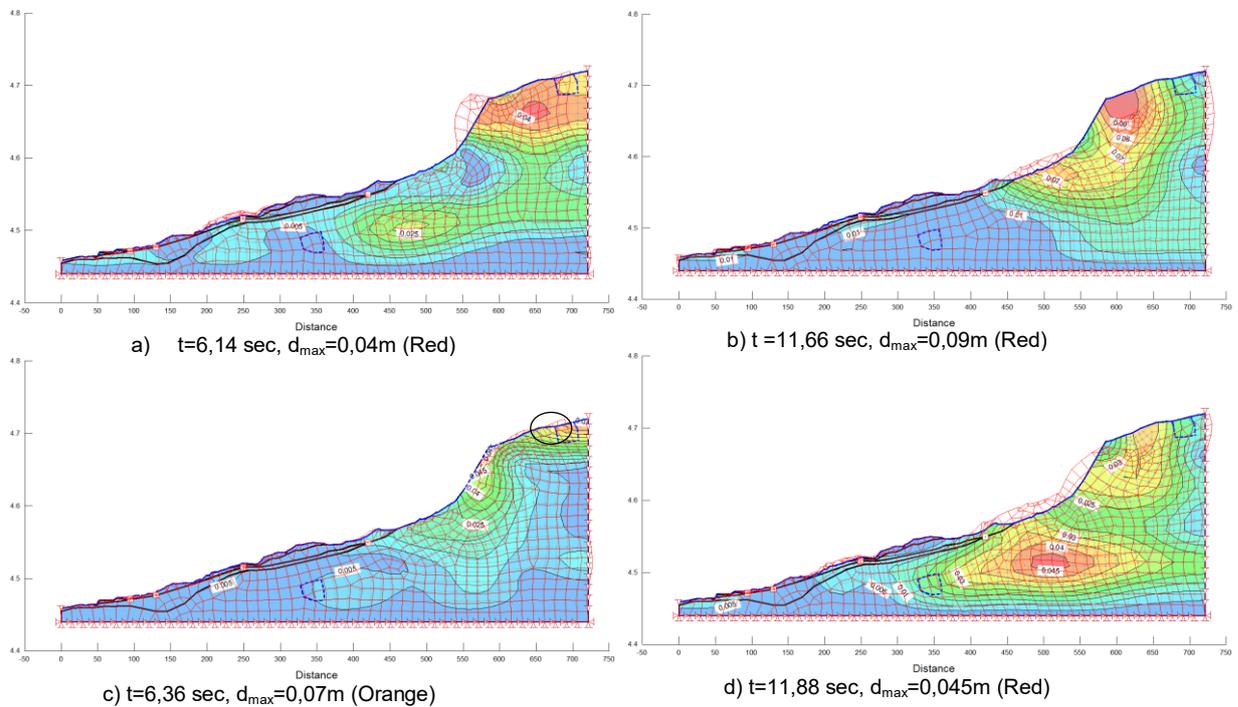


Figure 13 Relative displacement computed at several times.

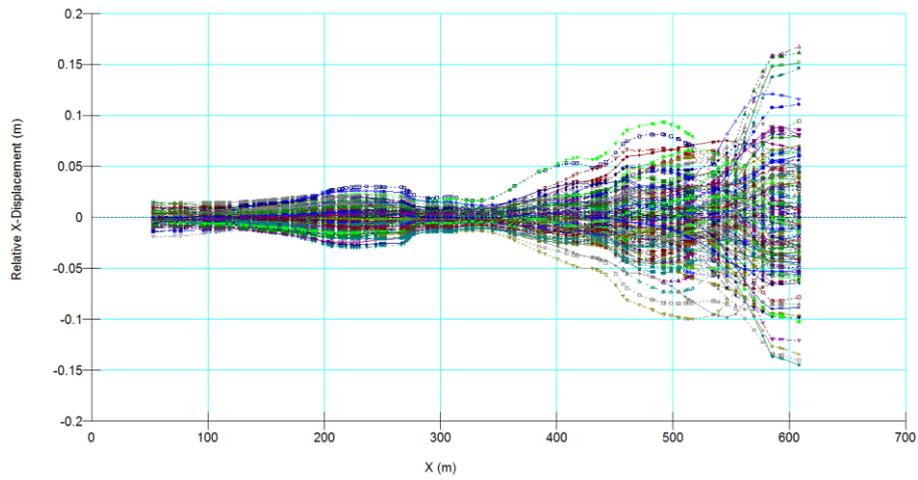


Figure 14 Maximum relative displacement reach on the surface

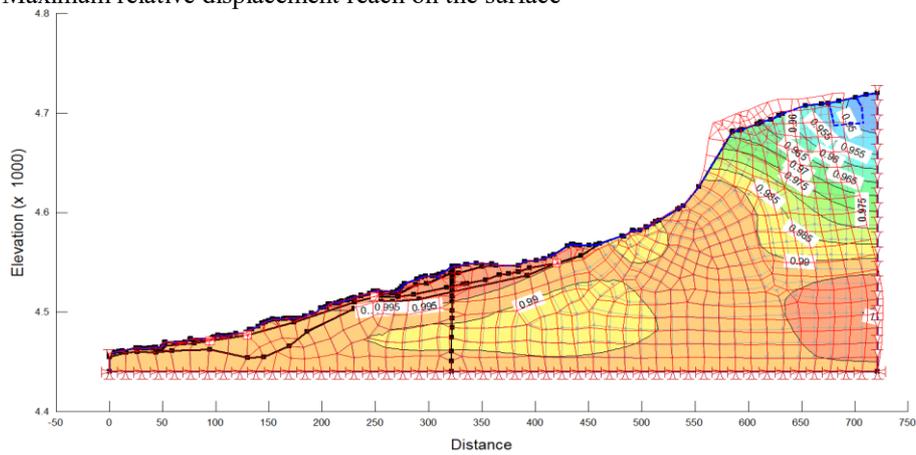


Figure 15 Total displacements at the end of analysis (30 sec.)

The history points PH1, PH2, PH3 and PH4 in the graph show that the maximum reached displacement is 1,00m. (Fig. 16)

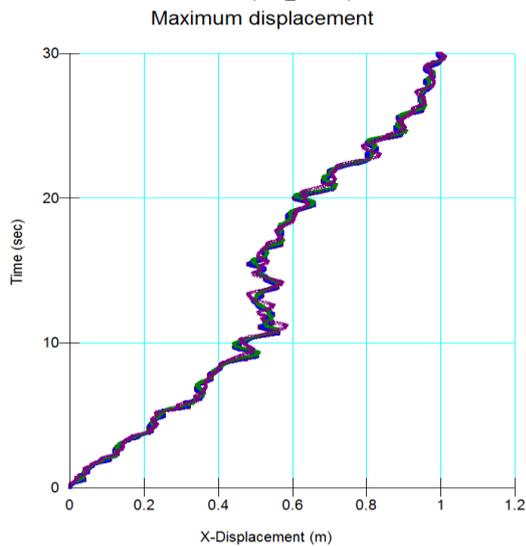


Figure 16 Displacement of the history point

In the Fig. 17 a graph of the relative X-displacement in the profile vs elevation is shown, collocated for dynamic analysis, which was collocated in the fault zone (same profile evaluate in 1D) reach 3cm.

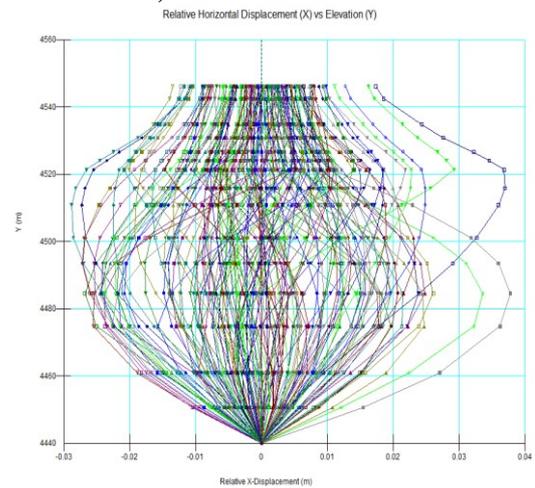


Figure 17 Relative X-Displacement on the profile

6 CONCLUSION

In this study the seismic behaviour of a tailings dam situated in an area of high seismic activity in Peru was analysed using 1D and 2D models.

The 1D model based on the propagation of vertical shear waves through a layered viscoelastic medium yielded relative vertical displacements smaller than 1cm while the 2D model, based on the finite element method, produced responses with relative horizontal displacements of 3cm. The permanent displacement reached a maximum of approximately 1,00m in the 2D analysis.

Along of the argillite surface, the maximum displacement reached is shown in the Fig 16.

The main reason of such difference becomes from the geometry of the left abutment since in the 2D simulation the maximum displacements are concentrated near the steepest slope, while in the 1D model it is assumed the maximum vertical displacement would occur at the profile where is located a sliding surface.

Finally, results from the 1D and 2D analysis for the same profile does not show much difference, although 2D analysis are more indicated for problems where a broader view of the entire displacement fields is necessary.

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