Vs PROFILES, H/V SPECTRA AND GEOTECHNICAL CLASSIFICATION AS PROXIES OF THE SOIL DYNAMIC BEHAVIOR IN LIMA, PERU

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Abstract

Starting in 2010, continuous revisions of the Microzonation map, originally presented in 2004, have been conducted by the Japan Peru Center for Earthquake Engineering Research and Disaster Mitigation (CISMID) and currently include data of the dynamic and vibrational characteristics of the underlying soil obtained by geophysical tests, such as single point microtremor measurements, Multichannel Analysis of Surface Waves (MASW) test and microtremor arrays.

Within the framework of this research, ellipticity curves of the fundamental mode of Rayleigh waves were estimated from shear-wave velocity profiles reaching 30 m of exploration and those including the deeper part. Comparison of the aforementioned curves with the H/V spectrum from microtremor measurements conducted in their vicinities show that the shallow 30 m are not representative of the overall dynamic behavior of the underlying soil in all cases. This discrepancy in the spectral shape and peaks of the predominant period of the expected amplification are, to some extent, associated to the particular geomorphological formation considered and the influence of the impedance ratio of deeper layers.

Keywords: shear-wave velocity profile; fundamental period; ellipticity curve; transfer function; Lima

1. Introduction

Peru, located in the central part of the western coast of South America, belongs to the Pacific Ring of Fire where most of the seismic activity in the world is concentrated. Its capital, Lima, is situated in the west-central part of the country. Throughout its history, this city has experienced numerous migration processes that have led to the encroachment of previously unpopulated places in the outskirts of the historical metropolitan area and, as a consequence, centralizes the third part of the total population, approximately ten million people.

Due to its social and economic importance, in addition to the analysis of the accumulated seismic energy in front of the coasts of Lima which may cause an earthquake of a magnitude of 8.5, in the last 15 years, several seismic microzonation studies have been carried out for the capital. In 2004 [1], on request of the Peruvian Association of Insurance Companies (APESEG), the Japan Peru Center for Earthquake Engineering and Disaster Mitigation (CISMID) developed the first microzonation map for Metropolitan Lima, mainly considering geotechnical information obtained from soil pits, Standard Penetration Test (SPT) and Light Dynamic Penetrometer (DPL) tests, and data of the fundamental period of vibration of the underlying soil, estimated by means of the H/V spectral ratio from single point microtremor measurements. Since 2010, constant revisions of the aforementioned map are being conducted by CISMID; financially supported by the Ministry of Housing and the Ministry of Economy, within the framework of the Nuestras Ciudades and the 0068 Programs, respectively, which considered the update of the information of, in average, five districts per fiscal year. As a result, a more detailed geotechnical and seismic microzonation maps are generated for the districts reanalyzed to date, by means of the inclusion of microtremor array measurements, Multichannel Analysis of Surface Waves (MASW) tests and complementary tests of the types carried out in 2004.

Given the fact that shallow, i.e. within the first 30 m of exploration, and relatively deep soil information is available in the form of shear-wave velocity (Vs) profiles, it is the objective of this research to evaluate their impact in the vibrational properties of the underlying soil. Therefore, comparisons of their ellipticity curves of the fundamental mode of Rayleigh waves with the closest microtremor single point measurement are conducted, for the different type of soil formations in Metropolitan Lima, and presented in the following sections.

2. Geological and Geotechnical Maps of Metropolitan Lima

In terms of its geomorphology, the city of Lima can be subdivided into the low lands of the Andes Cordillera, the coastal plain, the coastal headlands and the Holocene alluvial floodplain [2, 3]. On the other hand, the city can be mainly understood as the result of the erosional process caused by the Chillon, Rimac and Lurin rivers. Thus, the majority of the metropolitan area is built over the alluvial materials originated by the transportation of gravel, with boulders of medium size, along with sandy and silty-clayey lens within these deposits. In addition, eolian and marine materials can be encountered in the northern, southern and western regions of the city, as well as isolated areas of organic soils [4] (Fig. 1a).

As a result of the revision of the microzonation map, geotechnical conditions, in the form of the soil type map, were also reexamined. Fig. 1b shows the distribution of soil deposits of the capital divided in four zones. Thus, Zone I is related to the stiffest materials found in Metropolitan Lima, which consist of the rocky outcroppings in the eastern part of the city, as well as medium dense to dense alluvial gravel, commonly referred to as conglomerate, and dense sandy materials from the alluvial fan of the Rimac river. Zone II is related to medium dense sands and stiff clays/silts deposited as a result of the erosive effects of Chillon and Lurin rivers. On the other hand, loose to medium dense sand and soft to stiff clay/silt are classified as Zone III and are located, in a minor extension, in the northern, central and southern part of the city. Deposits with low mechanical properties, such as loose eolian sand, marine sand, swampy and liquefiable soils, as well as the populated steep slopes, are considered within Zone IV. Finally, punctual solid waste deposits are classified as Zone V.

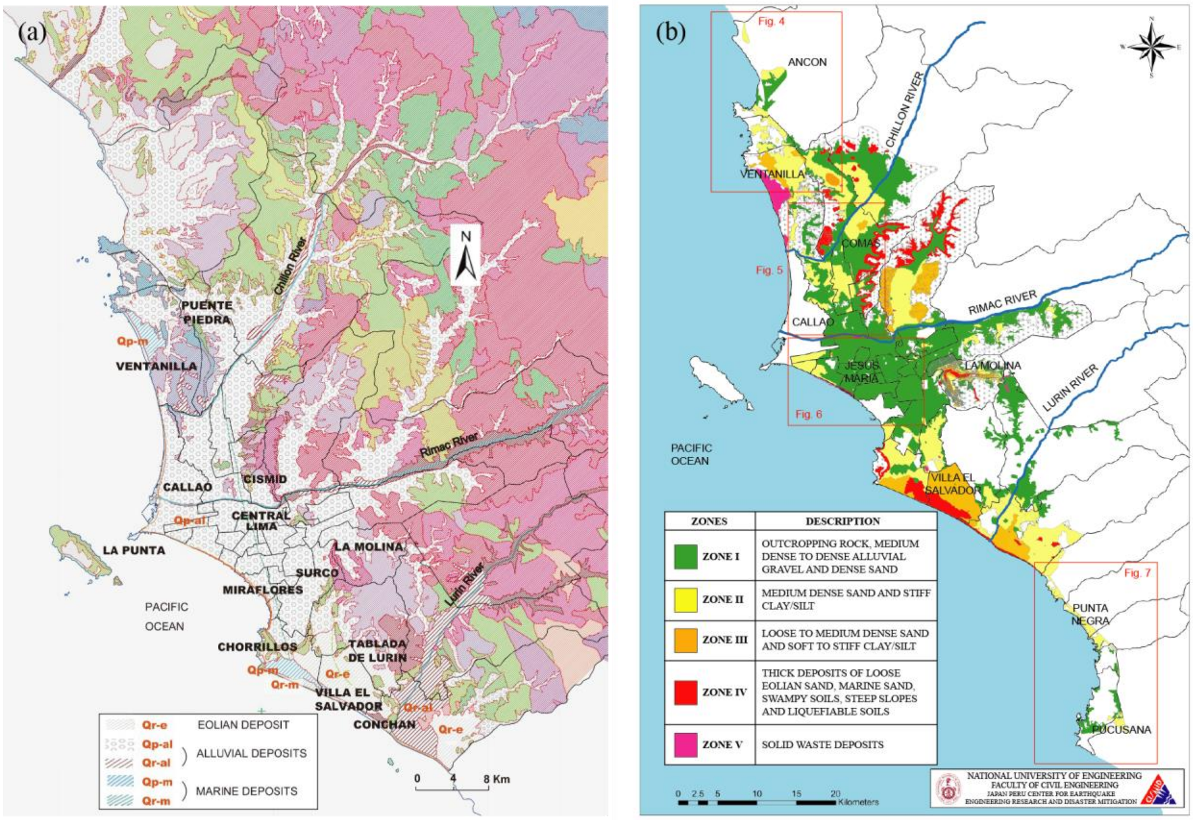

Fig. 1 – (a) Geological map, (b) Soil distribution map of Metropolitan Lima

3. Geophysical Field Surveys and Geophysical Maps

In order to estimate the dynamic and vibrational properties of the soil substructure throughout Metropolitan Lima, different types of geophysical field surveys were performed. In the first place, due to its ease of implementation, Multichannel Analysis of Surface Waves (MASW) tests [5] were adopted. Thus, within the framework of this study, MASW tests consisted on the deployment of 24 4.5 Hz-vertical motion receivers along a seismic line with a 10 kg-sledge hammer as the active source at each side of the line. Analogue signals for each of the receivers were digitalized in a multichannel seismograph, visualized in a portable computer for a preliminary processing and stored. The analysis of the waveforms in the frequency domain allowed the transformation into a velocity spectrum in which the dispersion curve for the fundamental mode is very likely to be inferred (Fig. 2a) [6] and permitted the reliable estimation of shear-wave velocity (Vs) profiles of, in average, 30 m depth.

On the other side, microtremor arrays measurements were implemented with the objective of estimating deeper Vs profiles when compared to those obtained by the MASW method. Recordings of low amplitude vibrations, generated from a variety of sources, are capable to reproduce the dispersive characteristics of surface waves by the identification of their phase velocities. In this study, we made use of continuous records in triangular arrays, with vertical-component sensors placed at each of the vertices, and an additional one in the center. The sensors employed in the observation of microtremors were of two types; first, for arrays smaller than 50 m radius, the moving-coil velocimeters model CR 435-1s with a natural period of one second connected to the acquisition system GEODAS 15HS portable logger, manufactured by Anet Co., Ltd., and, for arrays of larger size, the autonomous servo velocimeters CV-374-AV2 assembled by Tokyo Sokushin Co., Ltd. with synchronized GPS devices.

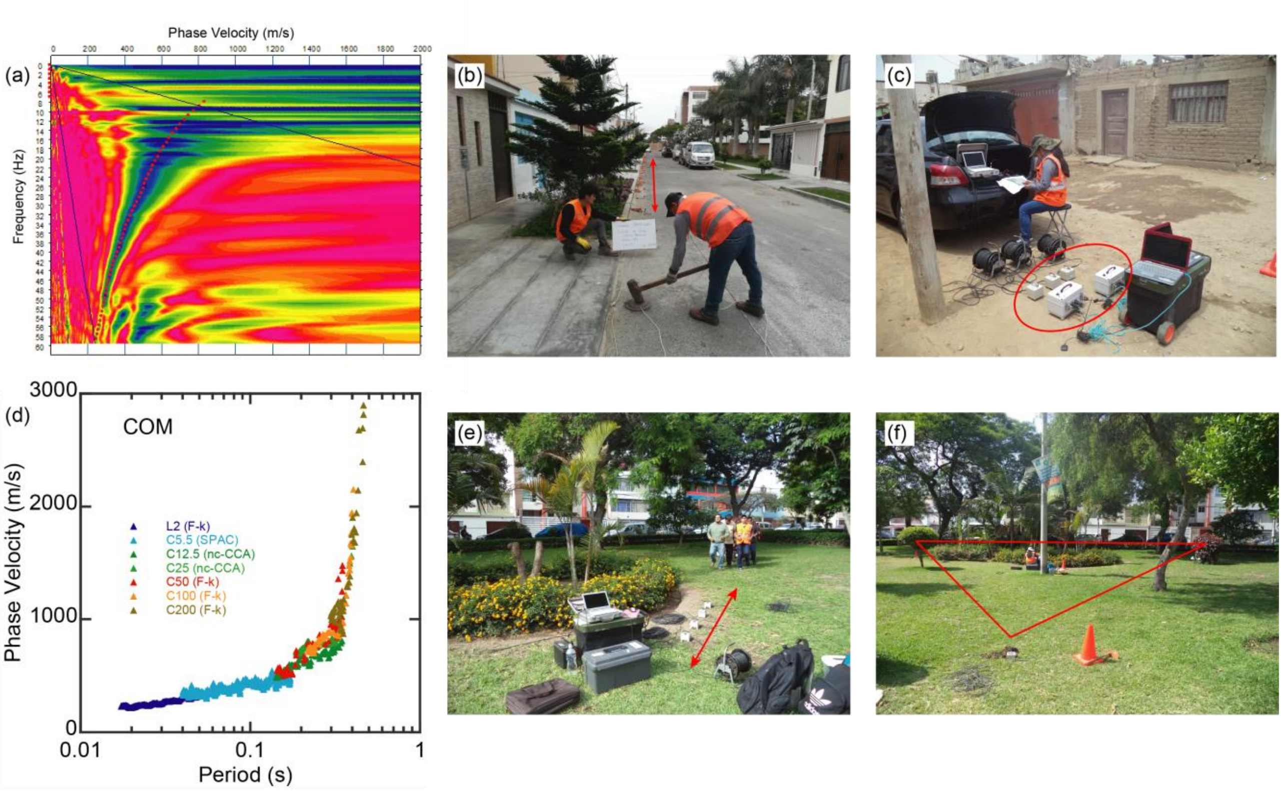

Fig. 2 – (a) Dispersion curve from MASW test, (b) MASW field survey, (c) Microtremor single point measurement, (d) Dispersion curve from microtremor arrays, (e) Linear microtremor array, (f) Circular microtremor array

In order to extract reliable information regarding the phase velocity variation for each of the conducted arrays (Fig. 2b), the high-resolution frequency-wavenumber (F-k) method [7], that makes use of arrays of arbitrary shape, and the spatial autocorrelation (SPAC) method [8], that utilizes arrays deployed in an inscribed polygon in a circle, were initially implemented. Subsequent analyses by two more recent approaches derived by the generalization of the SPAC method were also applied and permitted the exploration of subsurface structures for longer wavelengths. These are known as the centerless circular array (CCA) analysis [9] and the noise-compensated circular array (nc-CCA) analysis [10].

It is important to mention that, with the objective of estimating the shallowest part of the soil profile, linear arrays, with varying sensor spacing distances, were also implemented. Moreover, the inversion analyses of the obtained dispersion curves were performed by the nonlinear optimization technique known as Genetic Algorithms [11, 12] which makes use of random processes that explore regions where the solution is most likely to be found, in a way analogous to the evolutionary development of biological systems in nature. Finally, the reliability of the obtained profiles for microtremor arrays was ensured by the agreement between the H/V spectra of Rayleigh waves for the fundamental mode of the inverted profiles and their respective H/V spectral ratio of a single microtremor point, that corresponds either to the center of the circular sensor deployment or a location in the neighboring areas of the array.

Based on the generated geophysical information, approximately 800 MASW tests and 2000 microtremor single point measurements [13], maps of the distribution of the average shear-wave velocity in the first 30 m (Vs30) and the fundamental period of vibration were estimated by means of the interpolation method known as Kriging [14]. As it is observed in Fig. 3a, materials with the highest values of Vs30 are concentrated in the central part of the metropolitan area with a slightly lower range close to the intermediate zones of the Rimac, Chillon and Lurin rivers. On the other hand, the lowest computed Vs30 are placed in the outskirts of the city, corresponding to medium dense eolian sandy deposits and soft to stiff clays/silts. It is important to highlight that the Peruvian Seismic Code E.030 [15] defines the value of Vs30 of 500 m/s as the limit between soil profiles of Type 1 (rock or very stiff deposits) and Type 2 (Intermediate deposits), being the latter characterized by a larger site effect coefficient and a wider design spectrum.

Regarding the distribution of the fundamental period (Fig. 3b), the northern and central parts of the city present values lower of 0.20 s, with punctual areas of larger period mainly due to specific site conditions, such as considerable impedance contrast below the 30 m of exploration. The most flexible deposits are located in the northern most area and in the district of Villa El Salvador, geotechnically characterized as sandy dunes with periods of vibration slightly larger than 1 s, in some cases. Even though microtremor single point measurements are progressively being implemented in consulting geotechnical studies, their results, in the form of the values of fundamental period, are not yet included in the E.30 regulation as a key parameter to evaluate site effects, as it is recommended in other seismic codes worldwide [16].

4. Suitability of Shear-wave Velocity Profiles as Proxy of the Dynamic Behavior

Taking into consideration the soil distribution map for Metropolitan Lima shown in Fig. 1b, the analysis of the suitability of shear-wave velocity profiles obtained by the methods explained in the previous section was conducted. It is important to mention that this study only includes the districts reviewed from the microzonation projects since 2010, the cases in which the array microtremor measurement and its corresponding MASW test were conducted very close to each other and within the same soil distribution zone, and those situations in which the exploration depths of the arrays are larger than those inferred from MASW tests. Thus, the analyses are group in four cases depending on their soil type and particular geomorphology.

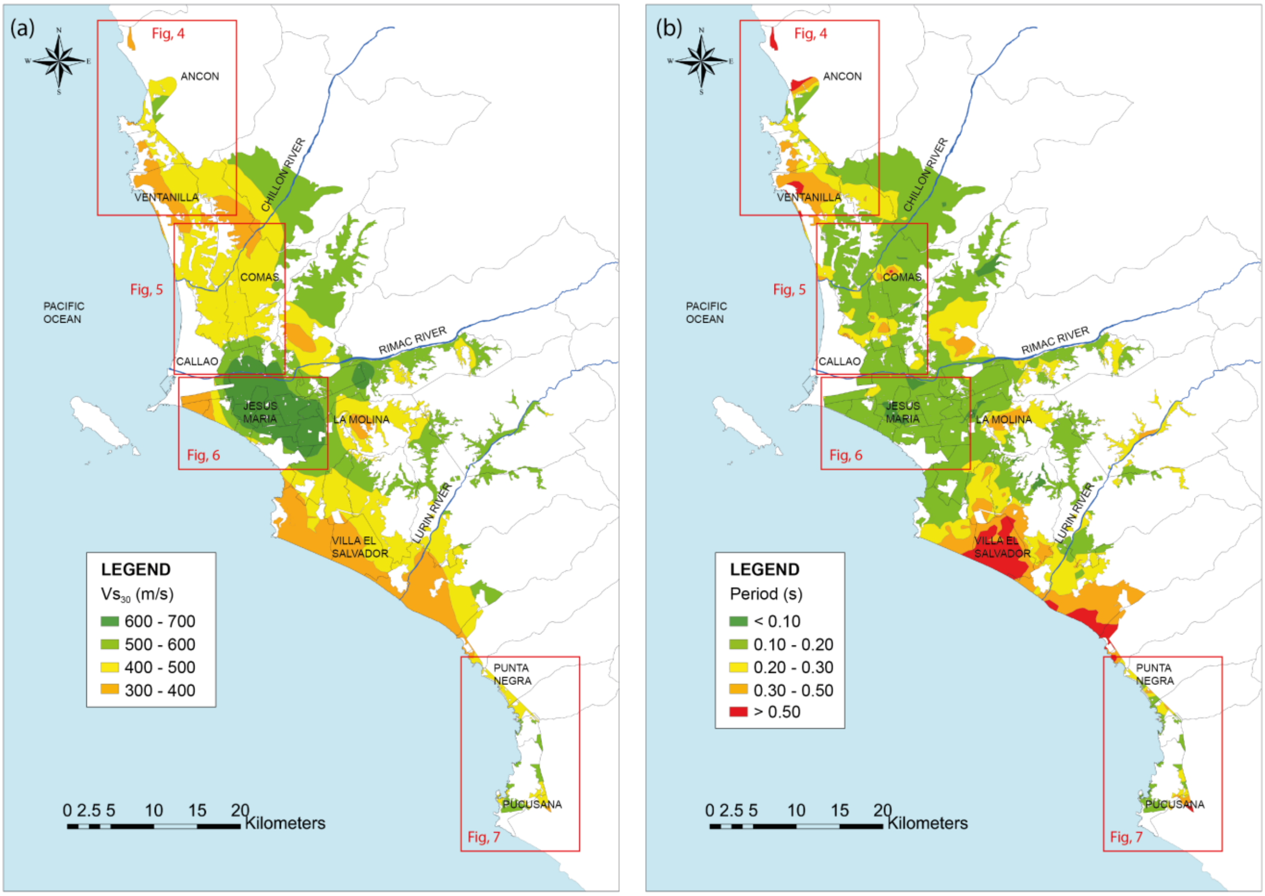

Fig. 3 – (a) Vs30 distribution map, (b) Isoperiod map for Metropolitan Lima

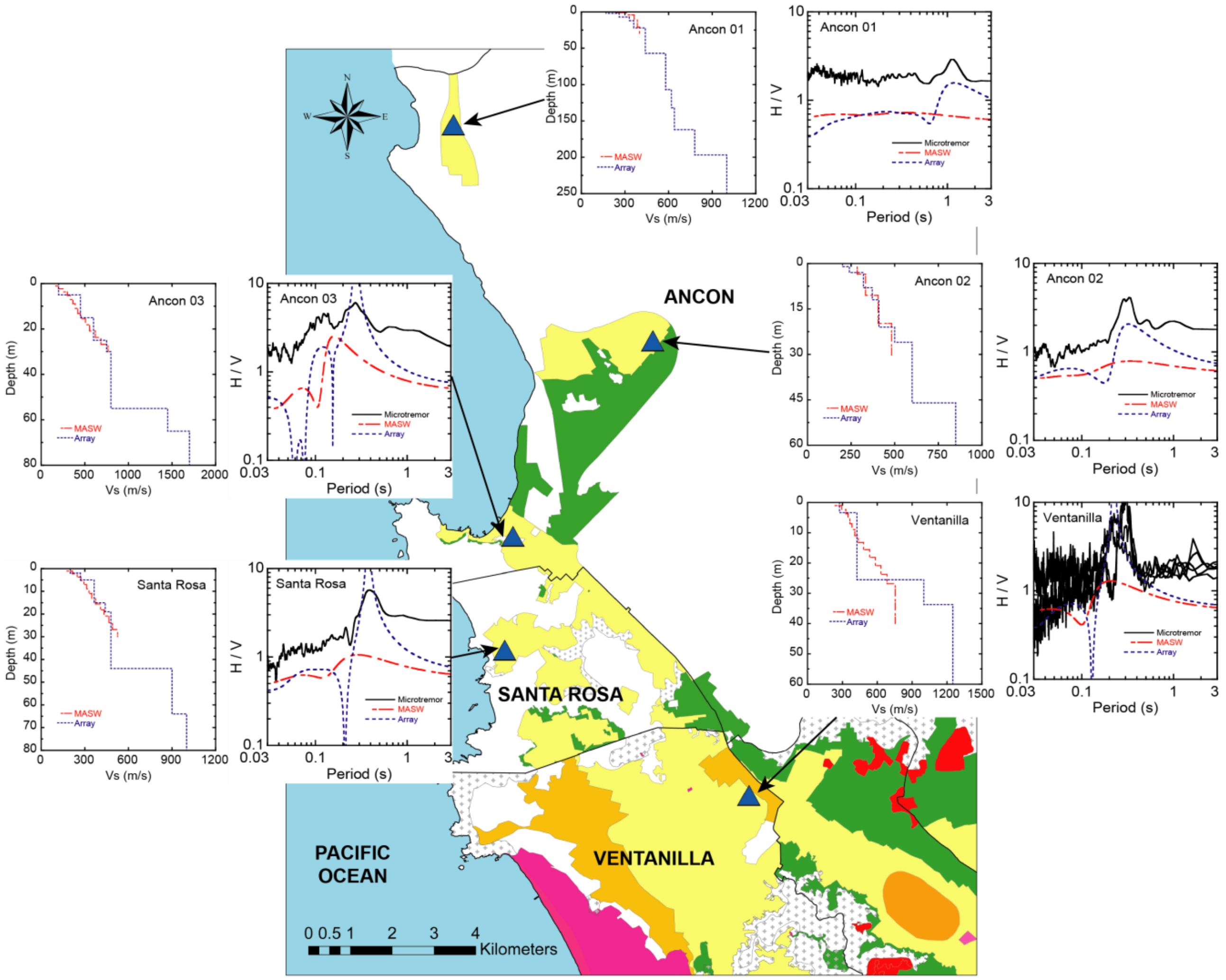

Fig. 4 – Comparison of the ellipticity curves from MASW and microtremor array measurement tests and single point microtremor measurements for the northern region of Metropolitan Lima

4.1 Northern Region

This region includes the districts of Ancon, Santa Rosa and Ventanilla in the northernmost region of the metropolitan area (Fig. 4). In terms of their geomorphology, these deposits are mainly composed of medium dense eolian sands, although the information of the Vs profile considered for Ventanilla is located close to the transition to medium dense to dense gravel deposits. In case of Ancon district, the profile coded as Ancon 01 shows one of the largest fundamental period estimated for the capital, which is slightly larger to 1 s, whose value decreases towards the southern areas. In addition, it is observed that all the deep Vs profiles considered, by means of their ellipticity curves, appropriately reflect both the shape and the peak of the H/V spectra obtained by microtremor single point measurements. Regarding Ventanilla, the ellipticity curve from the MASW results represents, to some extent, the vibrational characteristics of the underlying substructure maybe due to the impedance contrast reached at depths lower than 30 m, unlike the Santa Rosa district that appears to require deeper explorations to match the trend of the H/V spectrum. From the aforementioned, it is evident that the layer with a Vs value in the vicinity of 900 m/s governs the vibrational characteristics of the considered profiles.

4.2 Chillon and River Alluvial Fans

This section involves the analyses of the districts of Los Olivos, San Martin de Porres and Comas influenced by the alluvial fans of the Rimac and Chillon rivers. These profiles are located in deposits characterized either as medium dense sands and stiff clays/silts or medium dense to dense gravels with clayey shallow layers (Fig. 5). In case of Los Olivos district, the periods of vibration are within the range from 0.3 s to 0.4 s, adequately represented by the deep Vs profiles obtained from microtremor array measurements. On the other hand, the profile coded as SMP 01, in San Martin de Porres district, presents short values of period and a relatively flat H/V spectrum whose trend can be determined from shallow and deep Vs profiles. It is important to mention that, in case of Comas district, it was possible to conduct a large microtremor array that allowed the indirect exploration up to a shear-wave velocity value larger than 3000 m/s. This strong velocity contrast is the main cause of its particular H/V spectrum shape and its value of fundamental period, unlike the other districts in this region whose response is mainly governed by the impedance ratio with respect to a velocity value lower than 1500 m/s.

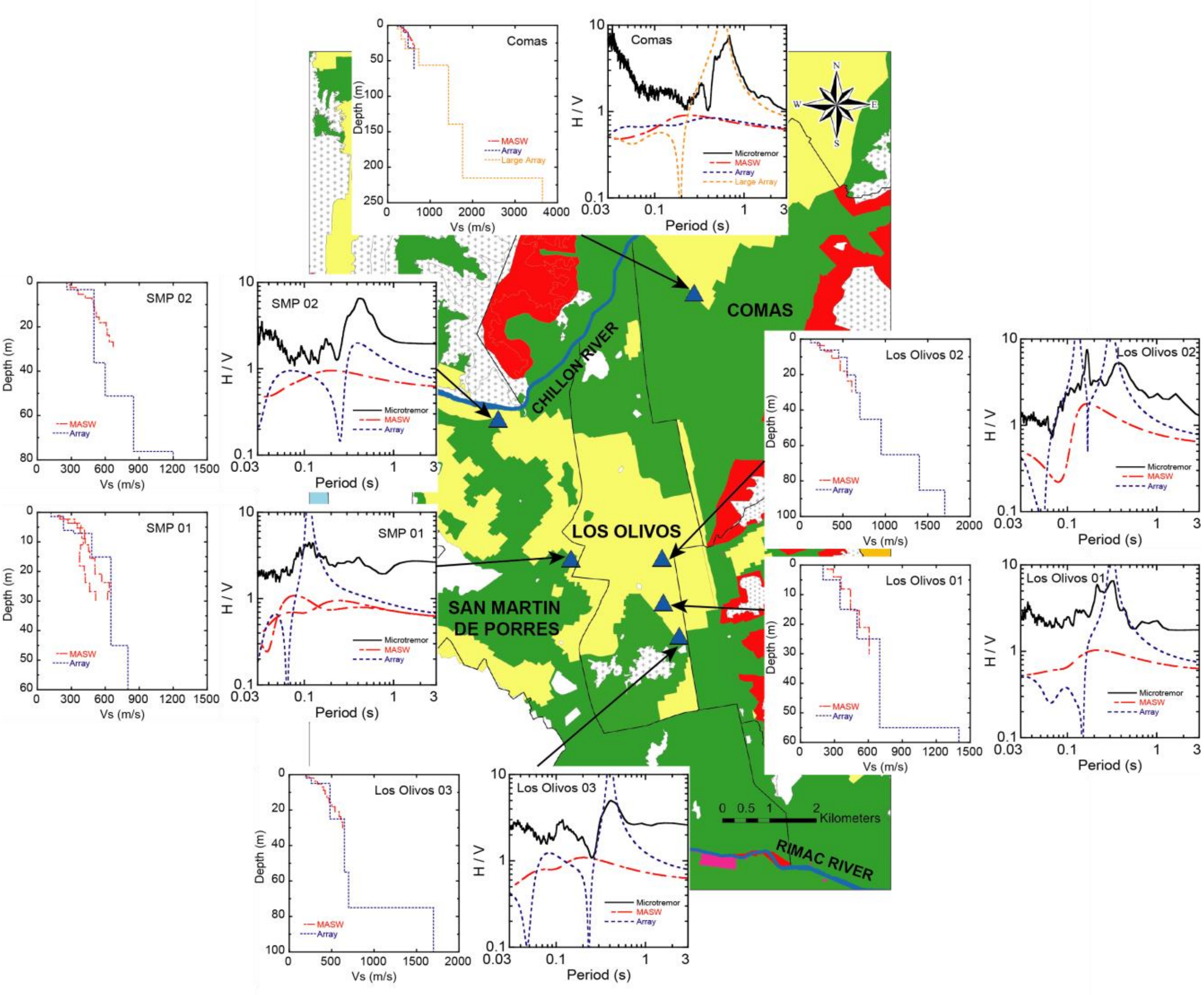

Fig. 5 – Comparison of the ellipticity curves from MASW and microtremor array measurement tests and single point microtremor measurements for the Chillon and Rimac River fans

4.3. Rimac River Alluvial Fan

The analysis of the corresponding areas of main influence of the Rimac river alluvial fan is divided in two. First, the central part, characterized as medium dense to dense gravel deposits, typically referred to as conglomerate, represents one of the stiffest regions throughout Metropolitan Lima, with the highest values of Vs30. As it can be observed in Fig. 6, the H/V spectra in all cases inside the region colored in green evidence either a flat response or very low values of fundamental period, which can be appropriately represented by the ellipticity curve from the MASW tests.

Conversely, the districts located on the west side, Bellavista and La Perla, are built over the transition from thick deposits of dense alluvial gravel or medium dense to dense sands. In case of Bellavista, it is observed that the profile obtained by the MASW test cannot properly reflect the vibrational properties of the underlying stratigraphy. In that sense, two large arrays were also carried out, including La Perla, and, despite the fact that they might present a velocity inversion at certain depth, relatively large periods of vibration are evident and caused by the deeper part of the soil substructure.

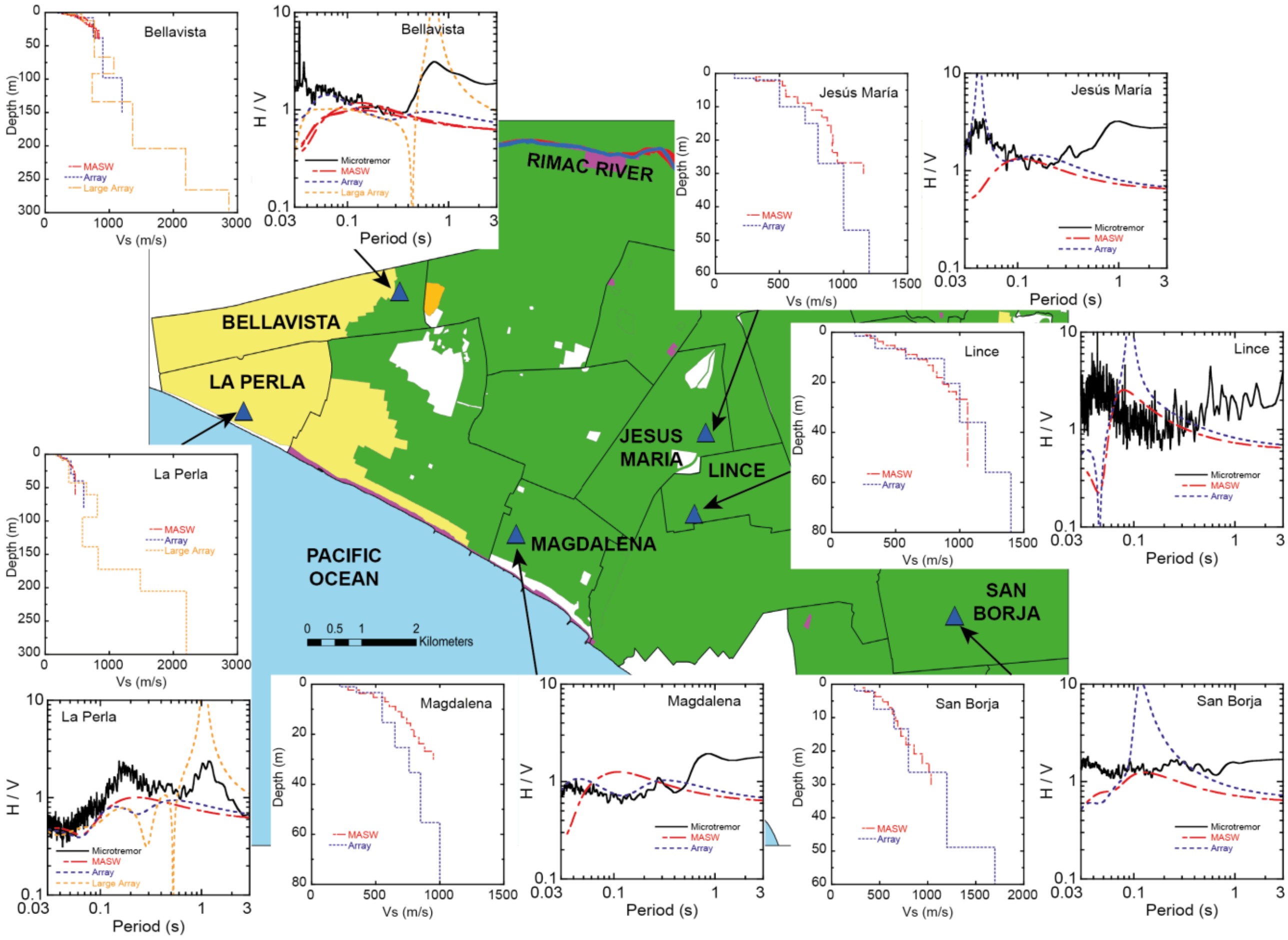

Fig. 6 – Comparison of the ellipticity curves from MASW and microtremor array measurement tests and single point microtremor measurements for the Rimac River fan

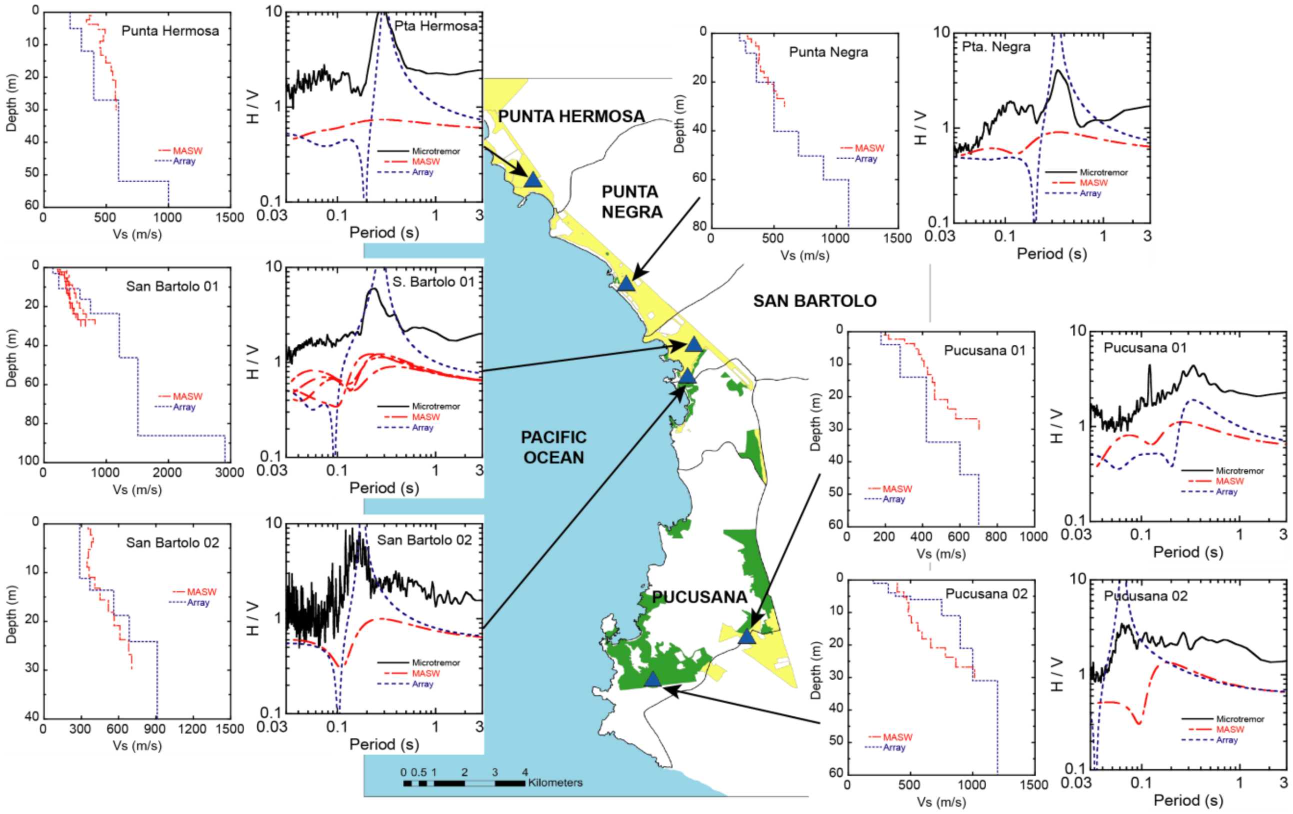

Fig. 7 – Comparison of the ellipticity curves from MASW and microtremor array measurement tests and single point microtremor measurements for the southern part of Metropolitan Lima

4.4 Southern Region

This region includes the coastal lands in the southernmost part of the metropolitan area known as Punta Hermosa, Punta Negra, San Bartolo and Pucusana districts (Fig. 7). In terms of geology, these areas are composed of medium dense to dense eolian sands and stiff clays/silts. Regarding the first two districts, it is evident that the deep soil profiles obtained from the microtremor array measurements adequately match the trends of the H/V spectra. Moreover, in case of San Bartolo, it presents values of fundamental period lower than 0.30 s and the profiles inverted from the MASW tests, to some extent, reflects the vibrational characteristics of the underlying soil. Finally, slightly higher values of fundamental period are found in Pucusana in which the estimation of the Vs profile down to the first 30 m suggests to be insufficient.

Finally, as it was mentioned before, three large arrays were conducted at the districts known as Comas, La Perla and Bellavista, with the objective of estimating the deep regions of the soil substructure and their impact in the dynamic behavior of these particular deposits. Table 1 and Fig. 8 show the distribution of the values of Vs with depth for each of the arrays and their respective transfer functions at different depths, respectively. As it is expected, when considering the shallow part only, the small values of amplification encountered are restrained within the short period range. Conversely, larger amplification factors are evident when analyzing the deeper part due to the significant impedance ratio observed. From these results, it is suggested that the correct estimation of the fundamental period, and when required the deeper substructure, could be importants parameter when analyzing apparent stiff deposits, such as the aforementioned, with Vs30 within a range of 400 m/s and 500 m/s.

Table 1 – Shear-wave velocity distribution of the large arrays conducted

	Comas		**La Perla**		**Bellavista**	
Layer	**h (m)**	**Vs (m/s)**	**h (m)**	**Vs (m/s)**	**h (m)**	**Vs (m/s)**
1	4.8	221	2.6	175	2.7	267
2	14.5	320	6.4	256	9.5	571
3	13.7	415	33.8	367	54.5	764
4	23.2	730	17.7	643	24.8	1072
5	83.1	1432	33.6	814	42.1	733
6	75.7	1752	44.5	580	70.2	1364
7	---	3643	33.9	825	61.9	2192
8			32.8	1482	---	2867
9			---	2203		

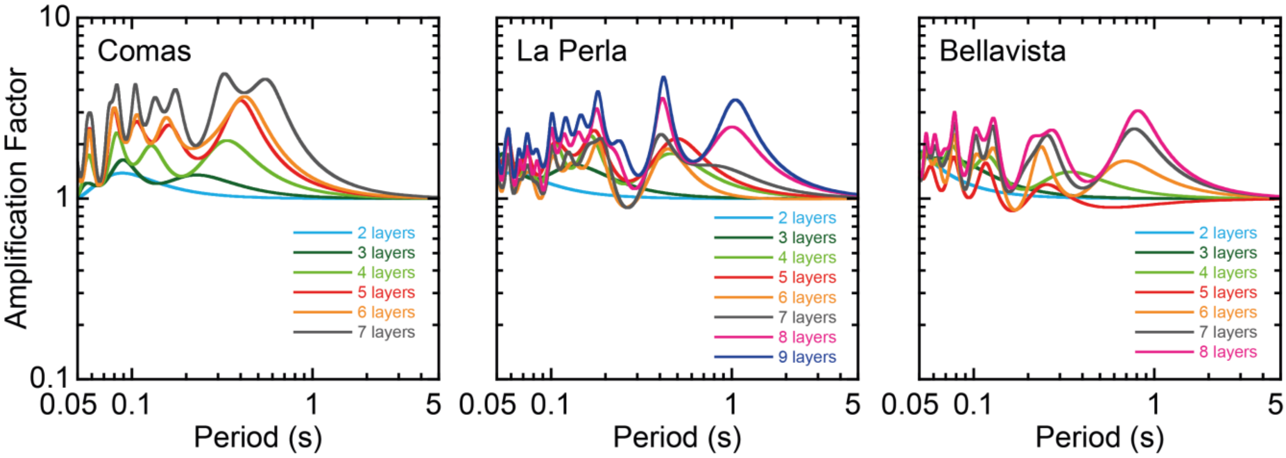

Fig. 8 – Transfer functions calculated for the large arrays conducted

5. Conclusions

In order to mechanic and dynamically characterized the urban zones of Metropolitan Lima, in 2004, a first attempt of a Microzonation Map was conducted. Since 2010, this information was reviewed and complemented by means of a more dense set of tests and the inclusion of information related to shear-wave velocity profiles (Vs) and the fundamental periods of the soil substructure.

The present study aimed to clarify the suitability of the characterization down to the first 30 m as a proxy of the vibrational behavior of deposits of different geological origin in the city of Lima. This was performed by means of the comparison of the H/V spectrum of a single point microtremor measurement and the ellipticity curves of the fundamental mode of Rayleigh waves for the Vs profiles estimated by both MASW tests and microtremor arrays.

The analyzed cases were grouped in four regions depending on their geotechnical classification. Results have shown that only for the case of stiff deposits, mainly consisting of alluvial gravel, commonly known as conglomerate, the first 30 m of exploration can be representative of the vibrational behavior. In any other case, the dynamic response is mainly governed by the impedance relationship with respect to a layer with a value of shear-wave velocity, in average, larger than 1000 m/s. Exceptional cases are found in the stiff deposits in the districts of La Perla, Comas and Bellavista, in which the deeper part appears to have a strong impact in the shape of the H/V spectra. Complementary analyses of recorded ground motions are required in order to clarify the presence of considerable response in the long period range for theses deposits.

Due to the lack of information in places built over particular soil conditions such as thick sandy deposits or swampy soils, these types of formations were not considered in this research. It is strongly advised to perform geophysical tests in these areas in order to have an overall understanding of the dynamic behavior of Lima city.

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