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DYNAMIC CHARACTERISTICS OF THE SURFACE SOILS IN LIMA, PERU

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Abstract: We have obtained dynamic characteristics of the surface soils at eight places in Lima, Peru; specifically we estimated the shear-wave velocity profile. The method we used was the inversion of dispersion curves calculated from array measurements. Small and large arrays of microtremors were carried out, and a new type of sensor was introduced for the large array measurement. Important results are the relative shallow stiff soil layer in the area classified as alluvial gravel deposit, that covers most of the area of Lima city; and the apparently deep soft soil layer in places identified as VSV and CMA. In these last places, it is recommended to complete the analysis with large array measurements.

1. INTRODUCTION

This study is 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.

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, specially in places like Lima that have scarce information of deep soil structures.

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

To accomplish this objective, microtremor array measurement campaigns were carried out at 8 places of the city; new long-period sensors of microtremor were introduced as part of the technology enhancement politics.

2. AREA OF STUDY

The study was developed over the Lima metropolitan area; where 8 points of measurements were located. Table 1 shows a list of these points with details of their exact location.

Figure 1 shows a map of the Lima’s surface soil distribution (estimated in 2005) and the distribution of the microtremor array measurement points.

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. SOIL CONDITION AND BORING DATA

As it can be seen from Figure 1, most of Lima area is covered by alluvial gravels that are found at few meter depth,; however, there are concentrated eolian, clays and

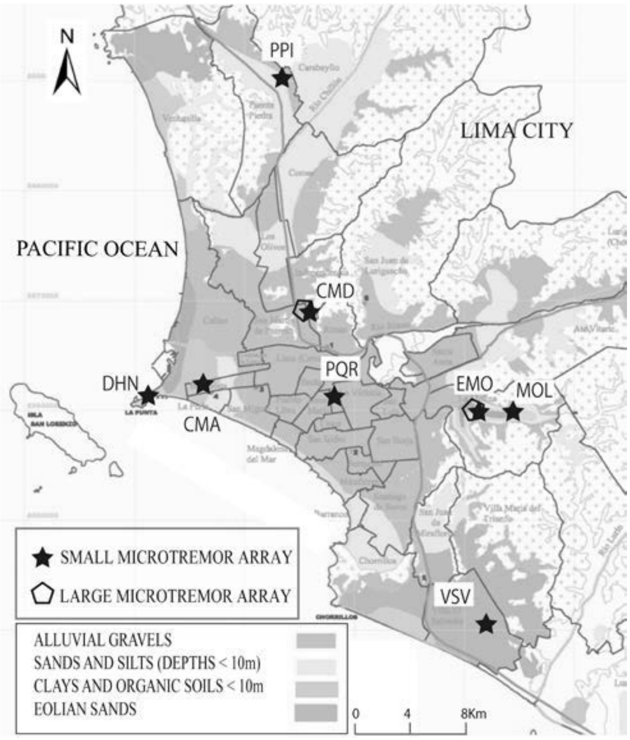

Figure 1. Soil distribution map (CISMID, 2005) and location of microtremor arrays.

silts deposits, of which depths to the base rock are in some cases unknown .

A typical soil profile of the alluvial gravel deposit is shown in Figure 2. The profile corresponds to a soil pit near the array set named CMD. In Lima, soil pits are more popular than SPT explorations because the stiffness of the soils in many areas does not allow the conduction of SPT explorations.

The majority of boring data available in Peru has a similar pattern of profile at CMD, it means the gravel is shallow and the depth of exploration is about 3m.

4. MICROTREMOR ARRAY MEASUREMENTS

One of the reasons to conduct array measurements was the limited depth in the available boring data and the practical way to perform it.

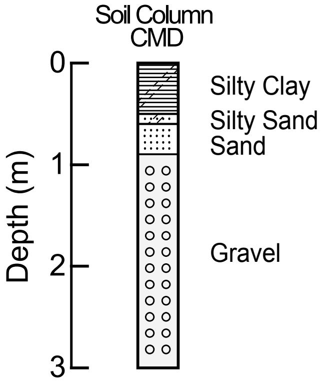

Figure 2. Soil Column CMD (collected data E13 of Rimac district in the study of CISMID, 2005) located at the National University of Engineering.

Two measurement campaigns were carried out, the first consists of 8 sets of small arrays (Figure 1); each set is made of linear arrays of 0.5 and 2m sensor distance, and circular arrays of 10, 20 and 45m radius.

The second campaign consists of 2 sets of large arrays, each set made of circular arrays of 100, 200, 400 and 800m radius.

4.1 Implementation of microtremor sensors

Two types of sensors of microtremors were introduced to Peru through this project. One was the well-known GEODAS sensor (with natural period of 1 second), and the other was a sensor produced by Tokyo Sokushin company with a natural period of 5 seconds.

5. ANALYSIS OF RESULTS

Array set CMD was chosen in this study to be the representative array set; in consequence we will show and comment the detailed procedure to come up with its shear wave velocity profile.

We used two methods to construct the dispersion curve; the high resolution F-k method proposed by Capon in 1979, and the Centerless Circular Array (CCA) proposed by Cho et al in 2006.

5.1 F-k spectrum

The F-k method uses the cross-spectrum between each pair of sensors as a factor to compute the F-k power spectrum. This can be seen with the formula of the F-k spectrum

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

where 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.

$q_{mn}(f)$ is the inverse of a Hermitian matrix whose elements are formed by the cross spectrum between channels m and n. (x_n, y_n) are the coordinates of the sensor n, and (x_m, y_m) are the coordinates of sensor m.

Since the cross spectrum is an important factor in the computation of the F-k spectrum, it is necessary to verify the cross-spectra to see if there is a good correlation between the signals. In general a well correlated cross-spectrum curve is a smooth descending or ascending curve from 0 to 360 degrees or vice verse. If the curve follows this trend the F-k spectrum is verified. Sometimes more than one smooth curve appears, in this case, in the period domain, the curve to verify should be the first at the right side. For example, in Figure 3(a) there are two curves but the one to verify is the curve from 0.025 to 0.07 s, and in Figure 3(b) the curve is from 0.2 to 0.4 s. We will expect that in the dispersion curve for the period ranges mentioned, the curve shows continuity for the array of 10 and 200m respectively.

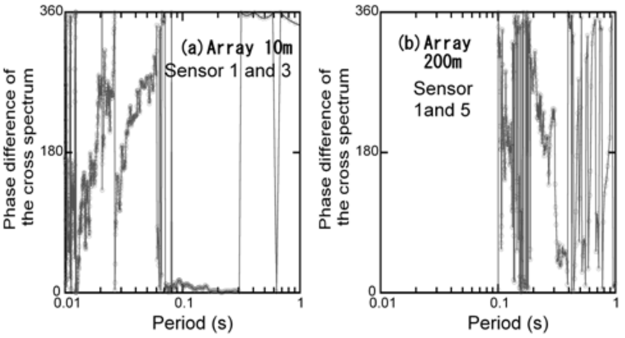

Figure 3. Cross spectra of CMD , (a) For the array of 10m, (b) for the array of 200m.

Figure 4 shows F-k spectra for different array sizes and different periods. It is well-known that a sharp peak develops for ideally noise-free data; from this statement we can conclude that the ratio of noise to signal is low for the periods shown in each F-k spectrum, because in almost all the cases the peak is sharp. This can be used as another way to verify the dispersion curve.

It is also known that the sharp of the peak vary with the coherence value, usually the coherence is high for sharp peak spectra. Another factor that affects the coherence is the number of peaks in the F-k spectrum, when more than one peak appears the coherence decreases. The presence of more than one peak may be due to external noise, in our case we can see that more than one peak occurs specially for the large arrays, which can tend to receive more noise.

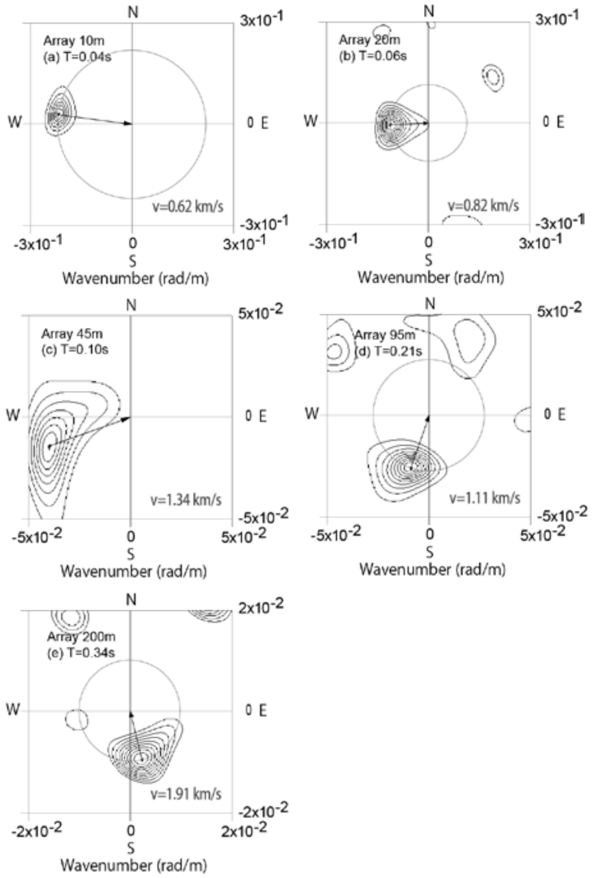

Figure 4. F-k Spectra for CMD arrays

5.2 Dispersion curve

Tokimatsu (1995) mentioned that to obtain reliable results of phase velocities, the effective wavelength range is related with the sensor distance as follows

$$Dmax > \lambda max/3$$
$$Dmin < \lambda min/2$$

which can be written as:

$$2Dmin < \lambda < 3\,Dmax$$

where *Dmax* and *Dmin* is the maximum and the minimum sensor distance respectively, and λ is the wavelength.

This criterion, together with the cross spectrum and the F-k spectrum verification were used to select the points of the dispersion curve when using the F-k method (Figure 5).

However, in the case of the CCA method; Cho et al (2004) found phase velocities at very long wavelength ranges, up to 30 meters the array radius. They stated that it is possible to calculate phase velocities at very long wavelengths when the signal to noise ratio is high, which occurs normally in few meter radius arrays.

In Figure 5 we can observed the continuity between the dispersion curves from array L0.5 (linear array of 0.5m sensor distance) to array C45 (circular array of 45m radius). Nevertheless, arrays C95, C200 and C400 follow another curve. The cause of this difference could be the fact that these large arrays were measured at a place separated about 800m from the place where the small arrays were measured, that is, the surface soil may be different in both places. Small array measurements in the second place are necessary to verify the dispersion curve of the large arrays.

5.3 Inversion of dispersion curves

Several methods of inversion are available, from the conventional least square methods to the genetic algorithm method. The genetic algorithm approach developed by Goldberg (1989) is recently 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.

In this study we applied the genetic algorithm (GA). To apply this method we input an observed dispersion curve, such as the one in dots in Figure 6(a). Previously we had determined this curve base on the dispersion curve of Figure 5.

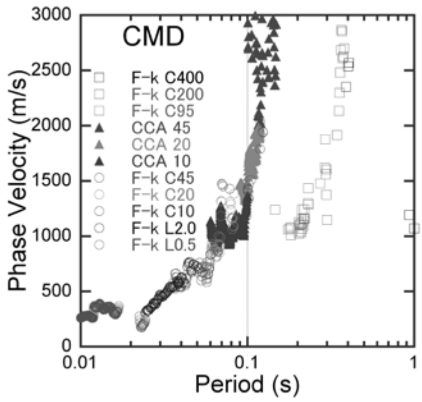

Figure 5. Dispersion curve

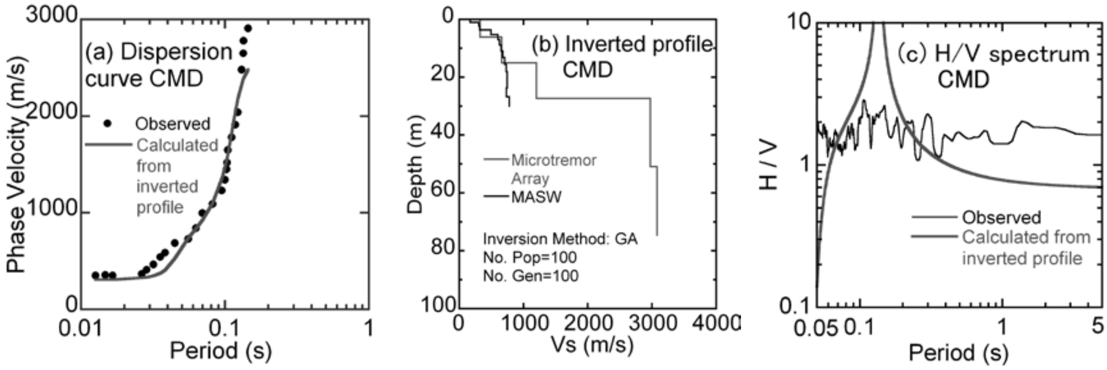

Figure 6. (a) Comparison between the observed and calculated dispersion curve, (b) Comparison between the profiles estimated by inversion of dispersion curves calculated by microtremor arrays and by MASW, (c) Comparison of H/V spectra

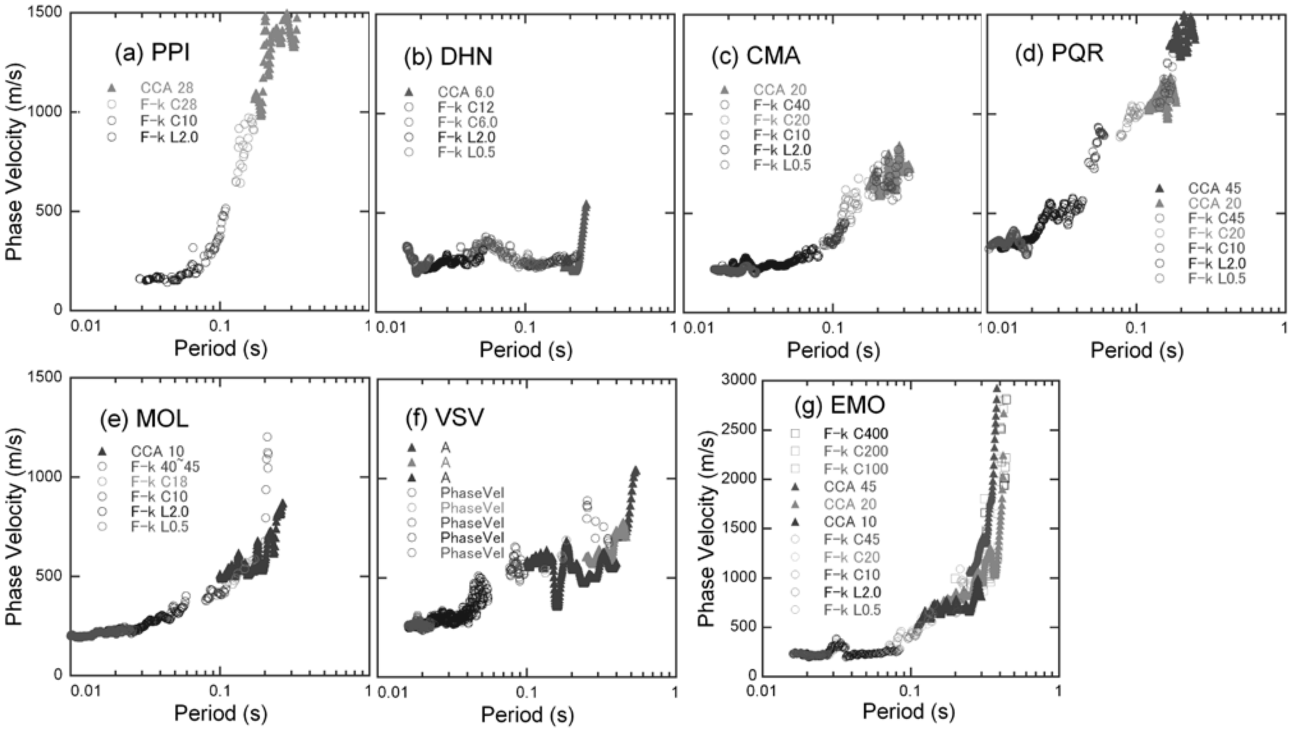

Figure 7. Dispersion curves

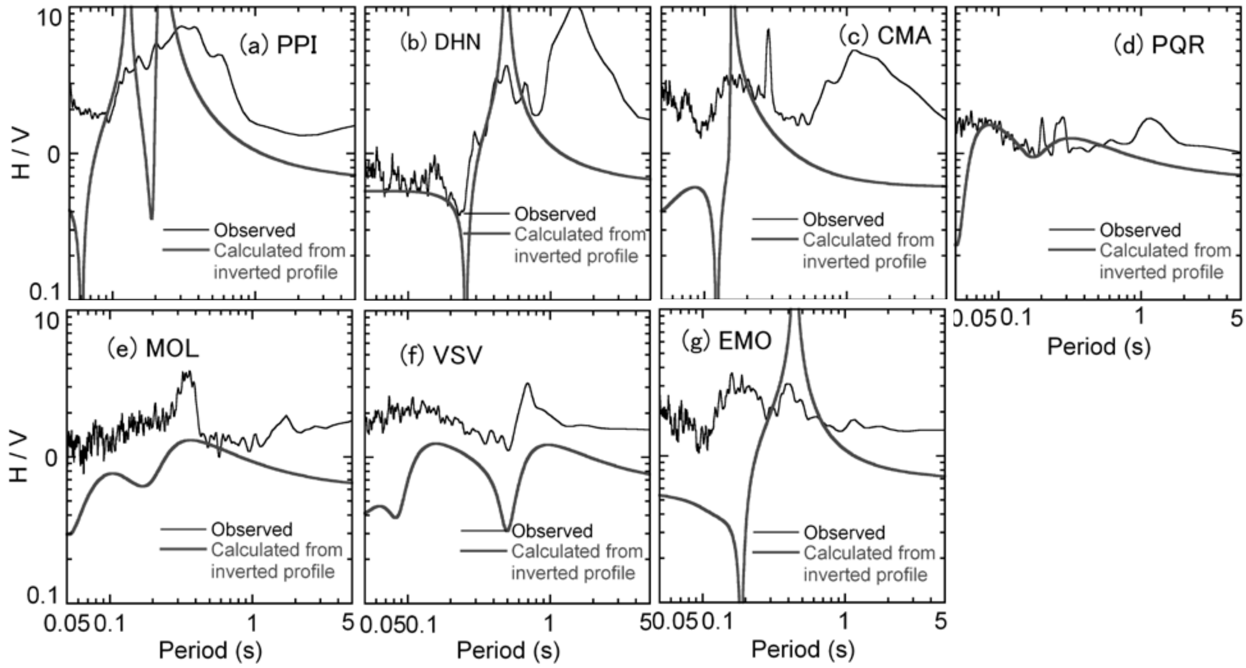

Figure 8. H/V Spectra

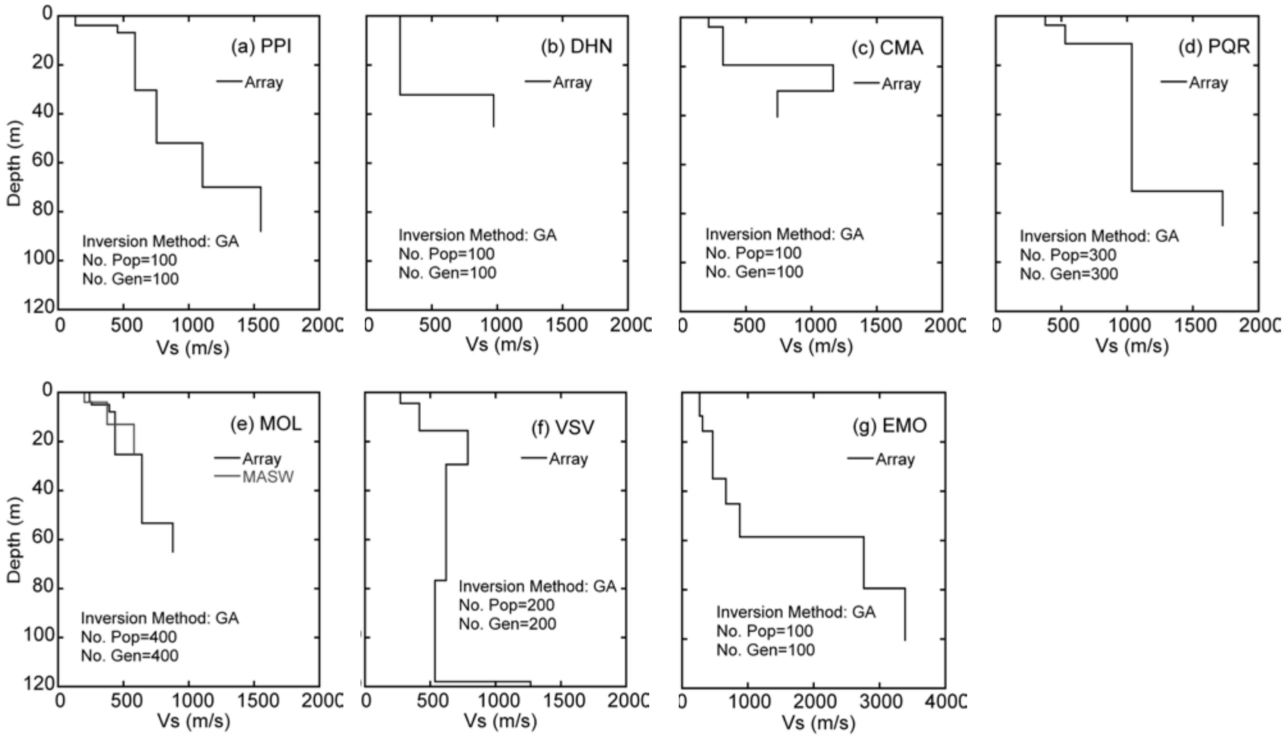

Figure 9. Comparison of Observed and Calculated H/V spectra

This observed curve or target curve, is used to compare all calculation curves obtained in the process of the inversion. The final calculated curve is the one that satisfy the ending criterion, which can be either a limit number of iteration (number of generation) or a minimum fitness value. In this study the first criterion was used, and the value of this limit was up to 100.

Figure 6(b) shows two profiles, one corresponds to the inversion of the dispersion curve calculated from microtremor arrays and the other corresponds to the inversion of the dispersion curve calculated with the MASW method. It is observable that both profiles are in good agreement until the depth of 15m more or less.

Finally to verify the profile obtained with the microtremor array, the H/V spectrum of this profile is calculated and compared with an observed spectrum. Figure 6(c) shows that there is an agreement between both spectra.

5.4 Additional Results

The same procedure taken for the calculation of dispersion curves and estimation of shear-wave velocity profile of study point CMD was used at the other study points.

Figure 7 shows the dispersion curves for the rest of the points of study, Figure 8 shows the the H/V spectra, and Figure 9 shows the shear-wave velocity profiles;

6. DISCUSSION

Looking at the dispersion curves we can see that the CMD place has the most rigid shallow surface soil, it can be explained from the rock formation proximity.

The places with apparent soft deep deposits are DHN, CMA, and VSV.

In the case of CMA, the dispersion curve at long period (array of 45m) does not show a clear curve, and it seems that there is a dip in this part of the curve; it could mean that there is a layer of high velocity overlying one of lower velocity, which is what we found in the inverted profile (Figure 9(c)). Indeed, the H/V spectrum of this place has three clear peaks (Figure 8(c)), one with a period of about 1s, this peak could belong to soft layer mentioned before. To verify this peak we need phase velocities at long period, which can be obtained with large array measurements.

For VSV, the inverted profile (Figure 9 (f)) apparently points out that there is an important contrast down to 100m. The H/V spectrum of the calculated and observed data shows an agreement. However to verify this statement, a large array measurement is necessary.

7. CONCLUSIONS

The results of this study brought the following conclusions:

1. Places located in the area of alluvial gravel of Lima, showed high shear-wave velocities at shallow depths.
2. In the majority of the places studied, the implementation of large array measurements is necessary to estimate the depth to the base-rock.
3. In order to verify the results of array inversion, additional studies, preferably direct exploration test, such as PS logging is of great importance.

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