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ESTIMATION OF VELOCITY STRUCTURES BENEATH MEXICO CITY USING MICROTREMOR ARRAY DATA

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ABSTRACT

Mexico City was heavily damaged by the Michoacan earthquake of September 19 in 1985, notwithstanding the epicentral distance was very large. The damage is considered to have been caused by the effect of very soft surface deposits in Mexico City, especially in the Lake Zone. The object of this study is to estimate surface velocity structures in heavily damaged area and damage free area in Mexico City.

Microtremor array observations were conducted at three sites, CA [Central de Abastos (Lake Zone)], CU [UNAM (Hill Zone)], MD [Madín (Hill Zone[mountain foot])]. Dispersion characteristics of phase velocities are derived from the array data at each site. Different dispersion characteristics are obtained at the three sites. Very high phase velocities, about 2 km/s at 1 Hz, are given at the MD site. At the CA site, observed phase velocities are very low, it is about 0.3 km/s at 1 Hz. Phase velocities at the CU site have intermediate characteristics between the Central de Abastos and the Madin sites, about 1 km/s at 1 Hz.

Velocity structures at the three sites are estimated with fitting the computed phase velocities of Rayleigh wave to those observed. The MD site is estimated to be located on bedrock judging from velocity structure derived from the microtremor array data. On the contrary, the CA site is considered to have very soft surface layers. The CU site is estimated to have sedimentary layers underlain by either the hard sediments or weathered rock that expose at the MD site region.

KEYWORDS

velocity structure, Mexico City, microtremor, array, F-K spectrum, dispersion, Rayleigh wave, inversion

1. INTRODUCTION

The fact that Mexico City 300 km away from from the epicenter was severely damaged by the 1985 Michoacan earthquake, made many engineering seismologists recognized strong effects of local subsurface structure on seismic motions. They have tried to reproduce the recorded seismic motions characterized by largely amplified long-lasting vibrations. However, they achieved only partial success primarily because of the lack of information of the subsurface structure for 2-D or 3-D modeling.

The subsurface structure is gradually clarified by the refraction and well-log surveys. However, the most influential elastic-layer model on seismic motions, in particular S-wave velocity structure, still remains unknown. Thus, the survey of the S-wave velocity is an urgent problem for the earthquake disaster mitigation in Mexico City.

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In this paper, microtremor array observations are conducted at three sites in Mexico City to estimate deep sedimentary structure, especially the S-wave-velocity structures. Figure 1 shows the location of the three sites, CA [Central de Abastos (Lake zone)], CU [UNAM (Hill zone)], MD [Madín (Hill Zone[mountain foot])]. The observation is held at seven stations with simultaneous microtremor measuring systems. With the common time data sets, laterally propagating surface waves from microtremor are detected by using the frequency-wavenumber power spectrum analysis (Capon, 1969). From a vertical component array observation, dispersion characteristics of Rayleigh wave are expected to be derived in the region. The dispersion curve is inverted to the deep sedimentary structure in the region (Horike, 1985). At every site, clear dispersion characteristics of Rayleigh wave were given. The dispersion characteristics are used to estimate the deep sedimentary structure.

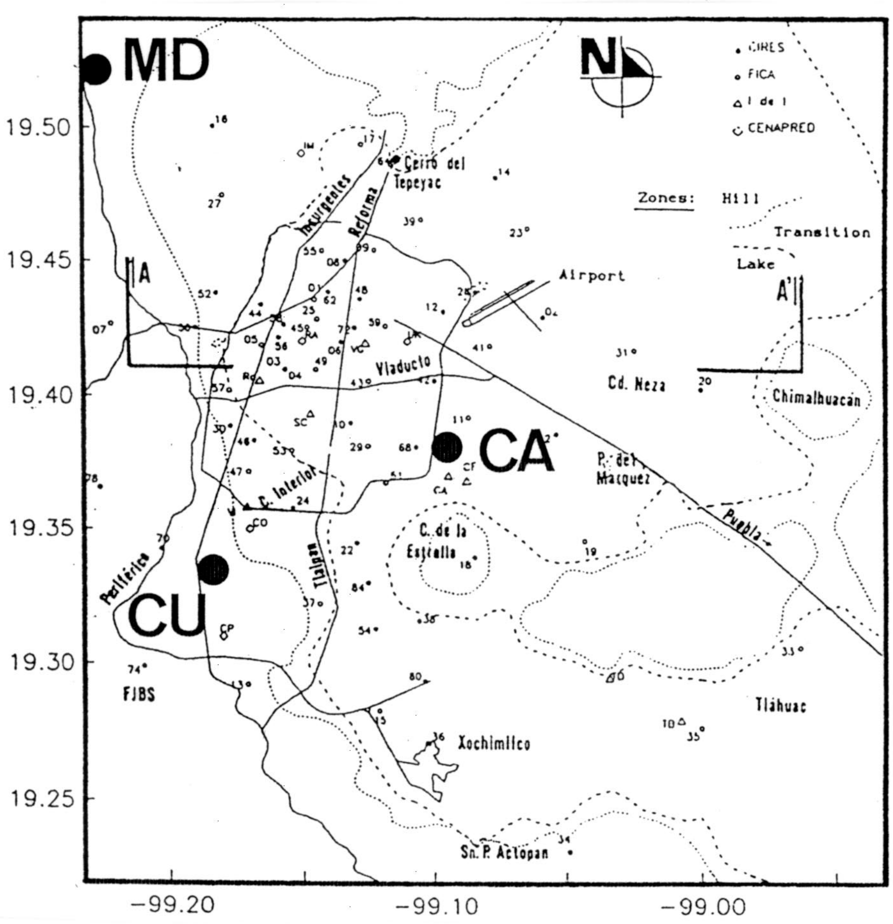


Fig. 1 Map of observation sites CU (UNAM), CA (Central de Abastos), and MD(Madín) together with the surface geological conditions and strong-motion observation sites.

2. INSTRUMENTATION AND DATA ACQUISITION

To make microtremor array observation, seven vertical component seismometers with natural period 7 seconds and 2 seconds were deployed. The microtremor was recorded by digital recorder with 16-bit accuracy through bridge circuit and amplifier with 4 Hz cut-off low-path-filter (Figure 2). BCD clock signals generated by a personal computer was sent with radio. The clock signal is received by transceiver and recorded at each observation point to keep common time. Photo 1 shows a snap of the field observation.

Photo 1. A snap of microtremor array observation.

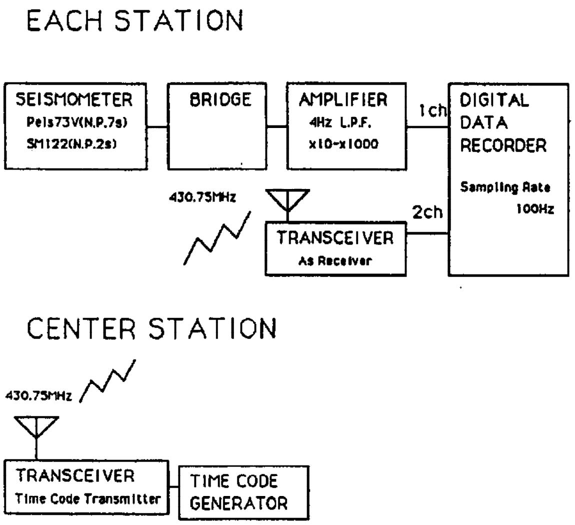


Fig. 2 Block diagram of microtremor observation system.

To get the dispersion in the wide frequency range, different size arrays to detect surface waves with different wavelengths must be deployed. Two to four series of array observation with different array diameter were conducted in this study. If propagation directions of the surface waves are not known, stations should be distributed uniformly to make the resolving power same for all directions. Seven observation points were distributed as triangle or cross shape at a series of observation. Figure 3 shows an example of an array configuration at a site.

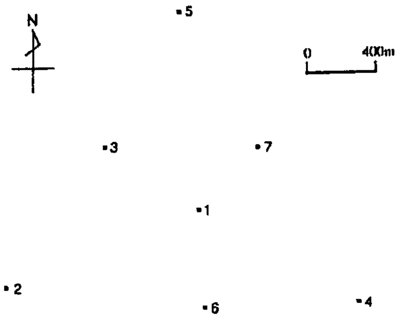


Fig. 3 An example of station distribution for an array.

As described before, BCD clock signal is recorded at each site. Figure 4 shows an example of recorded clock signal. Large numbers indicate BCD code number and small numbers show the digital sampling number where the BCD number started at the observation point. Sampling frequency at data acquisition was 100 Hz to keep time correction error within 10 ms. The sampling frequency of recorded data was reduced to 20 Hz after making common time correction.

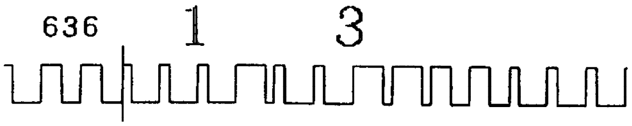


Fig. 4. An example of BCD clock signal recorded at a site. Small numbers show the digital sampling number where the BCD code shown by large number started.

Just before the observation, step response of the system was recorded at each point using a Maxwell bridge circuit. Figure 5 shows an example of step response data analysis. From the step response time series, natural period and damping factor were obtained to fit amplitude and phase spectrum. Using the derived factors, characteristics of each observation system were corrected to be common.

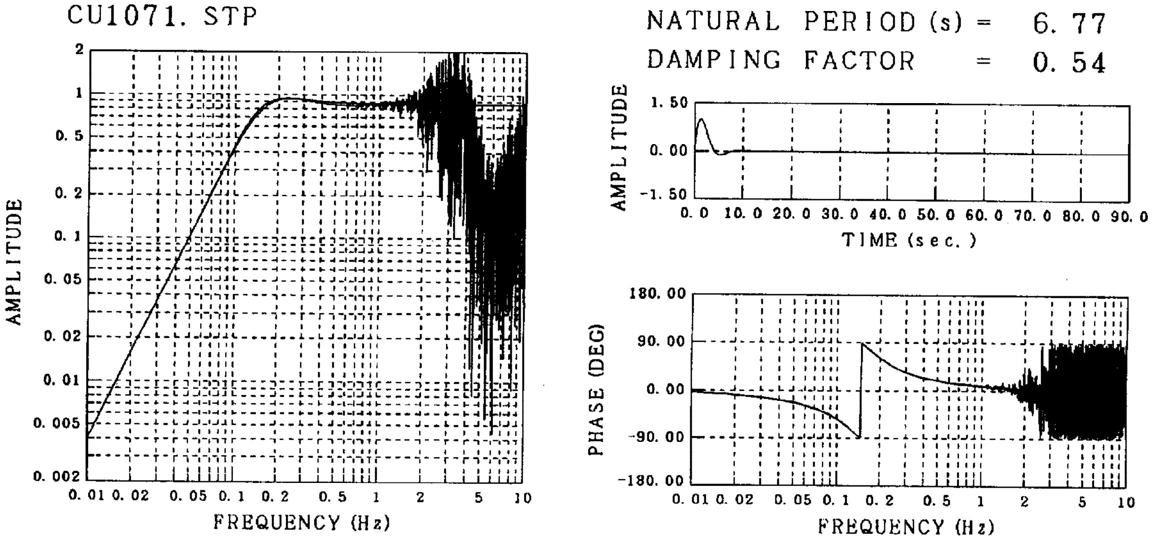


Fig. 5. An example of step response analysis of a overall recording system. Right-upper panel shows a step response time series. Left and right-lower panels show amplitude and phase spectrum of step response. In those panels, theoretical spectrum calculated by inverted natural period and damping factor.

3. ANALYSIS METHOD

The phase velocity C is estimated from the wavenumber at which the frequency-wavenumber spectrum (F-K spectrum) is extreme, using the equation,

$$C = f / (K_x^2 + K_y^2). \tag{1}$$

The F-K spectrum is inferred by the maximum likelihood method (MLM). This technique is devised by Capon(1969) and expressed by

$$P(f, k) = [\, \Sigma\, \varphi_{lm}^{-1} \exp(\, ik(X_l - X_m)\,)\,]^{-1}, \tag{2}$$

where P(f, k) is the F-K spectrum and φ_{lm} is the cross power spectrum for stations l and M. X_l and K respectively represent the location of station l and the wavenumber vector. Capon (1970) discussed the mean, variance, and confidence interval to estimate the F-K spectra in case that the direct segment method is used to infer the cross power spectra. In this study, we employ the conventional technique for inferring the cross power spectra. Data window LD and lag window LM maintain the relation,

$$LD / 10 < LM \tag{3}$$

for the stable inference of the cross power spectra (Jennings and Watts, 1968). The Bartlett window is employed as the lag window, and, thus, the frequency resolution is about 2 / (LM*DT), where DT is a sampling interval. To keep a high resolution of frequency, long data window is required. For the case of larger array, 45 minutes' record was obtained. For smaller case, 25 minutes recording time was used.

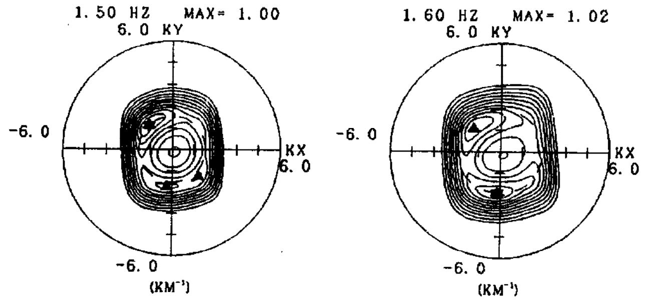


Fig. 6. Examples of F-K spectra. Star symbols indicate the peak of the F-K spectra from which the wave going away direction and propagating phase velocity are derived.

Figure 6 shows examples of F-K spectrum. The location of a contour peak (star symbol) indicates the wave going away direction and propagating velocity (phase velocity). Four different time series data without traffic noise were used to obtain a mean phase velocity and its standard deviation.

From the phase velocities derived from microtremor array observation data, underground structure beneath the site is estimated. Inverted parameter is restricted to the S-wave velocity because the dispersion curve is very sensitive only to the S-wave velocity. The inversion procedure is based on Jackson(1972) and Wiggins(1972).

4. FIELD EXPERIMENTS

We selected three observation points on different site conditions (Hill Zone, Lake Zone, and mountain foot) in Mexico City. The sites are UNAM (Hill Zone), Madín (Hill Zone[mountain foot]), Central de Abastos (Lake Zone). Hereafter, we give observation site codes CU for UNAM, MD for Madín, and CA for Central de Abastos.

For each observation, we set up seven stations installed in each size of array. For the CU site where a strong motion was recorded during the 1985 Michoacan earthquake, four different sizes of arrays, 2.0, 1.0, 0.75, and 0.5 km in diameter were deployed. We carried out most detail observation at the CU site to make it as a standard data in our study. At the MD site where a strong motion was recorded, we set two different sizes of arrays with 2.0 and 0.75 km in diameter. For the CA site, we used smaller sizes of arrays with 0.5, 0.25, and 0.1 km in diameter. Because in the lake zone, there is a thin surface layer whose S-wave velocity is very low and that means the wavelength of surface wave in microtremor is expected to be very short. The locations of observation sites were shown in Figure 1. At the CU and the MD sites, we made observations in the daytime. On the contrary, at the CA, we carried out the observations at night to avoid huge traffic noise in the daytime.

Figure 7 shows an example (CU smallest array) of field data sets by seven-stations-array after common time correction. Each trace is normalized by its maximum value.

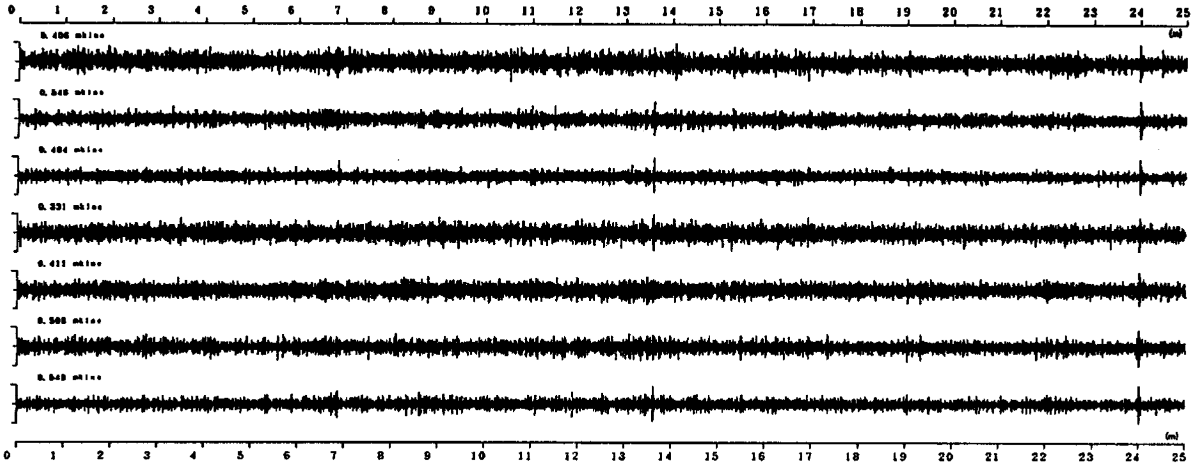


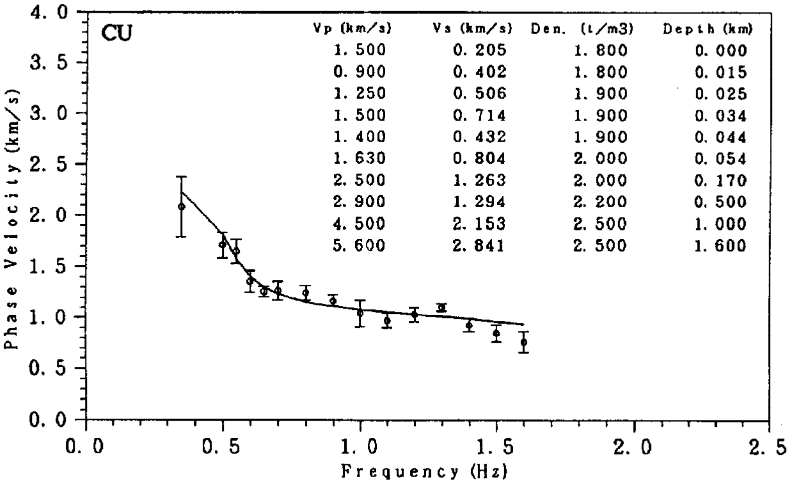
Fig. 7 Observed microtremors for the smallest array at the CU site. Each trace is normalized by its maximum value.

5. DISCUSSION

5.1. The CU (UNAM) site

In the CU array, clear dispersion characteristics of Rayleigh wave were obtained from microtremor array observation data (Figure 8). In the figure, center circles indicate the mean value of phase velocities derived from four different data sets. Vertical bars show standard deviation of phase velocities at each frequency. Because the phase velocities are higher than 1 km/s at the frequency range over 1 Hz, it is assumed that hard sediments with S-wave velocity over 1 km/s exist at shallow point.

From a gravity anomaly survey (Nozaki et al., 1993) and boring data, brief sedimentary structure was modeled for the CU site. Using the initial model, S-wave structure matching the dispersion curve for observed phase velocity was estimated. Through this estimation, the inversion technique we mentioned before was applied. In the Figure 8, a smooth line shows the phase velocity of Rayleigh wave calculated from the estimated structure that is also shown in the figure. From the result, sedimentary layer with S-wave velocity lower than 1 km/s is about 50 m. Beneath the sediment, weathered rock or hard sediments that has S-wave velocity about 1.3 km/s is estimated to exist down to 500 m.



Vp (km/s)	Vs (km/s)	Den. (t/m3)	Depth (km)
1. 500	0. 205	1. 800	0. 000
0. 900	0. 402	1. 800	0. 015
1. 250	0. 506	1. 900	0. 025
1. 500	0. 714	1. 900	0. 034
1. 400	0. 432	1. 900	0. 044
1. 630	0. 804	2. 000	0. 054
2. 500	1. 263	2. 000	0. 170
2. 900	1. 294	2. 200	0. 500
4. 500	2. 153	2. 500	1. 000
5. 600	2. 841	2. 500	1. 600

Fig. 8. Observed phase velocity at the CU site and phase velocity of Rayleigh wave from estimated structure. Center circles and vertical bars show mean value and standard deviation observed at each frequency. Smooth line shows phase velocity of Rayleigh wave calculated from the estimated structure that is also shown in the figure.

5.2. The MD (Madín) site

Figure 9 shows the observed phase velocities at the MD site with the ones at the CU site. In the frequency range lower than 1 Hz, the phase velocities are higher than 2 km/s. Even at 1.3 Hz, phase velocity is higher than 1.5 km/s. It is assumed that the MD site is underlain by baserock with weathered rock or very hard sediment, without soft sediments.

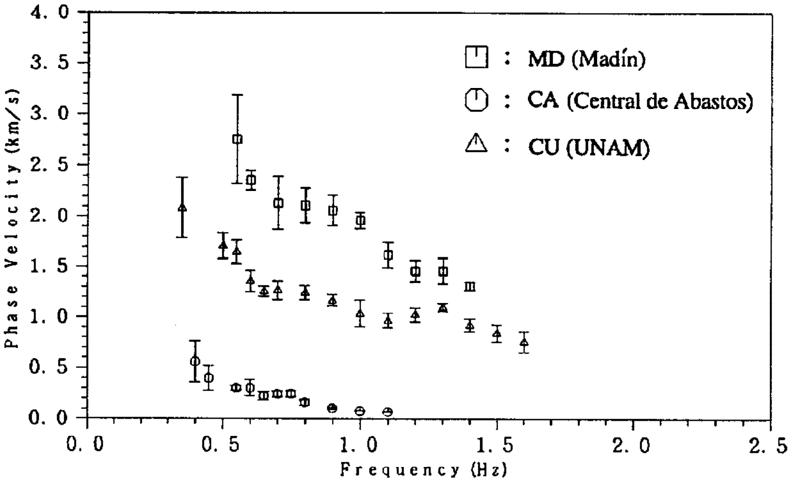
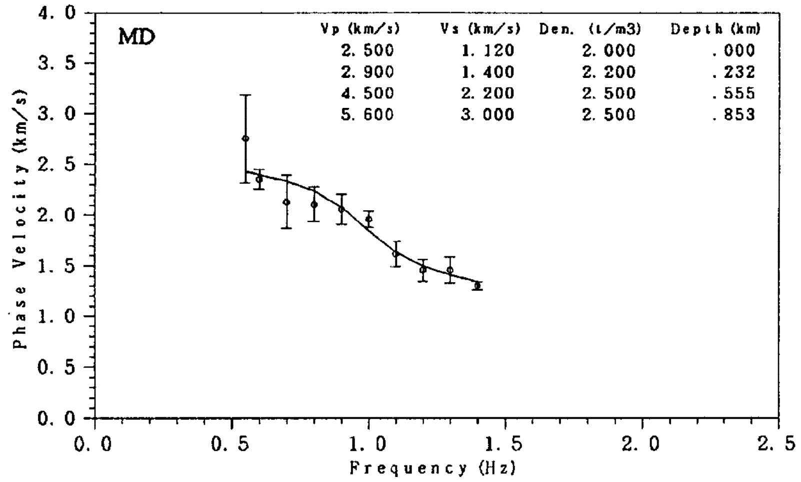


Fig. 9. Observed phase velocity at the MD and the CA sites with contrast to the CU site.

We tried to estimate a structure beneath the MD sites using an inversion technique. From the dispersion curve of microtremor, we assumed an initial model structure omitting shallower six sedimentary layers from the CU initial model. We made an inversion analysis and tried to obtain proper thicknesses of sediments. The result is shown in Figure 10. Thickness of layers that have S-wave velocity higher than 1 km/s is estimated about 800 m.

Both the MD and the CU sites have been considered to belong to Hill Zone. From the phase velocities derived from microtremor array observation, the MD site is assumed to be almost rock site. The phase velocities at the CU site are lower than those at the MD site. The CU site is considered to have sedimentary layers underlain by either the hard sediments or weathered rock that expose here at the MD region.



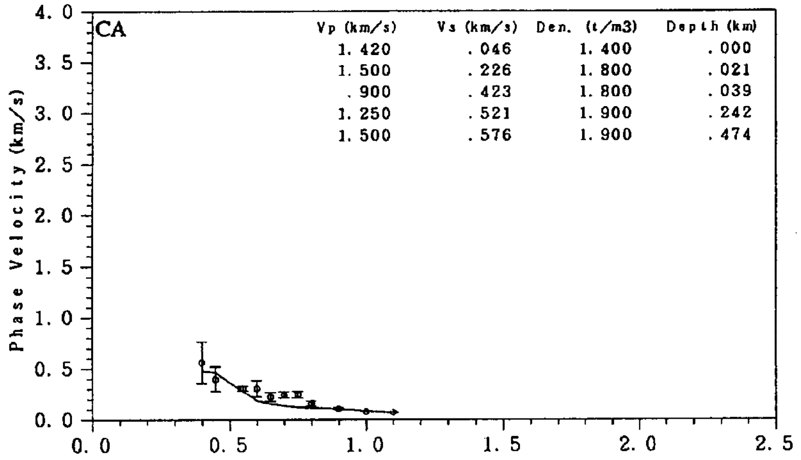
Vp (km/s)	Vs (km/s)	Den. (t/m3)	Depth (km)
2. 500	1. 120	2. 000	. 000
2. 900	1. 400	2. 200	. 232
4. 500	2. 200	2. 500	. 555
5. 600	3. 000	2. 500	. 853

Fig. 10. The same as Figure 8, but for the MD site.

5.3. The CA (Central de Abastos) site

Observed phase velocities at the CA site are also shown in Figure 9. In contrast to the CU and the MD case, it is easily estimated that soil condition at the CA site is very soft. Even at 1 Hz, phase velocity is about 100 m/s. It means that the Rayleigh waves with wavelength 100 m propagate at a speed of 100 m/s.

From the dispersion curve derived from microtremor, an initial model structure is assumed. In the model, deeper six layers for the CU initial model were neglected and a very soft sedimentary layer is added on the top of the model. The result of inversion in which a model parameter is thickness of each layer, is shown in Figure 11. The thickness of very soft layer is assumed to be about 20 m. Also the thickness of the layer with S-wave velocity higher than 0.7 km/s is estimated about 570 m. We consider that the phase velocities at the CA site have typical characteristics at Lake Zone.



Vp (km/s)	Vs (km/s)	Den. (t/m3)	Depth (km)
1. 420	. 046	1. 400	. 000
1. 500	. 226	1. 800	. 021
. 900	. 423	1. 800	. 039
1. 250	. 521	1. 900	. 242
1. 500	. 576	1. 900	. 474

Fig. 11. The same as Figure 8, but for the CA site.

6. CONCLUSION

Microtremor array observations were carried out at three sites with different site conditions, CU (Hill Zone), MD (Hill Zone[mountain foot]), and CA (Lake Zone). Through F-K spectrum analysis of field data, the results were obtained as follows.

1. At all site, dispersion curves of Rayleigh wave was well derived from the field data set of microtremor. Each dispersion curve has typical site characteristics that depends on the site condition.
2. With reference of gravity anomaly and boring data, deep sedimentary structure, especially S-wave structure, was estimated at the CU site. The phase velocities at the CU site are considered to have site characteristics of general Hill Zone.

3. Comparing the dispersion curve derived at the MD with that at the CU site, the condition of the MD site is assumed to be rock. The dispersion curve at the MD site represents a site condition at the Hill Zone and it is assumed to be rock site.
4. From the dispersion curve, the CA site is estimated to have very soft and thick sedimentary layers. This is considered to be typical characteristics at the Lake Zone.

Sedimentary structures derived from microtremor array observations are expected to be useful for seismic site response calculations, and to contribute seismic disaster mitigation in the future.

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