Characterization of Microtremor Records Using Simulated Microtremors

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ABSTRACT

The paper attempts to illustrate the potential application of simulation techniques for interpretation and characterization of microtremors. Simulations are performed with two types of source distribution models, both involving a large number of Dirac wave type sources randomly activated on the surface of a horizontally layered ground underlain by the half-space. Attempt is made to utilize the technique for the interpretation of microtremors at KASAI site in Chiba prefecture (Japan). The site has a deep base layer and weak impedance contrast. The parameter R_F, defined as the ratio between horizontal and vertical input forces at the source, is used as a measure of the proportion of Love wave components in combination with Rayleigh waves contained in simulated microtremors. The microtremor records at KASAI seem to correspond to the simulation with R_F =0.1, indicating predominance of the Rayleigh wave components.

INTRODUCTION

Microtremor measurement is a simple and economical method for evaluating the site effect in populated areas with seismic risk. Publications concerning microtremor observations have been prolific following the pioneering work of Prof. Kanai in the 60's (Kanai and Tanaka [1961]). However, efforts to explain the underlying theoretical basis have been quite limited. Lachet and Bard [1994] have made the first attempt at simulated microtremors based on the 2-D wave propagation theory. They utilized several types of source set randomly in a circular array. A random factor was assigned for the occurrence of each source, the force amplitude of the radial, tangential and vertical components remaining constant. The authors (Tokeshi *et al.* [2000]) proposed a simulation technique based on the 3-D wave propagation theory as a possible tool for the interpretation of microtremors at two sites. They utilized tri-directional point sources set randomly in a grid array. Two sites, one with shallow base layer and strong impedance contrast, and the other with a deep base layer and weak impedance contrast, were evaluated. The parameter R_F, defined as the ratio between horizontal and vertical simultaneous input forces at the source, was defined as an index of the proportion of Love wave components contained in simulated microtremors, with larger value of R_F indicating higher proportion. Based on the comparison of simulations with different values of R_F with the actual measurements R_F=0.7 for the site with strong impedance contrast and R_F=0.1 for the site with weak impedance contrast were found appropriate.

In this paper, results of simulation at site with weak impedance contrast , referred to as the KASAI site, is utilized to compare the model used by Tokeshi *et al.* [2000] with the model proposed by Lachet and Bard [1994] . The parameter R_F is introduced in the model proposed by Lachet and Bard [1994] for comparison purpose. The effectiveness of the simulation techniques is investigated based on the comparison with microtremors recorded by 1s and 5s sensors, as well as with earthquake ground motion records.

The value of R_F corresponding to a given microtremor is estimated based on the comparison of its spectra and the vertical orbit with those of the simulated microtremors with various values of R_F. Estimation of the average percentages of Love and Rayleigh wave components in the simulated microtremors for various values of R_F is also carried out following a simple approach. Results of simulation indicate that the horizontal components of the simulated microtremors tend to contain mainly Rayleigh waves when R_F=0.0 and that the Love wave content increases as R_F increases from 0.0 to 1.0. It appears that the microtremors at sites with deep base layer with weak impedance contrast between adjacent layers tend to be predominant in Rayleigh wave components.

SIMULATION OF MICROTREMORS

Mathematical models

Two types of model have been utilized: (1) a square surface divided into 100 elements of equal area (Fig. 1), referred as square model (Tokeshi *et al.*, [2000]) in this paper, and (2) a circular surface divided into 100 circular sectors of variable area (Fig. 2) and referred here as the circular model (Lachet and Bard, [1994]). Both models assume a horizontally layered ground underlain by a half-space.

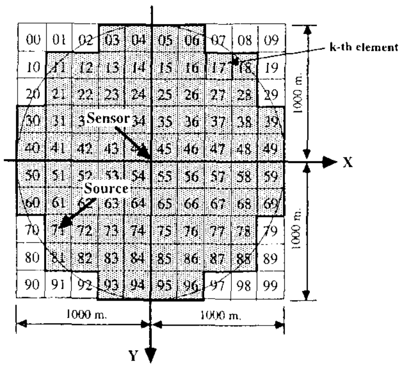

Fig. 1 Square model of source distribution on the surface

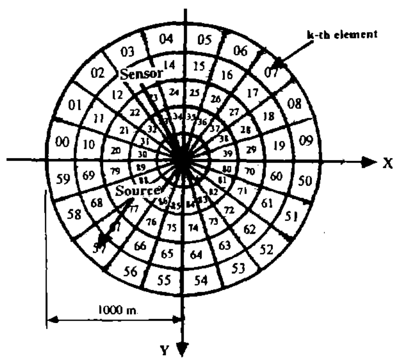

Fig. 2 Circular model of source distribution on the surface

Sensors for the three components of simulated microtremors, two horizontal along X and Y-axes and one vertical along the Z-axis, are assumed to be located at the center of respective model. Around 8000 tri-directional sources of pseudo-Dirac type (delta function) with predetermined constant amplitude are randomly distributed at the center of different elements and circular sectors at a random time between 0 and 80 seconds. Sources located within a radius of 1 km in each model are considered in the simulations. The applicable Green's functions due to point source are described in Tokeshi *et al.* [2000]. The total time duration of simulation is 80 seconds with sampling interval Δt of 0.01 seconds.

Characteristics of the simulated microtremors

The ratio R_F between the horizontal point source (Qh) and the vertical point source (Qv) as shown in eq. (1) has been proposed (Tokeshi *et al.*, [2000]) for the parametric evaluation of the characteristics of simulated microtremors.

$$R_F = \frac{Qh}{Qv} \qquad (1)$$

The horizontal force Qh acting at the center of each element has an arbitrary direction while its magnitude is made to change with assigned values of R_F as per eq.(1). The vertical force Qv remains unchanged in magnitude (Qv =1) and is made to act in downward direction. Simulations are carried out for values of R_F from 0.0 to 1.0 with steps of 0.1.

Average percentage of Rayleigh and Love wave components

Simple method of estimating the average percentages of Rayleigh and Love wave components for a given value of R_F proposed by Tokeshi *et al.*, [2000] is used. The method is based on a simple probabilistic distribution of the sources on a circular surface.

For a given value of R_F, the average percentages of Love and Rayleigh wave components are given by eqs. (2a) and (2b) respectively.

$$\Im i(\%) = \frac{\sum_{i=0}^{10}(Pi \times Li)}{\sum_{i=0}^{10} Pi(Li+Ri)} \times 100 \qquad (2a) \qquad \Re i(\%) = 100 - \Im i(\%) \qquad (2b)$$

Here, Ri and Li are the average displacement components of Rayleigh and Love waves for the distance Di between the source and the sensor. The probability Pi that a source is active at a distance Di from the sensor location is proportional to the area of a ring, whose radii Di in meters varies between $100i \pm 50$ ($0 < Di \leq 1000$, $i = 0, 1, \ldots, 10$). Table 1 shows these probabilities in percentages.

Table 1 Probabilities of occurrence of sources at various distances from source

Di (m)	0	100	200	300	400	500	600	700	800	900	1000
Pi (%)	0.25	2.00	4.00	6.00	8.00	10.00	12.00	14.00	16.00	18.00	9.75

Estimation of the predominant frequency of the ground

The similarity between record and simulations is evaluated through a combination of comparisons, consisting of (i) horizontal Fourier amplitude spectrum (Kanai and Tanaka [1961]), (ii) H/V spectral ratio (Nakamura, [1989]), and (iii) phase spectrum (Tokeshi *et al.*, [1996]). These spectral characteristics are normally utilized for the estimation of the natural frequency of the ground and are described in detail by Tokeshi *et al.*, [2000]. All the spectra are smoothed with Hanning filter, with a bandwidth of 0.025 Hz (number of iterations: 30).

As an additional tool for the comparison purpose, the shape of vertical orbit at the sensor location is quantified using the average absolute horizontal to vertical displacement ratio ***uh/uv***, as given by eq.(3).

$$\frac{uh}{uv} = \frac{\sum_{j=1}^{8000} |x_j|}{\sum_{j=1}^{8000} |z_j|} \qquad (3)$$

In eq.(3), x_j and z_j are amplitudes of horizontal and vertical components at a time $t_j = j \cdot \Delta t$ (j =1, 2, 3,..., 8000, Δt = 0.01s and time duration = 80s). The component x_j is used as representative of horizontal displacement because the shape of the horizontal orbit of simulated microtremors is expected to be close to a circle as a result of the random sources all around the sensor.

SIMULATION OF MICROTREMORS AT KASAI SITE

Microtremors, borehole information and earthquake records available at KASAI site are utilized in the investigation. The soil profile is summarized in Table 2, where the last column shows the fundamental resonance frequency of the ground under SH wave when the layer below is regarded as the base layer. The minimum impedance contrast is between 4th and 5th layers where $\rho_4 G_4 / \rho_5 G_5 = 1.1$. Ground motion with a maximum acceleration of 43 gals due to a small earthquake was recorded at 08:40 hrs JMT, 8 September 1997, about 22 km S-SE of KASAI site. Its epicenter was located at 35.5 N 140 E, with a magnitude of 5.1 and 105km depth. The N-S, E-W and U-D components of the recorded earthquake acceleration together with their Fourier amplitude spectra are given in Fig. 3. The phase spectra from one-side autocorrelogram of N-S and E-W components and H/V spectral ratio are also shown. The predominant frequency of Fourier amplitude spectra and the first intersection point in phase spectra for N-S as well as E-W components is noted to be 0.89Hz. This frequency in turn coincides with the fundamental resonance frequency under SH waves (0.89 Hz) when the fourth layer in Table 2 is regarded as a quasi-base layer. The H/V spectral ratio shows two predominant peaks, one at 0.63Hz and the other at 0.89 Hz. Larger peak appears at a frequency of 0.63Hz, which is lower than the predominant frequency (0.89 Hz) of horizontal accelerograms.

Comparison between recorded and simulated microtremors

Microtremors measured on the ground surface by sensors with short (1 s) and long (5 s) periods were available. Spectra for the recorded microtremors at KASAI are denoted by solid line in Fig. 4, where a predominant peak at about 3.67Hz can be clearly noted. Appearance this peak seems unrelated to ground

Table 2 Summary of physical parameters constituting the soil profile at KASAI site

Layer	Depth (m)	Thick(m)	Type of soil	Dens. (t/m3)	Vp (m/s)	Vs (m/s)	Qp & Qs	Freq. (Hz)*
1	0 -16.1	16.1	Silty sand	1.79	800	163	10	2.59
2	16.1 - 36.4	20.3	Silty clay	1.5	1490	142	10	1.02
3	36.4 - 55.7	19.3	Silty clay	1.63	1607	241	15	0.89
4	55.7 - 72.15	16.45	Sand	1.9	1510	361	20	0.86
5	72.15 - 90.6	18.45	Sand	1.86	1760	348	20	0.82
6	90.6 - 200	109.4	Sandy gravel	1.95	1946	558	40	0.72
7	200 - 1550	1350	Silty rock (Plio Pleistoc.)	2	2045	680	50	0.14
8	1550 - 2400	850	Miocene	2.3	2955	1500	100	0.13
Half-space	2400 - ∞	inf.	Pre Mioc., Pre Terciary	2.6	4620	3000	200	

* Fundamental resonance frequency of ground under SH waves considering the layer below as the baselayer.

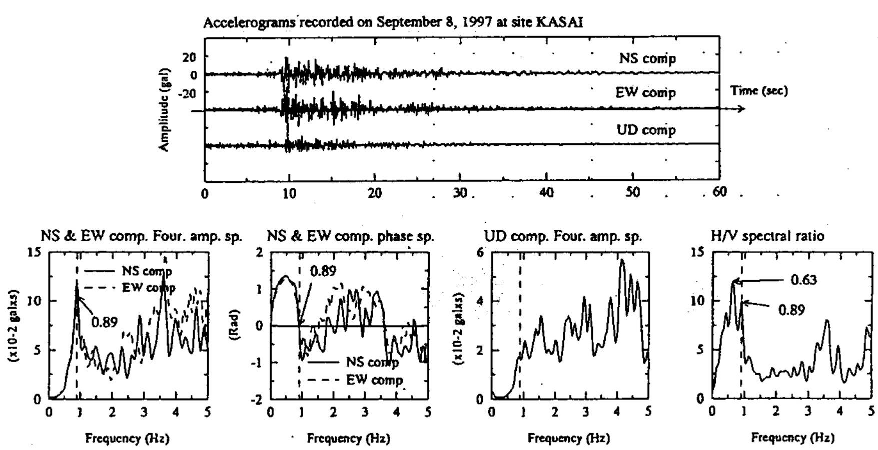

Fig. 3 Three components of earthquake acceleration record at the KASAI site and their spectra

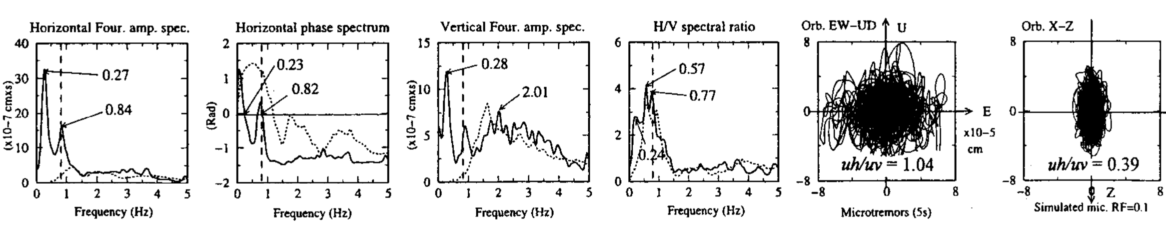

Fig. 4 Spectra of the original record (solid line) and modified record (dotted line), together with the respective vertical orbits, for the microtremors at KASAI site measured by 1s period sensor

condition, and it is suspected that the peak may correspond to an excitation of some vehicular traffic (Nishizaka and Fukuwa, [1997]). As such, the Fourier spectral amplitudes of the original record in the band of 3.55~3.75 Hz were modified to remove the peak, as shown by the dotted line in Fig. 4. Vertical orbits of original and modified records are also shown in Fig. 4. The ratio *uh/uv* changed from 0.33 to 0.39 after modification. The spectra and the vertical orbit of the modified microtremor records are shown again in the left column of Fig. 5 for comparison with simulations. The solid and the bold solid lines in the remaining six columns of Fig. 5 show the spectra of simulated microtremors based on the square and the circular source distributions models respectively. The trial simulations are for R_F = 0.0, 0.1, 0.2, 0.5, 0.7 and 1.0 from left to right. The corresponding spectra of the recorded microtremor are again shown by dotted line in all cases for direct comparison with simulations. The spectra displayed from to top consist of horizontal Fourier amplitude spectrum, the horizontal phase spectrum, the vertical Fourier amplitude spectrum, the H/V spectral ratio, and the vertical orbits of simulations by square and circular models. The simulated microtremors for different values of R_F are scaled to the same ratio of the average absolute amplitude of vertical displacements between records and simulations.

It may be seen in Fig. 5 that the vertical Fourier amplitude spectra of simulated microtremors for different values of R_F in both models remain practically similar. Overall, it may be noted that simulations with R_F = 0.0 ~ 0.5 for both models appear closer to recorded microtremors when compared to those with R_F = 0.5 ~ 1.0. Although the spectral shapes do not differ significantly for values of R_F = 0.0 ~ 0.5, the vertical orbit (*uh/uv*=0.39) and the H/V spectral ratio when

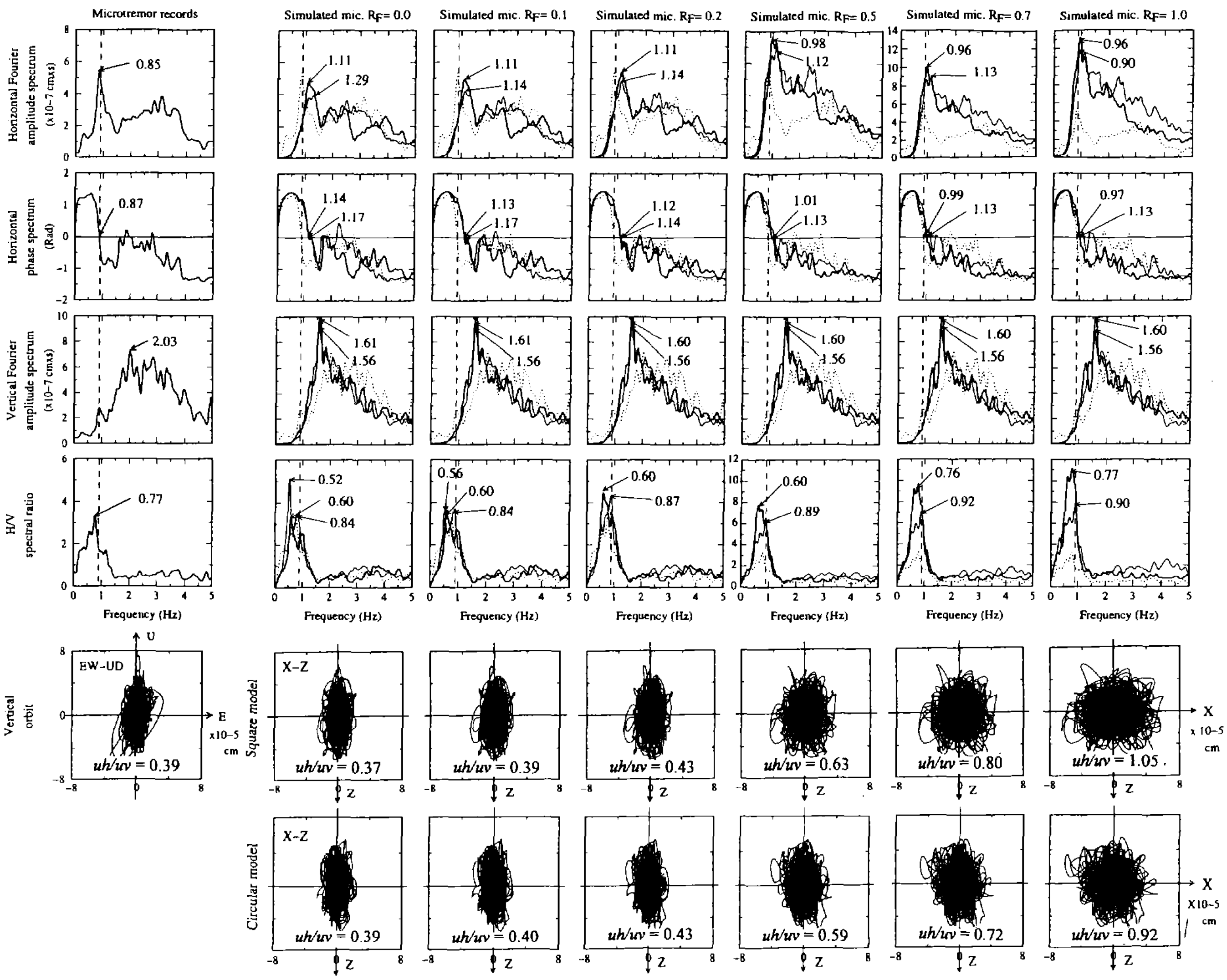

Fig. 5 Spectra and vertical orbit of a single trial simulations with square (solid line) and circular (bold solid line) models for various values of R_F compared with those of the recorded microtremors at the KASAI site. [Diagrams in the first column in the left are spectra of microtremor records, which are again shown by dotted lines in all subsequent columns for direct comparison with simulations for R_F =0.0, 0.1, 0.2, 0.5, 0.7, and 1.0. Numbers indicated by arrows are predominant frequencies and vertical dashed lines show the predominant frequency corresponding to the average horizontal acceleration record.]

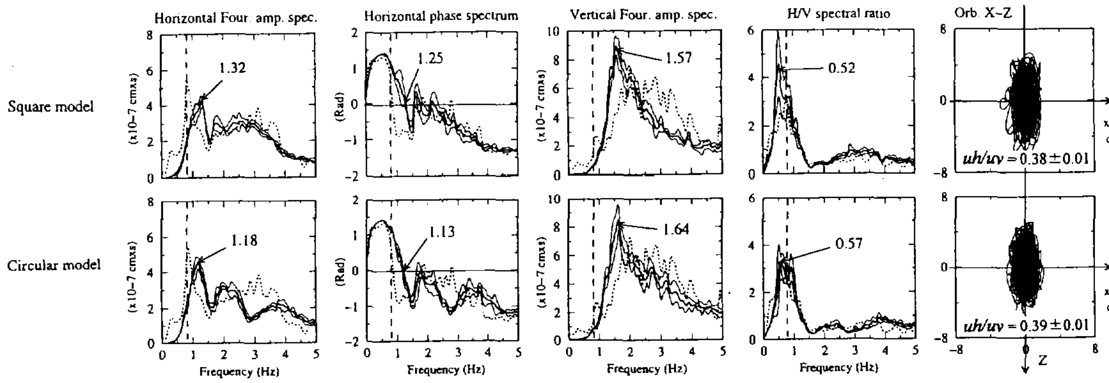

Fig. 6 Comparison of the spectra and vertical orbit of 5 simulation trials in square model(first row) and circular model (second row) for R_F =0.1 with those of the recorded microtremors at the KASAI site (dotted line). [Bold solid line represents the average of the spectra of five simulations and thin solid lines show the range of average ±standard deviation. Numbers pointed by arrows are predominant frequencies and vertical dashed lines show the predominant frequency corresponding to average horizontal acceleration record.]

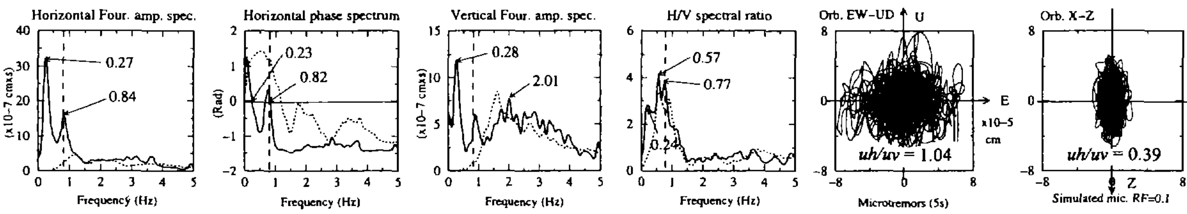

Fig. 7 Spectra and vertical orbit of the microtremors obtained with the sensor of 5s natural period (solid line) compared with those of the average of the 5 simulation trials by circular model with R_F =0.1 (dotted line) at the KASAI site

R_F = 0.1 in case of square model, as well as the vertical orbit (*uh/uv*=0.39 or 0.40) and the H/V spectral ratio when R_F = 0.0 and 0.1 in case of circular model, may be considered optimum in view of the vertical orbit (*uh/uv*=0.39) of microtremor record.

To evaluate the effect of random activation of sources distributed on the ground surface, five simulation trials were performed with both square and circular models for R_F =0.1. The average of the spectra and vertical orbit are displayed in Fig. 6, together with the corresponding range of standard deviation. It may be seen that the range of variation in spectra and vertical orbit in both models is quite small. It appears that the average of the H/V spectral ratio of the simulations with circular model tend to show closer correspondence to microtremor records.

Figure 7 compares the spectra of microtremors obtained with sensors of 5 sec period (solid lines) with the simulations with circular model (dotted lines) for R_F = 0.1. It may be noted that the horizontal and vertical Fourier amplitude spectra, as well as the H/V spectral ratio of microtremors measured by 5s sensor and the simulated microtremors obtained for R_F=0.1 are quite consistent in the range of 1～5 Hz. The consistency in this range can be extended to microtremors measured with 1s sensor. It is clear that the larger value of *uh*/*uv* =1.04 for microtremors recorded by 5s sensor is a direct consequence of larger horizontal spectral amplitudes than vertical spectral amplitudes in the range 0～1 Hz. The horizontal Fourier amplitude spectrum shows two predominant peaks at 0.27 Hz and 0.84 Hz. The latter is close to the predominant frequency at 0.85 Hz in the horizontal Fourier amplitude spectrum of the microtremors recorded by 1s sensor shown in Fig. 5. The simulation does not display the predominant frequency of 0.27 Hz in horizontal Fourier amplitude spectrum of microtremors. This predominant frequency may have resulted from the effect of deep sources such as microseism, or marine surge (between 3 or 4s), which are not considered in the simulation. Similar result is obtained for minimum intersection point (0.23 Hz) of horizontal phase spectrum. The second intersection point of 0.82 Hz is close to the predominant peak of 0.85 Hz in horizontal Fourier amplitude spectrum of microtremors, as well as to the predominant peak of 0.89 Hz in horizontal Fourier amplitude spectrum of accelerograms (vertical dashed line in Fig. 7). The H/V spectral ratio of simulated microtremors for R_F = 0.1 is, however, quite close to that of microtremor recorded by 5sec sensor, as indicated by the similarity in shape as well as the magnitude.

The H/V spectral ratio of fundamental Rayleigh waves mode, the H/V spectral ratio of microtremors (5s sensor), and the average of H/V spectral ratio of 5 trial in circular simulation model when R_F=0.1 are compared in Fig. 8. Very close similarity between the H/V spectral ratio of fundamental Rayleigh waves with simulated and recorded microtremors is seen in the frequency range of 0.5 ～ 5.0 Hz, indicating that the microtremors at the KASAI site consist primarily of Rayleigh wave components.

<u>Percentage of Love and Rayleigh waves in horizontal component of simulated microtremors</u>

The analysis (Tokeshi et al, [2000]) for the proportion of Love

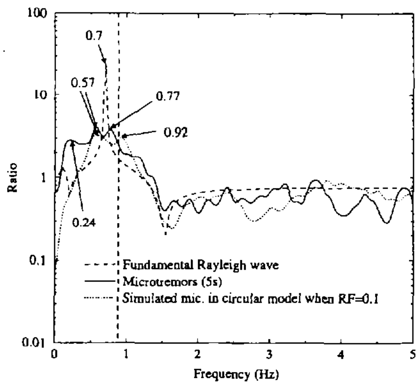

Fig. 8 H/V spectral ratio of the fundamental Rayleigh wave mode ,the microtremors measured by 5s sensor, and the simulated microtremors of 5 trials in circular model when R_F=0.1 at the KASAI site. [Numbers indicated by arrows are predominant frequencies and vertical dashed lines show the predominant frequency corresponding to average horizontal acceleration record.]

Table 3 Average displacement components of Love and Rayleigh waves for various distances and R_F values at the KASAI site (10^{-6} cm)

R_F	0.0	0.1	0.5	1.0	R_F	0.0	0.1	0.5	1.0
L_0	0.0	1.194	5.970	11.940	R_0	9.591	9.670	11.979	16.789
L_1	0.0	0.196	0.981	1.962	R_1	1.283	1.330	1.749	2.383
L_2	0.0	0.116	0.583	1.165	R_2	0.729	0.738	0.885	1.140
L_3	0.0	0.085	0.424	0.846	R_3	0.478	0.482	0.553	0.693
L_4	0.0	0.066	0.328	0.657	R_4	0.312	0.313	0.351	0.459
L_5	0.0	0.054	0.270	0.540	R_5	0.220	0.221	0.254	0.331
L_6	0.0	0.046	0.230	0.460	R_6	0.167	0.168	0.193	0.262
L_7	0.0	0.039	0.195	0.393	R_7	0.143	0.144	0.168	0.228
L_8	0.0	0.032	0.161	0.322	R_8	0.118	0.119	0.144	0.195
L_9	0.0	0.027	0.136	0.272	R_9	0.099	0.099	0.120	0.163
L_{10}	0.0	0.024	0.121	0.242	R_{10}	0.086	0.086	0.102	0.137

Table 4 Estimated average percentages of Love and Rayleigh waves at the KASAI site

R_F	Love waves $\Im i$ (%)	Rayleigh waves $\Re i$ (%)
0.0	0	100
0.1	17	83
0.5	47	53
1.0	57	43

waves in simulated microtremors as R_F increases from 0.0 to 1.0 is summarized in Table 3 and Table 4. Simulated microtremors for R_F =0.1 contain on the average about 17% Love waves. Small amplitudes at predominant peaks of H/V spectral ratio in record as well as in simulations (Fig. 7) are most likely due to the low proportion of Love waves at the KASAI site. However, the growth of sharp peak as the Love wave content increases with R_F, may also be recognized in the horizontal Fourier spectrum and H/V spectral ratio of simulated microtremors of Fig. 5. The sharp peak also corresponds to the predominant frequency of the ground noted in the earthquake record at KASAI. It is an indication that the proposed simulation technique may have the potential to explain not only microtremors but also the response due to moderate or intermediate earthquake. Further investigation would be required for more definite conclusion in this regard.

CONCLUSIONS

The potential of the simulation techniques for interpretation and characterization of microtremors is investigated. Although only one observation site is considered for comparison between recorded and simulated microtremors, the effectiveness of the simulation techniques with various values of R_F in explaining the nature of microtremors is clearly illustrated.

A method of estimating the value of R_F applicable to a site based on the comparison of various spectra and the vertical orbit of the simulations with recorded microtremors has been demonstrated by actual application at a site. The KASAI site considered in this study has deep base layer and weak impedance contrast and the applicable value of R_F is estimated to be 0.1. The low value of R_F for the ground profile at KASAI indicating the dominance of Rayleigh waves to be expected in the microtremors may be regarded as typical of urban areas in Japan.

As the Love wave content increases with R_F, a sharp peak of spectral amplitude develops in the simulated microtremors. The sharp spectral peak actually tends to develop at a frequency close to the predominant frequency of the ground estimated from earthquake motion record. This trend has the potential for its effective utilization in the estimation of natural frequency of the ground corresponding to moderate or intermediate earthquakes.

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