Paper:

Estimation of S-Wave Velocity Profiles at Lima City, Peru Using Microtremor Arrays

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Microtremor exploration was performed around seismic recording stations at five sites in Lima city, Peru in order to know the site amplification at these sites. The Spatial Autocorrelation (SPAC) method was applied to determine the observed phase velocity dispersion curve, which was subsequently inverted in order to estimate the 1-D S-wave velocity structure. From these results, the theoretical amplification factor was calculated to evaluate the site effect at each site. S-wave velocity profiles at alluvial gravel sites have S-wave velocities ranging from ∼500 to ∼1500 m/s which gradually increase with depth, while Vs profiles at sites located on fine alluvial material such as sand and silt have S-wave velocities that vary between ∼200 and ∼500 m/s. The site responses of all Vs profiles show relatively high amplification levels at frequencies larger than 3 Hz. The average transfer function was calculated to make a comparison with values within the existing amplification map of Lima city. These calculations agreed with the proposed site amplification ranges.

Keywords: Lima city, microtremors, S-wave velocity profiles, site response, $AVs10$

1. Introduction

The area used for this study, Lima city in, Peru, is situated in a seismically active region, due to the subduction of the Nasca Plate beneath the South American Plate. Numerous earthquakes ($M_w > 8.0$) have struck the region in the past. The city suffered substantial damage during the last strong ground motion (which took place on October 3, 1974 with a moment magnitude of 8.1), most of which was related to local subsurface conditions of the soil [1]. In relation to this, it was considered necessary to undertake a comprehensive study of Lima's soil dynamic.

At present, Lima counts on seismic microzonation maps [2] and an existing soil amplification map [3]. These maps based on geological and geotechnical information, and the H/V peak period from microtremor measurements show that Lima city mainly overlies Quaternary alluvial deposits. However, a dynamic analysis of these deposits is only in its preliminary stages due to a lack of information relating to the S-wave velocity structure [3, 4], which is a key parameter for use in assessing the potential for sediment amplification.

The use of microtremor array measurements to determine S-wave velocity distributions in soil deposits is being used more extensive globally because of its advantages of being affordable, non time-consuming, and possible to conduct in urban and crowded areas such as within Lima city. In this study, the spatial autocorrelation coefficient method (SPAC method) introduced by Aki (1957) [5] was used to extract S-wave velocity information from microtremor measurements.

The aim of the present paper is to determine the S-wave velocity structure at five selected sites and to analyze the site effect of each site. It is noteworthy that one of the study sites is located in the La Molina district, an area that has suffered extensive damage in previous earthquakes in relation to the local subsurface conditions [1, 4, 6, 7]. Also included in the study is a site located on the outskirts of Lima city (the Ancón district), which was chosen because of a lack of existing data.

2. Geological and Geomorphological Aspects

Lima city is the capital of Peru, and is the country's largest and most populated city. **Fig. 1a** shows the coastal location of Lima city within Peru. The geologic units of Lima city are composed of sedimentary and intrusive rocks from Cretaceous age, in addition to unconsolidated sediments, as shown in **Fig. 1b**. Cretaceous deposits from the Puente Piedra Group appear to the northwest of the city, while deposits from the Morro Solar Group are exposed in the southwest. In addition, rocks from the Casma Group outcrop in many parts of the city, and intrusive rocks are found exposed mainly in the eastern part of the

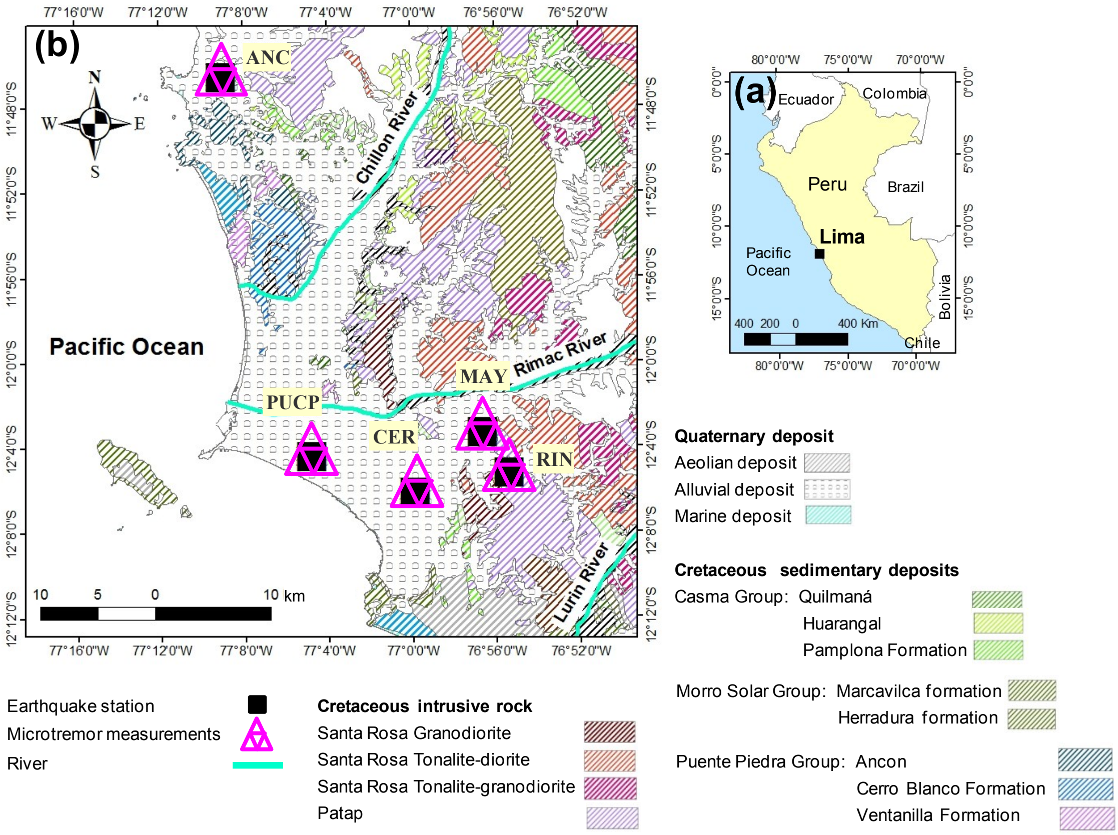

Fig. 1. Maps of microtremor exploration sites. (a) Location of Lima city within Per. (b) Geological map of Lima city [9] with locations of earthquake stations (squares) and recorded microtremor measurements (triangles).

study area.

The geological map shows that the main part of the city lies on Quaternary deposits represented by alluvial, marine, and aeolian materials. The distribution of the alluvial materials is very wide, and they have been formed by the rapidly flowing Rímac and Chillón rivers as seen in **Fig. 1b**.

The alluvial deposits extend from the ground's surface to the rock, and consist mainly of medium dense to very dense coarse gravel and sand with cobbles [1], known locally as Lima conglomerate. The thickness of this material (to the base rock) is reported to be over 100 m [1, 6, 8].

3. Field Measurements

3.1. Site Selection

For this study, target sites for microtremor measurements (triangles) were selected in relation to the location of the seismic recording stations (squares) as shown in **Fig. 1b**. The strong motion network at Lima city is currently composed of more than 15 stations, and operated by two institutions: the Japan–Peru Center for Earthquake Engineering, Research, and Disaster Mitigation (CISMID) and the Geophysical Institute of Peru (IGP). Calderon et al. (2012) [4] conducted microtremor explorations around a number of recording sites maintained by CISMID, and this study intends to estimate S-wave velocity (V_s) structures for the IGP stations. **Fig. 1b** shows the locations of the selected sites: PUCP, CER, MAY, RIN and ANC; all of them located on Quaternary alluvial deposits. **Table 1** shows information related to each site's name, location, geographical coordinates, and geology.

3.2. Array Configuration

A circular array configuration was applied for this observation. **Fig. 2** shows the schematic layout of the installation. Seven 3-component sensors were placed on the ground's surface: six were distributed at the vertices of two equilateral triangles inscribed within two circles of different radii, and one was placed at the center [10]. For each site, the size of the array (side length of equilateral triangle) varied from small to large. Small arrays (the smallest was 1.5 m) gave information of the near-surface layers, while the large ones characterized the deeper soil layers. Although large arrays with side lengths larger than 300 m were conducted for all the sites, the coherence was so low at a low frequency that it was not possible to use data from large arrays in the analysis for most sites. The size and number of deployed circular arrays that defined the observed phase velocity dispersion curve for each site are presented in **Table 1**.

The test equipment used in this exploration was a GPL-6A3P portable recording system designed by the Mitu-

Table 1. Array information.

Site ID	Location (District)	Latitude (deg)	Longitude (deg)	Geology	Array Min* (m)	Array Max* (m)	Number of deployed arrays
PUCP	San Miguel	-12.0734	-77.0796	Quatemary Alluvial	1.5	346.4	4
CER	San Borja	-12.1040	-76.9992	Quatemary Alluvial	1.5	48.0	3
MAY	Ate	-12.0549	-76.9441	Quatemary Alluvial	1.5	173.2	4
RIN	La Molina	-12.0873	-76.9240	Quatemary Alluvial	1.5	48.0	3
ANC	Ancón	-11.7767	-77.1510	Quatemary Alluvial	1.5	173.2	4

*Side length of equilateral triangle

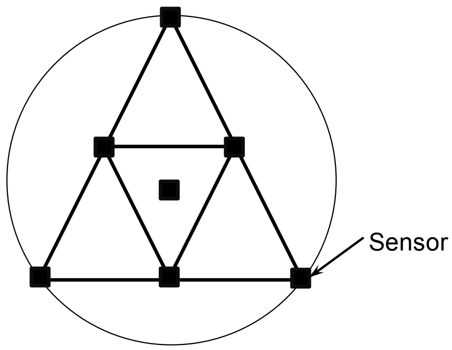

Fig. 2. Geometry used in the microtremor array.

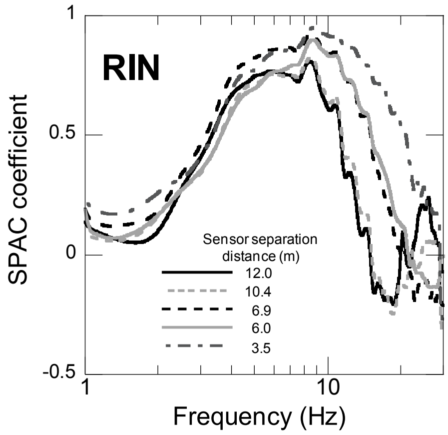

Fig. 3. SPAC coefficients as a function of frequency for different sensor separation distances at the RIN site (with a maximum side length of 12 m).

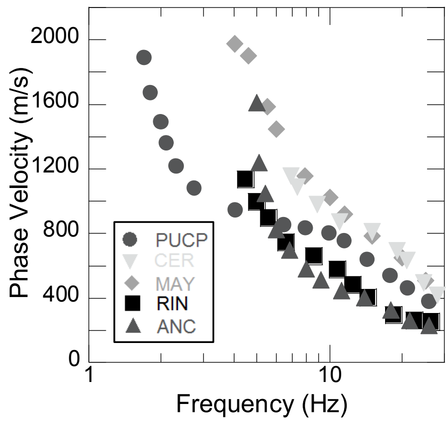

Fig. 4. Observed dispersion curves obtained from microtremor data using the SPAC technique.

toyo Corporation, which has a flat response in the frequency range between 0.25 to 25 Hz for estimating the phase velocity [10]. Each recording lasted between 10 and 60 min, and data were recorded at a sampling rate of 100 samples per second.

4. Estimation of the Dispersion Curve

The SPatial Autocorrelation Coefficient (SPAC) method was applied to define the observed dispersion curve of Rayleigh waves from the array data. This technique uses SPAC coefficients in the calculation of phase velocity at different frequency ranges. From the array configuration, the SPAC coefficient was computed using the cross-spectrum between records from the vertical components of the sensors at an equal interstation separation, and with different azimuths. Phase velocity at a certain frequency was estimated by fitting the SPAC coefficients to the Bessel function. Details relating to SPAC analysis can be found in literature [5, 11].

Using the assumption that Rayleigh waves mainly dominate vertical motion, vertical records from each sensor were analyzed in the processing of data. The microtremor recording data were divided into time segments with lengths of 81.92 sec, and time segments clearly contaminated by noise were removed. The SPAC coefficient obtained from every segment was averaged to obtain the phase velocity for the frequency range of interest. **Fig. 3** illustrates the SPAC coefficients for one of the microtremor arrays recorded at the RIN site. Because in this study, a seven-sensor configuration was used in the measurements, **Fig. 3** shows five SPAC coefficients that correspond to five combinations of sensor separation distances. These observed SPAC coefficients, as a function of frequency for a fixed distance, model the Bessel function at frequencies higher than 9 Hz.

Figure 4 shows the observed dispersion curves at the sites. For all sites, the phase velocities were estimated in the frequency range from 4 to 30 Hz, except for at the PUCP site, which had the widest frequency range until 1 Hz (due to the contribution from large arrays with a maximum side length of 346.4 m, exploring deeper the structure of the soil). In terms of the velocity, **Fig. 4**

shows that the phase velocity values vary between 200 and 2000 m/s. The PUCP and MAY sites reached the highest velocity values of ∼2000 m/s at frequencies of ∼1 Hz and ∼4 Hz, respectively. The high velocity layer (∼2000 m/s) at the MAY site suggests a shallower basement depth than that at the PUCP site.

5. Estimation of VS Profile

SPAC analysis provides the dispersion curve of Rayleigh waves, and this is subsequently inverted (using the Genetic Simulated Annealing Algorithm technique) to determine a 1-D S-wave velocity model at each of the examined sites. The inversion technique was introduced by Yamanaka (2007) [12], and it searches to fit (as much as possible) the observed model, $U_0(f_i)$, with the calculated values of phase velocity for fundamental mode Rayleigh waves, $U_C(f_i)$, by using the misfit function $\emptyset_j$ defined as:

$$\emptyset_j = \frac{1}{N}\sum_{i=0}^{N}\left[U_0(f_i) - U_C(f_i)\right]^2 \quad \dots\dots\dots \quad (1)$$

where N and f_i represent the number of the observed data and frequency, respectively. In the calculation of the final optimal V_s model, 10 inversions with 100 generations were conducted using different random numbers. In doing so, good models with a smaller amount of misfit were more likely to survive in the next generation, and poor models were replaced by newly generated ones. The unknown parameters to be determined in the inversion were V_s and thickness. P-wave and density of the layers were fixed. P-wave velocity value was calculated using the equation proposed by Kitsunezaki et al. (1990) [13] that correlates V_s and V_p values, as previously used by Calderon et al. (2012) [4] in the same study area. Density values were set from 1.8 to 2.5 g/cm^3, depending on the soil type. The fundamental mode of Rayleigh waves was assumed in the inversion, as well as V_s increases with depth. **Table 2** shows an example of the search limits at the RIN site.

Table 2. Search limits used for the determination of the optimal V_s profile at the RIN site.

	Search limits		
Layer	V_s (km/s)	Thickness (m)	Density (g/cm^3)
1	[0.20-0.30]	[1-15]	1.8
2	[0.30-0.45]	[1-15]	1.9
3	[0.45-0.60]	[1-15]	2.0
4	[0.60-0.95]	[25-55]	2.1
5	[0.95-1.45]	-	2.2

Figure 5 shows the extent that the calculated dispersion curve (solid line) fits the observed one (open circles) for all the selected sites. All models can sufficiently explain the observed phase velocity in the entire frequency range. The inverted 1-D V_s profiles for all the sites are shown in **Fig. 6** and **Table 3**. The deepest profile was obtained for the PUCP array, with a depth over 280 m (**Fig. 6a**) over the basement and an S-wave velocity of ∼2500 m/s, while the CER site (where the bottom layer has a lower velocity than the basement) only reached a depth of ∼50 m (**Fig. 6b**). The top layers at the PUCP, CER, and MAY sites show S-wave velocities of ∼400 m/s, whereas the RIN and ANC sites show S-wave velocities of ∼200 m/s (**Fig. 6b**); this is related to the phase velocity at the upper-limit of frequency. The phase velocities for PUCP, CER, and MAY at 30 Hz are relatively larger than those at the RIN and ANC sites (as show in **Fig. 5**). All the V_s profiles estimated in this study detected the engineering bedrock, with V_s larger than 500 m/s. A further description of the S-wave velocity structure is discussed in the following section.

To support the reliability of the results obtained from the inversion, the horizontal to vertical (H/V) spectral ratio calculated from the observed microtremor data (solid line) was compared with the theoretical ellipticity of the fundamental-mode Rayleigh wave from the inverted 1-D soil profile (broken line), as depicted in **Fig. 7**. The observed H/V spectrum was estimated from the recording data of the sensor placed at the center of the array configuration, which was smoothed using a Parzen window with a 0.05 Hz bandwidth. The comparison between the observed H/V and the computed ellipticity shows good agreement in the frequency range within 1 and 10 Hz. The dominant peaks observed in the spectral ratios of observed microtremor data were well modeled by the computed ellipticities of the Rayleigh waves.

6. Discussion

6.1. Geotechnical Description of S-wave Velocity Structure

All the selected sites in the present study are located on alluvial Quaternary deposits (**Fig. 1b**), but the subsurface condition for each site differs. Lima conglomerate is the predominant material over Lima city [1, 2, 6]. Overlying the conglomerate, shallow layers of unconsolidated material such as sand, silt, or clay are found, and their thicknesses range from ∼0.5 m to more than 30 m, depending on the location [1, 2, 6]. CISMID (2005) [6] proposed a soil distribution map of Lima city in order to obtain a more accurate picture of the distribution and properties of the various subsurface soils in Lima.

According to this soil classification map [6], the PUCP and CER sites are located on alluvial gravel. The V_s profiles at the two sites show that the Lima conglomerate extends from near the ground's surface, with a V_s larger than 500 m/s (**Fig. 6**). The PUCP site proves that Lima conglomerate, especially in the central part of the city, has a thickness of about 200 m, as previously reported by CISMID (2005) using water well records [6]. The S-wave velocity of the conglomerate increases gradually with depth from ∼500 to ∼1500 m/s, as shown in **Fig. 6a** (PUCP V_s profile).

In the eastern part of the city, sand and silt deposits

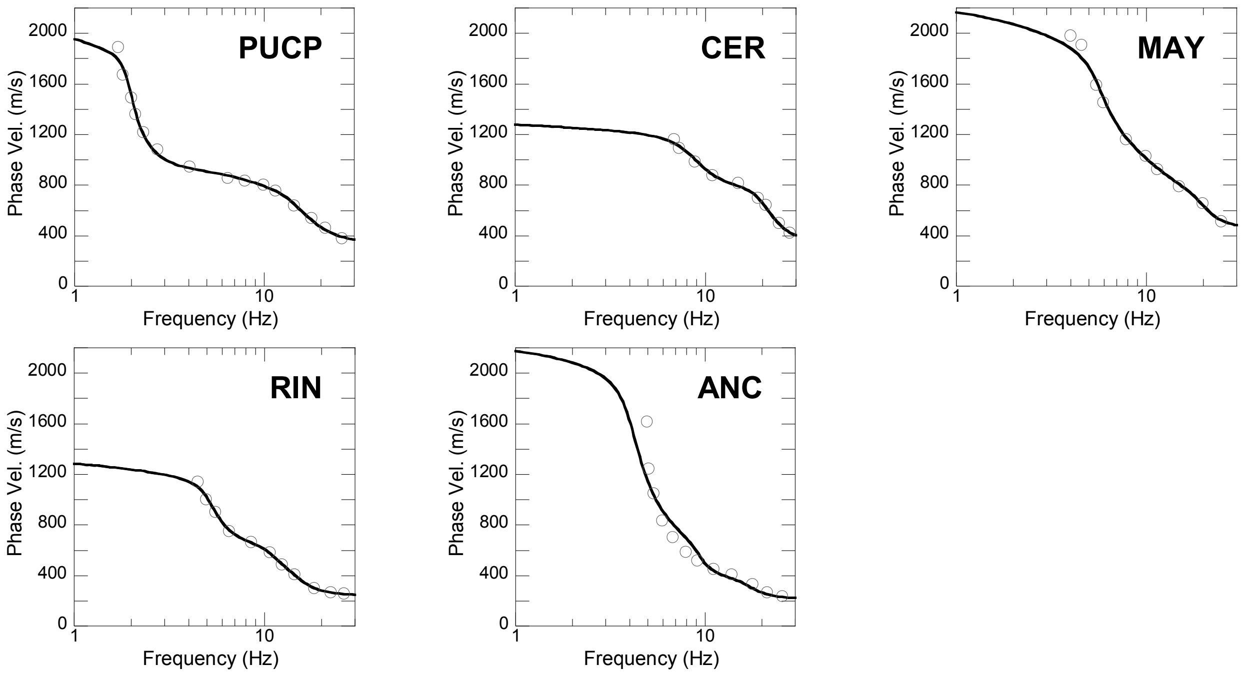

Fig. 5. Comparison between the calculated dispersion curves (solid line) for inverted models and the observed ones (circles) for all sites.

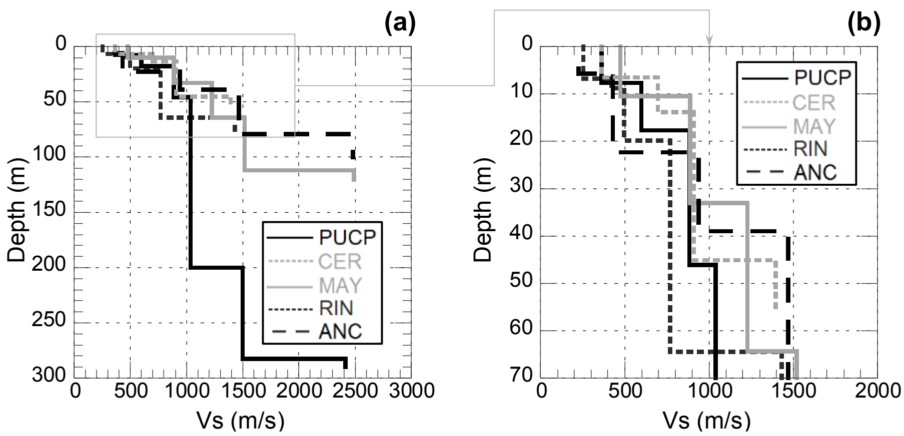

Fig. 6. Estimated shear-wave velocity profiles.

Table 3. Estimated S-wave velocity structures from array observations of microtremors.

PUCP		CER		MAY	
V_s (m/s)	Thickness (m)	V_s (m/s)	Thickness (m)	V_s (m/s)	Thickness (m)
362	7.7	364	6.6	474	10.4
596	9.9	695	7.3	888	22.6
884	28.5	911	31.2	1225	31.3
1038	153.8	1396	-	1518	47.9
1503	82.9			2492	-
2412	-				
RIN		**ANC**			
V_s (m/s)	Thickness (m)	V_s (m/s)	Thickness (m)		
254	6.8	225	5.7		
418	2.0	429	16.7		
496	11.0	938	16.7		
769	44.7	1468	40.2		
1431	-	2477	-		

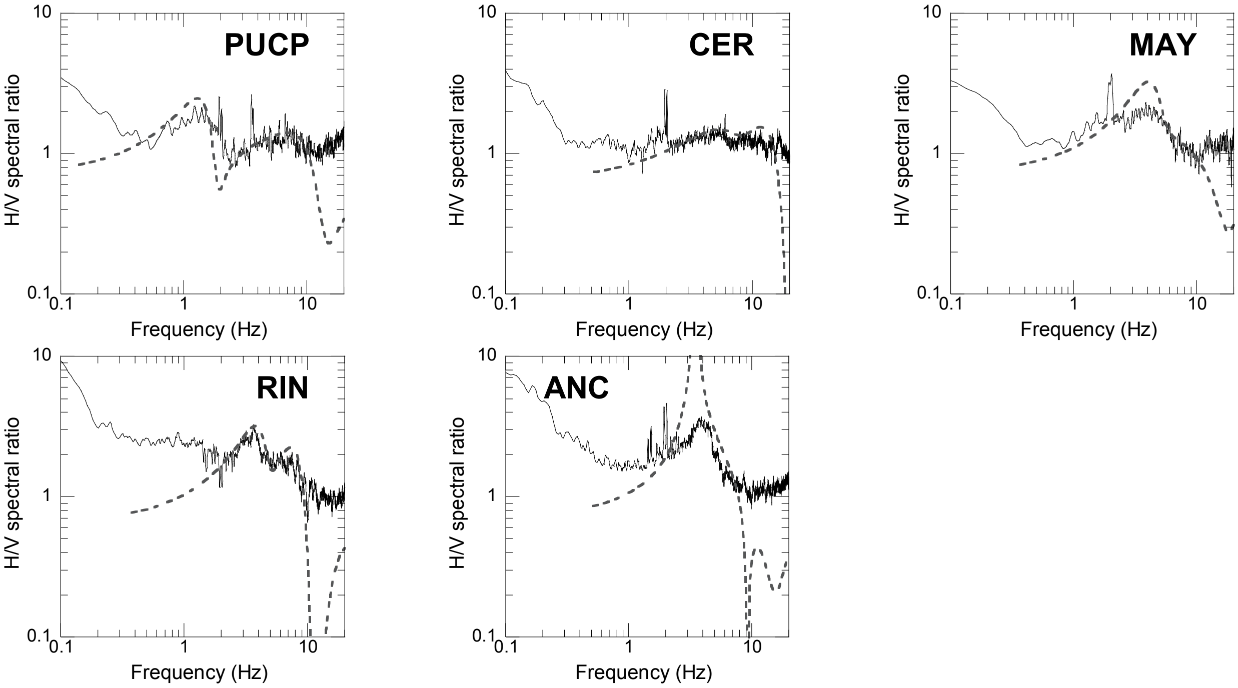

Fig. 7. Comparison of H/V spectra of microtremors (solid lines) with computed ellipticities of fundamental-mode Rayleigh waves based on the obtained S-wave velocity structure (broken lines).

overlie the Lima conglomerate [6], and MAY and RIN array measurements were carried out on these materials. Our results show that this deposit has S-wave velocities ranging within ∼200 and ∼500 m/s (**Fig. 6b**), which is similar to that reported by Repetto et al. (1974) using a down-hole test [1]. The RIN site is located in the La Molina district, a place where a high concentration of damage has previously occurred during previous earthquakes, due to the local subsurface conditions [1, 4, 7]. The V_s profile at RIN shows that the thickness of the sand and silt deposits is about 20 m, while the thickness in the V_s structure at MAY is about 10 m. Conglomerate is found underlying this unconsolidated material, with a V_s of between ∼500 to ∼1500 m/s. The MAY profile detected shear wave velocities of ∼2500 m/s at a depth of over 120 m, and this high velocity layer (∼2500 m/s) was also detected in the PUCP profile at a depth of over 280 m (**Fig. 6**); it is considered that this material may correspond to bedrock. Calderon et al. (2012) [4] reported that the bedrock at Lima city has S-wave velocity values of the order of 3000 m/s.

The ANC site is located on the outskirts of Lima city to the north (**Fig. 1b**). The soil distribution map of Lima city proposed by CISMID (2005) [6] provides scarce information related to the area where the earthquake observation station is located. Nonetheless, geological and geotechnical information indicates that layers of aeolian sand overlie alluvial gravel deposits [6]. The V_s profile at ANC shows the top layer has S-wave velocities between ∼200 m/s and ∼400 m/s, and this overlies thick high velocity layers (within ∼1000 m/s and ∼1500 m/s) and a very high velocity layer (∼2500 m/s).

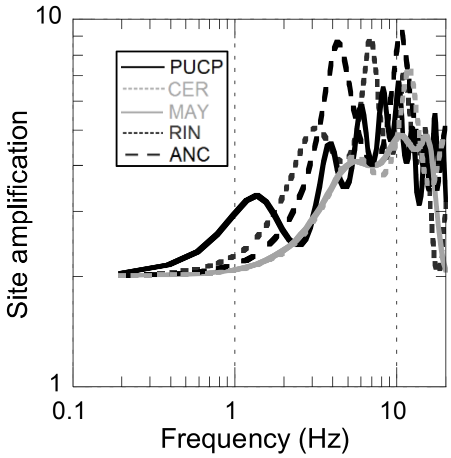

Fig. 8. Theoretical amplification factor for all sites.

6.2. Site Amplification

The 1-D V_s profiles obtained from microtremor data (**Fig. 6**) were used to calculate the site amplification factor (defined as the ratio between the surface motion and the input motion from the bottom layer). In this study, the bottom layer had a shear-wave velocity about 1500 m/s since we detected this velocity layer at all the profiles as shown in **Fig. 6**.

Figure 8 shows the theoretical amplification factor for each profile. Both PUCP and CER sites, which are located on alluvial gravel, show several peaks at frequencies above 3 Hz, corresponding to the site response of the Lima conglomerate. Using strong ground motion data, Quispe et al. (2012) [14] reported that this deposit suffers

Table 4. Average transfer function $AvTF$.

Site ID	Location (District)	$AVs30$ (m/s)	$AVs10$ (m/s)	$AvTF$ Eq. (2)	$AvTF$ proposed by Sekiguchi et al. (2013) [3], according to the location of the sites
PUCP	San Miguel	577.9	397.9	1.1	1.10–1.15
CER	San Borja	647.8	434.3	1.0	1.00–1.10
MAY	Ate	681.6	474.0	1.0	1.00–1.10
RIN	La Molina	447.8	294.3	1.2	1.15–1.20
ANC	Ancón	414.6	282.8	1.2	-

from high amplification at frequencies larger than 4 Hz. The PUCP site shows a small bump between 1 and 2 Hz, which is also identified in the observed H/V spectral ratio of the microtremor data (**Fig. 7**). This peak corresponds to the contribution of the deep structure. The PUCP site is located in the center of the city, where the Lima conglomerate is thicker than in other places, as previously mentioned.

MAY and RIN sites lie on layers of sand and silt. Both sites show peaks at frequencies larger than 4 Hz (**Fig. 8**), which represents the resonance between the top layer and the alluvial deposit. The RIN site shows a higher amplification than the MAY site due to its softer subsurface conditions. The site response at the RIN site also depicts a peak at a frequency of 3 Hz, which represents the first resonant mode at this site. Such a peak was also detected by Stephenson et al. (2009) [7] when analyzing the velocity response spectra for earthquake data.

The ANC site shows a prominent peak at a frequency between 4 and 5 Hz, which represents the first resonant mode related to the strong velocity contrast between the top layers (V_s ranging from $\sim$200 and $\sim$400 m/s) and the high velocity layers (V_s ranging from $\sim$1000 m/s and $\sim$1500 m/s).

6.3. Amplification Map for Lima City

Sekiguchi et al. (2013) [3] developed an amplification map for Lima city based on the correlation between the average S-wave velocity for the top 10 m of soils $(AVs10)$ and the Average Transfer Function $(AvTF)$ of S-waves. The proposed correlation is shown in the following equation:

$$AvTF = \frac{122}{AVs10} + 0.76 \quad \quad (2)$$

Table 4 shows the value of $(AVs10)$ and the calculated $(AvTF)$ for each site using Eq. (2). The calculated $(AvTF)$ for all the sites (except the ANC site) falls into the given range proposed by Sekiguchi et al. (2013) [3] as shown in **Table 4**.

Although the amplification map does not include the area where the ANC site is located, $(AVs10)$ and $(AvTF)$ were calculated in order to use the information in future updating of the map. The average shear-wave velocities for the first 30 m $(AVs30)$ in the profile are also shown in **Table 4**, as this value is adopted as an international standard for soil classification.

7. Conclusions

Microtremor measurements were carried out in order to estimate the S-wave velocity profiles at five selected sites, based on the location of strong motion stations. The PUCP and CER sites are located on Lima conglomerate, which extends from the ground's surface to the rock beneath. The V_s profiles show that this deposit has S-wave velocities ranging from $\sim$500 m/s to $\sim$1500 m/s, as previously reported [1, 4]. At the central part of Lima city, the thickness of the Lima conglomerate is larger than 200 m, as proved by the V_s profile at PUCP (the site response of Lima conglomerate is characterized by a high amplification for frequencies larger than 3 Hz). MAY and RIN sites are situated on sand and silt deposits overlying the Lima conglomerate, and the V_s of this unconsolidated deposit is between $\sim$200 and $\sim$500 m/s. The surface condition at RIN site is softer than at the MAY site, and therefore the site response at the RIN site is higher in terms of the amplification. The RIN site is located in the La Molina district, where excessive earthquake damage has previously occurred [1, 4, 7]. The V_s profile of RIN shows a distribution of the soil layers to a depth of up to $\sim$70 m. In this work, the V_s profile of ANC (located on the city's outskirts) was estimated up to $\sim$80 m depth. The site response here shows a predominant peak at 4 Hz, due to the strong velocity contrast between the top layers and the high velocity layers.

The S-wave velocity for the top 10 m of soils $(AVs10)$ and the Average Transfer Function $(AvTF)$ [3] were determined to compare with the Lima amplification map [3], and the calculated $AvTF$ shows agreement with the previously proposed $AvTF$ ranges.

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2012 Student in Doctoral Course, Tokyo Institute of Technology

Selected Publications:
• S. Quispe, H. Yamanaka, Z. Aguilar, F. Lazares, and H. Tavera, "Preliminary Analysis for Evaluation of Local Site Effects in Lima city, Peru from Ground Motion Data by Using the Spectral Inversion Method," Journal of Disaster Research, Vol.8 No.2, pp. 243-251, 2013.