July 2011, Volume 5, No. 7 (Serial No. 44), pp. 618-627
Journal of Civil Engineering and Architecture, ISSN 1934-7359, USA

Estimation of Deep Soil Profiles in Lima Peru

Diana Calderon[1], Fernando Lazares[2], Zenon Aguilar[2], Toru Sekiguchi[1] and Shoichi Nakai[1]

1. Department of Urban Environment System, Faculty of Engineering, Chiba University, Chiba, Japan

2. CISMID, Faculty of Civil Engineering, National University of Engineering, Lima, Peru

Abstract: Deep shear-wave velocity profiles at eight places in Lima Peru were estimated based on the inversion of dispersion curves. The dispersion curves were calculated from small and large microtremor arrays using two methods: the F-k proposed by Capon (1969) and the CCA proposed by Cho et al. (2004). For the purpose of large array measurement we introduced a new type of sensor. Important results are the relative shallow depths to the basement rock in the area classified as alluvial gravel that covers most of the area of Lima city; and the relative large depth to the bedrock in places identified as VSV and CMA. It is recommended that this study be complemented with PS loggings in order to verify the estimated profiles.

Key words: Microtremor array, dispersion curve, inversion, soil profile, H/V spectrum.

1. Introduction

This study is a part of the project "Enhancement of Earthquake and Tsunami Disaster Mitigation Technology in Peru", in which Japanese Government, represented by Chiba University, and the Peruvian government, represented by the National University of Engineering (UNI), are working together with the objective to estimate seismic risks, hazards and vulnerabilities in Lima, the capital of Peru, and two other cities of the country. In particular, the results of this study will focus on Lima city only.

Lima is situated in the central coast of Peru, bordered by the Pacific Ocean, in a zone of high seismic activity known as the Ring of Fire.

Lima has a long history of being hit by strong earthquakes, the latest big event occurred in 1974. At that time, severe damage in a few small scattered areas was reported [1], which suggests a soil effect may have occurred in these areas.

Due to the high seismicity of this area and to the rapidly growing urbanization, a study of the soil conditions that characterize areas of low or high probability to be affected by earthquakes is of great importance, especially in places like Lima that have scarce information as to deep soil structures.

In this context, the study aims to obtain a primary idea of the Lima's soil structure down to depths extending to the bedrock, which will make possible future analysis of the dynamic characteristics of the surface soils of Lima

To accomplish this objective, small and large microtremor array measurement campaigns were carried out at eight places in the city that are the most representative of the soil dynamic behavior and demographic aspects; for the large array measurements new long-period sensors of microtremor were introduced.

2. Area of Study

We have carried out microtremor array measurements at eight places distributed in the Lima Metropolitan area. Fig. 1 shows a map of the Lima's surface soil distribution estimated in 2005 [9], and the places where the microtremor arrays were measured.

Table 1 shows a list of the measured places with details of their exact location.

Corresponding author: Diana Calderon, PhD Candidate, research fields: microtremor array measurements, seismometer array measurements, estimation of dispersion curves, inversion of dispersion curve alone and joint-inversion of receiver function and dispersion curve. E-mail: diana_c@graduate.chiba-u.jp.

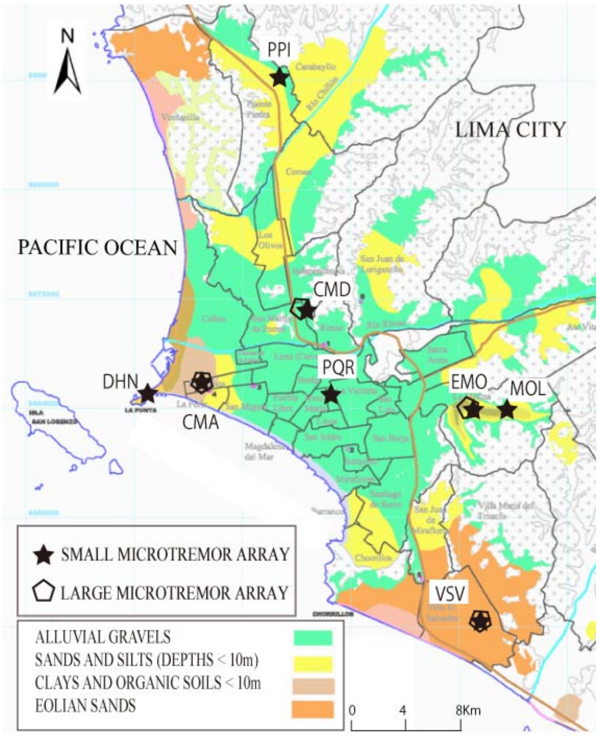

Fig. 1 Location of microtremor arrays over the soil distribution map [9].

Table 1 Symbols and location of the measured points in this study.

ID	District	Institution	Latitude	Longitude
CMD	Rimac	UNI-CISMID	-12.013995°	-77.050580°
PQR	Lima Cercado	Central Park of Lima	-12.071319°	-77.033171°
DHN	Callao	Direction of Hydrograph	-12.064413°	-77.155016°
CMA	Callao	School “Maristas”	-12.060734°	-77.123570°
VSV	Villa El Salvador	School “6066”	-12.213421°	-76.938803°
PPI	Puente Piedra	Private House	-11.852260°	-77.074035°
EMO	La Molina	University La Molina	-12.082051°	-76.938943°
MOL	La Molina	Municipality	-12.077994°	-76.917278°

3. Microtremor Array Measurements

Two measurement campaigns were carried out, the first consists of eight sets of small arrays (Fig. 1); each set is made of linear arrays of 0.5 and 2 m sensor distance, and circular arrays of 10, 20 and 45 m radius.

The second campaign consists of four sets of large arrays, each set made of circular arrays of 100, 200, 500 and 1000 m radius.

In almost all the arrays six sensors were used except in CMA and in VSV where four sensors were used.

The objective of these arrays measurements was to estimate the soil profile characteristics, such as the shear-wave velocities and the thicknesses of each layer constituting the soil profile.

3.1 Implementation of Microtremor Sensors

Two types of sensor of microtremors were introduced to Peru through this project. One was the well-known GEODAS sensor (with natural period of 1 second), which we used to measure small size arrays, with radius less than 50 m; in these arrays the sensors were connected with cables to the data acquisition hardware.

The other was a sensor produced by Tokyo Sokushin Company with a natural period of 5 seconds. These sensors were used for large array measurements because no cable is needed to make the measurements; the sensors are synchronized by a GPS device.

4. Method of Analysis

4.1 Phase-Velocity Dispersion Curve

We used two methods to construct the dispersion curve; the high resolution F-k method [2], and the Centerless Circular Array (CCA) method [3].

4.1.1 The high Resolution F-k Method

The calculation of the dispersion curve through the F-k method is based on the calculation of wave-numbers of predominant waves for different frequencies; these wave-numbers are obtained from the signal power spectrum that is the representation of the signal power in a wave-number space. From Ref. [2] the formulation of the power spectrum is given by:

$$P'(k_x,k_y,f)=\left[\sum_{n,m=1}^{K}q_{mn}(f)\cdot\exp\{-i2\pi[k_x(x_n-x_m)+k_y(y_n-y_m)]\}\right]^{-1} \tag{1}$$

where P' is the F-k power spectrum, K is the number of channels, k_x is the wave-number in the **x**-direction, and k_y is the wave-number in the **y**-direction, and f is the frequency. ($\mathbf{x_n}$, $\mathbf{y_n}$) are the coordinates of the sensor n, and ($\mathbf{x_m}$, $\mathbf{y_m}$) are the coordinates of sensor m. $q_{mn}(f)$ is the inverse of a Hermitian matrix whose elements are formed by the cross spectrum between channels m and n. This cross-spectrum or cross-power spectrum is calculated using the direct segment method. According to this method, the value of data point L in each channel is divided into M mono-overlapping blocks of N data points. That is, $L=M\cdot N$. If the Fourier transform of the data in the l_{th} segment, m_{th} channel and frequency f is $S_{ml}(f)$,

$$S_{ml}(f)=(N)^{-1/2}\sum_{r=1}^{N} a_r N_{m,r-(l-1)N} e^{irf} \tag{2}$$

$m = 1,\ldots..,K$

$l = 1,\ldots\ldots,M$

where a_r are weights which are used to control the shape if the frequency window used in estimating the cross-power spectral density, and for simplicity it is assumed that $a_r=1$, $r=1,\ldots.,N$.

Then the estimate of the cross-power spectrum is

$$p_{mn}(f)=\frac{1}{M}\sum_{l=1}^{M} S_{ml}(f)S_{nl}^{*}(f) \tag{3}$$

$m, n =1,\ldots,K$

*: conjugate

Another important parameter is the coherence of the noise between seismometers m and n, $coh_{mn}(f)$, given by

$$coh_{mn}(f)=\frac{E[p_{mn}]}{\sqrt{E[S_m^2]}\sqrt{E[S_n^2]}} \tag{4}$$

where E is the ensemble average and $0 <|coh_{mn}(f)| \leq 1$.

The physical significance of $coh_{mn}(\mathrm{f}) = 0$ is that the spectral components of the noise, at frequency f, observed on the m_{th} and n_{th} are uncorrelated. In addition, if $coh_{mn}(f)=1$ then the spectral components of the noise, at frequency f, observed on the m_{th} and n_{th} sensors are linearly related to each other.

4.1.2 The Centerless Circular Array Method

Cho et al. [6, 7] pointed out that the theory they developed is formulated in such a way that the microtremor records, obtained with sensors placed around the circumference of a circle, are first integrated into intermediary quantities called “spectral ratios” before information on the phase velocities is extracted from them.

This can be explain by considering a circular seismic array of radius r in a field of microtremors, whose vertical component is $\mathbf{z}(t,r,\theta)$, expressing their time histories in Fourier series with respect to θ

$$Z_0(t,r)=\int_{-\pi}^{\pi} z(t,r,\theta)d\theta \tag{5}$$

$$Z_1(t,r)=\int_{-\pi}^{\pi} z(t,r,\theta)\exp(i\theta)d\theta \tag{6}$$

Their power spectral densities are denoted by $G_{z0z0}(r,r;\omega)$ and $G_{z1z1}(r,r;\omega)$ respectively (where ω is the angular frequency), and are represented as:

$$G_{z0z0}(r,r;\omega)=4\pi^2\sum_{i=1}^{M} f_i(\omega)J_0^2(rk_i(\omega)) \tag{7}$$

$$G_{z1z1}(r,r;\omega)=4\pi^2\sum_{i=1}^{M} f_i(\omega)J_1^2(rk_i(\omega)) \tag{8}$$

where M is the number of Rayleigh wave modes present, $f_i(\omega)$ is the intensity of the i_{th} mode, $J_0()$ and $J_1()$ are the zeroth-and first-order Bessel functions of the first kind respectively, and $k_i(\omega)$ stands for the wave number of the i_{th} mode. The spectral ratio is given by

$$\frac{G_{Z0Z0}(r,r;\omega)}{G_{Z1Z1}(r,r,\omega)}=\frac{\sum_{i=1}^{M}\alpha_i(\omega)J_0^2(rk_i(\omega))}{\sum_{i=1}^{M}\alpha_i(\omega)J_1^2(rk_i(\omega))} \tag{9}$$

where

$$\alpha_i(\omega)=f_i(\omega)/f(\omega), \qquad f(\omega)=\sum_{i=1}^{M} f_i(\omega)$$

is the power partition for the i_{th} mode.

Once the spectral ratio on the left-hand side is known from measurements records, it is possible to estimate rk by inverting the above equation for each frequency ω. Since r is known, one can obtain the wave number k, and finally the phase velocity $c = \omega/k$.

4.2 Array Dimension

Tokimatsu in Ref. [5] stated that to obtain reliable results of phase velocities, the effective wavelength range is related with the sensor distance as follows

$$D_{max} > \lambda_{max}/3$$
$$D_{min} < \lambda_{min}/2$$

which can be written as:

$$2D_{min} < \lambda < 3\ D_{max}$$

where D_{max} and D_{min} is the maximum and the minimum sensor distance respectively, and λ is the wavelength.

4.3 Inversion Analysis

Several methods of inversion are available, from the conventional least square methods to the genetic algorithm method. We used the genetic algorithm (GA) approach [8] because it has become very popular; this method in comparison with the typical least square method has the advantage in which a search can be done for an optimal solution in the local and global space.

As input data the GA approach requires the number of layers and an initial model which consists of a range of shear wave velocities and thicknesses for each layer. In this study the number of layers adopted was from four to six, and the initial models were chosen in some cases based on available boring data and shear-wave velocity profiles that were estimated by surface wave methods, such as the Multichannel Analysis of Surface waves (MASW) and the Microtremor Array Measurement (MAM).

The number of generations and number of populations for the inversion process was from twenty to fifty.

5. Inverted Profiles

Applying the methodology explained above we have calculated the phase velocity dispersion curves for the eight microtremor arrays measured in Lima city (Fig. 2). Following Tokimatsu [14] we have considered the effect of higher modes in the inversion process since the dispersion curves showed an inversely dispersive trend.

Using the dispersion curves we have estimated the shear-wave velocity profiles shown in Fig. 3. The inversion process was carried out several times due to the non-uniqueness solution related to this process; and a total of five cases of results are plotted in the figure.

In order to verify the profiles we have calculated the H/V spectra of the Rayleigh waves for the fundamental mode and compared it to the observed H/V spectra measured at each place (Fig. 4).

A discussion to the estimated profile at each place is presented below. For depth to the bedrock we understand the depth at which the shear velocity is about 3000 m/s.

5.1 Estimated Profile at PPI (Puente Piedra District)

This district is located in the northern part of Lima city; according to the microzonation study [9] at shallow depths the sediments are from loose to dense fine sands, silty clays and landfills. In other parts there is a gravelly material composed of medium dense poorly-graded gravels with clays and silts. Underlying these materials there are poorly-graded sands of medium to loose compactness. According to the zonation map most of the urban area of the district is in the most competent zone from the seismic and geothecnical point of view. It is important to point out that the previous microzonation study at this place was made based on shallow soil exploration data.

The estimated shear-wave velocity profile found from the inversion analysis is shown in Fig. 3a. The maximum size of the arrays was a circle of 28 m radius. Based on the shear-wave velocity profile and the boring data near PPI a description of the soils is attempted. There is a shallow layer of about 5 m with soils of low velocity that can be regarded as loose sands, underlying this soil until about 60 m the soil velocity increases to values that may account for dense sand, down to 60m the soil velocity may correspond to a dense gravel deposit.

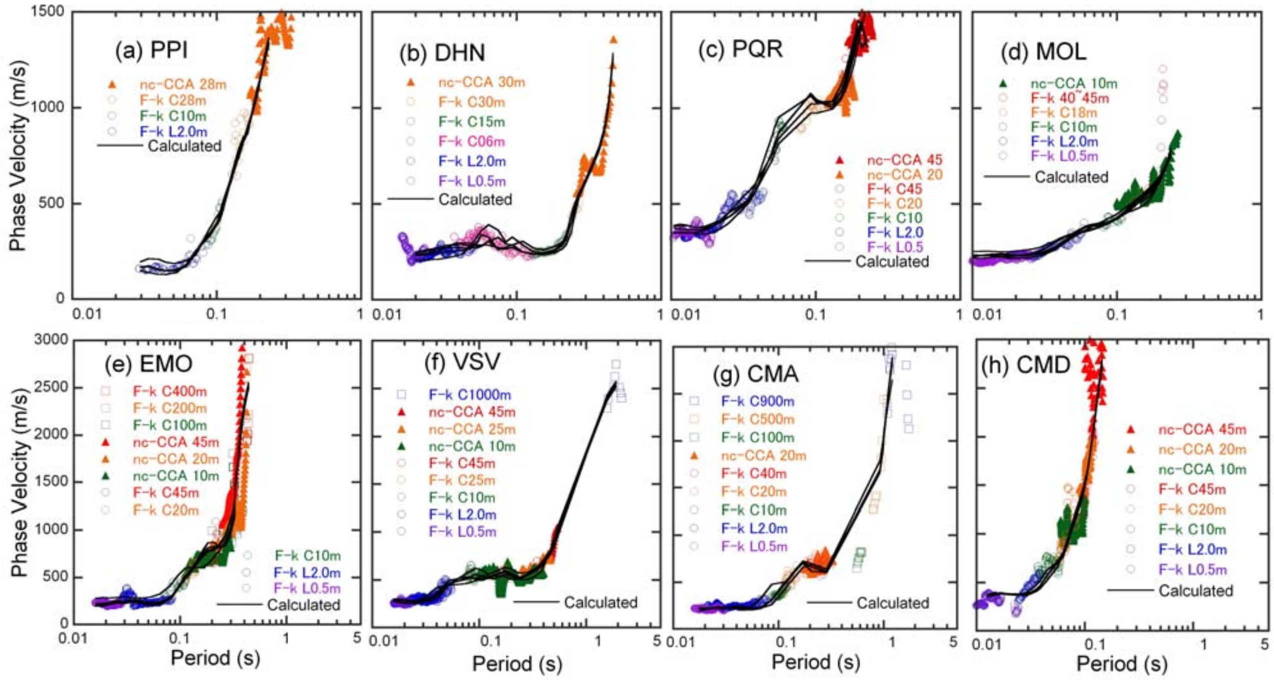

Fig. 2 Observed and calculated dispersion curves.

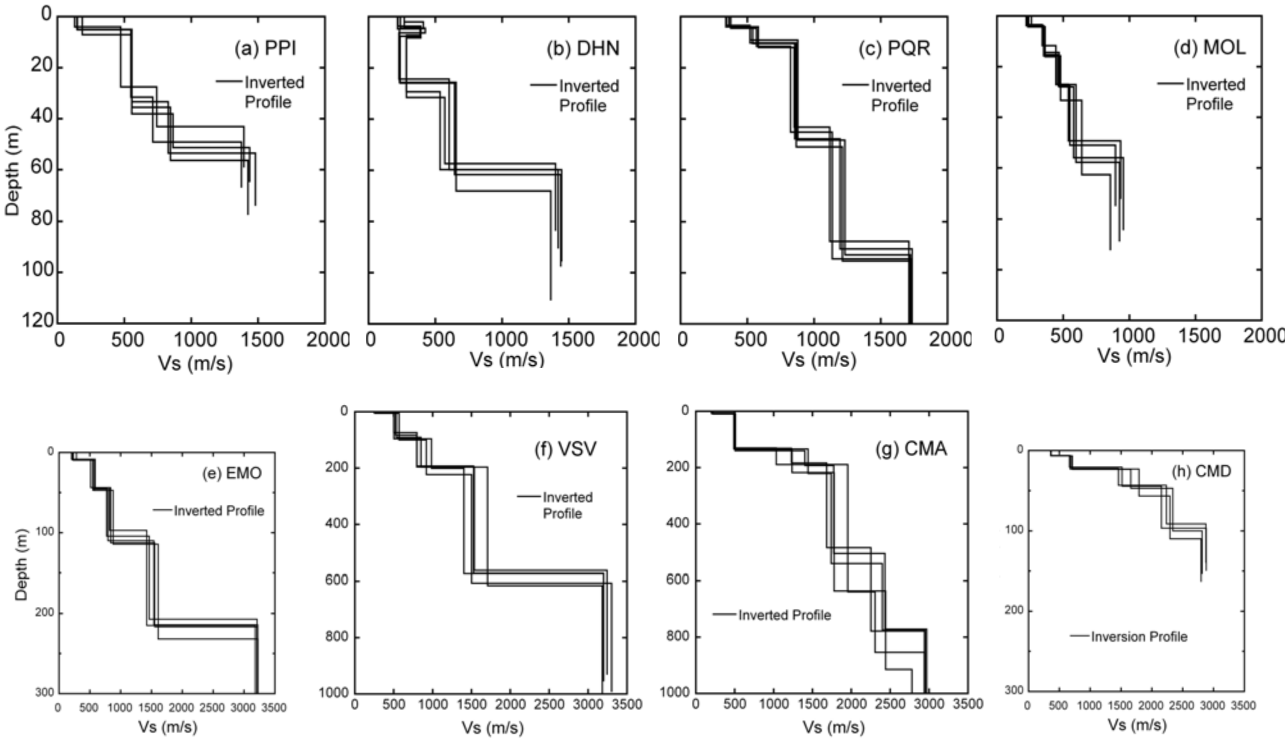

Fig. 3 Estimated shear-wave velocity profiles.

5.2 Estimated Profile at DHN (The El Callao District)

This place is located in the border between the El Callao district and the La Punta district.

The geological formation at this place is particular because the shallow materials have been taken by the sea from the cliffs located at the southern districts of Miraflores and Chorrillos [13].

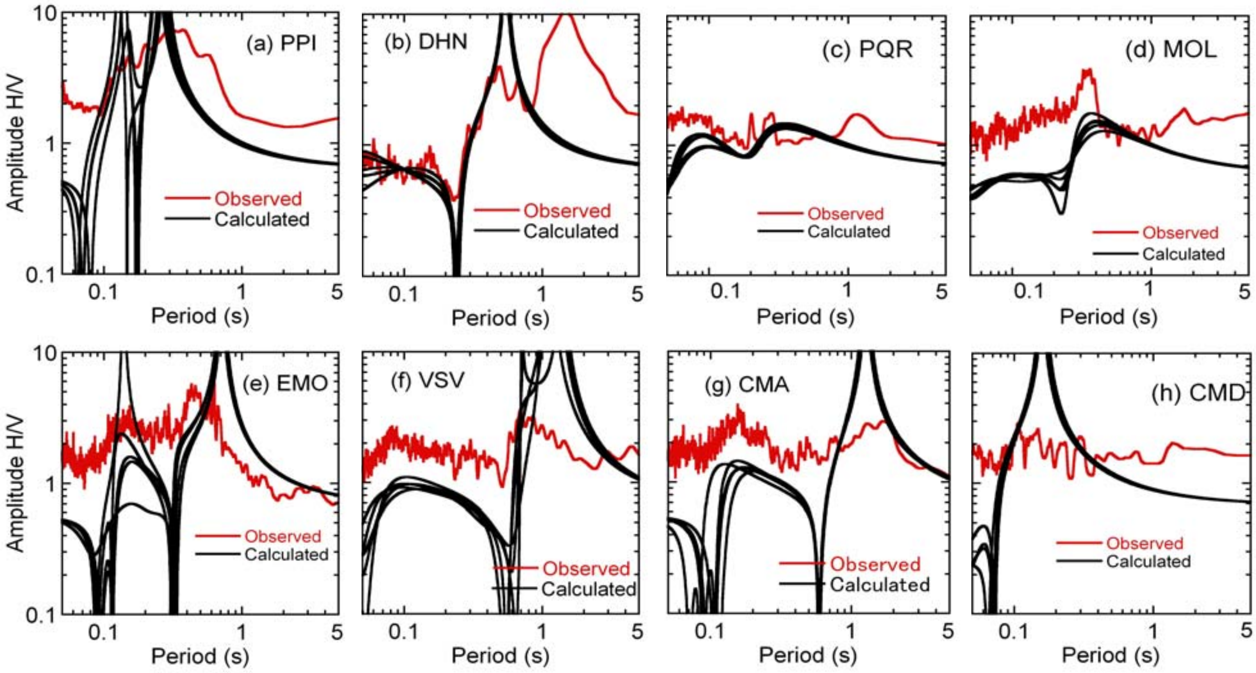

Fig. 4 Observed and calculated H/V spectra.

The soil profile here consists of a poorly-graded gravel layer overlying a dense sand deposit until about 15 m. Under this layer there is a fine sand deposit with silts and clays, organic clayey silt, and stiff high plasticity clays with about 20 m thickness. Finally, there is a dense sandy gravel deposit [9].

According to the micozonation study of 2005 [9] DHN is located at zone 4, which is characterized as the less competent soils that show high amplification and large period of vibration.

The estimated shear-wave velocity profile is shown in Fig. 3b. Based on this profile and boring data near DHN, we have observe that at few meters depth there is a change of velocities from large to low values that may be caused for the heterogeneous conformation of the deposit, underlying there is a layer with velocities that may account for stiff clays or silts until 35 m depth, the last layer estimated with the arrays shows a velocity value that is coherent with the dense gravel mentioned in Ref. [9].

5.3 Estimated Profile at PQR (Lima District)

Lima district is at the center of the Lima Metropolitan area. Stratigraphically the alluvial deposit covers most of the city soils and it is expected that the thickness to the base rock here be about 200 m [9].

The soil profile consists of a very shallow layer (about 1 m) of silts that overlay the conglomerate of the Rimac River. This conglomerate is medium dense at shallow depths and increases its compactness with the depth.

Based on the shear-wave velocity profile shown in Fig. 3c, there is a shallow layer of less than 5 m that may correspond to silt deposits, after this the soil velocity increases gradually until 100 m, that is the maximum depth of the estimated profile, the velocity values until this depth may account for the conglomerate.

5.4 Estimated Profile at MOL (The La Molina District)

MOL is one of the two places measured in the La 624 lina district. It is located in front of the district Municipality.

The land surface of the district is heterogeneous, varying from outcrops in the slope of the hills to colluvial soils in the lowlands near to the hills; and large fluvial-alluvial deposits in the plains of the valley at large distances from the hills. There are also areas covered by eluvial materials, specifically eolian sands deposited in large amounts in the depressions and on the hillsides. These heterogeneous materials make the stratigraphy of the area to be very variable [11].

According to the microzonation study [11] MOL is in the zone II that corresponds to colluvial gravel soils and poorly-graded sand layers of moderate thickness.

The estimated shear-wave velocity profile is shown in Fig. 3d. We can observe that the velocities increase gradually until about 30 m depth; from this depth to about 60 m (maximum estimated depth) there is significant change in the velocity value, which can be due to the presence of a very dense gravel deposit.

5.5 Estimated Profile at EMO (National Agrarian University Campus)

EMO is the second place of measurement in the La Molina district. It is located inside the campus of the National Agrarian University.

The shear-wave velocity profile estimated is shown in Fig. 3e, we can observe the gradual increase of the velocity until approximately 100 m depth. From this depth there is a thick deposit with a relatively large value of velocity of very dense gravels until it reaches the bedrock at the depth of about 200 m.

From the microzonation study of this district [11] four seismic zones are identified in the Campus; it means that there is high variability on the soils; therefore, an averaged estimated profile may fail to characterize a unique point of the array at large depths.

The effect of this soil variability can be observed in the mismatch of the second peaks of the H/V spectra (Fig. 4e).

5.6 Estimated Profile at VSV (Villa El Salvador District)

This district is located in the south of Lima, and consists of a coastal border composed by eolian sea deposits; plain areas covered by gravel and eolian sands transported from the Lurin River and from the beaches nearby; and a hill called Lomo de Corvina composed of eolian sands, transported during the Pleistocene epoch by winds from the adjacent beach [10].

Lithostratigraphic units that outcrop in the hill Lomo de Corvina and surroundings consists of sedimentary rocks of the early cretaceous epoch represented by the Pamplona formation, sea deposits and eolian deposits of the quaternary period [10].

According to the microzonation study in Ref. [10], the area of study belongs to zone III, and consists of loose eolian sand deposits of large depths and sea deposits. The shallow layer consists of landfill until 2 m depth, underlying this material there is a very thick poorly-graded medium to fine sand of loose compactness that increases with the depth.

Fig. 3f is the shear-wave velocity profile, from which we observe that there is a low velocity for the very few meters, this velocity accounts for a shallow soft sand deposit. From 10 m to 200 m depth the velocity increases gradually, with values that are characteristics of a very dense sand. Finally just above the bedrock, there is a layer with a thickness of 400 m with a uniform velocity layer of a very stiff soil or rock. The total depth to the bedrock is about 600 m.

5.7 Estimated Profile at CMA (“Marianistas” School)

This place is located in the Bellavista district that belongs to the Callao Province.

It is on the alluvial deposits that covers most of the central area of Lima city. Contrary to the soils in central Lima, the soils forming this deposit are fine.

These are clays of 15 m thickness that were deposited by the Rimac River during the Holocene epoch when the river sedimentation power had decreased [13].

According to Ref. [9] the soil conformation around CMA consists of soft and stiff organic clays of high plasticity, high humidity of about 10 m depth.

Underlying these materials there are fine soils of large depths such as clays of low and high plasticity, organic clays, and semi-dense silts until the alluvial gravel characteristic of Central Lima is found.

The estimated shear-wave velocity profile presented in Fig. 3g, shows a soft soil layer that is very shallow and may account for the organic soils described above. The next layer is of about 150 m, with a velocity characteristic of very stiff soils. It is noticeable that from 200 m down the layers show an increasing velocity and the thickness of these layers is very random. However, the depth to the bedrock can be regarded as about 800 m.

5.8 Estimated Profile at CMD (CISMID–Center for Seismic Research and Disaster Mitigation, UNI)

CISMID is a Research Center that belongs to the National University of Engineering. It is located in the alluvial deposit that covers most of the area of Lima city, and near the formation Puente Inga, which consist of igneous rocks. Due to the short distance to the hills the soils found here are stiff gravels at few meters depth.

The estimated shear-wave velocity profile is presented in Fig. 3h, it consists of a layer with a thickness of about 20 m in which the velocities are characteristics of a very stiff gravel. At this depth the velocity shows a sudden increase which may account for the presence of weathered rock, this increase in velocities continues until it reaches the bedrock at approximately 100 m depth.

It is worth pointing out that profile at this place is the more rigid and shallow among other profiles estimated in this study; therefore, it can be regarded as a reference site for future amplification analysis.

6. Discussion

We have obtained deep soil velocity profiles at eight points in Lima city; four of them with depths extending to the bedrock while the other four with depths reaching approximately 60 m, with velocities between 1000 to 1500 m/s. In order to validate the resulting profiles it is recommended to carry out PS loggings campaigns.

Among all the estimated profiles, the soil profile at CMD shows the shallowest depth to the bedrock; while the soil profile at CMA shows the largest depth to the bedrock. For future amplification studies in Lima, CMD could be regarded as a reference site.

In the dispersion curves of VSV and CMA (Fig. 2f and Fig. 2g respectively), there is a large range of periods where there are scarce or no values of velocities. This problem is studied particularly at VSV in Fig. 5; here we can observe that for the period range from 0.5 s to 1.5 s the dispersion curve is discontinue; moreover, when we look at the Fourier spectrum we observe that for the same range of periods the power of the wave is the minimum; therefore, the reason of the lack of points in the dispersion curve in that range of periods is the low power of the microtremors. A solution to complete the dispersion curve may be installing seismometers in an array configuration in order to analyze surface waves from earthquake records.

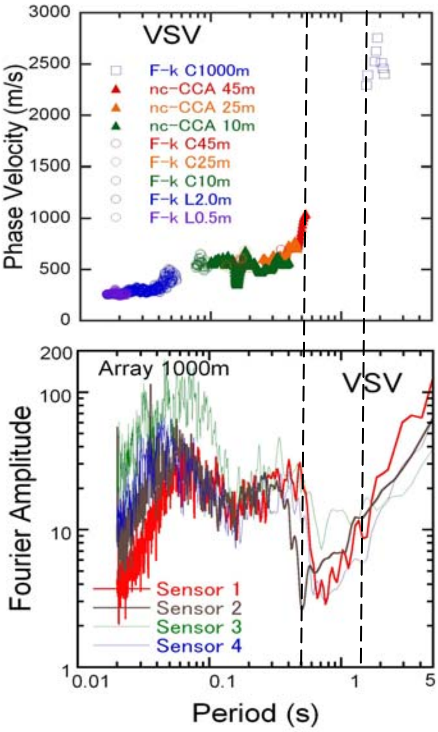

Fig. 5 Observed phase velocity dispersion curve and Fourier Spectrum for the VSV array.

From the H/V spectra at EMO (Fig. 4e), we could observe that the second peak of the calculated H/V spectrum is for a period larger than in the observed spectrum; to understand this behavior we have studied the spatial variability of soils at EMO.

Fig. 6 shows the distribution of the six sensors used in the array of 400 m radius at EMO. As we can observe the sensors are over three different types of soils. To verify the effect of the soil spatial heterogeneity we calculated the H/V spectra of three sensors shown in Fig. 7, sensor number six’s H/V spectrum showed a second peak in a period larger than in sensor number one and three’s H/V spectra.

For the mentioned above, we can conclude that the difference between the H/V spectra at EMO (Fig. 4e) is due to the spatial variability of soils inside the array, which may also cause low accuracy in the estimated profile.

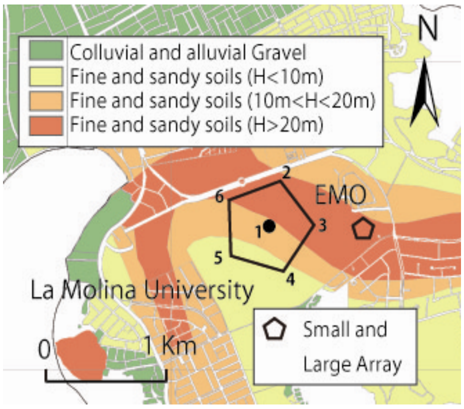

Fig. 6 Large array of 400m radius at EMO over the soil distribution map of the La Molina district [11].

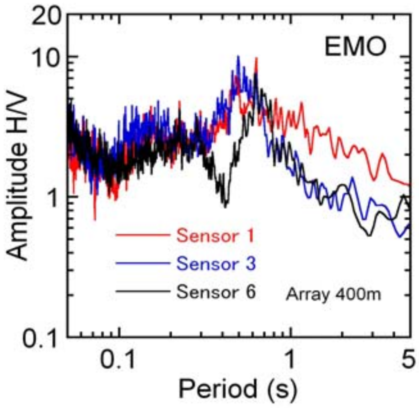

Fig. 7 Various H/V spectra of the array of 400m at EMO.

7. Conclusions

We have carried out small and large arrays measurements over Lima city in order to estimate deep soil profiles; in the process we have found the next conclusions:

a. We have obtained four profiles with depths that extend to the bedrock. The other four profiles reach velocities from 1000 to 1500 m/s at about 60 m depth.

b. The shallowest profile with 100 m depth to the bedrock is CMD. Thus, this place could be regarded as a reference site for future soil amplification studies.

c. We have identified a range of periods from 0.5 to 1.5 s at VSV where the signal power is low; and we have found that this is related to the discontinuity of the dispersion curve.

d. In order to complete the dispersion curves in the range of periods where the signal is low, it is recommended to make an array of seismometers, because seismic records contain surface waves with high signal to noise power.

Finally, it is recommended to perform PS logging in the places where arrays were measured in order to verify the estimated profiles.

Acknowledgement

We would like to express our gratitude to Eng. Miguel Diaz for his help in carrying out the surface wave measurements (MASW); the data of these measurements was very useful for the initial model of the inversion analysis.

References

[1] A. F. Espinosa, R. Husid, S. T. Algermissen and J. de las Casas, The Lima earthquake of October 3, 1974: Intensity distribution, Bulletin of the Seismological Society of America 67 (5) (1977) 1429-1439.

[2] J. Capon, High-resolution frequency-wavenumber spectrum analysis, Proc. IEEE 57 (8) (1969) 1408-1418.

[3] T. Tada Cho and Y. Shinozaki, A new method to determine phase velocities of Rayleigh waves from microseisms, Geophysics 69 (2004) 1535-1551.

[4] T. Tada., I. Cho and Y. Shinozaki, Analysis of Love-wave components in microtremors, in: Joint Conference

Proceedings, 7th International Conference on Urban Earthquake Engineering (7CUEE) & 5th International Conference on Earthquake Engineering (5ICEE), Center for Urban Earthquake Engineering, Tokyo Institute of Technology, 2010, pp. 115-124, available online at: http://staff.aist.go.jp/ikuo-chou.

[5] K. Tokimatsu, Geotechnical site characterization using surface waves, the first international conference on earthquake geotechnical engineering IS-Tokyo, 1995, pp. 1333-1368.

[6] I. Cho, T. Tada, and Y. Shinozaki, A generic formulation for microtremor exploration methods using three-component records from a circular array, Geophys. J. Int. (165) (2006a) 236-258.

[7] I. Cho, T. Tada and Y. Shinozaki, Centerless circular array method: Inferring phase velocities of Rayleigh waves in broad wavelength ranges using microtremor records, J. Geophys. Res. (111) (2006b).

[8] D. E. Goldberg, Genetic algorithms in Search, Optimization, and Machine Learning, Addison-Wesley Publishing Company Inc., 1989.

[9] Cismid, Study of the Vulnerability and Seismic Risk in 42 districts of Lima and Callao, Japan-Peru Center for Seismic research and Disaster Mitigation, National University of Engineering, Lima, Peru, 2005. (in spanish)

[10] Cismid, Seismic Microzonation of Villa El Salvador, Japan-Peru Center for Seismic research and Disaster Mitigation, National University of Engineering, Lima, Peru, 2010. (in Spanish)

[11] Cismid, Seismic Microzonation of the La Molina, Japan-Peru Center for Seismic research and Disaster Mitigation, National University of Engineering, Lima, Peru, 2010. (in Spanish)

[12] Cismid, Seismic Microzonation of Chorrillos, Japan - Peru Center for Seismic research and Disaster Mitigation, National University of Engineering, Lima, Peru (2010) (in Spanish).

[13] C. E. Huaman, Seismic Microzonation of La Punta and El Callao, Thesis, Faculty of Civil Engineering, National University of Engineering, Lima, Peru, 1991.

[14] K. Tokimatsu, Effects of multiple modes on rayleigh wave dispersion characteristics, Journal of Geotechnical & Geoenvironmental Engineering 118 (10) (1992) 1529-1543.