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GEOPHYSICAL EXPLORATION USING MICROTREMOR MEASUREMENTS

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ABSTRACT

Microtremors are used not only for the inference of dynamic properties of sediments to seismic motions but also for the exploration of subsurface structures. The two methods are proposed for the exploration. The first one employs the phase velocity and the second one the ratio of horizontal to vertical components. In this article we describe the present state of the two methods and the problems solved for the future development, and then show the example of the exploration using the microtremor phase velocity and the simulation of strong motions using subsurface structures obtained by this exploration method.

KEYWORDS

Microtremor exploration; phase velocity; inversion; horizontal-to-vertical ratios

INTRODUCTION

A major goal of the engineering seismology is the prediction of strong motions. To accomplish it we evaluate the effects of the three factors of seismic sources, propagation paths and local geology on seismic motions and link them. Although the third factor was seemed to be considered less important than the other two except Japan, recent earthquake damages world widely recalled the issues of the effects of surface geology to engineering seismologists and earthquake engineers.

In Japan, since a sharp spatial contrast of damage level in Tokyo by the great Kanto earthquake was concluded to be caused by the difference in local geology between hilly and coastal zones, many researchers have been devoted to find tools to evaluate the effects of the local geology conveniently at low cost. The measurement of microtremor is one possible approach, because it exists anytime and anyplace, its measurement and analysis are simple, and moreover the measurement does not generate environmental problems such as noisy sound and strong ground shaking. For the above-mentioned reasons the feasibility to evaluate the effects of local geological conditions from the measurements of microtremors was vigorously studied since the pioneering work by Kanai *et al.* (1954).

There are two groups of the study on the use of microtremors. The first group directly estimates site responses to seismic motion from microtremors. This group is further divided into three methods: The dominant period (Kanai *et al.*, 1954, Kubotera and Otsuka, 1970), the relative spectral amplification factor to a reference site (Irikura and Kawanaka, 1980, Kagami *et al.*, 1982) and the spectral ratios of horizontal component to vertical component (Nakamura, 1989). Since these techniques are based on several assumptions about incident microtremors that are difficult to be verified, site responses estimated from microtremors are not always trustworthy. This is a primary reason why microtremors are not used as a major tool. Specifically, the method estimating the dominant period assumes that microtremors are vertically incident S waves with flat spectral amplitudes, but this assumption is not true at almost all sites, because microtremors contain surface waves considerably, which discussed in a later section. The second method assumes a spatial uniformity of incident microtremors at least within microtremor-measurement areas. However, this assumption is not always true, because the level of human activities, main source of urban microtremors, are spatially variable. The third one assumes that vertical amplitudes of incident microtremor are almost same as that on ground surface. This assumption is not always true either, because P- and S- velocities of sediments increase with depth in most sediments.

The other group uses microtremors for the geophysical exploration. This group is also classified into two methods: the phase velocity of surface waves (Aki, 1957, Horike, 1985) and the spectral ratios of horizontal to vertical components for Rayleigh waves (Nogoshi and Igarashi, 1971, and Horike, 1980). An important point of the two techniques is that they are controlled only by subsurface structures (Haskell, 1953) and are free from assumptions about the spectra of microtremors incident to sediments. Therefore, they are potentially feasible to determine reliable subsurface structures.

A rapid progress of numerical simulation techniques makes it possible to predict realistic strong motion in wide sedimentary basins such as the Los Angels basin and the Mexico City basin using 3-dimensional subsurface models (Frankel, 1993 and Uebayashi *et al.*, 1992). However, the implementation of the 3-d simulation is practically impossible because of an obstacle to the 3-dimensional modelling of sedimentary basins for the lack of geophysical surveys. A main reason for it is that the cost of conventional geophysical surveys such as reflection and refraction methods are too high and these surveys are difficult to conduct in highly populated areas for the environmental problems. Meanwhile, because the geophysical surveys using microtremor are free from the above-mentioned difficulties, their applications are supposed to increase especially in urban areas. We therefore confine the description in this article to the geophysical surveys using microtremors.

We first summarize studies of the geophysical explorations using microtremors and then discuss the problems to be solved for the future development. We finally show examples of simulation of strong motions using 2-dimensional subsurface structure explored using microtremors.

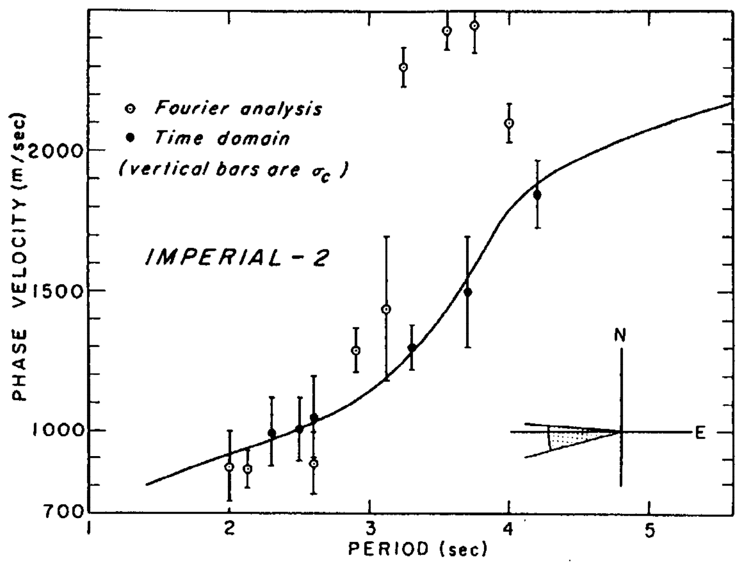

Fig. 1 Measured (circles) and computed (solid line) phase velocity[Toksotz(1964)].

EXPLORATION OF SUBSURFACE STRUCTURES

Application of the Phase Velocities of Surface Waves

The phase velocity of microtremors was first estimated by Aki (1957). He regarded microtremors as stationary waves in time and space and derived the spatial autocorrelation as a function of the frequency, the phase velocity and the distance between seismometers. Applying it to microtremors recorded at two sites changing the distance between them, he demonstrated from measured phase velocities that microtremors comprise surface waves. He furthermore determined the S velocity structure up to 5m in depth from estimated phase velocities of Love wave. Following this work, the phase velocities of microtremors were often estimated and it was confirmed that microtremors are primarily composed of surface waves (e.g., Akamatsu, 1961, Nogoshi and Igarashi, 1971, and Kudo *et al.*, 1976). This situation naturally led to the employment of the phase velocities of microtremors to the exploration.

The first attempt to explore subsurface structures with the microtremor phase velocities was made by Toksotz (1964). Figure 1 shows the estimated phase velocities and the dispersion curve calculated from the best-fitted model. His conclusion to the exploration of the microtremor phase velocity was potentially useful as the gravitation method, because the obtained phase velocities were scattered largely as can be seen in Fig. 1. The reasons for large errors were due to the limitation of recording system and low resolution in the estimation technique of the phase velocity. However, a high-resolution inference method of the F-K spectra by Capon (1969) and the development of digital-based instruments made it possible to estimate concentrated phase velocities from microtremors. In fact, the progress in the instruments and the estimation technique demonstrated that concentrated phase velocities were obtained from array microtremor data (e.g., Liaw and McEvilly, 1979, Douze and Laster, 1979). Furthermore, the inversion began to develop in the fields of the seismology and the geoexploration from the early 1970's (e.g., Wiggins 1972, Jackson, 1972). Therefore, all the tools necessary for the exploration of the microtremor phase velocities were prepared by the end of 1970's.

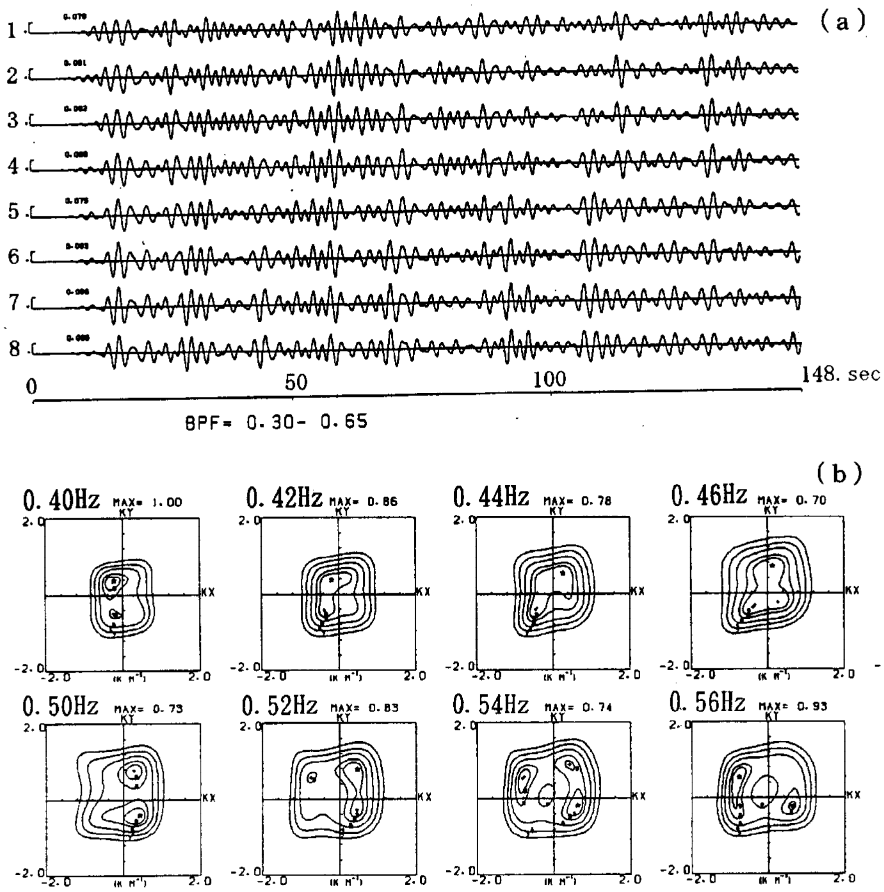

Fig.2 Example of microtremor array data (a) and the F-K spectra (b).

Horike (1985) applied the inversion to the microtremor phase velocities of Rayleigh wave estimated from vertical-component array data in urban areas by the F-K analysis and obtained reliable S-velocity structures of sediments, evaluating them with the resolution and the variance. The procedure of this inversion is as follows: First we acquire array microtremor data shown in Fig. 2(a), then estimate the phase velocity from peaks of the F-K spectra, and finally the phase velocities are inverted into the subsurface structure. Afterward, this technique was extensively examined its validity (e.g., Matsushima and Okada, 1990, Tokimatsu and Miyadera, 1992) and seems to be recognized as an exploration method for the S velocity structure of sediments at least in Japan.

The advantage of this method is that S velocity structures, being difficult to estimate with other methods, are determined down to the basement even in urban areas at low cost. However, there are several limitations to overcome. The first one is that the phase velocity of Love wave is not used for the inversion. The inversion of them results in more reliable S velocity structures than that of Rayleigh waves, because they are controlled only by the S wave velocity and the density,. Horike (1981) and Okada and Matsushima (1989) attempted to infer the phase velocities of Love wave from microtremors, but they were not so good as to employ for the inversion. The difficulty lies in picking out only Love wave from two-dimensional motions composed of various types of elastic waves. Therefore, the technique to pick out a single wave type from two-dimensional complicate wavefield is necessary for the inversion of the microtremor phase velocity of Love wave.

Another limitation is that the inversion is performed based on flatly layered models. Arakawa *et al.* (1994) showed that the microtremor phase velocity is potentially possible to determine irregular subsurface structures. They obtained two dispersion curves from microtemor array analysis. Assuming that they are the dispersion curves of the fundamental and the first higher modes, the subsurface structure was obtained by the inversion. It explained the two dispersion curves quite well. However, the inverted S velocity of basement rock was 2.1 km/s. This value is too small taking into account that it is expected to be about 3.0 km/s from the empirical relation between the P- and S- wave velocities of rocks. This means that the microtremor phase velocity contains the information of irregular structure. Therefore, if the theory of the phase velocities in such complicate structures is developed, irregular subsurface structures may be possible to be inverted from the microtremor phase velocity.

SPECTRAL RATIOS OF HORIZONTAL TO VERTICAL COMPONENTS

The spectral ratios of horizontal to vertical components (abbreviated as H/V) of Rayleigh waves are controlled only by subsurface structures as wel (Haskell, 1953). Therefore, if microtremor primarily consists of Rayleigh waves, the spectral ratios are possible to use for the exploration. It was first indicated by Nogoshi and Igarashi (1971). Figure 4 shows the comparison of the estimated spectral ratios with those of the computed ratios. As can be seen from the figure, the ratios do not agree in value, but the spectral shapes are similar. In particular, the dominant frequencies agree well. They furthermore suggested that an agreement of the predominant frequencies is obtained only for simple subsurface structures with high-impedance ratios, because the peak of the H/V ratios of Rayleigh wave becomes sharp in such structures. Therefore, the ranges of the application of this method seem to restrict only to simple subsurface structure such as two-layered model with high impedance ratios. The agreement of the dominant frequency in the H/V of microtremors with that of Rayleigh wave was confirmed by Shiono *et al.* (1978), Horike (1981), and Tokimatsu *et al.* (1993).

Geological information obtained from the dominant frequency of the H/V ratios is limited. To obtain more geological information, we should use not the dominant frequency but the H/V ratios themselves in wider frequency range. However, as was described previously, the H/V ratios of microtremors are different from those of Rayleigh waves. This is primarily because the horizontal spectra are the mixture of various types of elastic waves. Therefore, a method to pick out only Rayleigh waves from horizontal microtremors is necessary. That immediately reminds us that it is the same reason as the mictotremor phase velocity of Love wave is not estimated reliably. A technique to pick out individual elastic wave in microtremors is indispensable for the use for the exploration of the H/V ratios as well as the phase velocities of Love waves.

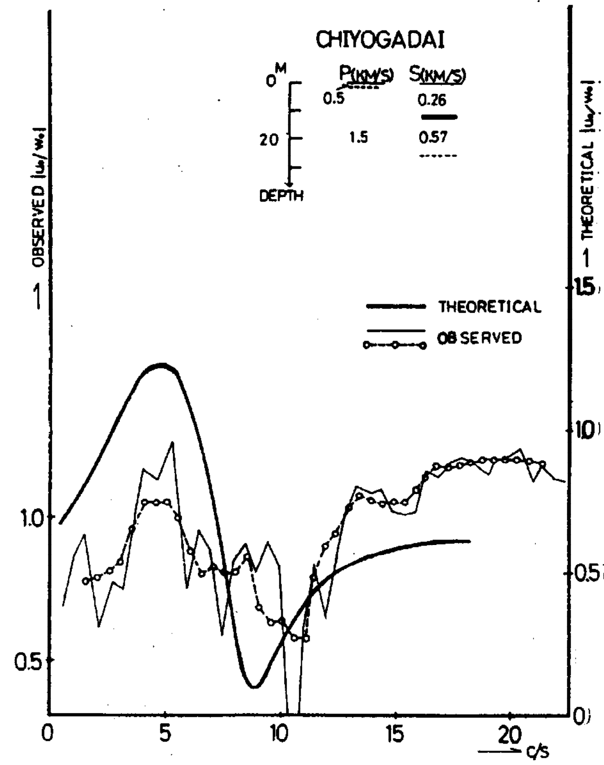

Fig. 3 Comparison of H/V ratios betwen microtremors and Rayleigh wave [Nogoshi and Igarashi(1971].

EXPLORATION USING THE MICROTREMOR PHASE VELOCITY

We here show examples of the exploration using the microtremor phase velocity. Figure 4 shows the map of the Osaka basin. In this basin there are several big cities such as Osaka and kobe and its total population is over ten millions. The establishment of the measures to mitigate earthquake damages is an important and urgent task for the municipal governments. Predicted strong motions are indispensable and fundamental information for this purpose. We have conducted various geological surveys for modelling of the 3-dimensional subsurface structure of this basin to predict strong motions, but now it is on the way. However, we completed the 2-dimensional modeling below the solid and thick line shown in Fig. 4 by the reflection surveys and the inversion of the microtremor phase velocity.

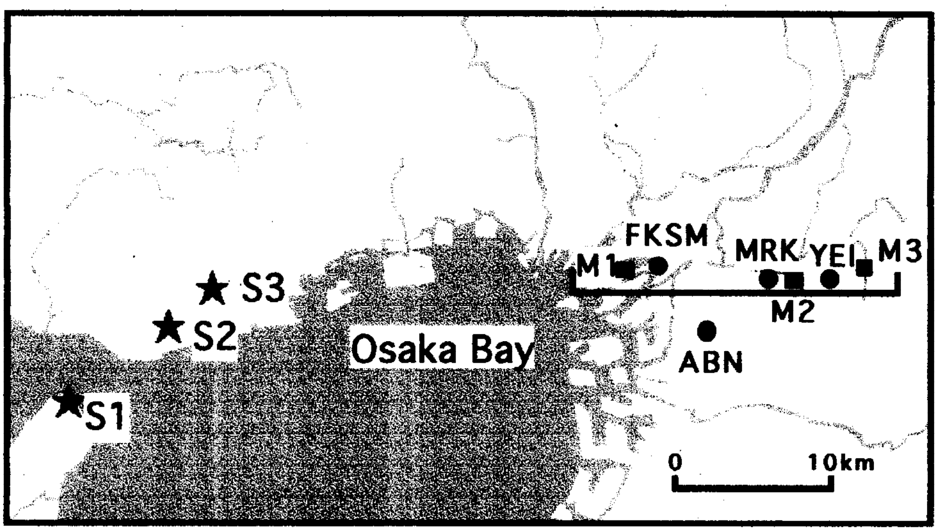

Fig. 4 Map of the Osaka basin. The asterisks denote main subfaults of the Kobe earthquake. Dark squares and circles denote the sites of microtremor array experiment and strong motions, respectively.

We made microtremor array experiment at three sites M1, M2, and M3 and estimated the phase velocities of Rayleigh waves from vertical-component microtremors. Figure 5 shows measured phase velocities at site M3 and Table 1 shows the subsurface structure inverted from them. The solid curve in Fig. 5 is the dispersion curve calculated from the inverted model and is well fitted with the measured phase velocities. At the remaining two experiment sites, the subsurface structures were successfully determined from the measured phase velocities.

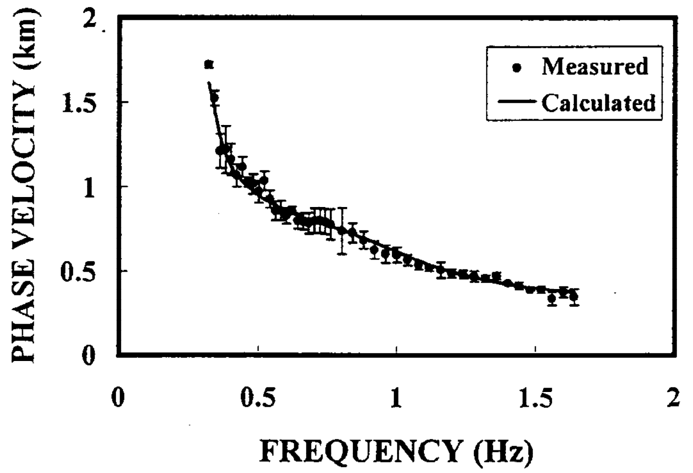

Fig. 5 Measured phase velocity (dark circles) and calculated phase velocity (solid curve) from the inverted subsurface structure shown in Table 1.

We next show an example of the simulation of strong motions using the inverted subsurface structures. Simulation is performed at 4 stations close to the line FKSM, ABN, MRK, and YEI (See Fig. 4) where strong motions of the 1/17 '95 Kobe earthquake were recorded. The procedure of the simulation is as follows: Incident motions to sediments are computed by the method by Boore(1983) and then corrected the effects of sediments by the Haskell method (1953), assuming vertically incident S wave. The locations of the seismic sources are denoted by the asterisks. They were obtained by Kikuchi(1995) using the waveform inversion. Figure 6 shows the recorded and simulated horizontal motions at FKSM. They agree well in peak acceleration and duration. At the other three stations, they are in good agreement as well. The agreement between simulated and recorded strong motions means the microtremor phase velocity is a useful and practical tool for the exploration.

Table 1 Subsuface structure inverted from the phase velocties shown in Fig. 5.

LAYER	P VELOCITY (km/s)	S VELOCITY (km/s)	DENSITY (g/cm^3)	THICKNESS (km)
1	1.5	0.306	1.73	0.05
2	1.6	0.357	1.76	0.07
3	1.8	0.594	1.79	0.10
4	1.9	0.752	1.85	0.08
5	2.0	0.845	1.92	0.17
6	2.1	0.905	1.94	0.23
7	2.2	1.18	2.09	0.30
8	2.3	1.21	2.14	0.90
9	5.4	3.20	2.70	

CONCLUSION

The H/V ratios of microtremors are employed in the Nakamura method as well. He interpreted the ratios assuming that microtremors are composed of body wave, whereas the H/V ratio is interpreted in this article as those of Rayleigh wave. Therefore, we here discuss the relation between them. A comprehensive understanding is possible taking into account of the numerical study of microtremors by Lachet and Bard (1994) and the experimental study by Nogoshi and Igarashi (1971). They showed that the dominant frequency of H/V ratios of microtremors agrees with that of S wave responses in simple and high-contrast sediments, suggesting that the H/V ratios are primarily controlled by the fundamental mode of Rayleigh waves.

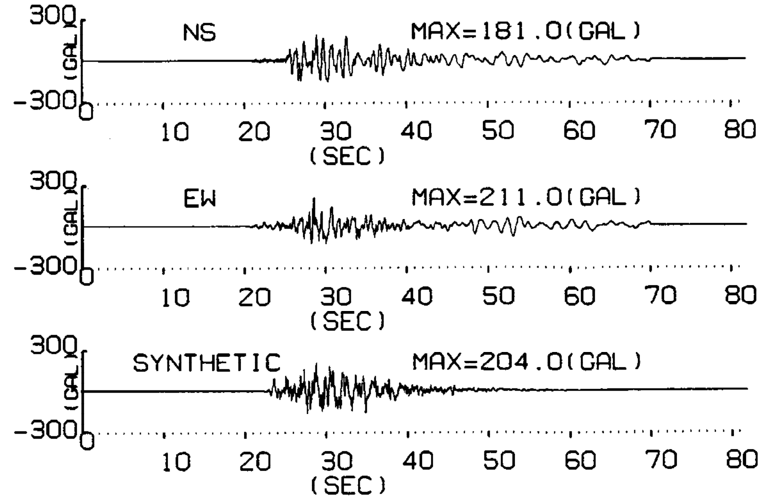

Fig. 6 Comparison of recorded and synthetic strong motions.

It is supposed that surface waves such as Love and Rayleigh waves prevail in microtremors, because of surface sources of microtremors and small geometrical spreading factor of surface waves compared with that of body waves. Consequently horizontal microtremors are supposed to contain Love wave considerably. Allam and Shima (1967) showed that the dominant frequency of Love wave agrees with that of shear wave responses in simple and high-contrast sediments. After all, the three dominant frequencies may agree well in simple high-contrast sediments: the shear wave response, the H/V ratios of microtremors, and the power spectra of horizontal microtremor . In facts, this was found by Zhao *et al.* (1995).

We finally recapitulate the state of the study of microtremor exploration.The microtremor phase velocity of Rayligh waves is established as a practical tool for the exploration, but that of Love wave is not because a method to select only Love wave from horizontal microtremor does not exist. Now, the microtremor phase velocity of Rayleigh wave is attempted to determine irregular structures.The estimates of the H/V ratios from microtremors are roughly similar to the ratios of Rayleigh waves. In particular the peak frequency of the H/V ratios is fitted with that of Rayleigh wave in case of the simple and high-contrast sediments. However, to use for the exploration, the method to pick out Rayleigh waves from horizontal microtremors is necessary.

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