Paper:

Estimation of Deep Shear-Wave Velocity Profiles in Lima, Peru, Using Seismometers Arrays

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[Received November 12, 2012; accepted January 22, 2013]

The estimation of the shear-wave velocity profile in Lima, Peru, was originally performed through surface wave observation in microtremor arrays. In the observation of these surface waves, a low signal problem for long periods was identified that resulted in a poorly done correlation between signals recorded by sensors and, consequently, in difficulty obtaining deep velocity profiles with good resolution. As an alternative, surface wave observation from seismic records was proposed. To confirm the feasibility of this methodology, seismometers were installed in an approximately circular configuration on the campus of the National University of Engineering in Lima. The procedures used to carry out analysis are similar to those used when analyzing microtremor arrays, with the exception that only the coda of seismic records is used for analysis. Results show that the dispersion curve obtained from seismometer arrays agree well with dispersion curve obtained from microtremor arrays and are predominant in a large period range. Finally, the estimated profile is verified using the observed H/V spectrum.

Keywords: surface wave, microtremor, seismic record, shear-wave velocity profile

1. Introduction

The city of Lima, Peru, is located in the Pacific Ring of Fire, a seismically active zone enclosing the Pacific Ocean, where most earthquakes worldwide occur. Lima has been experiencing a seismic silence since more than 30 years ago. This fact, together with the large urbanization process developing in the city during the last three decades, highlights the necessity for studying the dynamic characteristics of soil vibration in Lima.

To estimate the characteristics of vibration, it is necessary to obtain the soil velocity profile. A well-known method for doing this is through the measurement of surface waves in microtremor arrays. Microtremors have proven to estimate velocity profiles well, but a difficulty arises when the power of the signal is low, leading to highly uncertain estimated profiles.

The analysis of surface waves from seismometer arrays was examined as an alternative to solving the problem of low signal power.

Preliminary studies in this matter of seismometer arrays were presented in [1] and [2]. The coherence of seismic records from an array of seismometers was examined in [1], and the characteristics of Love wave propagation were studied in [2].

The objective of this study was to validate the analysis of seismometer arrays. For this purpose, results from microtremor arrays and seismometers measured on the campus of the National University of Engineering in Lima, Peru, were compared. The procedures and results of analysis are discussed here.

2. Measurements in Lima City

The area of study is the city of Lima, capital of Peru, situated on the central coast of the country and bordered on by the Pacific Ocean.

Aiming to estimate the underground structure, surface waves from microtremors and from seismic records were measured around the city. Measurement consisted of single-point microtremors, microtremor arrays and seismometer arrays.

Large numbers of single points of microtremors were measured during many years. These points were gathered and plotted on a map that showed their characteristic periods of vibration (**Fig. 1**). The period of vibration of these data was obtained observing the peak in the H/V spectrum.

Regarding array measurements, a total of eight profiles resulted from microtremor arrays (**Fig. 1**) and one profile was found from the array of seismometers.

2.1. Microtremor Arrays

Analysis and results of microtremor arrays measurements carried out in Lima were presented extensively in a previous study [3] and therefore here we will explain

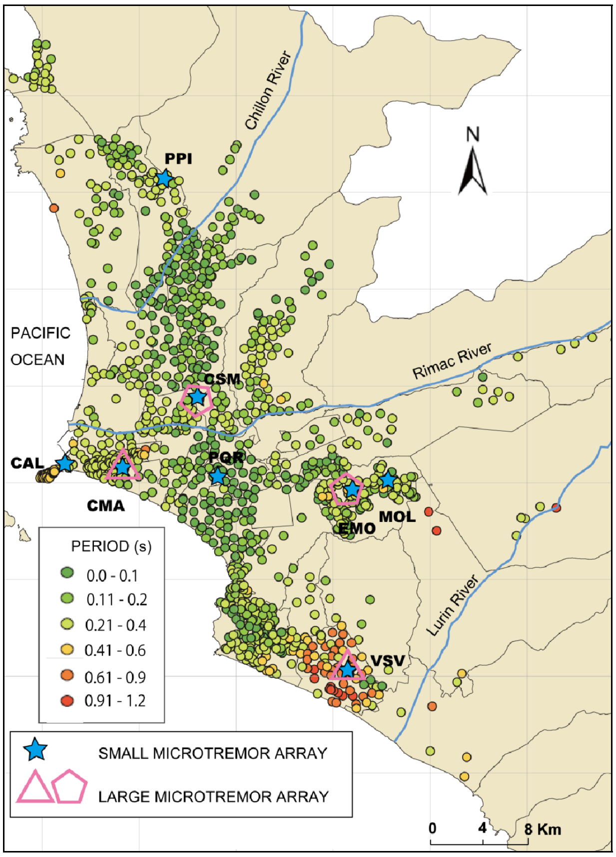

Fig. 1. Location of arrays over the single-point microtremor measurement map of Lima.

the analysis only briefly and address the results and the difficulties found in the process.

When microtremor arrays are analyzed, a good correlation is desired between waves recorded by the sensors. If this condition is accomplished, then a clear dispersion curve can be observed that results in a high resolution shear-wave velocity profile.

A good correlation is related to a signal level that is high compared to noise in recordings. In Lima, resulting profiles obtained from the inversion of microtremor dispersion curves extended some meters in depth and to very large depths in some cases. Some deep profiles, such as the ones in El Callao and the Villa El Salvador district (CMA and VSV in **Fig. 1**, respectively) showed high uncertainty [3].

Uncertainty in estimated profiles is related to the low resolution of dispersion curves. An example of this low resolution is shown in **Fig. 2(a)**, where the dispersion curve shows a range of periods from 0.5 to 1.5 s with low resolution. This problem is due to the low signal-to-noise ratio in Lima. The analysis of surface waves from seismic records was attempted as a way to overcome this limitation.

2.2. Seismometers Arrays

The methodology for analyzing the surface waves of seismic records is the same as the one used for mi-

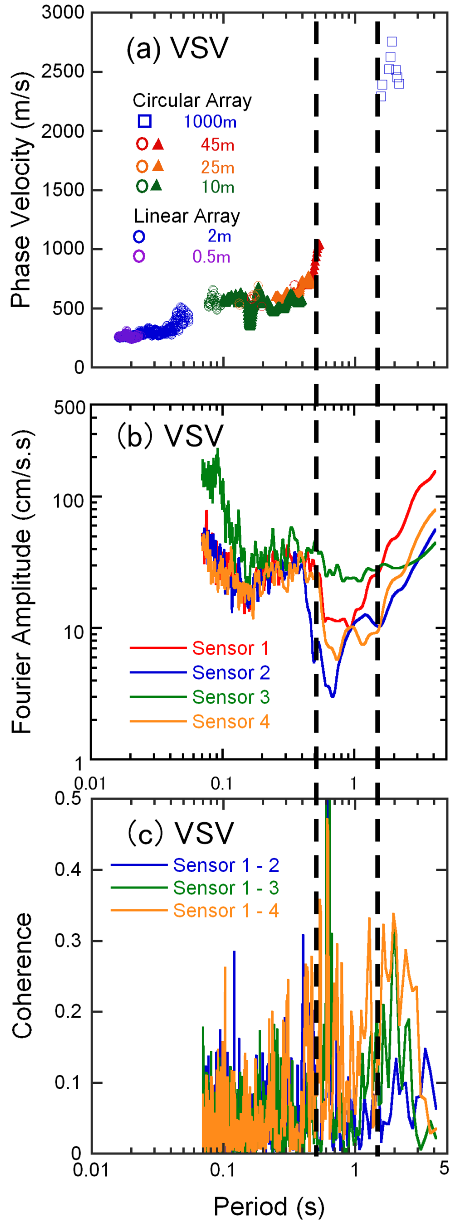

Fig. 2. The (a) observed dispersion curve, (b) Fourier Spectrum and (c) coherence spectrum for the circular array of 200 m radius at VSV (Villa El Salvador). Sensors 1, 2, 3, and 4 form the array.

crotremors. However, surface waves have to be identified first in seismic records to continue with correlation analysis. The case that we studied was the array of seismometers located on the campus of the National University of Engineering (UNI) in Lima. The four seismometers installed there were placed in an almost circular shape with a radius of approximately 150 m (**Fig. 3**).

2.2.1. Seismic Records

Two earthquakes were considered in the analysis, one on August 24, 2011 (M_W7.0) and one on October 28, 2011 (M_W6.8). The locations of these earthquake epicenters are shown in **Fig. 4**. As can be seen in **Fig. 5**,

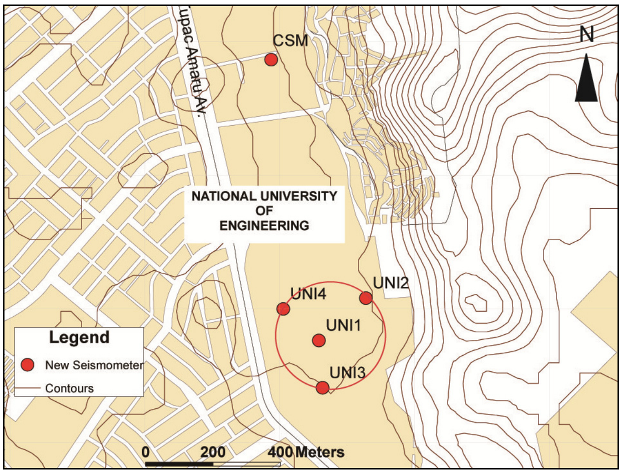

Fig. 3. Location of the array of seismometers in the campus of the University.

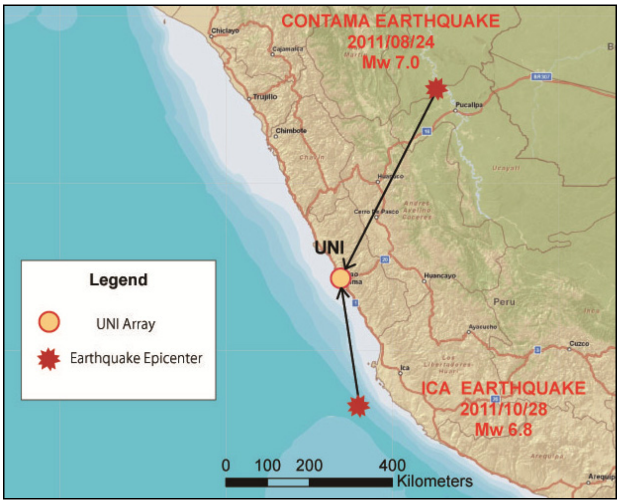

Fig. 4. Location of the earthquake's epicenters.

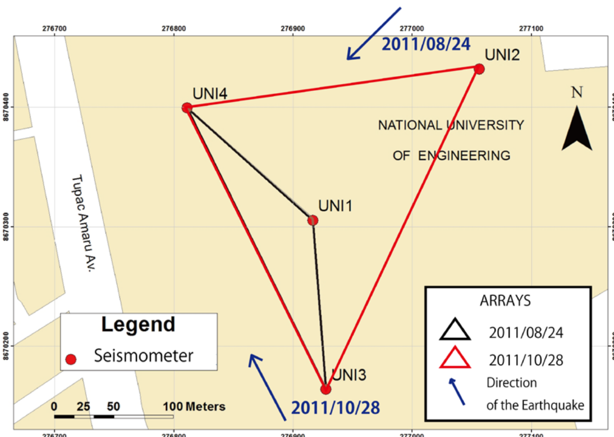

Fig. 5. Arrays configuration with seismometers located at the National University of Engineering.

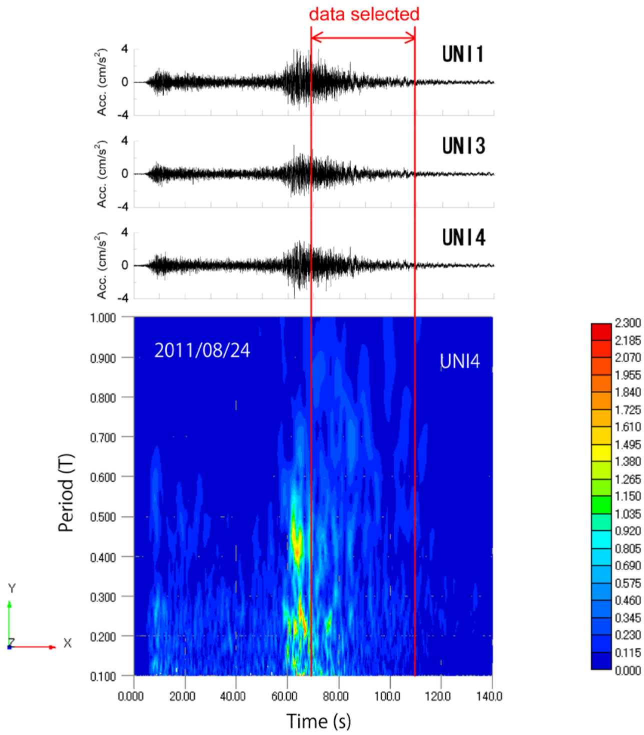

Fig. 6. Time histories and nonstationary spectrum for the August 24, 2011, earthquake at station UNI4.

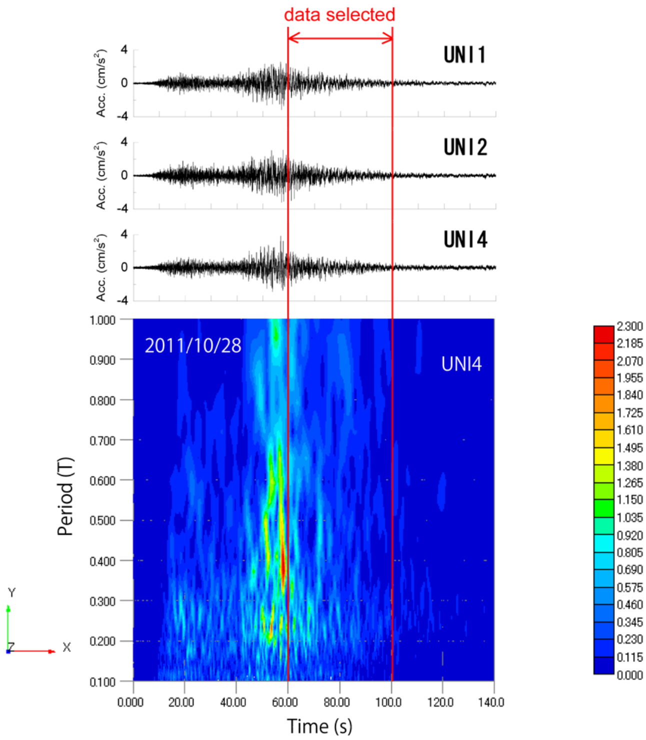

Fig. 7. Time histories and nonstationary spectrum for the October 28, 2011, earthquake at station UNI4.

the October 28 earthquake was recorded by the four seismometers but the August 24 earthquake was recorded by only three. This figure also shows the direction of the earthquake epicenter.

2.2.2. Selection of the Data

As an example of the data selection procedure followed for seismometer arrays at UNI, time histories and nonstationary spectra [4] for the two earthquakes are plotted and shown in **Figs. 6** and **7**. They correspond to the vertical

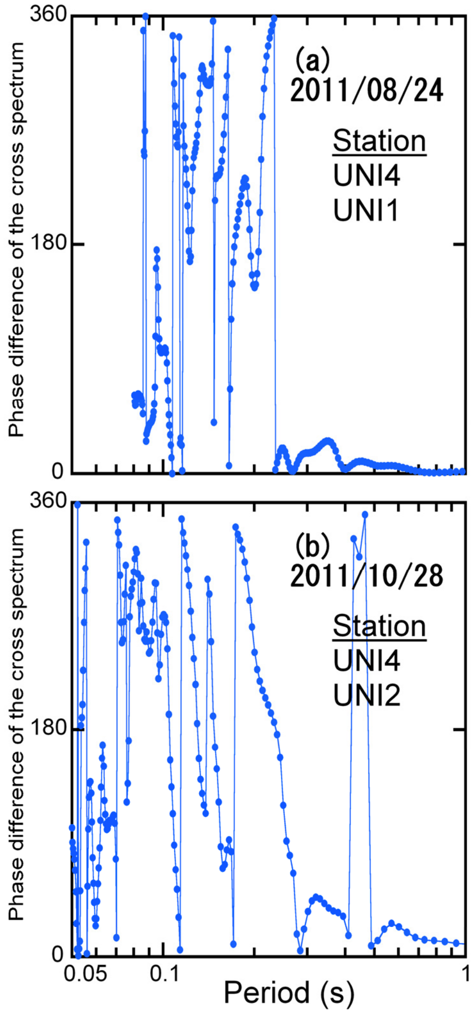

Fig. 8. Cross-spectra between (a) stations UNI4 and UNI1, and (b) UNI4 and UNI2 for the August 24, 2011, earthquake.

component (U-D) of seismic records.

Observation of time-histories enables the arrival of P and S waves to be observed and the nonstationary spectrum enables the range of influence of surface waves to be identified. We consider that the surface wave starts after the main shock (S-wave) vanishes and that it lasts until the acceleration value no longer shows major variations.

In the case of the August 24 earthquake (**Fig. 6**), the range of surface waves considered for calculation was from 70 to 110 seconds, and in the case of the October 28 earthquake (**Fig. 7**), the range was from 60 to 100 seconds.

Once data for calculation is identified, the cross-spectrum of each pair of seismometers is evaluated. Since the cross-spectrum is one of the factors in the computation of the F-k spectrum and this last one for the calculation of the dispersion curve, it is important to observe the characteristics of the cross-spectrum, especially the range of periods in which the curve goes from 0 to 360 degrees or vice versa.

In **Figs. 8(a)** and **(b)** correlations between the two stations decrease from 360 to 0 degrees from a period of 0.2

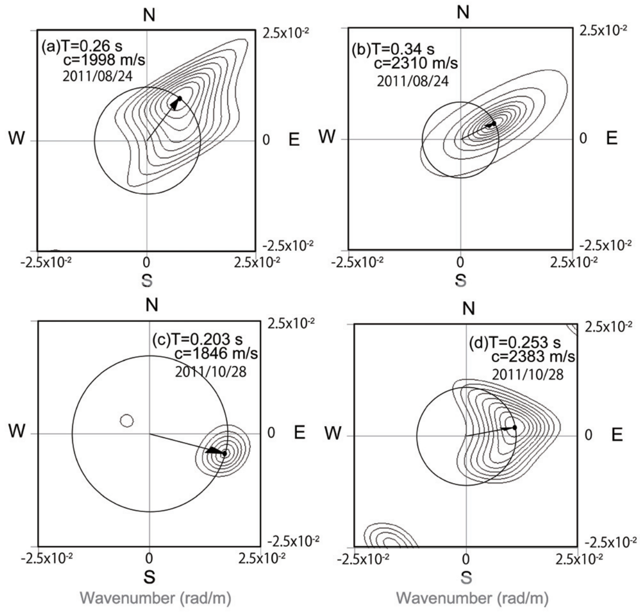

Fig. 9. F-k spectra (a) and (b) for the August 24, 2011, earthquake and (c) and (d) for the October 28, 2011, earthquake.

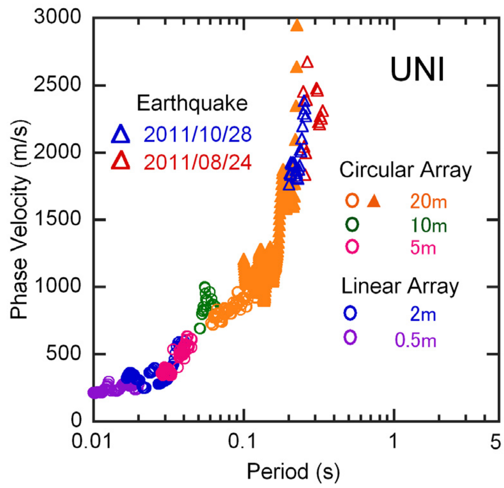

Fig. 10. Dispersion curves from microtremor arrays and seismometers. Circles refer to the F-k method, the filled triangle to the nc-CCA method [4] in microtremors and the unfilled triangle to the F-k method in seismic records.

to 0.3 seconds.

The next procedure is to calculate F-k power spectra [5]. **Fig. 9** presents some F-k spectra for the arrays of August 24 and October 28, 2011. In a comparison of the direction of the earthquake with the direction of the main peak in F-k spectra, it is possible to confirm the validity of points that will form the dispersion curve.

2.2.3. Calculation of the Dispersion Curve

Finally, the dispersion curve is calculated and shown in **Fig. 10**. Not only the dispersion curve found from the seismometer arrays but also the dispersion curve calculated from microtremor arrays is shown in this figure.

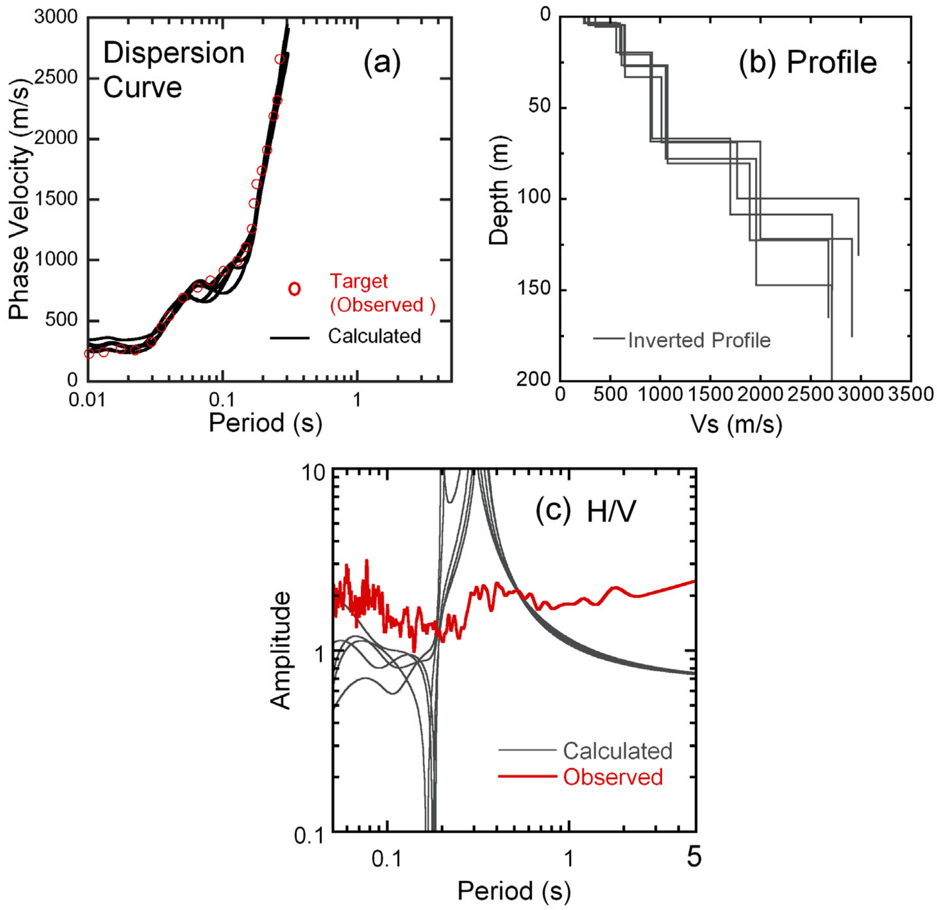

Fig. 11. (a) Target and calculated dispersion curves, (b) Inverted profiles, and (c) Observed and calculated H/V spectra, estimated at UNI near the seismometer array.

Table 1. Boundary matrix for the inversion process.

UNI		
Layer	Vs (m/s)	Thickness(m/s)
1	[200-500]	[1-10]
2	[500-750]	[15-30]
3	[800-1250]	[30-80]
4	[1500-2000]	[30-80]
Half-space	[2500-3000]	-

The continuity of dispersion curves calculated by using microtremor arrays and seismometer arrays is observed. This fact supports the use of seismometer arrays for dispersion curve calculation.

2.2.4. Inversion of the Dispersion Curve

The dispersion curve calculated from microtremor and seismometer arrays in UNI (**Fig. 10**) is inverted in order to estimate the shear-wave velocity profile. This process is carried out using the methodology of Genetic Algorithms (GA).

The search space is defined in **Table 1**. This model was determined taking as a reference the profile estimated in CISMID [3] due to his short distance to UNI. Inversion was carried out five times and the numbers of generations and populations was 20 each. In addition, the effect of higher modes was considered in the inversion process [7].

Figure 11(a) compares the five computed dispersion curves with the target one (red circles). The computed ones approach the target one well and an inversion trend is identified at about 0.1 second.

Estimated profiles are shown in **Fig. 11(b)**, where it is observed that the variance is small in the first layers but large for the last layer, even though, as an average, the maximum depth can be considered to be 120 meters. Finally **Fig. 11(c)** shows observed and computed H/V spectra. The prominent peak of computed spectra may be related to the abrupt change in velocity values in the estimated profile, which may be different from the real profile. The gradual change of velocity profile may be one possible reason of the difference between the H/V spectra. The limited number of layers considered in the inversion process may influence as well the difference between the H/V spectra. Although large number of layers is always desired in the inversion process, it is time consuming and requires a high computer capacity.

3. Discussion

The estimation of shear-wave velocity profiles is necessary to estimate amplification and other dynamic characteristics of soil vibration in Lima. Eight shear-wave velocity profiles with depths to hundreds of meters and sometimes to the seismic bedrock were estimated by performing microtremor arrays measurement.

In general, microtremors were good enough for estimating deep soil velocity profiles in Lima, although for the range of periods from 0.5 to 1.5 s, low signal power was observed. As a result, some dispersion curves were not well defined, introducing uncertainty into estimated profiles.

Due to the low signal-to-noise ratio found during microtremor analysis, the use of seismic records was proposed as an alternative because of the high power associated with seismic records.

To confirm the methodology of the seismometer array, an array of four seismometers was located on the campus of the National University of Engineering. Two seismic events were analyzed; these events were chosen because the location of their epicenters is separated far enough and the magnitude is large enough to create surface waves at the University.

The dispersion curve of the seismometer array showed a continuous curve for the period ranging from 0.2 to 0.4 s. Microtremor array measurement was carried out in the same place in order to compare results. Good agreement was found between dispersion curves of microtremors and seismometer arrays. This fact supports the use of seismometer arrays in calculating dispersion curves.

Although microtremors were enough to calculate the dispersion curve at UNI, there were other places, such as VSV (**Fig. 1**), where microtremors showed a low resolution dispersion curve (**Fig. 2**) and where the analysis of seismometer arrays could allow for the calculation of a continuous dispersion curve.

Through the F-k spectra showed in **Fig. 9** the verification of the earthquake direction was carried out. In the case of the August 24 earthquake, a slight variation was observed in the direction of the earthquake. The reason for this small change could have been influenced by the Andes Cordillera. In the case of the October 28 earthquake, the variation was more noticeable. The reason could have been wave propagation characteristics in this direction. To determine this, however, more seismic events coming from that direction should be analyzed in order to support this hypothesis.

4. Conclusions

Deep shear-wave velocity profiles that define the dynamic characteristics of soil vibration in Lima have been estimated and the following conclusions found from microtremor and seismometer array measurement.

1 In general microtremors were good enough for estimating velocity profiles. In some areas of deep profiles, however, low signal power generated uncertainty in estimated profiles, such in the case of the Villa El Salvador district.

2 Seismic records were a good alternative to the low signal power of microtremors. The resulting dispersion curve was compared with the dispersion curve of microtremor arrays and good agreement was observed.

Acknowledgements

This study was developed in the framework of the "Enhancement of Earthquake and Tsunami Disaster Mitigation Technology in Peru" project sponsored by the Japan International Cooperation Agency (JICA) and the Japan Science and Technology Agency (JST).

The authors are grateful to JICA and JST for supporting these research activities and for introducing new equipment such as seismometers and sensors for microtremor measurement to the National University of Engineering in Lima, Peru.

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