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Dynamic Characterization of a Tailings Dam Embankment Using a Dense Seismic Array: Preliminary Results

César Pastén[1,3], Diana Comte[2,3], Gerardo Peña[3], José Burgos, and Andreas Rietbrock[4]

1. *Department of Civil Engineering, Universidad de Chile*
2. *Department of Geophysics, Universidad de Chile*
3. *Advanced Mining Technology Center, Universidad de Chile*
4. *Anglo American, Chile*
5. *Karlsruhe Institute of Technology, Germany*

ABSTRACT

The dynamic characteristics of a tailings dam embankment are relevant for estimating the dynamic performance of the tailings deposit during large earthquakes. This paper reports the deployment of a dense seismic array installed over the 80m height cycloned-sand embankment dam of a tailings deposit located in Central Chile. The network consisted of 28 short-period seismic stations with triaxial 4.5Hz geophones that continuously recorded ambient seismic noise and earthquakes during four weeks. The seismic stations were deployed along the embankment crest, the downstream slope, and the foundation soil. Single-station records were processed using the H/V spectral ratio method to estimate the embankment dam predominant vibration frequency using both ambient seismic noise and earthquake records. The results from the H/V spectral ratios from both types of signals are consistent and show that the foundation soil is stiffer than the embankment dam, that the predominant vibration frequency of the embankment is about 1 Hz, and there are differences in the vibration frequency along a cross section of the downstream slope. Finally, the results of the H/V spectral ratios are compared with standard spectral ratios calculated between the crest and the foundation of the embankment wall using the available earthquake records. Both methods are consistent in terms of the predominant vibration frequency and amplification factors.

INTRODUCTION

Earthquakes are among the most common triggers of tailings dam failures (WISE Uranium Project, 2019). Villavicencio et al. (2014) reported that 31 out of 38 incidents in Chilean sand tailings dams were related to earthquake loading. The seismic response of a tailings dam depends upon the geometry and the stiffness of the materials that compose the embankment wall, as well as the input ground motion, among other factors. The stiffness of the materials can be estimated through the shear wave velocity, a parameter that can be measured in-situ with invasive and non-invasive geophysical techniques. Another dynamic parameter that combines the geometry of the deposit and its stiffness is the predominant vibration frequency that represents the natural vibration frequency of the earth structure (Verdugo et al., 2017). If an earthquake induces a ground motion with high energy content around the predominant vibration frequency, the embankment wall may resonate, increase its dynamic displacements, and eventually produce damage, which may compromise the physical stability of the entire tailings deposit.

In earthquake engineering, the most common method to determine the amplification function of a soil deposit is the standard spectral ratio (SSR) method, computed as the spectral ratio between the response at the site of interest with respect to the response of a reference point (Steidl et al., 1996). The reference point can be either the base of the deposit where the input motion is applied or a reference station that ideally is installed on a site not affected by the local soil conditions, either on stiff soil or hard rock. The predominant vibration frequency is estimated from the amplification function as the lower frequency where the amplification function peaks.

Another method to estimate the amplification function is the single station horizontal-to-vertical H/V spectral ratio (HVSR), also known as the Nakamura's method (Molnar et al., 2018). This method was originally developed with continuous records of ambient seismic noise, usually more than 30 mins long. However, it has been proved in soils deposits that the HVSR curves from ambient seismic noise and earthquake records yield similar results, hinting that the HVSR is a relatively constant site characteristic (Fernandez et al., 2019).

Since tailings dams build with cycloned sand in Chile have embankment walls with very gentle downstream slopes (H:V varying from 3:1 to 4:1), the use of the HVSR method could be a simple method to estimate its dynamic properties. The use of the method has been tested and validated in natural sloped terrains (Diaz-Segura, 2016).

In this paper, we show the main features of a seismic array deployed in a tailings deposit in Central Chile and the preliminary results of the single-station and standard spectral ratios that allow determining the dynamic properties of the embankment wall.

SEISMIC ARRAY

The embankment wall of the studied tailings deposit is constructed with cycloned sand using a center line method. The current height of the embankment wall is about 80 m with a downstream slope of H:V = 1:3.5 (Figure 1).

The seismic array consisted of 28 stations, each one equipped with a short period 3-component 4.5 Hz geophone, an Omnirecs DataCube3 Ext datalogger recording at 200 samples per second, a GPS antenna for time synchronization, and a sealed gel deep cycle battery. The stations recorded continuously for about one month (from August 29, 2018 to September 26, 2018). Figure 1 shows the location of the 28 seismic stations deployed in the tailings deposit. Eleven stations were installed in the crest of the embankment wall, 6 installed in the downstream slope, and 11 installed at the downstream slope toe. The last group of stations were deployed at an average distance of 5 m apart from the embankment wall due to restrictions imposed by underground infrastructure. The stations were buried in a sealed plastic container and the GPS antenna was raised 50 cm to the surface.

Figure 2 shows an example of the daily continuous record at the station T08 in the north-south (NS) component. The amplitude of the velocity time history (Figure 2a) increases during the operation time of the day, between 9am and 6pm. Figure 2b shows a normalized spectrogram with the frequency content of the time history signal. The frequency content remains relatively constant before the operation work starts at the tailings dam. However, the frequency content changes considerably between 2 and 15 Hz during the operation period.

During the time that the seismic array was under operation, at least 11 earthquakes of different magnitude were recorded by the seismic stations. The earthquakes moment magnitudes range from 3.9 to 5.8 and the epicentral distances vary from 10 to 410 km.

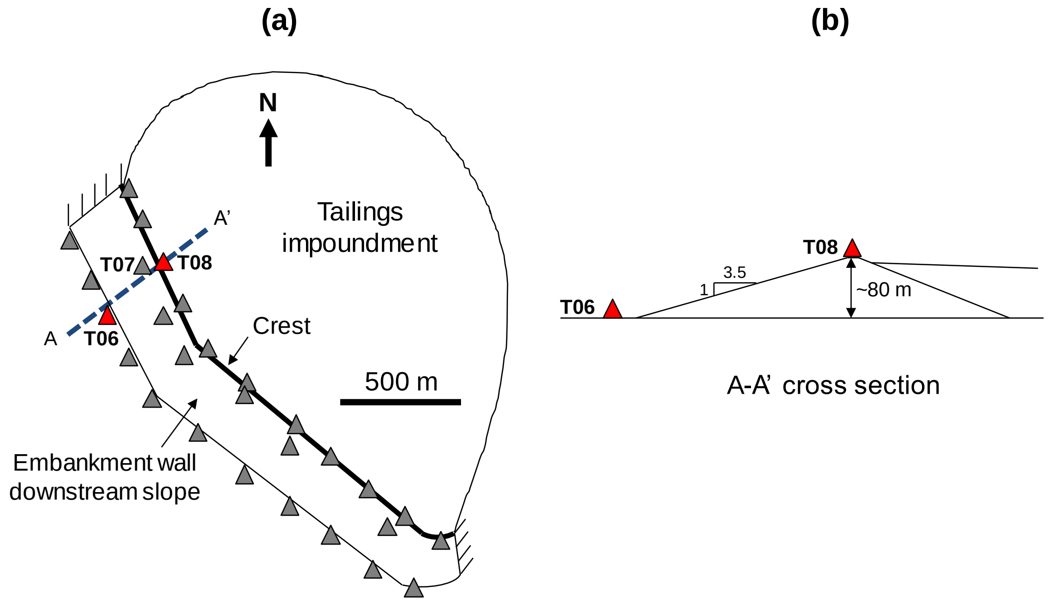

Figure 1 Seismic array deployed at the tailings deposit in Central Chile. (a) Schematic plan view of the deposit and (b) cross section of the embankment wall. Triangles represent the location of the seismic stations

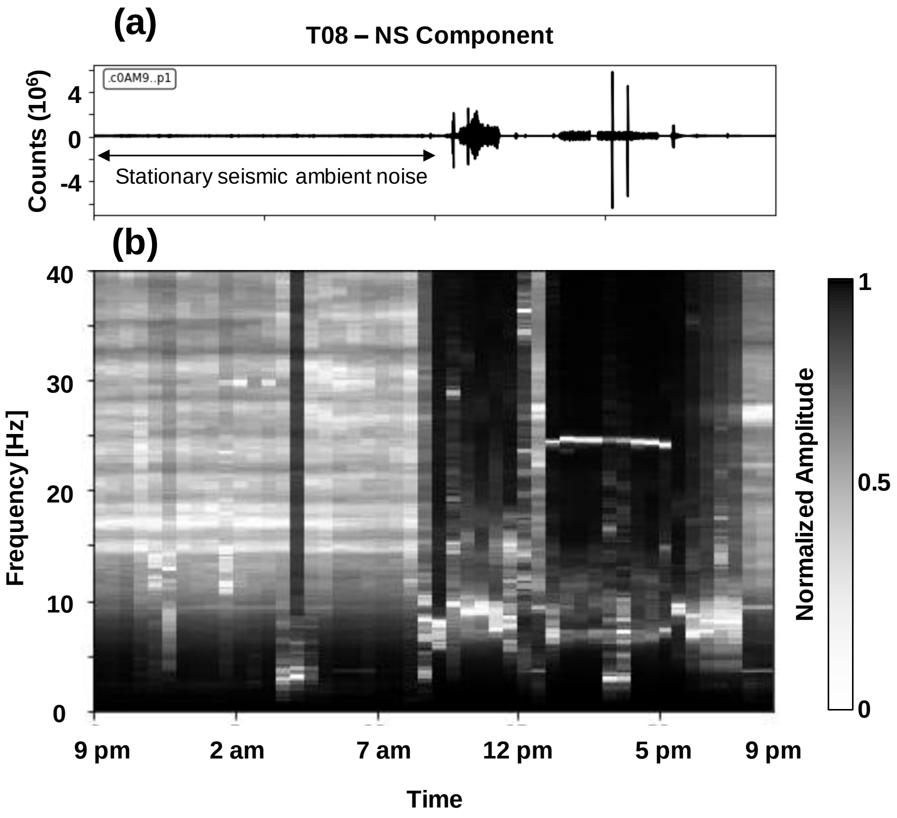

Figure 2 Example of a continuous daily record at station T08 in the north south component (September 14, 2018). (a) Velocity time history and (b) normalized spectrogram (lighter tones represent larger amplitudes)

DATA PROCESSING AND RESULTS

We processed separately data from ambient seismic noise and earthquake records. First, horizontal-to-vertical spectral ratios HVSR were calculated using the 12 hrs of stationary ambient seismic noise recorded from 9pm to 9am, before the operation starts (Figure 2a). We followed the methodology described in Pastén et al. (2016), using 30 s windows automatically selected from the amplitude STA/LTA ratio between 0.5 and 2, with a short time period $t_{STA} = 1$ s, and a long time period $t_{LTA} = 60$ s. The horizontal component was calculated as the squared average of north-south and east- west components. The calculations were performed using the open-source software Geopsy (www.geopsy.org).

Figure 3 shows the HVSR calculated as the ratio between the combined horizontal component and the vertical one of 3 stations located at the crest (T08 in Figure 1), at the downstream slope (T07 in

Figure 1) and at the embankment toe (T06 in Figure 1) in the cross section A-A′ (Figure 1a). The HVSR curves indicate a predominant vibration period associated to the peak spectral ratio amplitude. The station T08 has a predominant frequency of about 1.0 Hz whereas station T06 has it at 1.7 Hz. It seems that the HVSR at the station T07 is a combination of the curves at the crest and toe of the embankment wall.

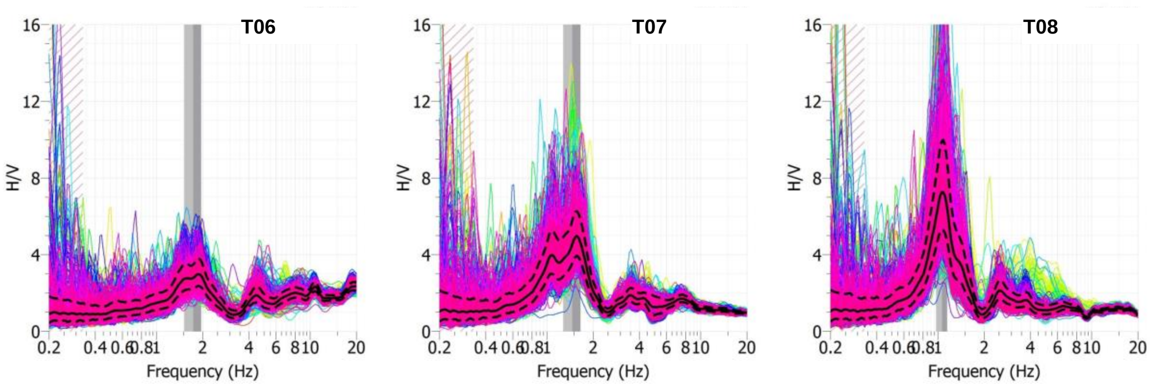

Figure 3 Examples of HVSR calculated from ambient seismic noise at stations T06, T07, and T08 installed on the cross section A-A′ in Figure 1. The thick black curve is the mean of the curves in color

The eleven earthquakes recorded by the seismic array were used in each station to calculate HVSR. First, the amplitude Fourier spectra from the velocity records are calculated in each component and smoothed with a running average window. Then, the north-south and the east-west components are divided by the vertical one. Figure 4 shows examples of HVSR in stations T08 and T06. The average curves are similar to the average HVSR computed from seismic ambient noise. Interestingly, the predominant frequencies using ambient seismic noise and earthquake records agree at 1.0 Hz in station T08 and 1.7 Hz in station T06.

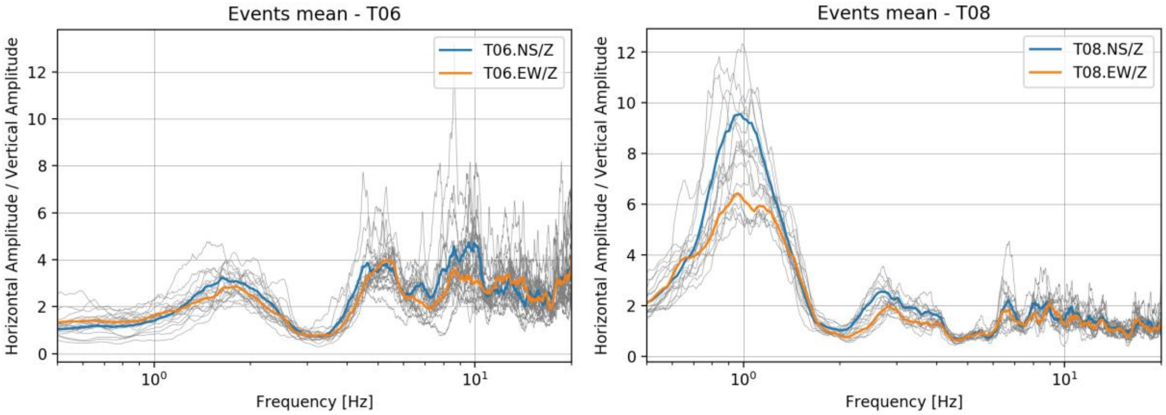

Figure 4 Examples of HVSR calculated from earthquake records at stations T06 and T08 installed on the cross section A-A′ in Figure 1

Standard spectral ratios SSR were calculated from earthquake records in the station at the crest (T08) with respect to the station at the downstream toe (T06). Figure 5 shows an example of the SSR of one of the earthquakes (2018-09-07, Mw 5.8), considering separately the ratio between the horizontal (NS and EW) and vertical (Z) components.

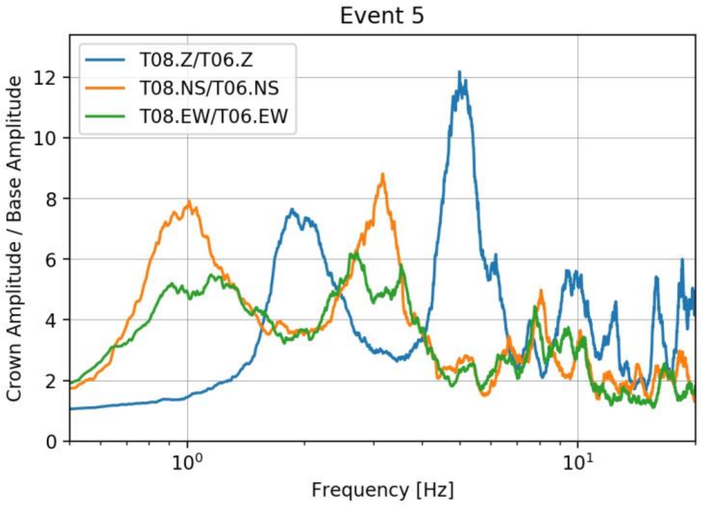

Figure 5 SSR calculated between stations T08 at the crest of the embankment wall and T06 at the toe

DISCUSSION

The predominant vibration frequency changes with the thickness of the embankment wall where the stations are located. For instance, at station T08 on the crest of the wall where the underlying cycloned sand is thicker, near 80m, the predominant vibration frequency is lower than the predominant frequency at the downstream toe where the station T06 is installed directly on the foundation soil. In addition, the amplitude of the HVSR increases with the thickness of the underlying cycloned sand layer. The HVSR of station T08 nearly doubles the amplitude in station T06.

The predominant frequency of the stations installed in the foundation soil may be affected by the thickness of the foundation sediments in the valley and also by the interaction with the embankment wall. Decoupling these two effects may require further analyses that will be performed during the following stages of this project. Ideally, the stations in the foundation soil should be installed at a distance from the wall that would not influence their response. However, there is not clear rule of thumb for such distance in this type of earth structures.

The HVSR calculated from earthquake records retains most of the features of the HVSR calculated from ambient seismic noise. In particular, the predominant vibration frequency and the peak amplitude are almost identical in both cases. This result suggests that the predominant vibration period can be recovered in tailings dams from earthquake recorded by accelerometers, which is the type of sensor most commonly used in this type of structures (Campaña et al., 2016).

The SSR in the horizontal components shows that the largest amplification between the two stations occurs at about 1 Hz and 3 Hz, the fundamental and first harmonic horizontal vibration mode of the earth structure. The fundamental frequency is similar to the value obtained from HVSR calculated from both earthquake records and ambient seismic noise. Note that the ratio between these two vibration frequencies is 1:3, similar to the prediction of the one-dimensional shear wave propagation theory. The SSR in the vertical component peaks at higher frequencies (2 and 5 Hz) which can be explained since the vertical component strongly depends on the P-wave velocity of the earth structure.

CONCLUSIONS AND FINAL COMMENTS

The results from the H/V spectral ratios from ambient seismic noise and earthquake records are consistent and show that the foundation soil is stiffer than the embankment dam, the predominant vibration frequency of the embankment is about 1 Hz, and there are differences in the vibration period along a cross section of the downstream slope.

The results of the H/V spectral ratios were compared with standard spectral ratios calculated between the crest and the foundation of the embankment wall using the available earthquake records. Both methods are consistent in terms of the predominant vibration frequency and amplification factors.

The predominant vibration frequency is a parameter that can be used to calibrate numerical models that are often developed to determine the seismic response of tailings dams when subjected to large earthquakes.

In the future, the results from this passive experiment can be combined using ambient seismic noise tomography tools to obtain a 3D shear wave velocity map of the embankment dam, which can be contrasted and complemented with traditional geotechnical data, such as pore water pressure and deformation measurements, to improve the understanding of the dynamic performance of tailings deposits.

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NOMENCLATURE

HVSR	H/V spectral ratio

SSR	standard spectral ratio

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