Using Seismic Records to Determine the Predominant Vibration Frequency of a Tailings Dam Embankment: First Results

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ABSTRACT

A large number of tailings deposits in operation, non-active, and in abandonment are located mainly in the northern and central Chile where the seismicity threatens the stability of these large and saturated geostructures. The importance of the physical stability of these deposits is relevant since it directly influences the life of mine, its closure plan, the impact on the environment, and the surrounding communities. A common practice is that tailings deposits are instrumented with different technologies to measure pore water pressure inside the wall, water levels, infiltrations, deformations, and seismic accelerations. The monitoring and understanding of the information collected is essential to ensure the stability of the deposit and its operational continuity. This work seeks to determine the predominant vibration frequency of an instrumented tailings dam embankment of 45 m height constructed from borrowed material by calculating empirical amplification transfer functions and by using the horizontal to vertical spectral ratio method (HVSR). Then, the equivalent linear wave propagation method is used to explain the observed predominant vibration frequency considering estimations of shear wave velocity profiles of the embankment dam.

INTRODUCTION

The most common tailings dam failures in the World are related with slope instability, internal erosion, and overtopping (ICOLD 2001). In Chile, the most critical threat to a tailings dam is the occurrence of large earthquakes (Villavicencio et al., 2014). To prevent a failure of the deposit, it is necessary to develop a deep understanding of the seismic behavior of the embankment and a good estimation of the relevant geotechnical parameters. The seismic response of a deposit is related with the geometry and the material properties that compose the wall, such as the stiffness that can be obtained from the shear wave velocity. Also, the predominant vibration frequency of the structure allows predicting the behavior of the embankment subjected to seismic loads. The predominant vibration frequency of the structure can anticipate the occurrence of resonance that could increase the risk of a catastrophic failure.

To determine the predominant vibration frequency of an earth structure, the horizontal-to-vertical spectral ratio (HVSR), also known as the Nakamura's method, can be calculated from continuous ambient seismic noise records (Diaz-Segura 2016, Molnar et al. 2018). Moreover, the HVSR can also be estimated by using earthquake records, providing similar results than ambient seismic noise (Fernández et al. 2019). Using seismic stations installed on a cycloned-sand embankment dam, Pastén et al. (2019) have demonstrated that the HVSR calculated either with ambient seismic noise or earthquake records are similar. This result raises the question whether the HVSR method can be used in embankments constructed with borrowed materials.

In this study, the predominant vibration frequency of a tailings dam embankment is obtained from earthquake records using the HVSR method and empirical amplification transfer functions. Also, a 1D shear wave velocity profile for the embankment is analyzed with the equivalent linear method to understand the amplification pattern observed in the earthquake records.

TAILINGS DAM AND SEISMIC STATIONS

The analyzed deposit corresponds to a tailings dam located in the northern Chile, the retained wall is an earth fill compacted wall that has grown by the downstream construction method, currently has a maximum height of 47 m, an upstream slope ratio of 1.8: 1 (H: V) and a downstream slope ratio of 2: 1 (H: V).

The tailings dam is monitored with 3 seismic stations, two installed in the crest of the embankment and one installed in natural ground, on soil foundation, which is considered as the free field station. In this paper, the data recorded by the basal station and the one located in the section with the highest elevation of the deposit will be considered. Figure 1 shows a schematic of the tailings deposit and the approximate location of the stations.

The seismic stations are Obsidian triaxial accelerographs from Kinemetrics with 3 + 1 record channels, configured with a trigger of 0.01% and sampling frequency of 200 Hz. The stations remain in constant operation, recording events that have accelerations larger than 0.001g.

The records used in this study correspond to low intensity earthquakes that occurred in the vicinity of the tailings deposit during January 2018. In addition, there is 5.3 magnitude earthquake record with epicentral distance of 50 km, with the largest acceleration and duration (0.1 g and 200 s). Each record has three components: one in the vertical direction, the horizontal direction perpendicular to the wall axis (transverse component) and the horizontal direction aligned with the wall axis (longitudinal component).

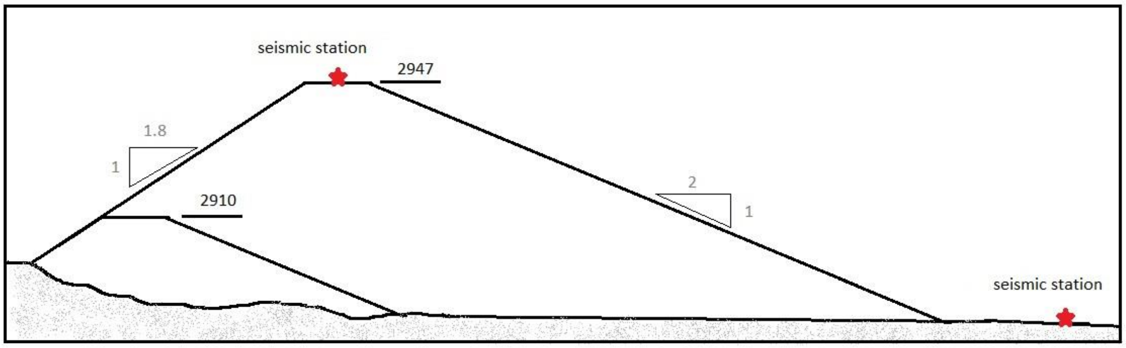


Figure 1 Schematic profile of the deposit and location of the seismic stations

H/V SPECTRAL RATIOS AND EMPIRICAL TRANSFER FUNCTIONS

We calculated the horizontal-to-vertical spectral ratios (HVSR) using the seismic records of the stations installed on the crest and on the toe of the embankment, using a window of 30 seconds that contains the largest amplitude of the record, then the Fourier transfer function is calculated for each component, the curve is smoothed and then divided the horizontal to vertical curve. The geometrical average is calculating and represented by the black curve. The calculations were performed using the open-source software Geopsy (www.geopsy.org). The HSVR curves in Figure 2a indicates a lack of a predominant vibration frequency at the sensor located on the toe of the embankment, which is characteristic of stiff soil deposits with low impedance contrast with the underlying bedrock. Figure 2b indicates a predominant vibration frequency, according to the peak spectral ratio amplitude, at approximately 4 Hz for the transverse and longitudinal components. This is the predominant vibration frequency of the embankment wall.

Figure 3 shows the empirical transfer functions in the transverse and longitudinal components. To obtain the empirical transfer function, the same analysis is performed considering just the vertical or the horizontal components. Both average curves in the figure show a peak spectral ratio at about 4 Hz that is consistent with the results from the HVSRs.

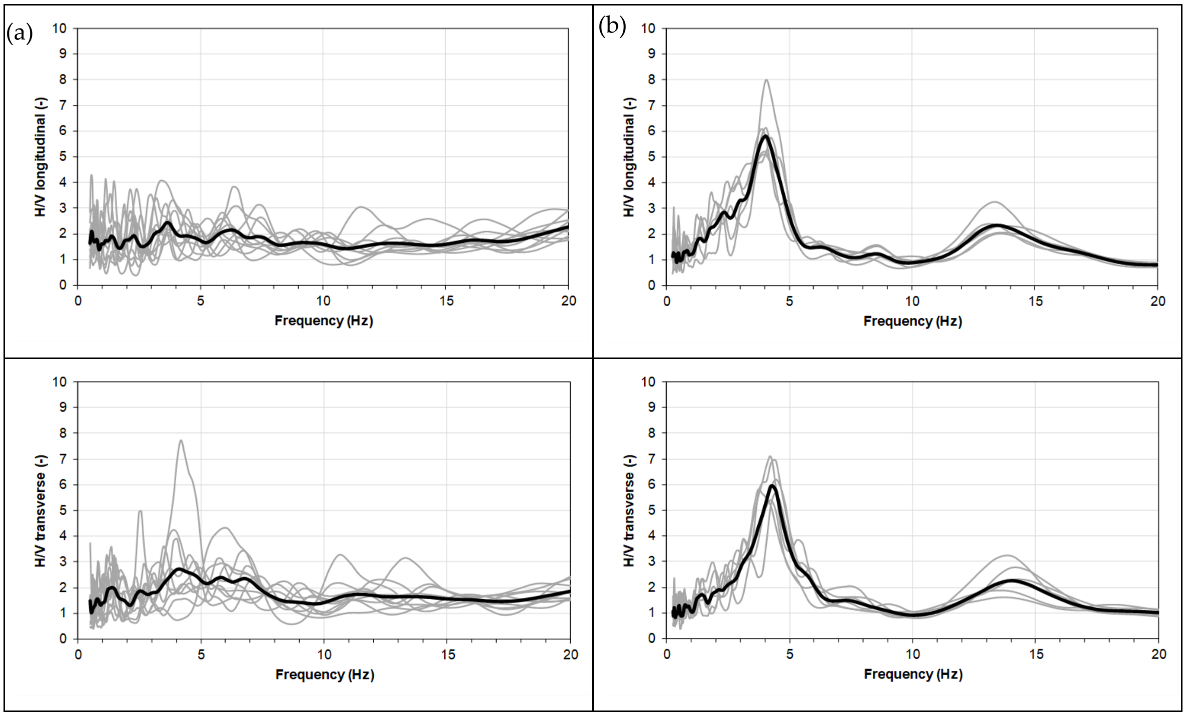


Figure 2 HVSR calculated for the toe sensor (a) and for the crest sensor (b). The gray curves are the HVSRs of every analyzed earthquake record. The black curve is the mean of all the gray curves

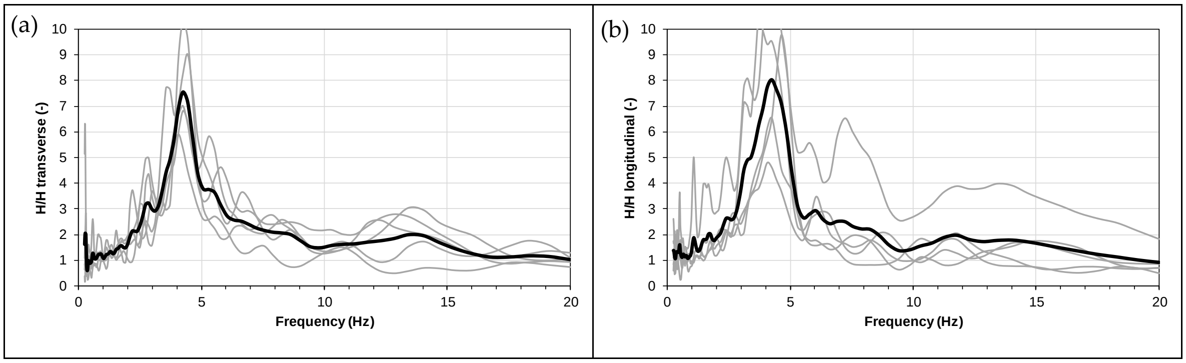


Figure 3 Empirical transfer functions calculated for the transversal component(a) and for the longitudinal component (b). The gray curves are the HVSRs of every analyzed earthquake record. The black curve is the mean of all the gray curves

1D WAVE PROPAGATION ANALYSIS

One-dimensional (1D) equivalent linear analyses were performed, considering two shear wave velocity profiles that represent the stiffness variation of the embankment wall with depth. The input ground motion used in the analyses is the earthquake record of the basal sensor with the largest peak acceleration. According with the soil material used in the construction of the wall, the mean curves for sand proposed by Seed and Idris (1970) were considered in the analysis for the normalized shear modulus reduction and damping curves. Then, the calculated acceleration time history is compared with the motion recorded in the crest sensor for the same earthquake. These analyses were performed using the open-source software DeepSoil (http://deepsoil.cee.illinois.edu).

The 47 m-depth shear wave velocity (Vs) profile assumed for the deposit, according with the lift stages, is shown in red in Figure 4. This profile is a three-layer model with an increase of the Vs with depth. The geotechnical properties of the model materials are shown in Table 1. Another multi-layer Vs profile obtained from MASW and ReMi tests performed in the embankment wall is shown in black in the Figure 4 for comparison. The results of these tests show an increase of the Vs with depth, starting with a Vs of about 400 m/s at the crest of the wall and a Vs of 1200 m/s at the base. The high values for the shear wave velocities and the increase of the Vs with depth agree with the type of material used in the several lift stages of the wall and the technical specification for soil layer compaction recommended by de designer.

Table 1 Geotechnical properties of the 3-layers model in Figure 4

Layer	Thickness (m)	Unit Weight (kN/m^3)	Shear Wave Velocity (m/s)
1	8	20	600
2	30	20	650
3	10	20	700
Bedrock	-	21	1900

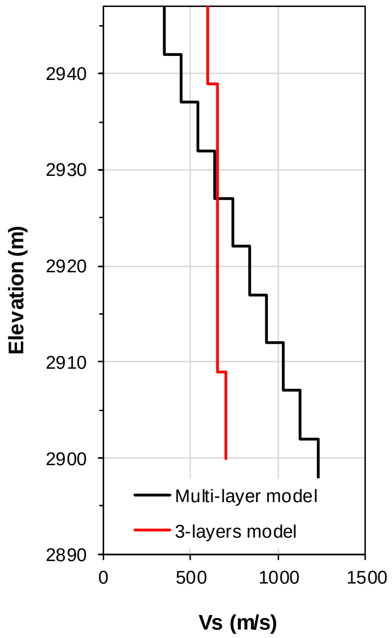
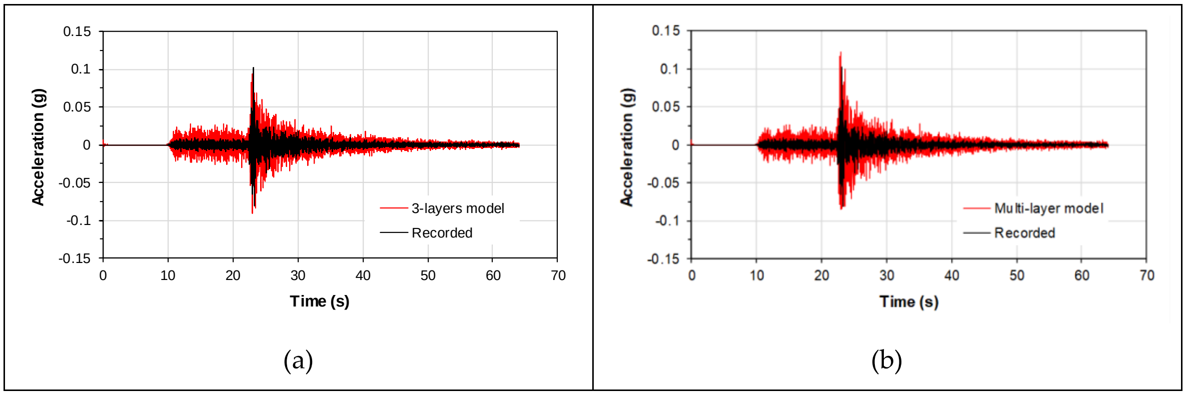


Figure 4 Shear wave velocity profiles of the embankment wall

The comparison between the actual earthquake record and the acceleration time histories obtained with DeepSoil for the Vs models presented in Figure 4 are shown in Figure 5. Both Vs models respond similar in terms of peak ground acceleration (0.09g for the three-layer model and 0.12g for the multi-layer model); however, the overall amplitudes of the predicted signals are larger than the recorded one.



(a)

(b)

Figure 5 Comparison between equivalent linear method results at the surface of the Vs models in Figure 4 and recorded motion. (a) 3-layers model and (b) multi-layer model. registered

To validate the shear wave velocity models, their theoretical transfer functions were calculated with the Deepsoil software (Figure 6). The fundamental frequency of the three-layers profile is 4.2 Hz and the fundamental frequency of the multi-layer profile is 4.2 Hz, values similar than that obtained from the HVSR method and the empirical transfer functions.

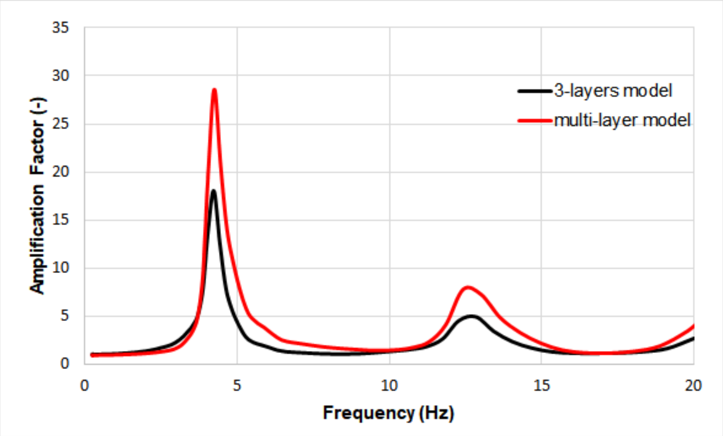


Figure 6 Theoretical transfer function of the three-layer Vs model in Figure 4

CONCLUSIONS

The horizontal to vertical spectral ratio method and the empirical transfer functions calculated from earthquake records predict a predominant vibration frequency of 4 Hz, which is a value consistent with the high stiffness of the compacted earth fill dam.

The analysis with the equivalent linear method shows that the peak ground acceleration and the predominant vibration frequency can be explained with a simple three-layer model. This result suggests that the seismic response of the embankment wall can be relatively well approximated by a one-dimensional model when subjected to low magnitude earthquakes. The methodology followed in this study seems to be valid to estimating the dynamic properties of a tailings dam embankment and to improve the understanding of its seismic behaviour.

NOMENCLATURE

HVSR	H/V spectral ratio
HHSR	H/H spectral ratio
T_0	predominant vibrating period
Vs	shear wave velocity

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