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Improved Site Characterization for Improved Seismic Analysis of Rock Slopes.

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Abstract

For a proper risk assessment it is necessary to consider all parameters and variables that play an important role in a particular phenomenon. For the case of co-seismic rock slides, we believe that current methodologies for stability analysis do not accomplish that goal, given the lack of information in their models, which leads to uncertainties in risk analysis. It has been evidenced that site effects may have an important role on potentially unstable slopes [1, 2, 3, 4] and that also depth changes of shear wave velocity, and three-dimensional effects of this same parameter generate significant effects on seismic amplification on slopes [5]. Using ambient vibration records this work combines different techniques in order to characterize a sandstone landslide occurred on the Maule earthquake, Chile, 2010. Passive seismic tomography based on noise cross-correlations is used to map lateral and vertical changes in the shear wave velocity of the surficial soil layers. Horizontal-to-Vertical spectral ratios, are used to estimate the predominant Eigen frequency of the system and of the upper layers of the slope. The used methodologies proved to be a reliable source of information, retrieving inner heterogeneities and dynamic properties which improves characterization, and have probably a significant influence on the dynamic response and stability.

Keywords: Rock Slope Stability, shear-wave velocity structure

1. Introduction

Co-seismic landslides are a significant source of loss of life and structural damage. This is especially the case in areas in which rockslides are the most abundant; about 60% of events, and 95% of fatalities are caused by disrupted landslides [6]. A better comprehension of the factors and mechanisms that lead to failure is now a priority for geotechnical earthquake engineering, which attempts to reduce risk in areas threatened by these phenomena. Currently, a key tool for stability analysis of rock slopes, and complex failure mechanisms, is numerical modelling based on discrete elements [7, 8]. However, one of the main problems of this modelling lies in the limited available information regarding joints properties, such as stiffness, which cannot be obtained from laboratory tests, and this assumption can lead to miscalculations. In addition, several authors have reported evidence that co-seismic landslides can be significantly influenced by surface motion amplification related to topography [4, 9] and/or with subsoil physical characteristics [10]. More specifically, it has been found that 1D, 2D, and 3D variations in shear-wave velocity greatly influence amplification on slopes [5], possibly even more significantly than topographic effects [11]. Considering all this, there is a need to incorporate additional information into models, which will help to better represent and calibrate the global behavior of a rocky hillslope, incorporating variations in stiffness of the material within it, so as to represent and quantify the relevance of phenomena such as site effects, and directivity. In this work, a characterization is performed for a sandstone landslide, located in the southern zone of the Arauco Gulf in central Chile, which occurred during the 2010 Mw 8.8 Maule earthquake. Using triaxial seismometers, a series of small arrays were deployed along the edge of the rock hillslope, and between each pair of stations within the array, cross-correlation was performed in order to obtain phase-velocity dispersion curves [12, 13], which are then inverted following the methodology proposed by Pilz et al, 2012 [14], validated for hillslopes [15] having as final product a three-dimensional image of the shear-wave velocity structure along the hillslope. Additionally, broad band seismometers were deployed at the top and bottom of the slope in order to estimate the Eigen frequency of the structure, and the small arrays also provided the Eigen frequency for the upper layers in each zone of the hillslope. This improved characterization of the slope, used in conjunction with lab testing and numerical modelling, is aimed to generate a robust back analysis of the failure, which in turn will shed light into improved seismic analysis methodologies.

2. Study area

The Arauco Peninsula is part the Coastal Plain of the eighth region in south central Chile (~37.25°S), is mostly composed by sedimentary rocks of very young ages in geological scale. The main sedimentary units are Trihueco (Eocene), Millongue (Eocene), Ranquil (Miocene), and Tubul (Pliocene) formations, and recent alluvial and coastal deposits. The Tubul formation, which contains the studied hillslope, corresponds to a sub-horizontal sedimentary succession, is constituted at its base by very fine sandstones, with some calcareous content and very fossiliferous. On it, is disposed a succession of massive, very fine, silty sandstones with few shallow marine fossils, and leaves impressions. The hillslope, represented by the last mentioned characteristics, has a maximum height of approximately 90 meters, having a baseline length of about 360 meters, facing a coastal deposit as shown in Figure 1. Its location, referring to the Maule earthquake, is 160 kilometers from the epicenter with a 220° azimuth, being within the estimated rupture area, and close to one of the three major co-

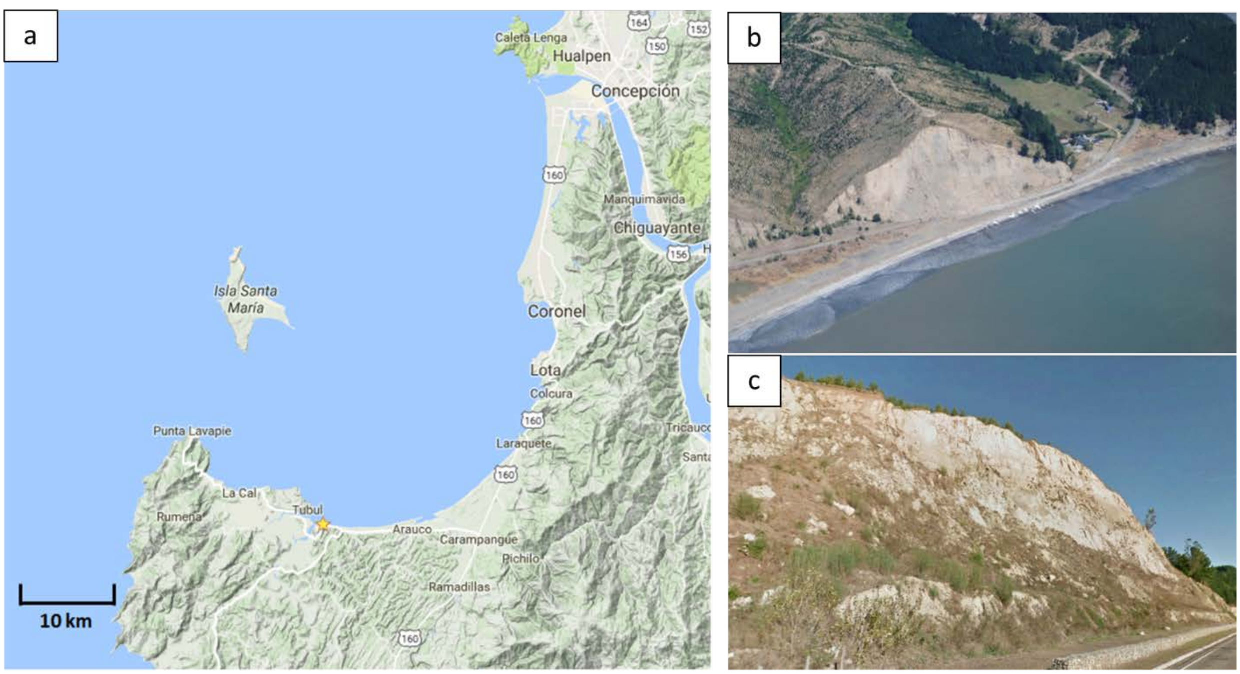


Figure 1. (a) Location of the studied co-seismic landslide within the Arauco Peninsula. (b) Aerial photograph of the landslide, 10 days after the main event. (c) Recent photograph of the hillslope in which the co-seismic landslide occurred.

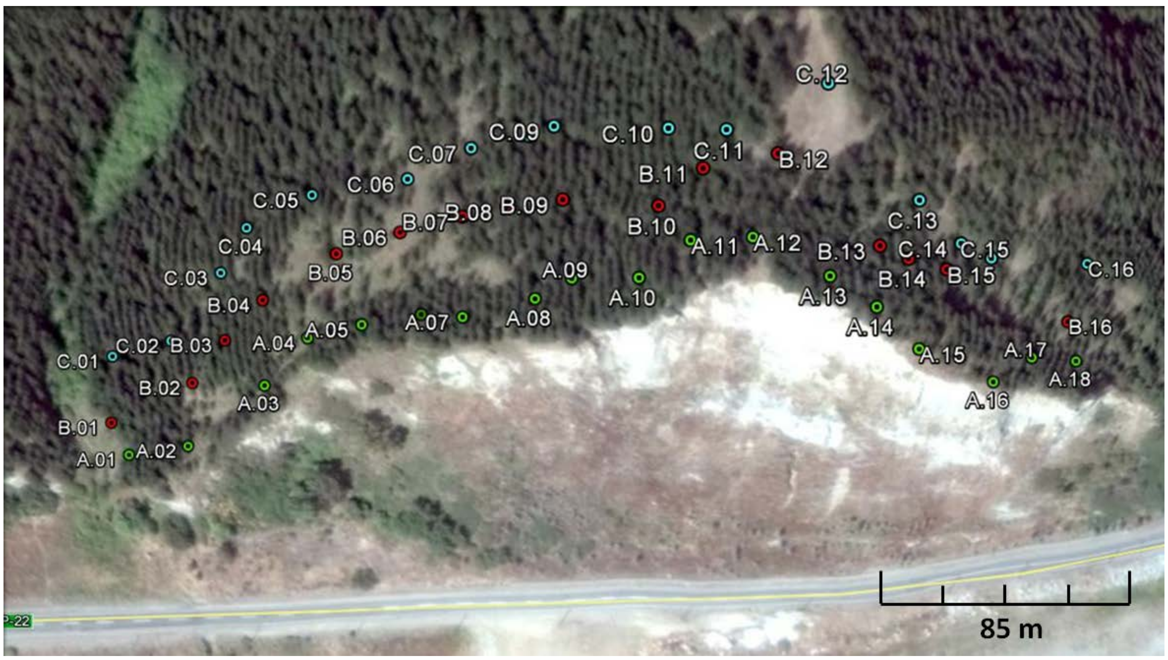
seismic slip zones [16].

South-central Chile was considered before the 2010 earthquake a very likely mature gap, specifically the Concepción – Constitución area (35-37°S), which last well-documented megathrust events occurred in 1730, 1751, 1835 and 1928 [17]. Even though the great earthquake of 1960 (Mw 9.5) corresponds to another segment of the subduction boundary, it must obviously has to be taking into account as a relevant event for the landslide area, which is consider by many authors as the northern limit of the rupture area of that event [18]. Considering also the 2010 Maule earthquake (Mw 8.8), the area has been affected for 6 great events in the last 300 years, which means that on average, a megathrust earthquake is expected to affect the landslide area once every 50 years.

3. Field experiments

In order to characterize the hillslope, three different type of measurements were made in field. First, a combination of SPAC (Spatial AutoCorrelation) and MASW (Multichannel Analysis of Surface Waves) were performed at the base using 4 triaxial seismometers of 4.5 Hz Eigen frequency, using a triangular and linear array respectively. The purpose of the base measurement is to obtain a 1D shear wave velocity profile in order to be able to create a synthetic record of the Maule earthquake at the site. Secondly, to obtain a three-dimensional shear wave velocity tomography, a series of consecutive small aperture arrays were deployed along the edge of the slope using 5 synchronized seismometers with inter-station distances from 20 to 50 meters approximately (Figure 2). In total, 17 synchronized measurements of ambient vibrations were made along the slope between November 14 and November 25, 2015. The length of each measurement was around 2 hours, using a sampling frequency of 128 Hz. Finally, two broadband seismometers, with an Eigen period of 120 seconds, were installed at the top and bottom of the hillslope in order to obtain the natural frequency of the structure. The recording time of this last measurement was around two and a half hours using a sampling frequency of 100 Hz.

Figure 2. Total locations of the instruments on the hillslope for Vs tomography purpose



4. Methodology

4.1. Spectral Ratio H/V

Initially proposed by Nigoshi & Igarashi (1970) and later popularized by Nakamura (1989), it consists in estimating the ratio between the horizontal and vertical Fourier spectrums of an ambient vibration record. The most extensive use of this technique, and purpose under which it was developed, is the analysis of site effects since it implies representing the transfer function of soil deposits on the surface. This method allows the estimation of the predominant frequency of a site, which has been correlated by several authors with the first peak of the spectral ratio [19]. To identify the Eigen frequency at each station, the data was processed fulfilling the reliability criteria for the curves and peak proposed by the SESAME project [20] and related literature [21, 22]. It's worth mentioning that although much of the theory is based on a wavefield composed mostly of Rayleigh waves, it has been shown that the method provides useful results whether the record consists of body or surface waves [23]. Although this methodology was conceived for the analysis of flat stratigraphy sedimentary basins, its use has become extensive for complex topographic conditions with good results. Most of the last studies have focused on directivity analysis of potentially unstable hillslopes or co-seismic landslide [1, 2, 5, 13, 21, 22, 24, 25]. Additionally, Méric *et al*, 2007 [3] estimate, based on the theoretical equation that calculates the Eigen period of a sedimentary basin ($fo = V_S/4H$), the depth to the bedrock for different zones in two landslides having acceptable results in both cases.

4.2. Phase velocity

In order to capture subsurface heterogeneities, which are expected in an environment like a slope, traditional methodologies, such as SPAC, are not enough given that provide average results within the used array. It has been shown recently that is possible to substitute the azimuthal average of the auto-correlation curve obtained by SPAC, for the auto-correlation curve, processed either in time or frequency domain, from a single pair of stations [12]. Thus the use of cross-correlation, and if we speak in frequency domain, of cross-spectrum, becomes attractive to assess subsoil variations between each pair of stations, however, given that the real part of the cross-spectrum depends both on the background noise and processing non-lineal effects, is not possible to obtain information with total reliability from the entire cross-spectrum. Nevertheless, the zero-crossings of the cross-spectrum are in theory insensitive to variations in the power spectrum of the background noise and are hence a reliable source of information to estimate phase velocity values. Following Ekström *et al*, 2009 [13], and given that the normalized cross-spectrum must follow in theory, according Aki, 1957, the first kind and zero-order Bessel function (Jo) as follow,

$$\rho\,(r, f\,) = Re\left[\frac{S_{oj}(r,\theta,f)}{\sqrt{S_o(f) * S_j(r,\theta f)}}\right] = J_o\left(\frac{2\pi f}{c(f)}r\right) \tag{1}$$

where ρ is the auto-correlation curve between both stations, S_{oj} the cross-spectrum, S_o and S_j the power spectrum of each signal, r the inter-station distance, f the frequency and $c(f)$ is phase velocity, which can be obtained discretely as,

$$c(f_n) = \frac{2\pi f_n}{Z_n} * r \tag{2}$$

where f_n correspond to the nth zero-crossing of the cross-spectrum and Z_n is the nth argument of Jo. It's worth mentioning that prior to the mentioned processing, and to obtain the dispersive properties, is necessary to correct and prepare the signals which has the primary function of attempting to enforce the assumption of isotropic wave-field (Aki, 1957), where some kind of normalization is required for each signal. For the initial process of correcting the signal, it was taken as reference the work of Akkar and Bommer, 2006 [26], to remove the mean and trend from the signal. Afterwards, a Butterworth high-pass filter was applied to the signal using a corner frequency of 0.9 Hz, which improves the SNR for higher frequencies and also the cross-correlations [27]. On the other hand, regarding the normalization process, a combined time-frequency normalization (TFN) was preferred [13], rather than a separated process in time and after in frequency domain. For the process a series of 0.5 Hz band-pass filters were applied to the signal, normalizing each signal with their envelope and combining them afterwards. When low frequency information on the phase velocity dispersion curve could not be retrieved from the zero-crossings, a non-lineal iterative inverse process based on the least squares criterion was performed [12, 28] from the lower frequency to the first zero-crossing, always taking into account the Henstridge (1979) limits in which results can be considered valid.

One aspect to consider is that topographic effects may impact the vertical component of ground motion by the refraction of incoming SV waves due to the free face of the slope [29], generating amplification and/or de-amplification on different locations at the top. Given the complexity of the phenomena and the lack of knowledge about the noise sources, it is not possible to confront this situation from an analytical perspective, nevertheless, we believe this does not affect significantly the correlation coefficients (and hence the Vs structure), given that these are normalized either by the product of the norms from each record in time domain, or the product of the power spectrums in frequency domain, which means that the energy contrast of two stations do not play an important role regarding the phase velocity estimations.

4.3. Three-Dimensional surface wave tomography

Typically two or three-dimensional inversion procedures are composed by two steps, the first one to obtain several 1D shear wave velocity profiles, and the second to create a 2D or 3D image. As previously mentioned this work follows the procedure proposed by Pilz *et al*, 2012 [14], which is a single step inversion procedure to create a three-dimensional shear wave velocity image, and was proven to work on complex conditions like hillslopes [15]. It is an iterative procedure, which like every iterative method, is based on a linearization of the inversion problem. The main issue about this kind of simplification, is that requires an initial model which normally influence the final solution. To overcome this situation and achieve a reliable solution independent from the initial model, the methodology includes parameters and weights that constrain the solution taking into account the damping coefficient, different penetration depths of individual frequencies and the slope topography, among others.

5. Results

5.1. Geophysical methods

Horizontal-to-Vertical Spectral Ratio (HVSR)

Using the data obtained from the broadband instruments the Eigen frequency of the structure was estimated normalizing the top HVSR by the calculated at the bottom of the slope (Figure 3), both on the slope direction. The peak frequency of the structure was found to be on average 0.117 Hz, which is considerably low, but low values where expected according to a prior numerical model of the slope, slope dimensions and rock quality.

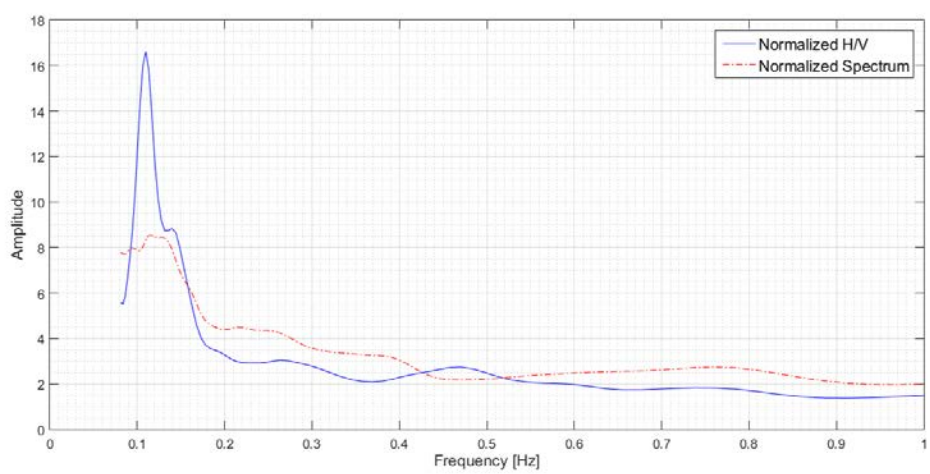


Figure 3. Mean normalized HVSR curve (top/bottom) of the slope. Peak frequency of 0.129 Hz.

Alternatively, the spectrum at the top in the same direction was normalized by the one at the bottom (i.e. horizontal to horizontal spectral ratio, HHSR), finding a peak at 0.110 Hz, which represents the Eigen frequency of the system. On the other hand, regarding the peak frequencies (fo) of the subsurface layers by HVSR, it was found that the curves in the entire frequency range [1 – 10 Hz] were, as expected for a stiff material, flat with maximum values that do not exceed the value of 3. Even though it is not possible to clearly define unique peaks in spectral ratios according to SESAME project [20] criteria, and in consequence identify peak frequencies, it is possible to see some local peaks and trends in the HVSR curves for different zones (Figure 4), which we interpret to correspond to the Eigen frequency of specific areas or points. Differences between the zones highlights the idea of a highly heterogeneous structure, as expected in a hillslope. On the other hand, given that the HV spectral ratios between different directions do not exceed 2, there is no evidence of strong directivity effects, however there is presence of orthogonality [22]. We cannot establish directivity effects on the slope in its current condition, and neither some potential unstable zones, the evidence confirms the fact that the medium is highly heterogeneous.

Figure 4. Arbitrary zones to illustrate HVSR local differences, in each of them fo is estimated from the average of the highest peaks in HVSR within the zone. Respectively, fo(A)=2.05 ±0.05[Hz], fo(B)=3.16 ±0.09 [Hz], fo(C)=2.71 ±0.34 [Hz], fo(D)=4.45 ±0.63 [Hz].

Shear wave velocity structure:

Given the relatively short inter-station distance, the first zero-crossings of the cross-spectrum normally did not occurred at frequencies where the bedrock was represented, as a cause of the short wavelengths characterized. Typically, the values of the first zero crossing were approximately between 9 Hz, for closest instruments, and 4 Hz for the farthest pairs. In most cases the phase velocity dispersion curve (PVDC) was obtained combining the non-linear inversion, between the Henstridge limits, and the zero-crossings (Figure 5). The chosen parameters for the non-linear inversion are those where σ^2 is 300 (m/s), and Δ = 0.4 [12]. On the other hand, the zero-crossings proved to be a reliable source of information, which was compared with active source experiments performed in others sites, showing that both methods produce comparable results. In general, no corrections were needed as a cause of extra or missed zero-crossings [13], we believe this mostly to be consequence of the TFN (time frequency normalization) which fulfilled the isotropic assumption and improves the signal especially in the higher frequency range, where the zero-crossings are found. Both methods show good agreement and provide reliable information in their respective frequency ranges, even when overlapping (Figure 5).

The retrieved heterogeneities from the HVSR can also be retrieved from the phase velocity dispersion curves, for which, especially in high frequencies show significant variations among them. This difference is clearer when the station pairs analyzed are further apart on the top of the slope. This implies that shear wave velocity structure is strongly variable, both lateral and in depth for the weathered rock closest to the surface (Figure 6). The thickness of the weathered rock varies along the slope, where general trends can be found at each side of the hillslope. Also, at each side of the slope local variations are found between station pairs within each zone.

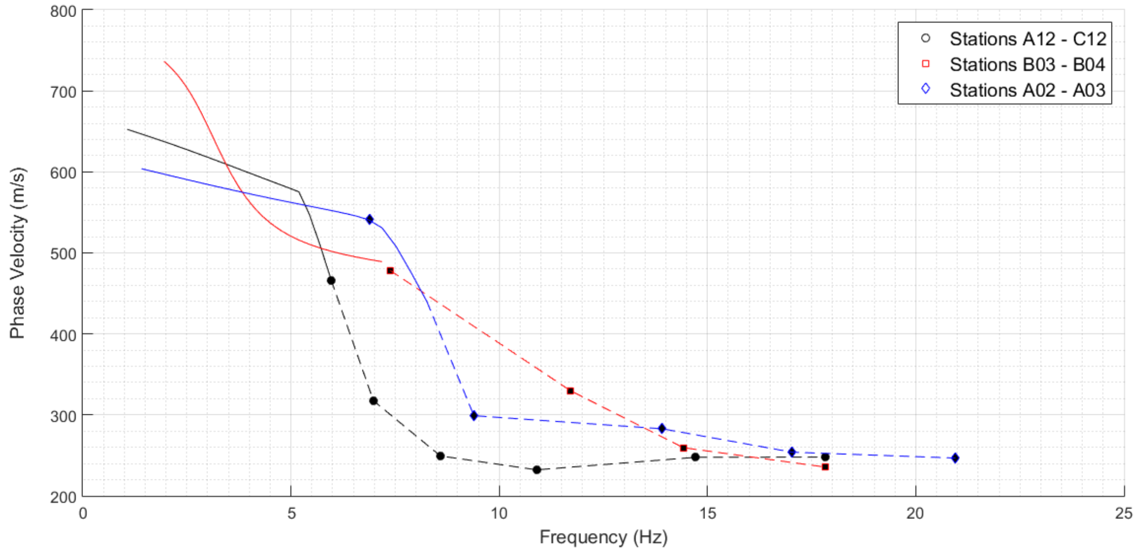


Figure 5. Dispersion curves obtained in different zones of the hillslope. For low frequencies the information is obtained from non-lineal inversion, meanwhile for higher frequencies, from zero-crossing of the cross-spectrum.

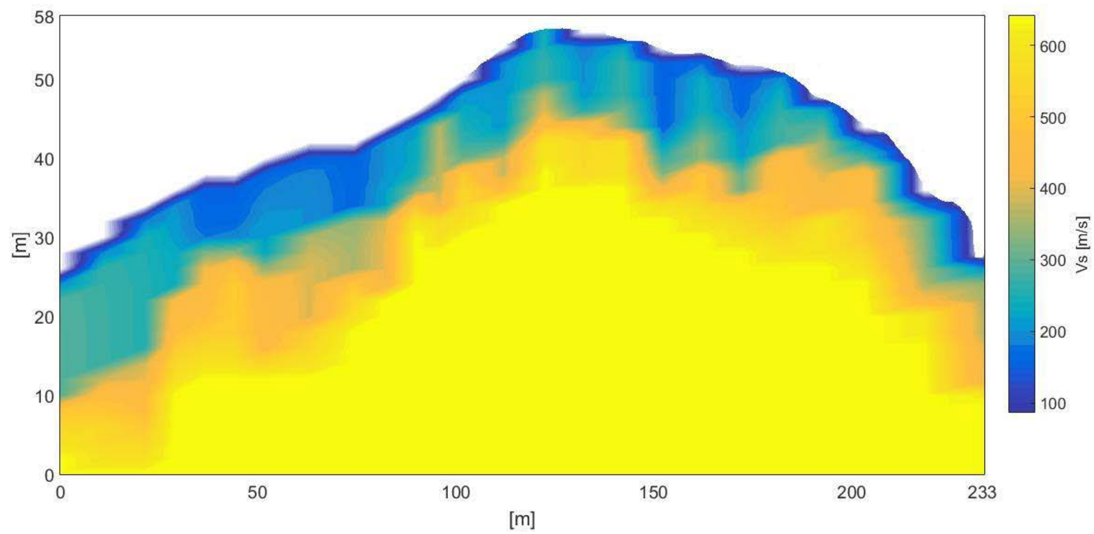


Figure 6. Longitudinal cross-section of shear wave velocity structure from the central part of the slope obtained using only the stations closest to the edge.

6. Conclusions

Traditional geophysical methods have proven to be a reliable source of information for site characterization, unfortunately regarding shear-wave velocity, they often provide an average result within the array, a situation that may have strong impact on forward analyses when the medium is highly variable, as in this case. In this matter, the use of cross-correlation between a single pair of stations has become a reliable solution for multiple conditions and dimensions. Particularly for natural hillslopes, there are not many experiences using this recent methodologies, where we believe heterogeneities must be characterized and included in the analysis to appropriately assess seismic risk.

Results show that these techniques work on a complex environment, and they complement each other, providing reliable information about the subsurface structure, not only regarding shear wave velocity, but also Eigen frequencies for the upper weathered rock. Regarding the Eigen frequency for the entire slope (90 m high) it is found that the HVSR at the top of the slope is a reliable estimate of the fundamental vibration mode of the slope by comparing it with the spectral ratio between the vibration at the top and at the bottom of the slope. This should allow a better dynamic response characterization in forward analyses, by matching global behavior retrieved from the Eigen frequencies of the system, information that should be taken into account for stability analyses. For the case shown herein, both geophysical methods showed compatible results, proving the simplicity and robustness of the methodology.

All of these characterization techniques have proven to work, and are a major source of information for which we still do not know its impact on the dynamic response and stability. However, it is safe to assume, especially about inner heterogeneities, that they should affect both ground motion and global stability. Numerical modelling for this case study, considering all different characterization techniques, is the next step to understand co-seismic rock slides phenomenon, work that is currently in progress by the author team.

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8. References

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