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Soil Profile Confirmation through Microtremor Observation

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It was shown first that the H/V spectrum method is useful in an examination of a two layered soil structure model presumed. Then on a site having an intermediate support layer, microtremor observation was conducted for about 5 months, and it was shown that the peak frequencies of the H/V spectrum appear between two predominant frequencies corresponding to the shallower surface layer and the deeper one. Furthermore, another site where soil velocity structure model was made in detail based on logging survey data was taken up. It was shown that discrepancies between soil amplification characteristics calculated by the soil model and observed ones led to a correction of the model. The microtremor array observation method was successfully used to revise the soil model.

INTRODUCTION

A discussion of the Soil-Structure Interaction effect requires the clarification of the circumference ground soil velocity structure for the building foundation concerned. To discuss kinematic interaction effects especially, a soil structure model to a depth of a certain hard support layer and a width to some lateral extent is required. The soil structure model is commonly based on pinpoint logging data or/and on a limited number of boring data. The present paper shows the usefulness of applying the microtremor measuring method to confirm the presumed soil structure model, including supporting case notes.

The horizontal-to-vertical (H/V) spectrum method is one of the microtremor observation methods used for soil structure surveys. The relevance of the H/V spectrum ratio and underground soil structure has been pointed out (Nogoshi and Igarashi 1971) and examinations of the applicability of this method to soil structure surveys have been performed by many researchers. Studies have put forth that the multiple reflection of a body wave can explain the formation of H/V spectrum peaks (Nakamura and Ueno 1986), that a

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surface wave motion may produce the peaks (for example, Wakamatsu and Yasui 1995) and that the mode ratio of the surface wave can also explain the generation of the peaks (for a recent example, Arai and Tokimatsu 2004). Those causes being set aside, the H/V spectrum shows peaks at the predominant frequency, if the contrast of the surface layer to the lower layer is strong, and it has been used successfully as an aid in soil structure investigation.

The microtremor array observation method was first advocated by Aki (1957), an alternative method was proposed by Capon (1969), and the development towards utilization was made by Horike (1985) and Okada and Matsushima et al. (1990). According to the array observation method, the soil velocity structure, fitted for the obtained dispersion curve of surface wave's phase velocity, can be directly searched through inverse analysis. The H/V spectrum method and the array observation method are economical and good in mobility, and it is extremely important to use the exact application conditions.

The present paper shows that the H/V spectrum method is effective in confirming the soil structure model based on the boring data, being applied in a line of this model. Then, a site with an intermediate support layer is considered, the features of the H/V spectrum at a site that does not have a gradually increasing velocity structure is described, and the limits of model applicability are shown. Examination of the microtremor observation results and earthquake observation results is performed for a point where earthquake observation is conducted both on the ground surface and directly under ground, demonstrating that correction of the soil velocity structure based on logging data is needed, and that the H/V spectrum method and the array observation method play important roles in the process of these examinations.

CONFIRMATION OF SOIL PROFILE MODEL

The target area is the Fukui plain, where a magnitude 7.1 earthquake occurred in 1948, and 3,769 people were lost. The Fukui prefecture government produced a soil structure model with every 500 m mesh based on existing boring data, and performed earthquake damage evaluations using this model. Since this soil model was created with a limited number of unevenly distributed data, examination needs to be completed using certain methods. In this chapter, the examination example based on the H/V spectrum method is described (Yasui 2003).

The target map and measured points of the area are shown in Figure 1. Microtremor observation was conducted for 32 points distributed every 500 m on the cross line, the center of which is Itagaki town (ITG) where there is Point FKI003 of K-NET that is the only observatory station in Fukui plain. Where, K-NET and KiK-NET, to be mentioned later, are earthquake observation systems covering all of Japan and are served by the National Research Institute for Earth Science and Disaster Prevention

The microtremor measurement direction is horizontal, 2 components, and vertical, 1 component, which intersect perpendicularly. Measurements were collected for 5 minutes using 100 Hz sampling frequencies, the H/V spectrum was calculated using 30,000 digit data. The spectra of the microtremor records' horizontal 2 components are compounded as the horizontal spectrum (H), divided by the spectrum of the vertical component (V), resulting in the H/V spectrum, with a Parzen Window bandwidth of 0.2 Hz.

The H/V spectrum of the N-9 point is shown in Figure 2 as an example. Two peaks are seen in this spectrum (Wakamatsu and Nobata 1998). Table 1 shows the presumed Fukui prefecture soil model at N-9. The lower peak is approximately 0.6 Hz, and is considered the predominant frequency of the surface layer, upwards from the upper surface of the tertiary rock ground. The higher peak is approximately 1.7 Hz, and is considered the predominant frequency of the alluvium layer upwards of the diluvium upper surface.

Figure 3 shows a comparison about the two peaks between the peak periods of the H/V spectrum, and the peak periods by the Fukui prefecture corresponding model along the NS measured line. Although the observation value and the value by the assumption model are generally in agreement, it may be necessary to reexamine the assumption model at the point where the inconsistency is large. The peak periods according to the Fukui prefecture soil model are the primary peak period of the soil amplification function over the tertiary upper surface and the diluvium upper surface, calculated using SHAKE based on the assumption soil column model at each measuring point, respectively.

In addition, research using the microtremor observation method, which examined the Fukui plain, referring to the Fukui prefecture soil model for a 1 minute mesh was recently reported (Kojima and Yamanaka 2004).

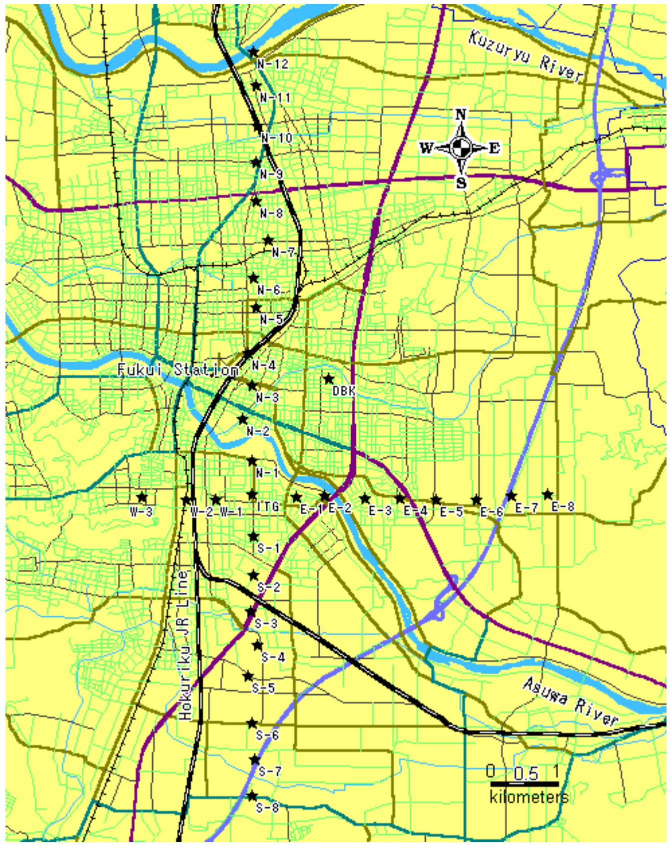


Figure 1. Measuring points in the south of Fukui plain

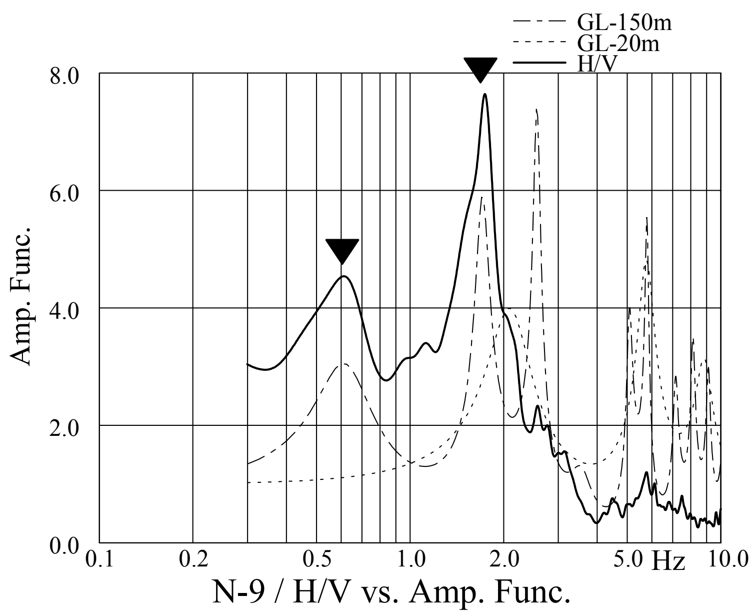


Figure 2. H/V Spectrum and soil amplification function (N-9)

Table 1. Fukui prefecture soil structure model at point N-9

Depth (m)	Hi (m)	Geological Layer		ρ i (ton/m3)	Vsi (m/sec)
0	4	Alluvial	Clay-1	1.6	100
4	5		Sand-1	1.8	150
9	7		Clay-2	1.7	150
16	4		Sand-2	1.9	200
20	25	Diluvial	Gravel	2.1	500
45	15		Clay	1.8	300
60	15		Sand	1.9	400
75	30		Gravel	2.1	500
105	20		Clay	1.8	300
125	10		Gravel	2.1	500
135	10		Clay	1.8	300
145	5		Gravel	2.1	500
150	—	Tertiary	Volcanic Rock	2.5	1,000

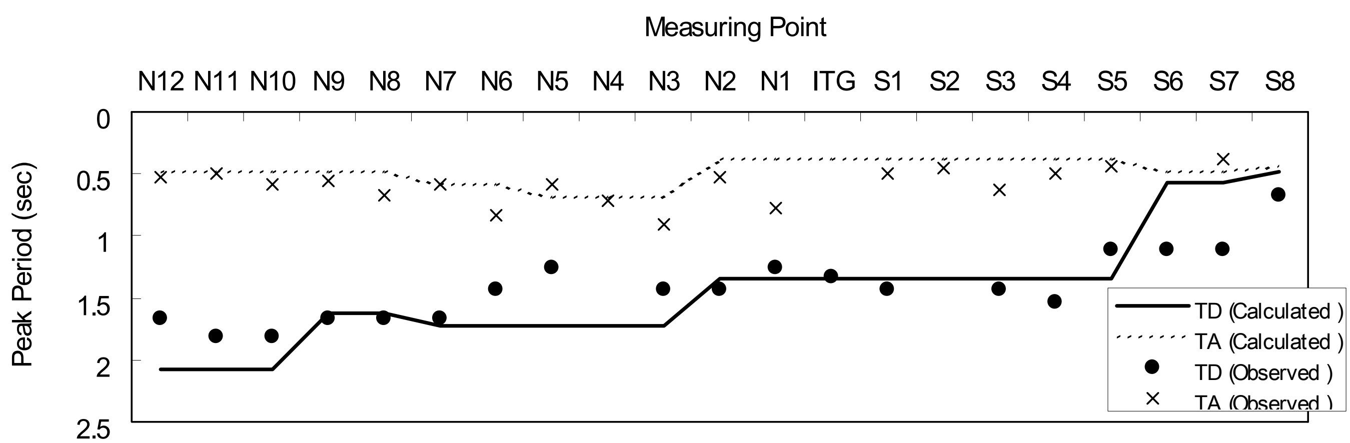


Figure 3. Comparison of the H/V spectrum peak periods with ones from the Fukui prefecture soil model

H/V SPECTRA OF SOIL WITH INTERMEDIATE HARD LAYER

The Doboku office observation point (DBK) in the Figure 1 map is one of a few points for which the PS logging survey is performed in the Fukui plain. The H/V spectrum method requires the soil velocity structure to be investigated precisely, thus, DBK point has been used often as the reference point until now. The soil velocity structure of this point is shown in Table 2, revealing a hard layer in the middle, and suggesting that the H/V spectrum peak may have been influenced by this intermediate layer.

Examples of the H/V spectra for this point are shown in Figure 4. Calculation of the H/V spectrum is performed for the same conditions as the case shown in Figure 2. The soil amplification functions using SHAKE are also shown in this figure with the H/V spectra on October 21 (Date A), 2003 and February 25 (Date B), 2004. These soil amplification functions are shown for the middle support layer in the GL-24 m case, and the downward support of GL-150 m case. The peak frequency of 1.7 Hz on Date A corresponds to the former peak (f_A=2 Hz), and the peak frequency of 1.2 Hz on Date B corresponds to the latter peak (f_B=1 Hz), demonstrating that the peak frequencies change with measurement days. In addition, although not shown in Figure 4, the peak value of the soil amplification function for the GL-54 m base is approximately 3.50 with 1.35 Hz (=f_C).

The observation period was approximately 5 months, with observations conducted at 15:00. Calculation of the H/V spectrum was made under the same conditions as in the Figure 2 case. The peak frequencies and peak values read from the H/V spectra are shown in Figure 5 (a) and (b). The peak frequencies corresponding to f_A and f_B did not alternate, but were arbitrarily distributed between both values. The average value of peak frequency, 1.34 Hz (with a standard deviation value of 0.2 Hz), is almost equal to f_C. In contrast, the peak value presents the aspect distributed from 3 to 12, making it difficult to be termed as stable, and the average value is 6.41 (with a standard deviation of 1.64). This average value is close to the peak value of the soil amplification function at f_B (see Figure 4).

Table 2. Soil profile at DBK

Depth (m)	Hi (m)	Geological Layer		ρ i (ton/m3)	Vsi (m/sec)
0	4	Alluvial	Fill	1.8	80
4	12		Fine-Medium Sand	1.7	155
16	8		Sandy Clay	1.8	225
24	8	Diluvial	Gravel	2.1	590
32	22		Fine Sand	1.8	290
54	96		Gravel	2.1	660
150	—	Tertiary	Volcanic Rock	2.5	1,800

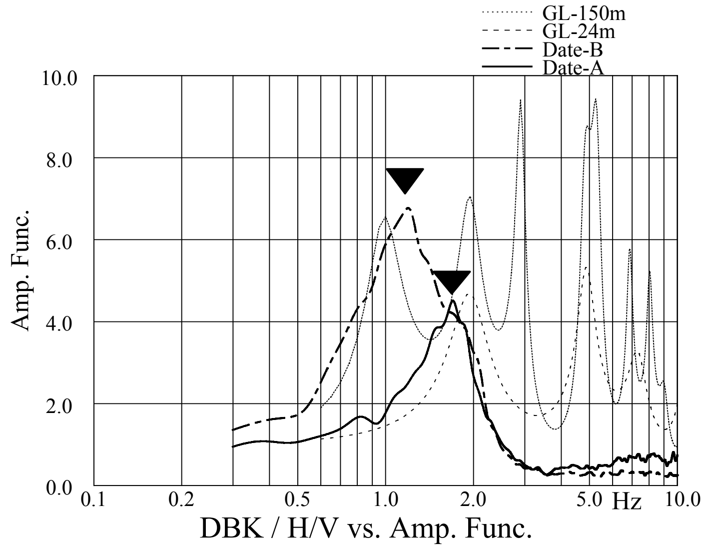


Figure 4. H/V spectrum and soil amplification function (DBK)

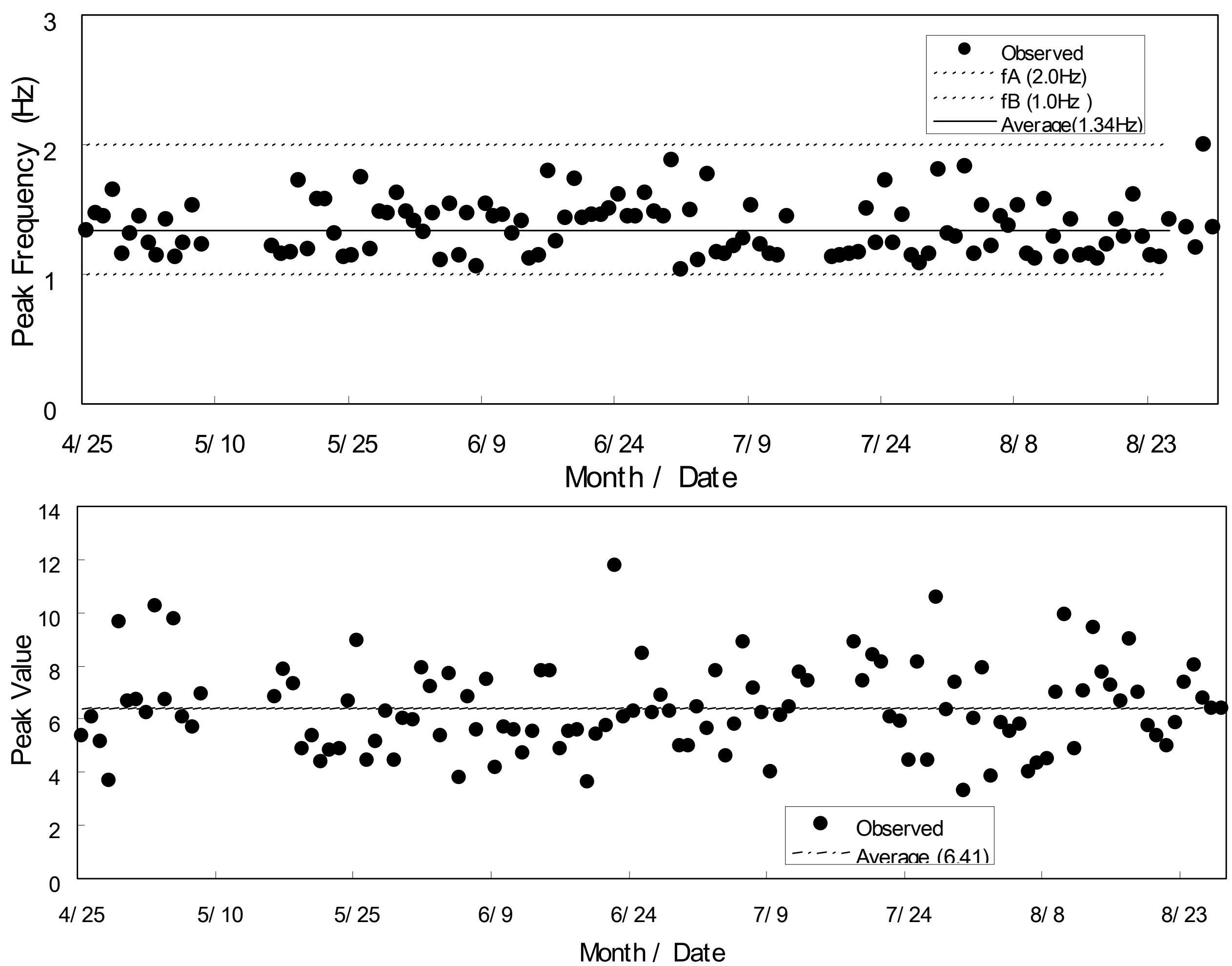


Figure 5. (a) H/V Spectrum peak frequencies and (b) peak values

INSPECTION OF LOGGING DATA

There are 11 K-NET and 7 KiK-NET earthquake observatory stations in Fukui prefecture. The seismometers in the K-NET system are set only on the ground surface. In the KiK-NET system, the sensors are set at the ground surface and the underground base rock. In the current study, the Eiheiji station (FKIH01) of the KiK-NET system is the target and the sensor is set at ground surface and GL-103 m. Earthquake records from this station could be important data for the examination of the input earthquake motion on this plain because this station is close to Fukui plain. The soil velocity structure of this point, based on the logging survey, is shown in Table 3. Table 4 shows the dimensions of the four observed earthquakes at the target site.

The Fourier spectrum ratios of earthquake records of the ground surface to GL-103 m are shown in Figure 6. During the calculation, the total length of each datum is set as 120 seconds, containing the whole duration of a seismic wave with sufficient succession zero portion, and sampling time is 0.005 seconds. As the observed spectra, eight spectrum ratios of both NS and EW for the four earthquakes are written in piles. The soil surface amplification functions over the E+F input in GL-103 m, calculated using SHAKE, are also shown in this figure, which reveals that the calculation value and the observation values are not in agreement.

The H/V spectra calculated from the earthquake records at ground surface are shown in Figure 7(a). Figure 7(b) shows the H/V spectrum calculated based on microtremor observations conducted near the earthquake observation station. The calculating conditions are the same as in Figure 2 or 4. The soil surface amplification functions over 2E input in GL-4 m, calculated using SHAKE, and GL-19 m are shown in this figure, which reveals that the calculation value and the observation value are not in agreement.

The microtremor array observation was then performed using the SPAC method (Okada and Matsushima et al. 1990) to examine soil velocity structure. The array radii are set at 3 m, 10 m, and 28 m. Figure 8 is the dispersion curve of the surface wave phase velocity obtained from the array observation results, and the theoretical dispersion curve simulated by trial and error is also written together. It became necessary to change the thickness of the top surface layer into 9 m from 4 m as a result of this examination. The correction velocity structure is shown in Table 5. The soil surface amplification function over the E+F input in GL-103 m of the corrected soil model and the soil surface amplification functions over 2E input in GL-9 m and GL-19 m are shown in Figure 9 and Figure 10, respectively. The calculated value and the observed value are mostly in agreement.

Table 3. Original soil profile at FKIH01

Depth (m)	Hi (m)	Geological Layer	ρ i (ton/ m^3)	Vsi (m/ sec)
0	4	Sand	1.8	150
4	2	Gravel	2.2	1,000
6	6	Granite	2.2	1,650
12	7	Andesite		
19	46	Granite	2.5	2,100
65	38	Alternation of Granite and Andesite	2.5	2,500
103	—	Andesite	2.5	2,500

Table 4. Dimensions of earthquakes examined

Year	Month/ Date	hr. : min : sec	Latitude	Longitude	M	△ (km)	D(km)	Amax(Gal)
2003	6/ 5	23:14:00	36.3	136.3	4.1	24	10	36.3
2003	2/ 11	18:34:00	36.05	136.34	4.0	5	6	156.2
2002	9/ 8	0:11:00	35.97	136.57	3.9	23	10	45.2
2002	8/ 18	9:01:00	36.13	136.18	4.5	17	11	35.8

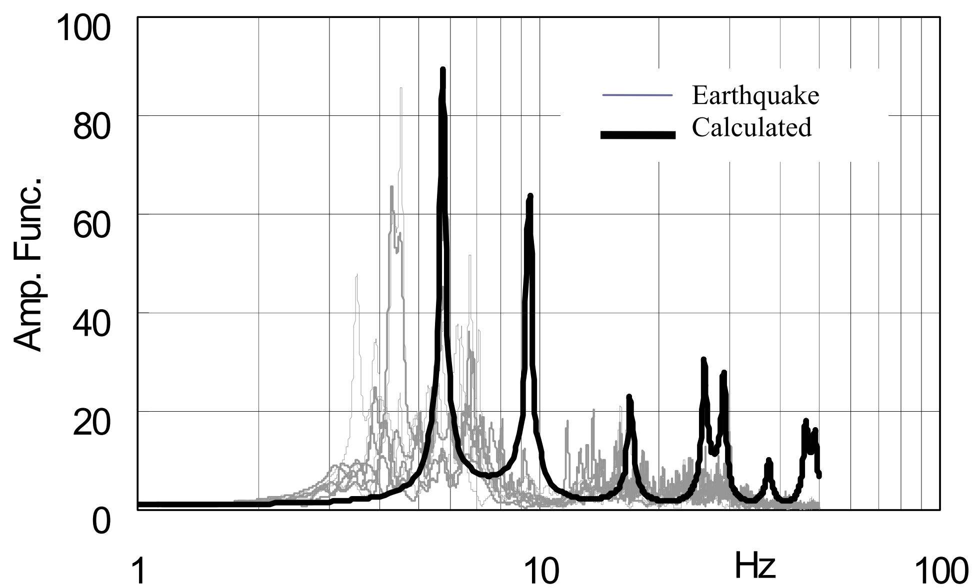
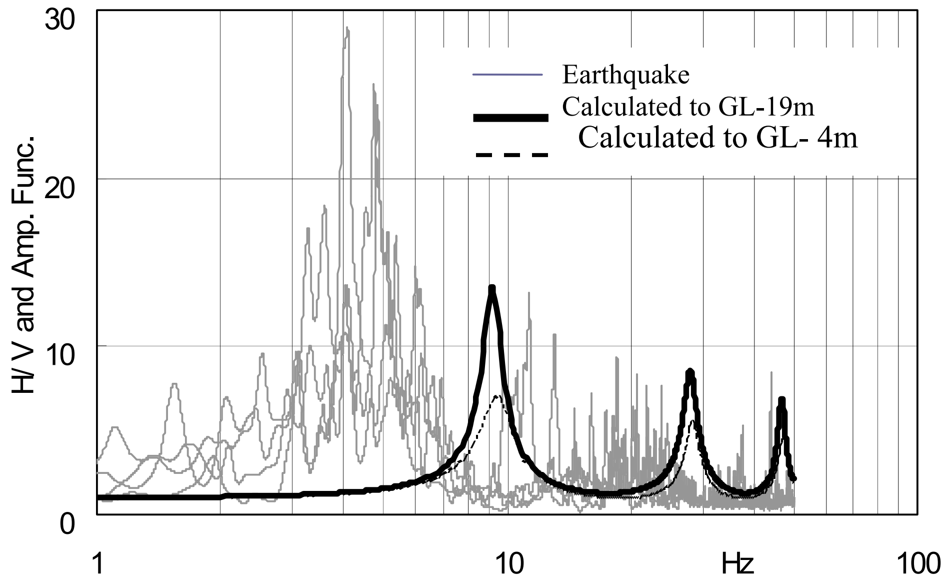


Figure 6. Calculated soil amplification function of $GL \pm 0m$ to GL-103m for (E+F) input using original soil profile model compared with observed earthquakes



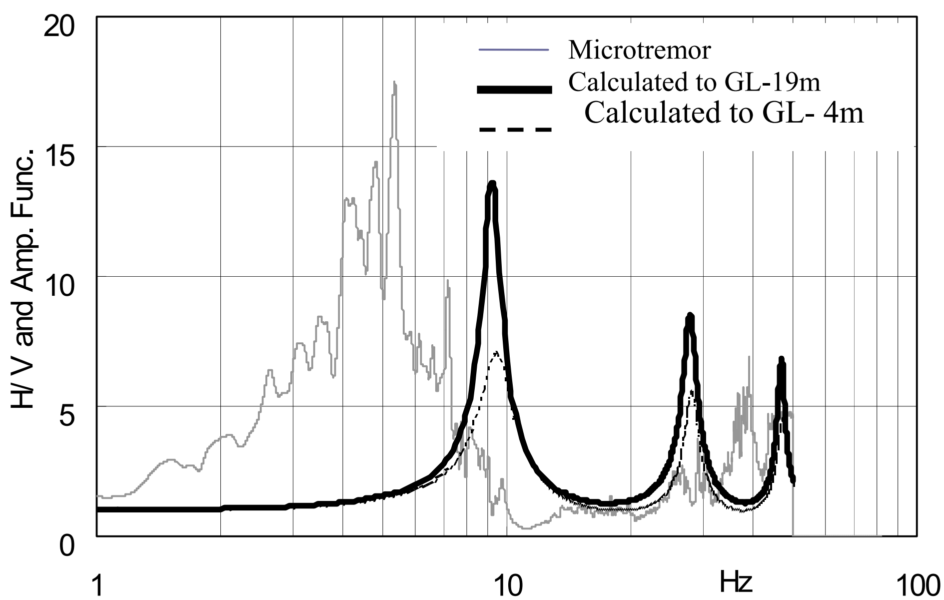


Figure 7. H/V spectrum for (a) observed earthquake and (b) microtremor observation, compared with calculated soil amplification functions of $\mathrm{GL}\pm 0m$ to GL-4m and to GL-19m for 2E input using original soil profile model

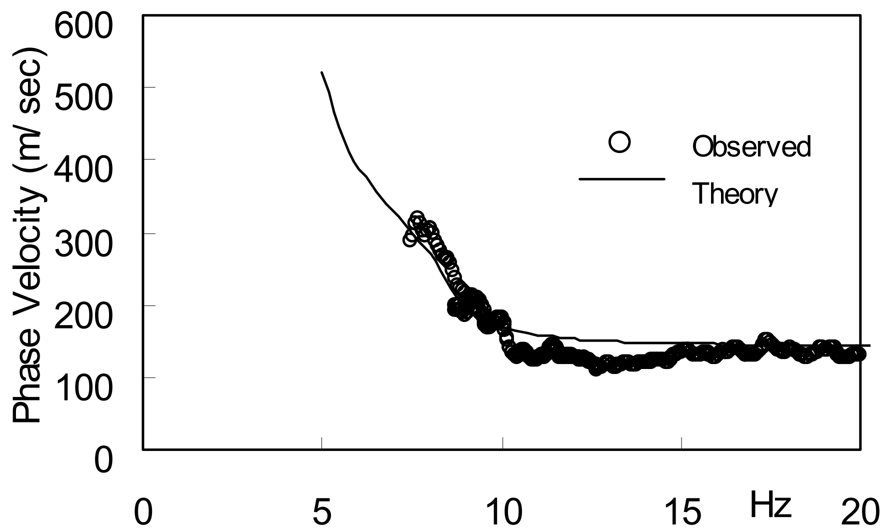


Figure 8. Obtained dispersion curve of phase velocity from microtremor array observation compared with theoretical calculation

Table 5. Modified soil profile at FKIH01

Depth (m)	Hi (m)	Geological Layer	ρ i (ton/ m3)	Vsi (m/ sec)
0	9	Sand	1.8	150
10	3	Granite	2.2	1,650
12	7	Andesite		
19	46	Granite	2.5	2,100
65	38	Alternation of Granite and Andesite	2.5	2,500
103	—	Andesite	2.5	2,500

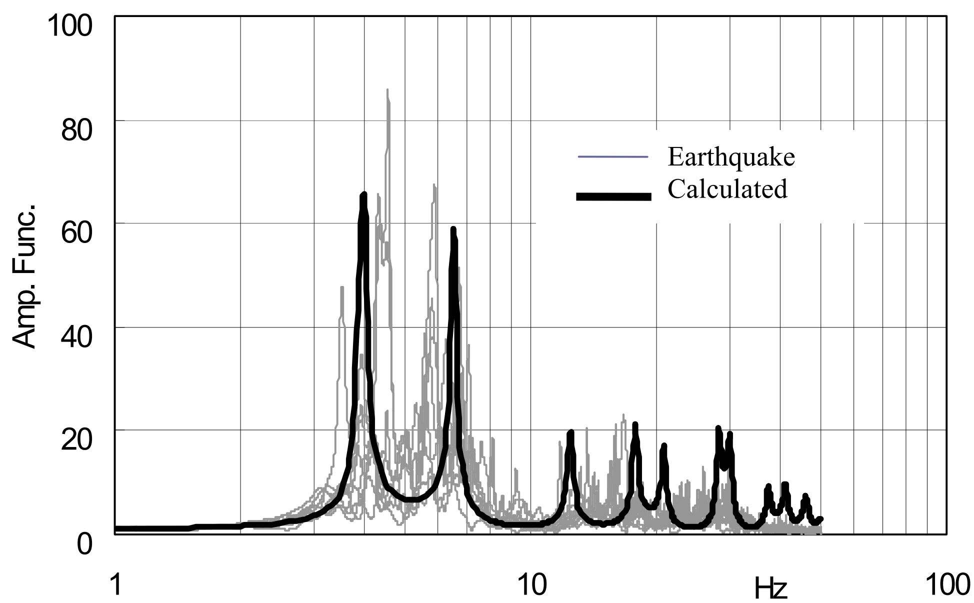
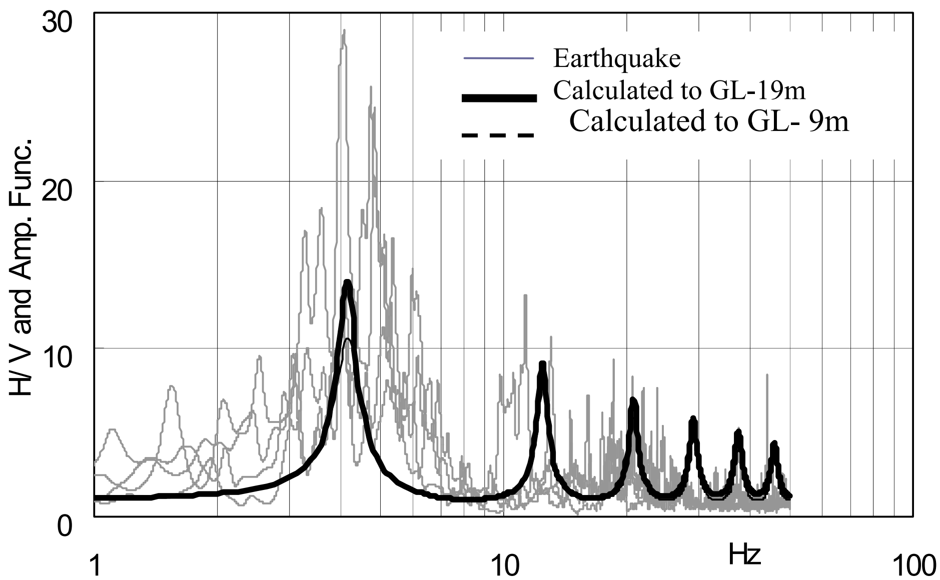


Figure 9. Calculated soil amplification function of GL$\pm 0m$ to GL-103m for (E+F) input using modified soil profile model compared with observed earthquakes



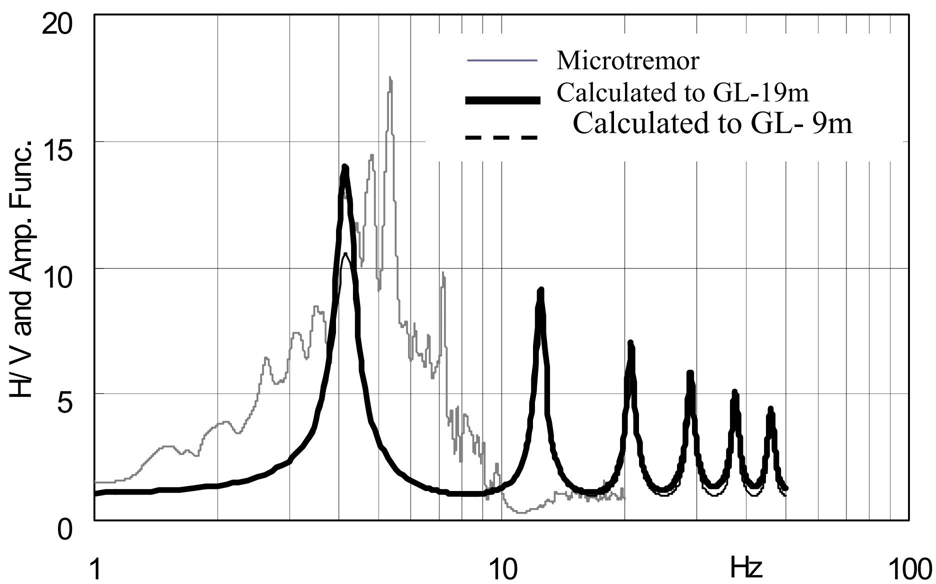


Figure 10. H/V spectrum for (a) observed earthquake and (b) microtremor observation, compared with calculated soil amplification functions of GL $\pm 0m$ to GL-4m and to GL-19m for 2E input using modified soil profile model

CONCLUSIONS

A possibility that the thickness of the alluvial and diluvial layer could be presumed utilizing two peaks of the H/V spectrum was shown.

The peak frequency of the H/V spectrum of the site which has an intermediate support layer showed the tendency to be arbitrarily distributed between the shallower predominant frequency and the deeper one.

Confirmation of the soil structure by the H/V spectrum method even at the point where detailed soil velocity structure was acquired by logging survey is recommended. When making a revised soil model, the microtremor array observation serves as an effective method.

REFERENCES

Aki, K., 1957: Space and time spectra of stationary stochastic waves with special reference to microtremors, Bull. Earthq. Res. Inst. Tokyo University, 35,pp.415-456,

Arai, H., and Tokimatsu, K., 2004. S-wave velocity profiling by inversion of microtremor H/V spectrum, Bulletine of the Seismological Society of America, Vol. 94, No. 1, pp. .53-63.

Capon, J.,1969. High-Resolution frequency-wavenumber spectrum analysis, Proc. Of the IEEE,Vol.57,No.8,pp.1408-1418

Fukui Prefecture, 1997. Report on estimation of earthquake damage in Fukui Prefecture (in Japanese).

Horike., M., 1985. Inversion of phase velocity of long-period microtremors to the S-wave-velocity structure down to the basement in urbanized area, Journal of Phys. Earth 33, pp. 59-96.

Kojima, K., and Yamanaka, H., 2004. Estimation of quaternary structure of Fukui plain based on microtremor observation, Journal of Structural Mechanics and Earthquake Engineering, Japan Society of Civil Engineers, No. 752/Ⅰ-66, PP. 217-225(in Japanese).

Nakamura, Y., and Ueno, M., 1986. A simple estimation method of dynamic characteristics of subsoil, Proceedings of 7-th Japan Earthquake Engineering Symposium, pp. 265-270(in Japanese).

Nogoshi, M. and Igarashi, T., 1971, On the amplitude characteristics of microtremor (Part2), Zishin 2, 24, pp.26-40 (in Japanese).

Okada, H., Matsushima, K., Moriya, T., and Sasatani, T., 1990, An exploration technique using long-period microtremors for determination of deep geological structures areas, Geophys.

Explor., Vol.43, No.6, pp.402-417 (in Japanese).

Yasui, Y., 2003. Examination on the ground model in the southern part of Fukui plain using H/V spectrum method, Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, B-2, Structures Ⅱ, pp. 289-290(in Japanese).

Wakamatsu, K. and Nobata, A., 1998. Underground structure of Fukui plain and interpretation on the damage of Fukui earthquake in 1948, Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, B-2, Structures Ⅱ, pp. 227-228(in Japanese).

Wakamatsu, K., and Yasui, Y., 1995. Possibility of estimation for amplification characteristics of soil deposits based on ratio of horizontal to vertical spectra of microtremors, J. Struct. Constr. Eng., AIJ, No. 471, pp. 61-70(in Japanese).

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