Paper:

Estimation of the Dynamic Properties and Seismic Response of a Populated Slope in Lima, Peru

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During the last fifty years, the city of Lima has experienced an immigration process that has led to the urbanization of the Andean foothills surrounding the capital. With the aim of analyzing the dynamic response of these new populated places, a target area in a district called Independencia is chosen. Seven microtremor array measurements are carried out at different points on the flat level and along the slope in order to evaluate the variation in the depth of the bedrock. In addition, a seismometer is installed on the slope with the objective of determining if amplification due to topography exists in the area of study.

Keywords: populated slope, topography, Lima, microtremor, seismic amplification

1. Introduction

Peru is located in the central part of the western coast of South America and belongs to the Pacific Ring of Fire, where most of the seismic activity in the world is concentrated. Lima, its capital, is situated in the west-central part of the country with an estimated population of nearly ten million people in the year 2015 [1]. It is well-known that most of the area of Lima is covered by materials from the alluvial fan of the Rimac River, such as boulder gravels, rounded cobbles and dense sands [2]. There are also some rocky outcrops in some specific places due to the proximity of the Andes Mountain Range to the metropolitan area (**Fig. 1a**).

Throughout their history, the inhabitants of Lima have populated the central and coastal parts of the city, but it was in the 1950's that an immigration process from the provinces to the capital started. This process had its peak during the late 1970's, when the unpopulated Andean foothills began to be considered as potential places to live [3]. According to official sources from the Metropolitan Municipality of Lima, around one million people are currently living on these hillsides [4].

Previous investigations [5, 6] have studied the influence of the geology and topography on the seismic response of rocky hills in Chile. In Peru, the dynamic behavior of the so-called populated slopes in the city of Lima has not been studied before. Therefore, the present work attempts to be not only the first approach to its evaluation through the use of existing methodologies but also a reference for future studies, since similar cases could be found in other countries of South America that are also geographically affected by the Andes, such as Colombia, Ecuador and Chile, where the estimation of their vulnerability under strong motions is of particular significance.

To accomplish this objective, a populated slope located in the north part of Lima is chosen as the target area for this study. The estimation of the dynamic properties and the comparison of the seismic records at different points along the slope and in the flat area are presented and discussed in detail.

2. Area of Study

2.1. Location

The district of Independencia is located in the north-central part of Lima (**Fig. 1a**). It is further divided into six zones, being the adjoining area to the National University of Engineering called La Unificada (**Fig. 1b**). In this area, six human settlements are established, and the one named as Villa El Carmen was chosen as the target area for the present study (**Fig. 1c**).

2.2. History

The urbanization process of the target area in this study is inextricably linked to the governmental recognition of the School of Civil Constructions and Mining Engineers as the National University of Engineering in 1955 [7]. Since a new campus was built in the adjacent district of Rimac, the authorities decided to grant the farmlands next to the university to the workers so they may build houses on them. Consequently, 75 workers in total settled in

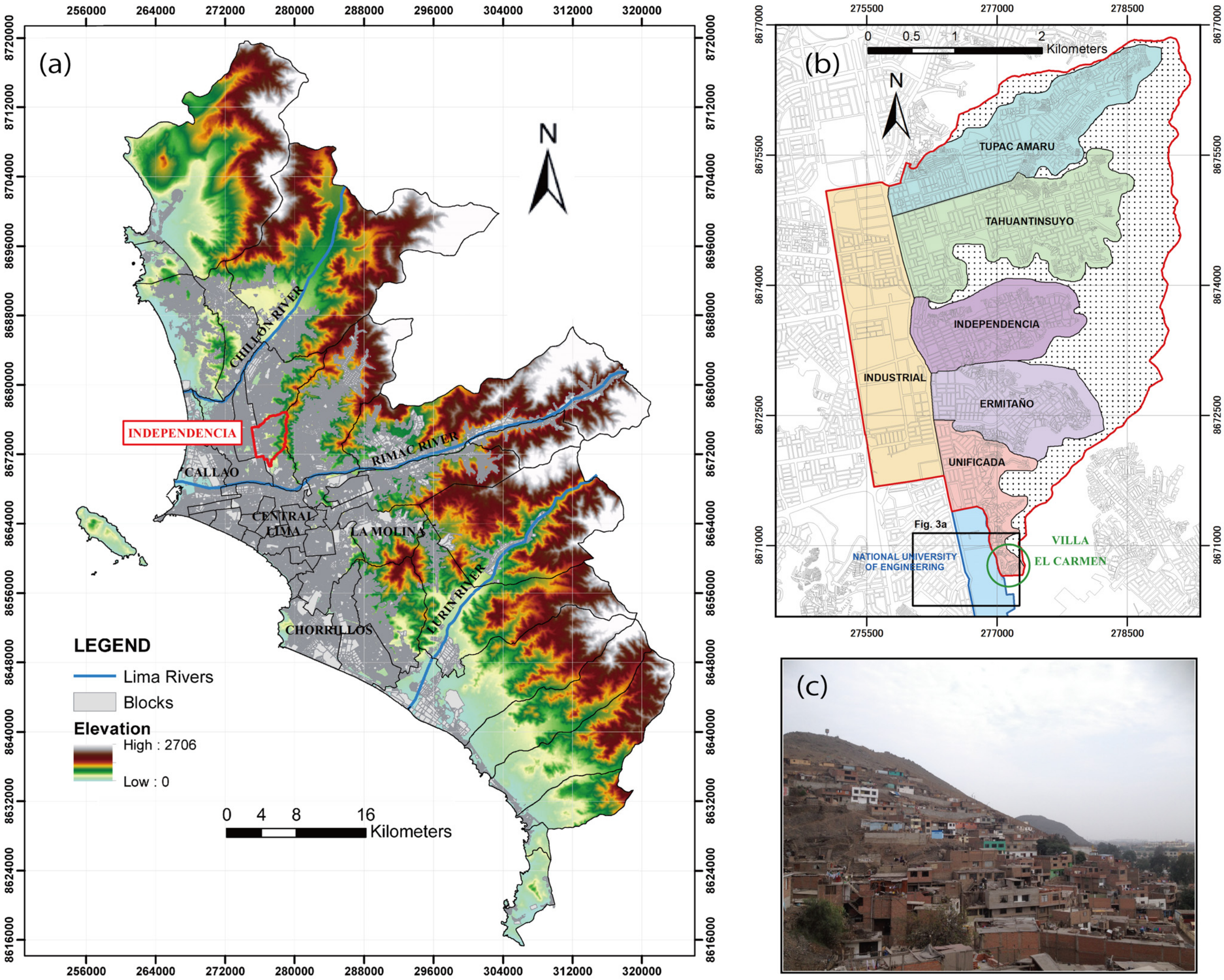

Fig. 1. (a) Elevation map of Lima city. (b) Zones of Independencia district. (c) Panoramic view of Villa El Carmen.

the flat level of the foothills around the university, and these workers became the first inhabitants of Villa El Carmen [8].

Since the late 1950's, Lima has been considered the industrial and commercial center of the country. That has encouraged people from the provinces to migrate to the capital in hopes of finding better conditions to improve their lives. Hence, years later, immigrants from the provinces and a few other districts of Lima encroached not only on the areas corresponding to the valley of Lima but also on desert areas and slopes near the capital, including the foothills of Villa El Carmen, in a complex urbanization process which has led to the establishment of new districts, Independencia being one of them.

Most of these places were populated in the late 1970's, after the last big earthquake that lashed Lima (October 3, 1974, Mw 8.1), so a study which focuses and analyzes the real behavior of these areas is necessary.

2.3. Geological Characteristics

The flat areas of Independencia, like most of the zones of Lima, are built on the alluvial fan formed by the Rimac River during the Quaternary Period. The river deposited diverse materials, such as rounded pebbles, small amounts of fine sand and silt in the valley. These materials are characterized by having high bearing capacity, and geologists refer to them as conglomerate (Qp-al).

On the other hand, the upper areas of the district include various types of geological formations and super units (**Fig. 2**) which cover ages from the Late Cretaceous, Tertiary and Quaternary, to the most recent.

In the area of study, the foothill is composed of rock from two main formations: Marcavilca and Herradura [9]. These are part of the Morro Solar group, which dates back 170 million years. The rock formation known as Marcavilca (Ki-ma) is composed of whitish-gray quartzite and a lower portion of siltstone. The Herradura Formation (Ki-he) presents quartz sandstone with a yellowish-greenish tone, followed by gray and black siltstone, which changes its tonality to red when it is weathered.

3. Methodology

The objective of this study is to clarify if an amplification of strong motions due to the topography can be found in a target populated slope in Lima. It was therefore

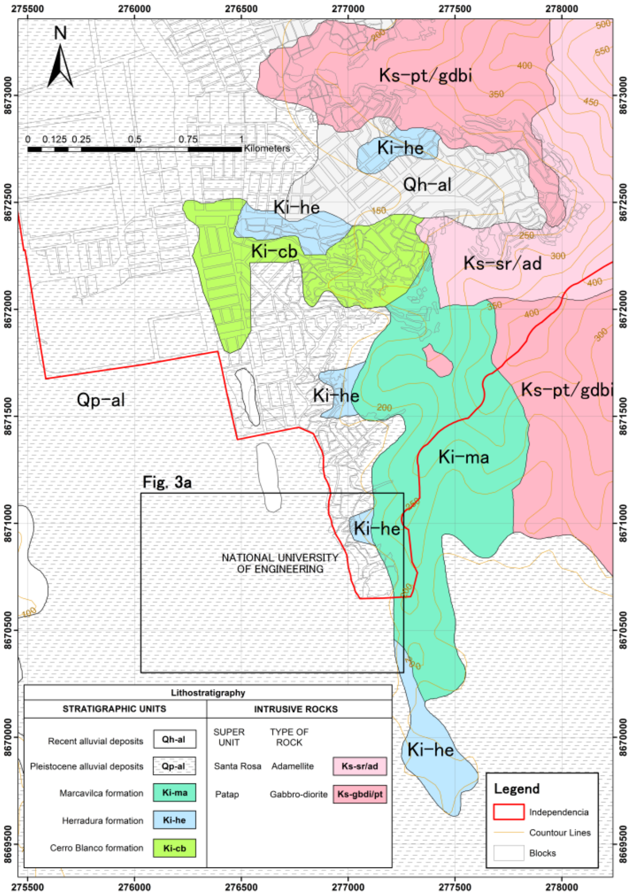

Fig. 2. Geological map of the area of study.

necessary to calculate the dynamic properties of the soil along a line which includes the flat level and the slope of the foothill. For this purpose, microtremor array and single point measurements were conducted at specific locations along the line, and a comparison of strong motions recorded both in the flat and sloping zones was done as well. **Fig. 3a** shows the location of the microtremor measurements conducted and the seismometers installed along the line A-A$'$.

3.1. Microtremor Array Measurements

In previous studies [10, 11], the efficiency of the use of shear wave velocity profiles in Lima as a tool to adequately characterize the seismic response was demonstrated. The change in the dynamic properties of the soil can give us a clue to any difference in the response of the soil under the effect of strong motions.

For that reason, seven microtremor array measurements were conducted along the line of study. The size of each of the conducted arrays and the method of analysis are shown in **Table 1**, where P stands for arrays carried out on the flat level and S for those on the populated slope.

The type of sensor used for the measurements was the moving-coil velocimeter CR 435-1S with a natural period of one second. These sensors were connected by a cable to a logger, GEODAS 15HS, manufactured by Anet Co., Ltd.

In general, two different types of arrays were used based on the geometrical configuration of the sensors and the source of the recorded signals: on one hand, linear arrays with different distances between sensors and an active source (human hops) at a considerable distance to generate surface waves (**Fig. 3c**) in order to explore shallow layers; and on the other hand, circular arrays in which the value of the radius was changed with the objective of recording ambient vibrations (microtremors) with different wavelengths (**Fig. 3b**) which allowed to penetrate into deeper regions.

It should be noted that, due to space limitations, the locations of the tests were restricted to open spaces, such as parks on the flat level, and the execution of only small circles or linear arrays for tests on the slope.

3.1.1. Dispersion Curves

In order to extract the required information about the subsurface structural model, a dispersion curve of surface waves was calculated for each of the sites specified in **Fig. 3a**.

Four methods were used to construct the dispersion curves from the microtremor data: the High Resolution Frequency-Wavenumber (F-k) method [12], the Spatial Autocorrelation (SPAC) method [13], the Centerless Circular Array (CCA) method [14], and the Noise-compensated Centerless Circular Array (nc-CCA) method [15]. For each of the sites, except for S_Array4, both linear and circular arrays were conducted. At the first stage of analysis, random points were obtained and then extracted by taking into consideration different criteria, such as the associated mode of vibration, value of coherence, peak spectral value (depending on the method), etc. Also, the overlapping of the segments obtained by different methods is important in determining the reliability of the results. In the end, only the most reliable points were considered to construct the observed dispersion curves (**Fig. 4**). For S_Array4, since all previous results showed good agreement and a continuous trend between the linear and circular arrays, and in addition to the space limitations, the decision was made to conduct only linear arrays.

3.1.2. Inversion Analysis

The current engineering practice of determining an optimal shear wave velocity profile involves a procedure called inversion analysis. In this inversion process, a structural model is determined by fitting the observed dispersion curve with a theoretical curve. Historically, the dispersion and inversion analysis assumed a wave propagation problem in a horizontally layered medium. Recent investigations [16, 17] have dealt with the Rayleigh wave propagation towards ground with irregularities, where the parallel layer assumption was not established. In these studies, in which a combination of the thin-layered and the two-dimensional finite element approaches was applied to the sub-structure method, even if a complex wave propagation pattern and the appearance of different types

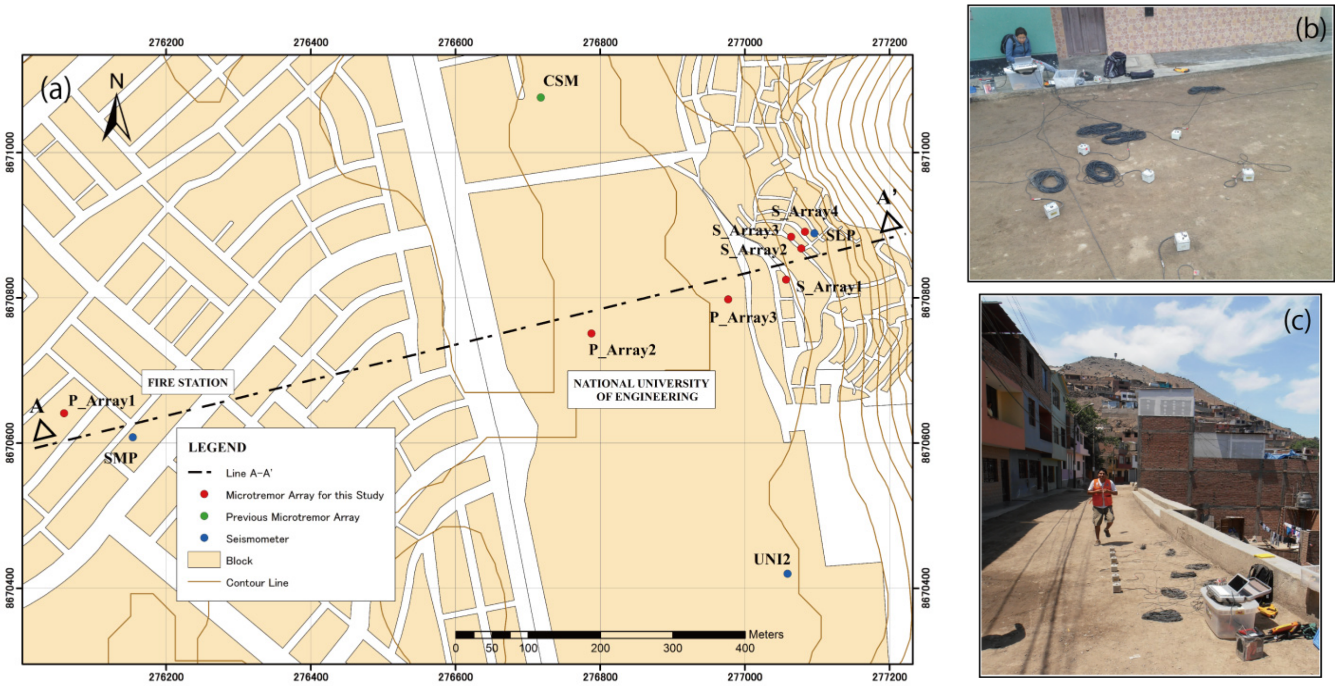

Fig. 3. (a) Location of conducted microtremor arrays and seismometers. (b) Small circular array. (c) Linear array.

Table 1. Array dimensions and applied methods of analysis.

ID	**Array Dimensions**							
	Linear (sensor distance in meters)		***Circular (Radius in meters)***					
	0.5	**2.0**	**1.0**	**2.5**	**4.0**	**5.0∼9.0**	**10∼20**	**20∼30**
P_Array1	○	○				△ ◊	□	□
P_Array2	○	○				○ □	○ □ ◊	
P_Array3	○	○				△	□	○ ◊
S_Array1	○	○			○ ◊	○ ◊		
S_Array2	○	○	◊	◊				
S_Array3	○	○		△ ◊				
S_Array4	○	○						

○ : Frequency-wavenumber (F-k) spectral method
□ : Spectral Autocorrelation (SPAC) method
△ : Centerless Circular Array (CCA) method
◊ : Noise-compensated Centerless Circular Array (nc-CCA) method

of Rayleigh wave modes as well as body waves were found due to the existence of the irregularity, there was evidence of the influence of these body waves only in the vicinity of the natural frequency of a layered soil. Therefore the methods previously described are still applicable to the current problem under analysis. In general, the dispersion curve is a nonlinear function of some soil properties, such as shear and compressional wave velocity, and the density and thickness of each layer. Hence, a method that includes this nonlinearity of the problem should be implemented to obtain an answer with a minimum value of a misfit function. In this study, we used the nonlinear optimization method called Genetic Algorithms (GA) [18], which makes use of random processes and explores the search space of solutions through procedures which are analogous to the way that biological systems evolve to produce more successful organisms.

In the implementation of GA, the search space is represented by a certain number of layers; each layer requires a range both for shear wave velocity and thickness within which the probable answer could be found.

3.1.3. Estimated Shear Wave Profiles

In total, seven shear wave profiles were obtained along the line of study A-A′. Due to the non-uniqueness of the solution, the inversion analysis was performed five times for each inverted profile. In the GA process, the number of individuals per population, generations and preliminary parallel runs was 50, and the effect of multiple Rayleigh

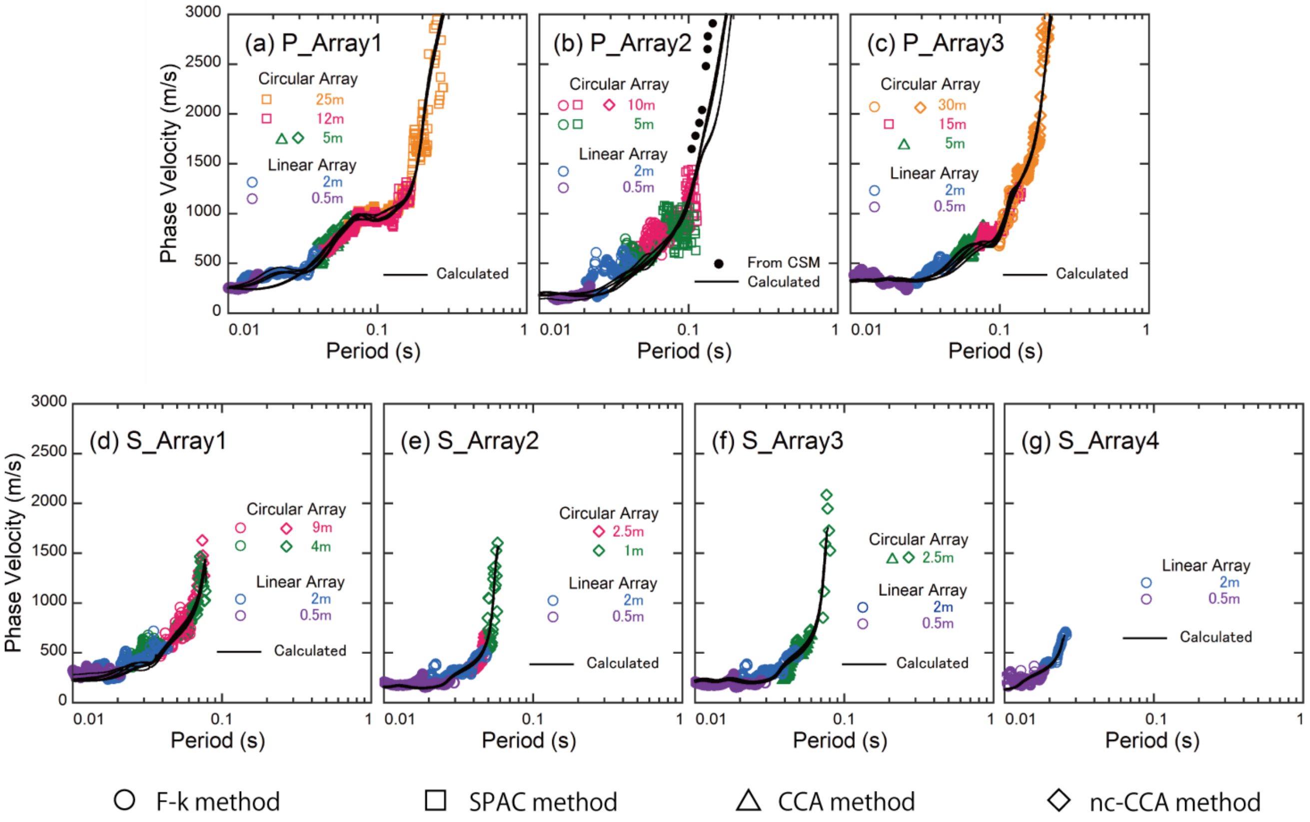

Fig. 4. Observed and calculated dispersion curves.

wave modes was included in the calculation. A comparison of the dispersion curves obtained from microtremor arrays and the calculated curves by GA can be observed in **Fig. 4**.

In order to ensure the reliability of these results, the H/V spectra of Rayleigh waves for the fundamental mode were calculated and plotted on the H/V spectral ratio of a single microtremor point (**Fig. 5**) recorded in a place at or near the center of the array. Finally, the estimated shear wave profiles for each of the runs performed and their averages are shown in **Fig. 6**.

3.2. Seismic Records

3.2.1. Equipment

As a part of the SATREPS project [19], ten new seismometers, developed by Tokyo Sokushin Co. Ltd., were introduced and installed in different zones of Lima, and local site effects were studied in detail [20].

Since one seismometer was already located in a fire station (SMP) and another one, although it did not belong to the line of analysis, was installed at the foot of the slope (UNI2), the decision was made to reinstall a seismometer in a house located about 25 m higher (SLP) in order to compare the seismic records in these three places and to make sure that amplification due to the topography was affecting the part of the slope where houses had been built. The location of the equipment can be seen in **Fig. 3a**.

3.2.2. Analysis

The seismic records were analyzed by comparing their respective Fourier spectra (**Fig. 7**). The results for three earthquakes are presented and a summary of the parameters is shown in **Table 2**.

4. Discussion

In total, seven microtremor arrays were conducted at different points along the line of study A-A′ in order to analyze the variation in the depths at which the bedrock could be found.

P_Array1 (**Fig. 6a**) was carried out in a place close to the SMP seismic station; therefore, the obtained shear wave velocity profile can be considered the characteristic profile for this station and be useful for further analysis as well. In this case, the depth to the bedrock is about 150 m.

As we approach the bottom of the slope, the natural period of vibration gradually decreases from 0.35 s (for P_Array1, **Fig. 5a**) to 0.25 s (for P_Array2, **Fig. 5b**, and P_Array3, **Fig. 5c**). This can explained by the reduction of the bedrock depth for P_Array2 and P_Array3 (**Fig. 6b** and **Fig. 6c**, respectively) in which the depth to a layer with a shear wave velocity of about 3000 m/s, what we consider to be bedrock, remains constant at approximately 100 m. It is noteworthy that because of the limited size of the place where P_Array2 was conducted, the corresponding dispersion curve was completed by using information

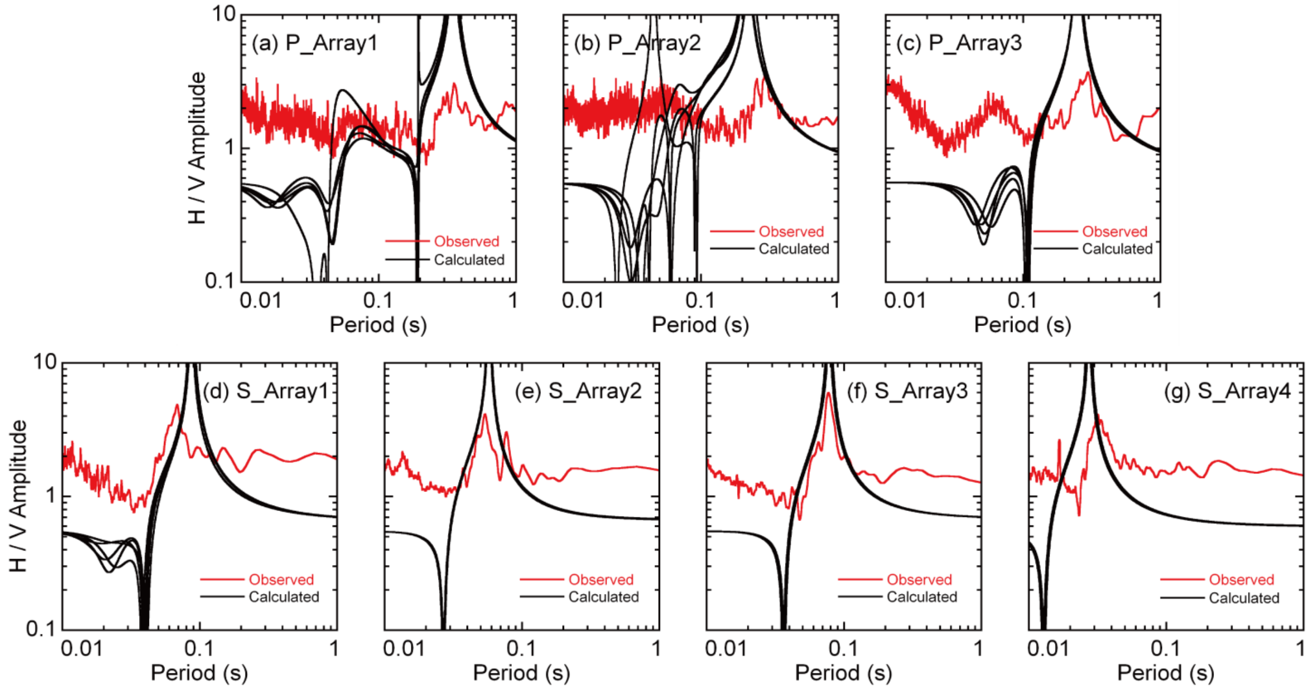

Fig. 5. Observed and theoretical H/V spectra.

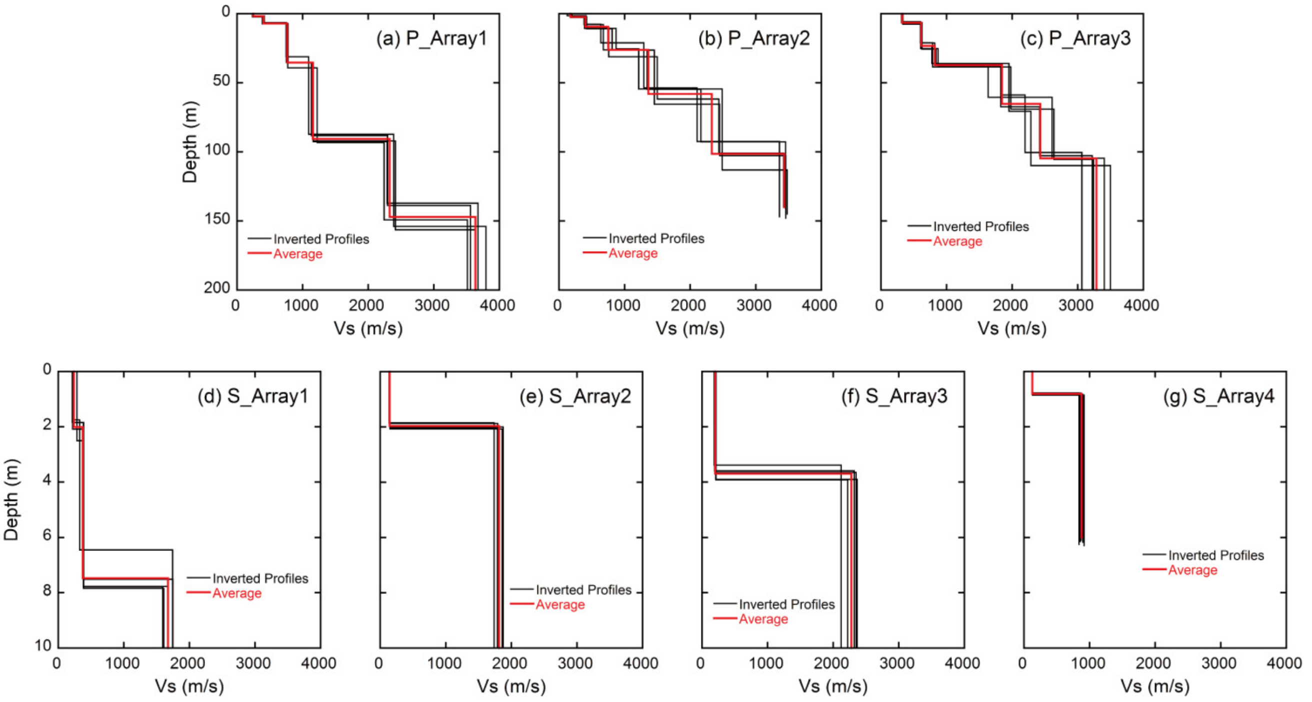

Fig. 6. Calculated shear-wave velocity profiles.

from the CSM array [20], which was situated 350 m away (**Fig. 3a**) because it showed the same trend and was conducted almost at the same distance from the foothill.

Furthermore, a maximum shear wave velocity of about 1700 m/s was found in S_Array1 (**Fig. 6d**) at a depth of 7.5 m. Comparing this result with the one obtained for P_Array3, we found that about the same velocity was reached at 36 m for P_Array3, indicating a drastic reduction in the depth to stiff layers in these two points only 70 m apart (**Fig. 8**). As the difference in height between the two points was merely 5 m, the outcrop of stiff materials must follow a line with a slope of about 50%.

Since flat surfaces are required for houses and roads to be constructed on the slope, the earthmoving technique known as "cut and fill" is commonly used (**Fig. 8**). In this method, part of the slope, which mostly consists of

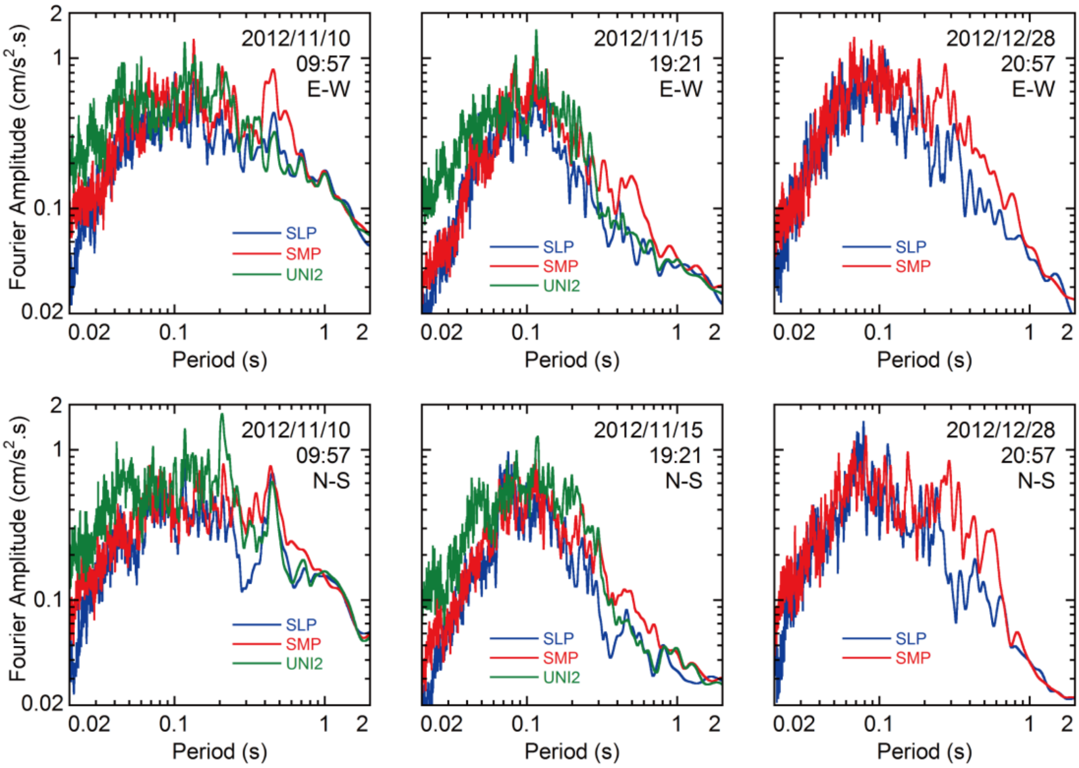

Fig. 7. Fourier spectra for the recorded seismic events.

Table 2. Parameters of the analyzed earthquakes.

Date	*Local time*	*Longitude (deg.)*	*Latitude (deg.)*	*Magnitude (ML)*	*Depth (km)*	*Hypocentral distance to SMP (km)*	*Peak Ground Acceleration (cm/s^2)*		
							SMP	*UNI2*	*SLP*
2012/11/10	09:57	-8.89	-75.12	6.0	146	431	2.60	4.07	2.29
2012/11/15	19:21	-13.30	-76.68	4.8	57	158	2.72	2.93	1.94
2012/12/28	20:57	-11.37	-76.86	4.3	96	122	5.55	—	4.67

rock, is cut and then used for constructing retaining walls. Alternatively, to produce the required flat filled areas, in most cases borrow materials brought from landfills are used, but these obviously have poor dynamic properties.

This is evident in S_Array2, S_Array3 and S_Array4 (**Fig. 6e**, **Fig. 6f** and **Fig. 6g**, respectively). The first two were conducted on an artificial road constructed in the way described above. The top layer has a shear wave velocity lower than 200 m/s, and its thickness ranges from 2 to 4 m. For the last array, due to the limitation of space, only linear arrays were performed, and the obtained profile shows a surface layer with very low shear wave velocity and a thickness of less than 1 m. The same pattern can be found in the majority of houses and roads in the slope with some variations in the thickness of this shallow layer.

In most of the tests presented, good agreement between the observed and theoretical H/V spectra (**Fig. 5**) was obtained with slight differences in specific cases because of the distance between the center of the array and the conducted single microtremor point.

Regarding the seismic events simultaneously recorded on both the flat level (SMP) and on the slope (SLP), the analysis of their respective Fourier spectra (**Fig. 7**) shows that no amplification due to topography was found. Indeed, the Fourier amplitudes are practically the same for periods up to 0.1 s. For the SLP station, those amplitudes are lower for longer periods. In all cases, the Fourier amplitudes for SLP and SMP stations are lower than the one obtained for UNI2 which, though is 400 m far from P_Array3, can be considered to be located at the bottom of the hillside. It is noteworthy that, considering the results obtained up to this point, the slight difference in the values of the Fourier spectrum amplitude is due to the variation in depth to the bedrock at the points where the strong motions were recorded.

Another aspect that deserves to be highlighted is that, even though the comparison of the Fourier spectra of the events recorded at SMP, UNI2 and SLP does not evidence a significant variation, under the effect of strong motions, the area under study might fail due to landslides or rock falls of the heavily weathered material or the unstable flat filled areas in which houses and roads are built.

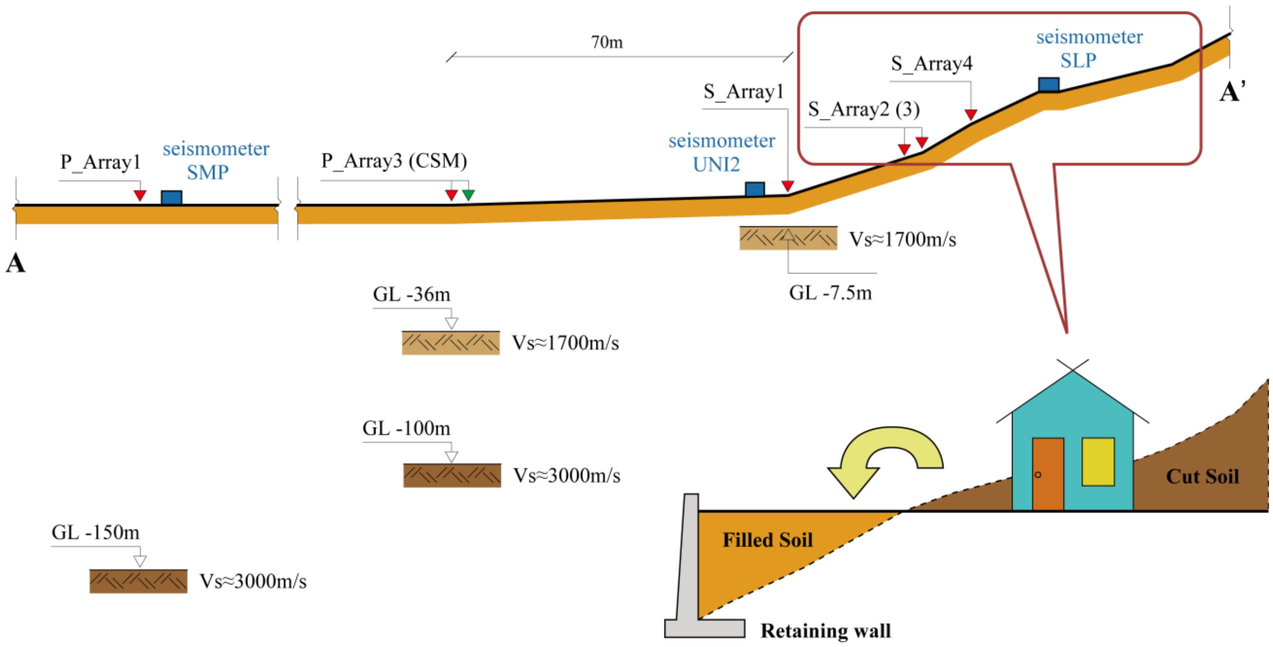

Fig. 8. Cross section along line A-A′ and "cut and fill" technique.

5. Conclusions

The hillsides surrounding the historically populated areas of Lima have experienced an erratic urbanization process. In the more than thirty years that have passed since this phenomenon had its peak during the 1970's, new districts have been created in places where previously industrial and agricultural activities had taken place.

One of these newly established districts is called Independencia, and the area known as Villa El Carmen within it was chosen as our subject of study.

The present study has aimed to analyze two central aspects of a populated slope in Lima: first, the variation in the dynamic properties of the soil along a chosen line (A-A′), and second, the possibility of finding amplification in the seismic response due to the topography of the slope.

To accomplish the first objective, seven microtremor arrays were conducted: three on the lower part and four along the slope. The obtained results showed, as expected, that the depth of the bedrock gradually decreases as we approach the foothill, and the bedrock appears as rocky outcrops on the hillside. On the other hand, a thin shallow layer of borrowed materials with very low shear wave velocity overlies the rock in the housing and road areas.

To manage the second aspect, a seismometer was installed on the slope. In comparing the Fourier spectra for different events recorded previously, no amplification of the seismic response due to the topography could be found. Stronger events may be required to induce the rock body into a higher deformation state.

Special attention should be drawn to the cut and fill areas and the heavily weathered rock on the surface that, although they would not be affected by an increase in seismic energy, could fail under the effect of strong motions, causing landslides or rock falls. This is because of their low strength and poor mechanical properties.

The acquired information will be useful for further mathematical models in which the dynamic properties of the soil are required as input data, and such studies are planned by the authors.

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Selected Publications:
- "Seismic Microzonation of Lima," Japan-Peru Workshop on Earthquake Disaster Mitigation, Japan-Peru Center for Earthquake Engineering and Disaster Mitigation (CISMID), 2005.

Academic Societies & Scientific Organizations:
- American Society of Civil Engineers (ASCE)