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APPLICABILITY OF MICROTREMOR H/V METHOD FOR KIK-NET STRONG MOTION OBSERVTION SITES AND NOBI PLAIN

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SUMMARY

In this research, we examined the applicability of microtremor H/V method by earthquake observation data recorded at the strong earthquake motion observation networks of KiK-net, K-net and Nobi Plain which have been established in Japan in recent years. We observed the microtremors at ground surface of total 221 sites where the S wave velocity of base rock is more than 1500m/s, and compared the microteremor H/V spectrum ratio with that of earthquake data. As the result of examination, the followings were clarified. A clear predominant peak appears at a high rate in microtremor H/V. The microtremor H/V spectrum ratio is very similar not only to that of earthquake record on the ground surface, but also to several spectrum ratios of earthquake motions between surface and bedrock. This implies the microtremor H/V reflects the response characteristics based on the both of horizontal and vertical motions in the surface layer. Then, we tried to propose an engineering method in presuming the horizontal incident wave response characteristics of surface layer by using the relation between microtremor H/V and earthquake observation data.

INTRODUCTION

As for so-called the microtremor H/V method which corresponds to transfer function for horizontal motion of surface layer (Nakamura, 1989), although many researches have been carried out and now it is widely used in the world due to its convenience, it seems some questions are thrown at the applicability of this method, because it dose not has a clear theoretical background and also verification by earthquake observation is not fully performed.

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On the other hand, the microtremor H/V spectral ratios are used for understanding of various phenomena. For example, the long-period microtremor H/V spectral ratios were investigated as a possible tool for extrapolation in 3D basin structure modeling (Uebayashi, 2003) and the possibility for simulation of vertical ground motions using microtremor H/V spectral ratios was examined (Zao and Horike, 2003). However, there is almost no example as which it discussed about the relation between microtremor and amplification characteristics of surface ground especially by the incident seismic wave. Therefore, in this research, we investigate the validity of the method by comparing the microtremor H/V with the earthquake observation data at first, and we try to propose some new engineering methods in estimation of the horizontal motion amplification characteristics of surface layer by using the relation between microtremor H/V and transfer functions deduced from earthquake observation data.
In order to examine the applicability of the H/V method, it will be effective to observe the microtremor on the site where ground structure data such as P and S wave velocities and earthquake observation data are obtained. For this reason, we catch up the KiK-net strong motion earthquake observation network, which has been established in Japan in recent years. The station of KiK-net network has a borehole with PS logging data, and strong earthquake motion seismographs are settled on the ground surface and borehole bottom. Since KiK-net is also intended as an ultra-high gain seismograph station for observation of microseism, most stations locate at comparatively hard ground near mountainside. So, we also catch up the earthquake observation sites in the Nobi Plain and K-net as the investigation for the ground with soft and thick deposition layer. We observe microtremors at these sites, and contrast those with earthquake observation data and the earthquake amplification characteristics.

MICROTREMOR OBSERVATION SITES

KiK-net

KiK-net network is composed of 660 stations now. We selected 161 sites among them for microtremor observation site based on next conditions.

(1) The site where the borehole data is exhibited.
(2) The sites where S wave velocity of base rock exceeds 1500m/s: Although it is desirable that Vs of base rock is about 3000 m/s, corresponding to seismic basement, since such the base rock was restricted, we selected the site with 1500m/s or more in Vs at borehole bottom as a base near this.
(3) The site whose primary resonance frequency of the surface layer calculated theoretically is about 10Hz or less: It is thought that an artificial vibration due to traffic, construction etc. excels in the higher frequency range than about10Hz.

The selected observation sites are shown in Figure 1. Many sites locate in the west part of Japan, because a depth of hard base rock increases at the east part of Japan. Figure 2 shows the distribution of borehole depth of observation sites. The depth of borehole has most 100m classes as 63 % of the whole, and, subsequently 200m class occupies 25 %. There are several sites with deep borehole exceeded 1000m in KiK-net. As these sites locate at near the city region, Osaka and Nagoya, we count these as the site of Nobi plain group in convenience.

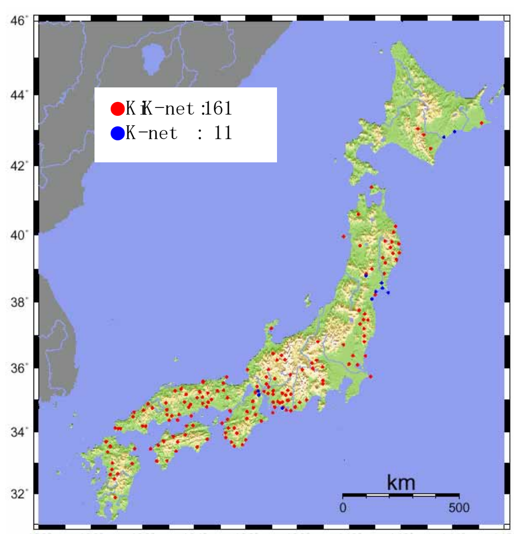


Figure 1 Observation Sites of microtremor in KiK-net and K-net

Nobi Plain and K-net sites

The observation site in Nobi Plain is classified as follows.

(1) Deep borehole sites: There are 3 sites in Nobi Plain and 2 sites in Osaka plain. Among them, for one locates near

center of Nagoya city, we performed PS logging survey, and observed earthquake data on ground surface and borehole bottom.

(2) Strong earthquake motion observation sites: There are 44 sites installed strong motion seismograph on the ground surface by several self-governments.

(3) Reflection survey lines sites: There are 54 sites of about 1.5km intervals along three reflection survey lines performed by Aichi Pref. in Nobi Plain. These sites are used for examination of relation between predominant frequency and depth of bedrock.

(4) K-net sites: 11 sites are additionally added in order to enrich the data near 1Hz of predominant frequency as shown in Figure 1.

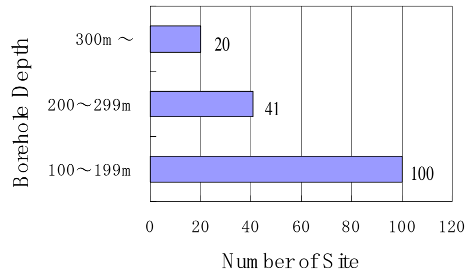


Figure 2 Frequency distribution of borehole depth

The distribution of observation sites in Nobi Plain is shown in Figure 3.

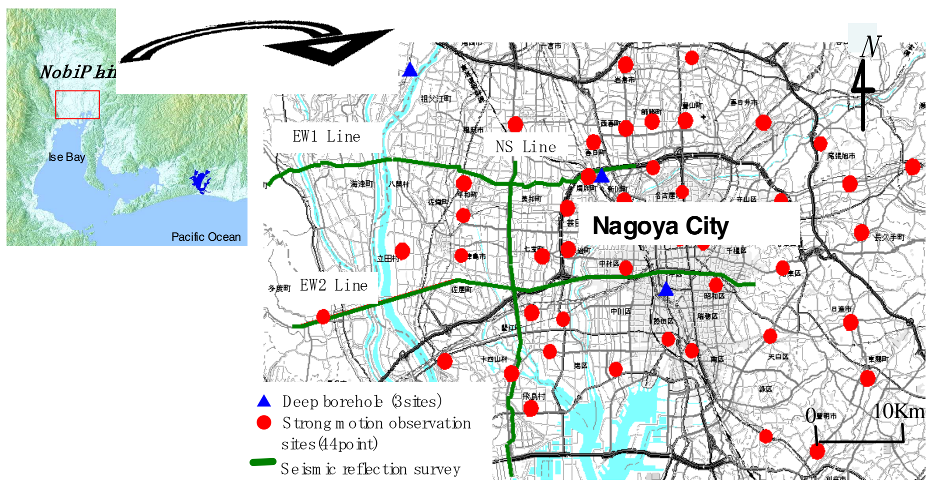


Figure 3 Observation sites of microtremor in Nobi Plain

OBSERVATION OF MICROTREMOR AND ANALYSIS

Observation

The main specifications of measuring instrument for microtremor observation are as follows.

Seismograph: High sensitivity, 3-component velocity type seismograph, of which natural period is extended to 5s by electric circuit, was mainly used.

Recorder: The personal computer with 16 or 24bit A/D converter was used for recording of signals.

3-component observations (NS, EW, UD directions) were performed on the ground surface near the earthquake observation institution, and the observation time zone was not limited. We observed the data which artificial noises, such as traffic vibration, are not mixed as much as possible. Data length per time is about 90 seconds, and we obtained at least 10 sets of data with 40 seconds length in KiK-net and 5 sets of 80 seconds in Nobi Plain. Sampling frequency was 100Hz, and low-pass filter of 10Hz was used for recording to reduce high frequency noises.

Analysis

Fourier spectrum of each data was obtained using FFT, and the smoothing by the Parzen window was performed in order to make easy to show the peak of spectrum. The bandwidths of window were 1.0Hz for

KiK-net and 0.05Hz for Nobi Plain, respectively. Next, the H/V spectrum ratios were obtained using the following formula, $H/V = \sqrt{NS \times EW}/UD$. The arithmetic average of a ten-set (for KiK-net) or five-set (for Nobi Plain) H/V spectrum ratios was carried out, and this was made into the microtremor H/V spectrum ratio of the site.

EATHQUAKE DATA AND ANALYSIS

Selection of data

Since there is a vast quantity of earthquake observation data at each site of the KiK-net, the earthquake observation data were selected for every site under the basis of the selection conditions shown below.

(1) Earthquake magnitude is more than 3.
(2) Maximum acceleration is more than 3 gals.
(3) Epicentral distance is less than 200km.
(4) Focal depth is more than 10km.

These selecting conditions were decided in order to secure the resolution of data and to obtain data with as much as possible little mixing of a surface wave. Five sets of earthquake data, which fulfills such conditions, were collected in principle at each observation site.

As for the sites of Nobi Plain, although many data could not be found like KiK-net, it analyzed about at least three earthquake data.

Analysis

The analysis was performed for about 10 seconds after S wave arrival time in data of KiK-net observation site and for about 40 seconds in data of Nobi Plain. We calculated smoothed Fourier spectrum of data, and obtained the several spectrum ratios. The smoothing of spectrum was conducted as same condition to the microtremor observation data. We calculated next spectrum ratios.

(1) Earthquake H/V ($S_{H/V} = H_S/V_S$): Horizontal to vertical spectrum ratio of observed data on the ground surface.
(2) Transfer function H/V ($T_{H/V} = (H_S/V_S)/(H_B/V_B) = (H_S/H_B)/(V_S/V_B)$): Horizontal to vertical spectrum ratio between surface and base rock.
(3) Horizontal transfer function ($T_H = H_S/H_B$): Horizontal component spectrum ratio between surface and base rock.
(4) Vertical transfer function ($T_V = V_S/V_B$): Vertical component spectrum ratio between surface and base rock.

Here, H, V indicate the horizontal and vertical component motions, respectively, and suffices S, B denote ground surface and base rock. The arithmetic average of set of each spectrum ratio was made into earthquake spectrum ratio of the site. In addition, at any sites other than KiK-net, since the observation data is limited on the ground surface, above (2)-(4) cannot be calculated.

COMPARISON OF MICROTREMOR H/V WITH EARTHQUAKE DATA

Rank of similarity of spectrum ratio

Table1 Classification of degree of similarity

Rank	KiK-net	Nobi Plain	K-net	Total (%)
A	37	23	7	67 (30)
B	85	23	4	112 (51)
C	39	3	0	42 (19)
Total	161	49	11	221 (100)

At first, we make a comparison between microtremor H/V spectrum ratio and above four earthquake spectrum ratios. Figure 4 shows some examples of comparison. In the figure, although above four spectrum ratios are shown for KiK-net site, only spectrum ratio (1) is illustrated for Nobi Plain comparing with microtremor H/V. Generally speaking, it may be said that microtremore H/V resembles

Earthquake H/V ($S_{H/V}$) or Transfer function H/V ($T_{H/V}$) and shows quite small amplitude compared with Horizontal transfer function (T_H). The predominant frequency of Vertical transfer function (T_V) is higher than that of Horizontal transfer function (T_H). These observation facts strongly suggest that the microtremor H/V does not express only the response characteristic of horizontal motion but reflects the response characteristics due to both horizontal and vertical motions.

Then, we classified the observation sites as the rank A, B, C according to the degree of similarity between microtremor H/V and Earthquake H/V ($S_{H/V}$). The evaluating items on a classification are the primary predominant frequency, primary peak amplitude and overall spectrum form. Result is indicated in Table 1 and the example of each rank is also shown in Figure 4. From the Table, 67 sites correspond to about 30% of the whole are recognized as a rank A. Total sites of rank A and B is reached about 81% of whole. Rank C is 19% of the whole, and the most of rank C belongs to KiK-net sites.

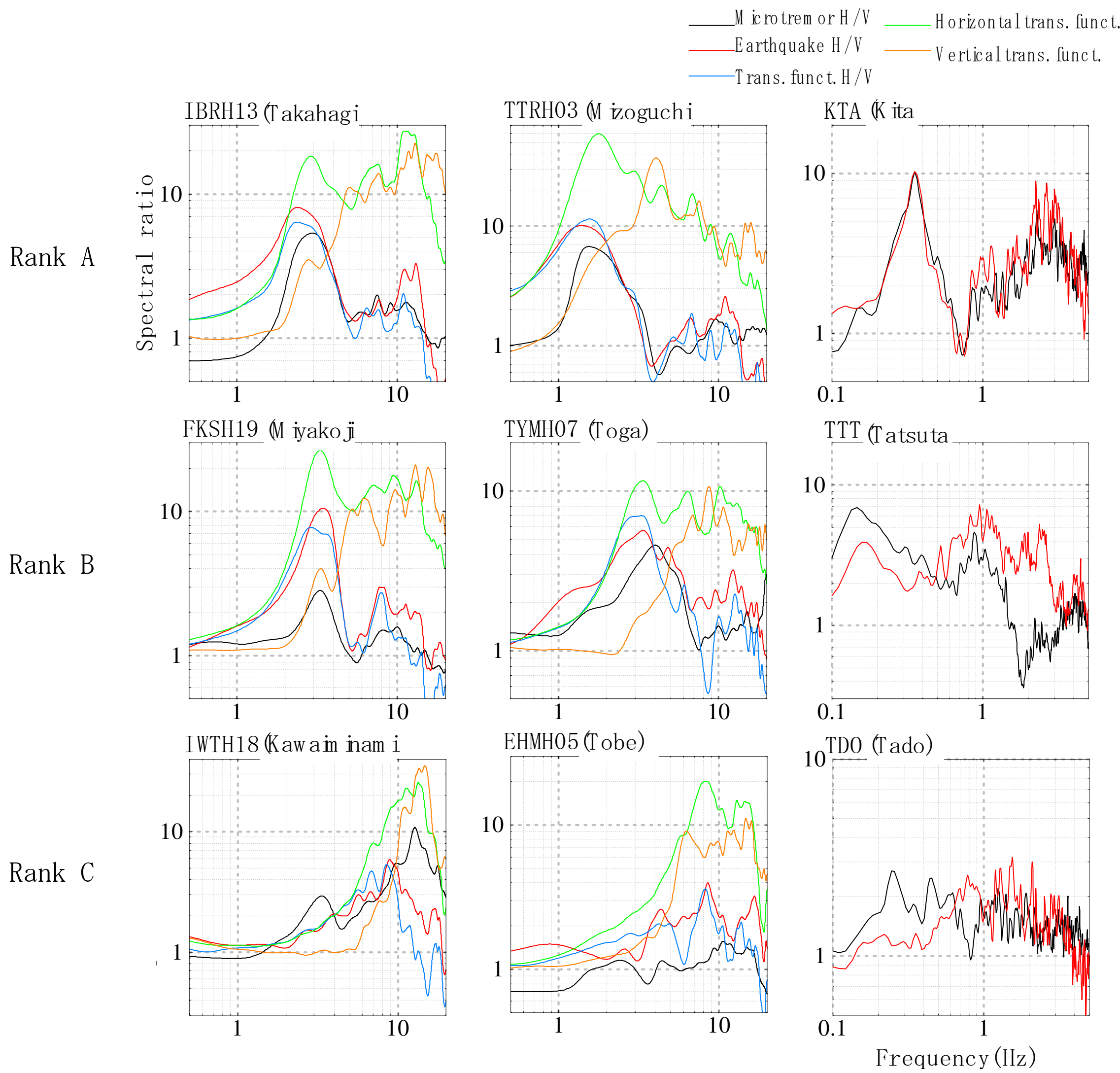
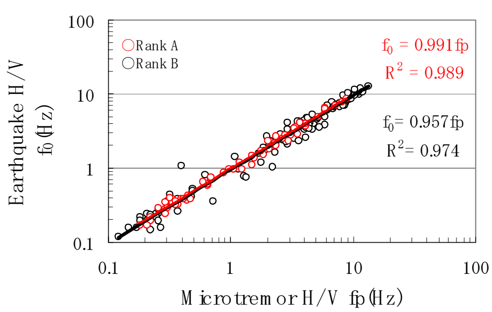


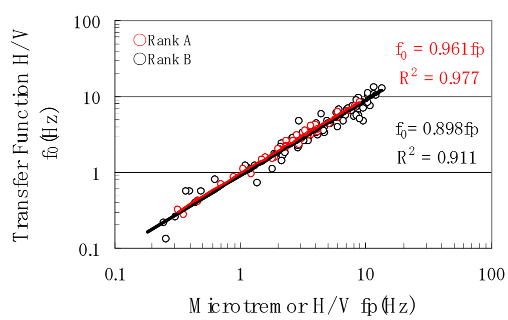
Figure 4 Example of comparison of microtremor H/V and various spectral ratios of earthquake motion

On the case of rank C, it is frequently checked that the peak of mocrotremor H/V did not appear. Since many sites of KiK-net are located in hard foundation near mountainside, where a surface layers is comparatively thin, the predominant frequency exists in high frequency range than 10Hz. Moreover, it is thought that the microtremors at some sites may have been affected by the wind, traffic vibration, etc, because the observation is performed only once.
Any way, since it is thought that the data of the site as a rank C does not fit in this examination, subsequent examination shall be performed to the data of rank A and rank B.

Predominant frequency

The predominant frequency of microtremor H/V (fp) was compared with that of each earthquake spectrum ratio (f_0). Results are shown in Figure 5. In the figure, the red character indicates approximation formula for rank A and the black one for whole data. In the wide frequency range of 0.2Hz-10Hz, the predominant frequencies of microtremor H/V well correspond to those of Earthquake H/V ($S_{H/V}$) with the quite small variation. The same thing can be said also regarding to the correspondence with Transfer function H/V ($T_{H/V}$) and Horizontal transfer function (T_H).
It is well known that the predominant frequency of microtremor H/V expresses that of the ground in many past research results. In our investigation, it was confirmed that microtremor H/V correspond well to not only Earthquake H/V on ground surface but to the transfer functions related to the earthquake response of the upper layer (surface layer) from a base rock.
Consequently, by microtremor H/V, it can be said that it is possible in the various kind of foundation with from thin to thick deposition to presume the predominant frequency of the earthquake response characteristic.





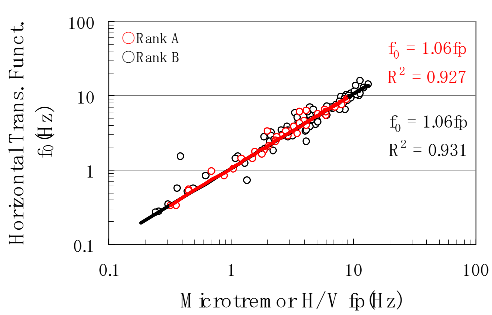


Figure 5 Comparison of predominant frequency of microtremor H/V and those of earthquake spectral Ratios

Peak amplitude

The relation between predominant peak amplitude of microtremor H/V (A_M) and those of Earthquake H/V and Horizontal transfer function (A_0) are shown Figure 6. In the figure, although the variation in data is large and the correspondence of microtremor H/V and earthquake spectrum ratios is hard to be referred to as good, the tendency for the peak amplitude of earthquake spectrum ratio to become large is recognized so that the peak amplitude of microtremor H/V becomes large generally. Table 2 indicates the average and standard deviation values of peak amplitude ratios. The average of the peak amplitude ratios for microtremor H/V to Earthquake H/V ($S_{H/V}$) and Transfer function H/V ($T_{H/V}$) are 1.3 and 1.4, respectively, and so much difference is not seen. However, it attracts attention that the peak amplitude ratio of microtremor H/V to Horizontal transfer function (T_H) serves as a high value of 3.8 times on an average. That is, if it considers that the microtremor H/V is corresponds to Horizontal transfer function, there is a possibility of underestimating the earthquake response characteristic in horizontal motion.

Table 2 Peak amplitude ratios (A_0/A_M)

Earthquake Spectral Ratio	Average	Stand. Dev.
Earthquake H/V	1.30	0.69
Transfer Function H/V	1.41	0.63
Horizontal Trans. Funct.	3.83	2.16

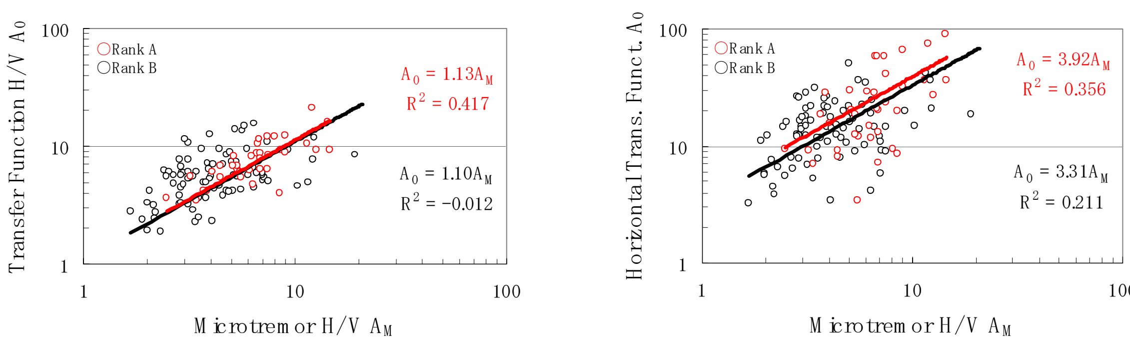


Figure 6 Relation between peak amplitude of microtremor H/V and those of earthquake spectrum ratios

Spectrum intensity

Supposing the spectrum intensity is expressed by integrating a spectrum along frequency 0 to 10Hz, the values divided the spectrum area of Earthquake H/V ($S_{H/V}$) or Horizontal transfer function (T_H) by that of microtremor H/V are plotted on a vertical axis of Figure 7, and the predominant frequency of microtremor H/V is plotted on a horizontal axis. These ratios have frequency dependability, and become large as frequency becomes lower. This tendency is considered to mean that the microtremor H/V spectrum ratio becomes smaller than earthquake spectrum ratio in the higher frequency range than the predominant frequency of microtremor H/V. Therefore, it should be thought that it is difficult to presume horizontal response characteristics in surface layer directly using the microtremor H/V.

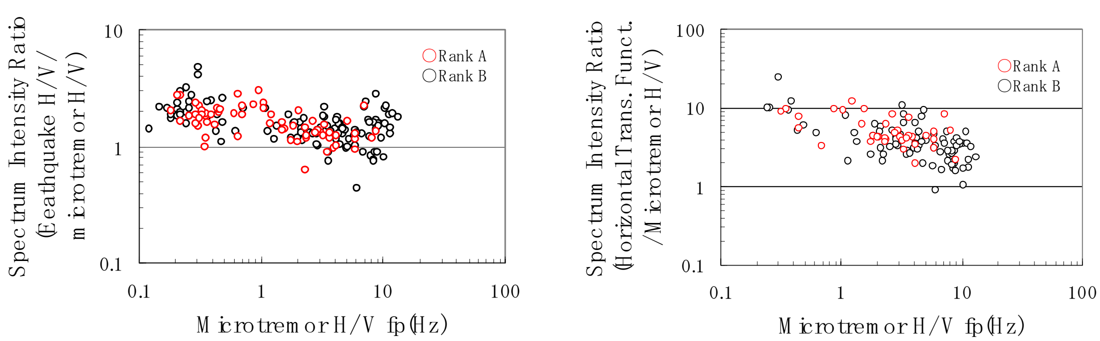


Figure 7 Spectral intensity ratios vs. frequency

ESTIMATION OF INCIDENT WAVE RESPONSE CHARACTERISTICS OF SURFACE LAYER

On evaluating the earthquake response characteristic of the foundation, the incident wave response for horizontal motion is most important. As shown in the previous chapter, it is possible to presume the predominant frequency of incidence response for horizontal motion from microtremor H/V. However, it does not argue about the method of presuming the peak amplitude or spectrum of incidence response using microtremor H/V yet until now.
Although it agrees that we have many various arguments about whether the microtremors are constituted by what kind of waves, we want to consider the technique of presuming the incident wave response (horizontal amplification characteristic) of the surface layer using the microtremor H/V from an engineering viewpoint.

Peak amplitude ratio of microtremor H/V and Horizontal transfer function (T_H)

To evaluate the incident wave response of surface ground, we attend a peak amplitude relation between microtremor H/V and Horizontal transfer function (T_H).
First, as shown in Table 2, the peak amplitude ratio of microtremor H/V to Horizontal transfer function (T_H) is about 3.8 in average, although its variation is large. Figure 8 shows the ratio of both spectral peak amplitudes against to predominant frequency of microtremor H/V.
Although the variation in data is also large in this case, the value of ratio seems to approach 1.0 in a low frequency side. That is, the relation between the peak amplitude of microtremor H/V and Horizontal transfer function (T_H) may be expressed by approximation curve as shown in the figure 8.

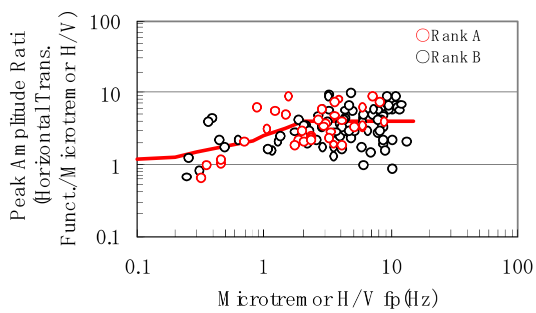


Figure 8 Peak amplitude ratio and formulation curve

$$T_{obs}(f_p) = \alpha * A_M(f_p) \quad \text{------------------------- (6.1)}$$

Here, α: coefficient, $T_{obs}(f_p)$: peak amplitude of Horizontal transfer function (T_H) at predominant frequency f_p, $A_M(f_p)$: peak amplitude of microtremor H/V. The coefficient α is approximated by next formula.

$$\left.\begin{array}{ll} \alpha = 1.5 f_p + 1 & (f_p < 2Hz) \\ \alpha = 4.0 & (f_p \geq 2Hz) \end{array}\right\} \text{---------------- (6.2)}$$

The coefficient α will be used as a compensation value of the average incidence response characteristic presumed from the predominant frequency of microtremor H/V shown in the following paragraph.

Estimation of a depth of base rock

From the examination in this research, it is suggested that there is a certain kind of relevance between the predominant frequency of microtremor H/V and the depth of base rock. Then, it considers the relation between the predominant frequency (f_p) of microtremr H/V and the depth of base rock about KiK-net sites. Here, we defined S wave velocity of the base rock is more than 1500 m/s.

The predominant frequency is governed by S wave structure of the foundation. Figure 9 shows the relation of a depth (h) of base rock and an average S wave velocity ($\bar{V}s$) of surface layer. The average S wave velocity is obtained from the following formula.

$$\frac{h}{\overline{\overline{V_S}}} = \frac{h_1}{V_{S1}} + \cdots + \frac{h_n}{V_{Sn}} \quad \text{----------------- (6.3)}$$

h_n: thickness of layer n, V_{sn}: S wave velocity of layer n

As shown Figure 9, the following loose relations are seen between h and $\bar{V}s$.

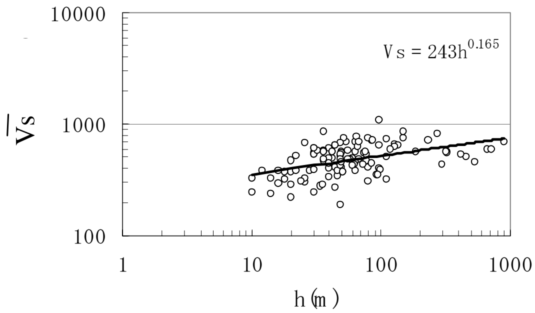


Figure 9 Relation between average S wave velocity and depth of base rock

$$\overline{V_S} = 243h^{0.165} \quad \text{------------------------- (6.4)}$$

Assuming the predominant frequency of the foundation follows a 1/4-wave length rule ($\overline{V_S}/h = 4f_p$).

$$h = 137 f_p^{\ 0.835} \quad \text{------------------------- (6.5)}$$

Figure 10 shows the relation between predominant frequency f_p and depth of base rock h. In the figure, blue circles are data for KiK-net sites, and it may be said that a formula (6.5) fits these data in general. However, orange circles, which are obtained from data on reflection survey lines in Nobi Plain (Sawada et al., 2001), deviated from this formula. Consequently, we get a new approximation formula by forward modeling.

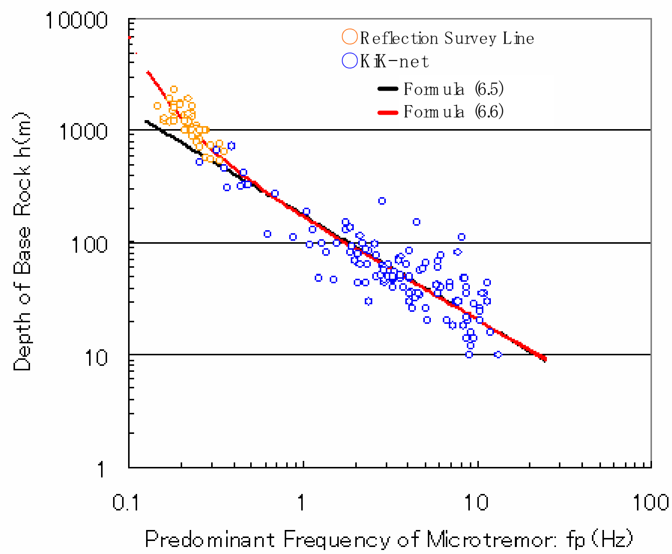


Figure 10 Relation between predominant frequency of microtremor H/V and depth of base rock

$$h = 150 f_p^{\ -(0.85+0.1/f_p)} \quad \text{----------------- (6.6)}$$

By using this formula, it may becomes possible to presume an average depth of base rock from the predominant frequency of microtremor H/V for various kinds of foundation from a hard foundation like KiK-net to a thick deposition plain like Nobi Plain.

Estimation of incident wave response by using two-layered model

When microtremor H/V is observed at a certain site, a technique of presuming the rough earthquake incidence response characteristic in the site is described.

First, two layered model as shown in Figure 11 is assumed as a most easy case. The thickness of surface layer and its average S wave velocity are obtained from the predominant frequency of microtremor H/V using formula (6.6) and (6.4), respectively. Although S wave velocity of base rock in this investigation is more than 1500m/s and the average value is about 2000m/s, we suppose it to be 3000m/s, which correspond to the seismic basement, and assume also the suitable values for densities and Q-values. As for Q-value of surface layer, we use 15.5 here according to the research result of KiK-net sites (Sawada et al., 2002). If there is some suitable information about the physical properties and layered structure model, of course, you can assume other values and multi-layered structure, though it is necessary to determine that S wave velocity of each layer is in agreement with an average S wave velocity of surface layer.

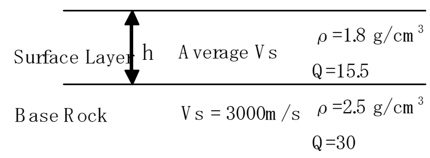


Figure 11 Two-layered model

Next, according to two-layered model, we calculate the earthquake response characteristics for incident wave (T_{in}) (transfer function for an incident wave) and the earthquake response characteristics for observation wave (T_{obs}) (transfer function for an observation wave). It can be said that the two earthquake response characteristics acquired in this way, so to speak, give the average response characteristics of various foundations of having one predominant frequency, because we only pay the attention to the predominant frequency of microtremor H/V. However, even if each foundation has the same predominant frequency, depth of base rock and S wave velocity of surface layer are various, and these have the relation of a trade-off to predominant frequency. The amplitude of the earthquake response characteristics depends on the contrast ratio of a base rock and surface layer, and generally, it is thought that the peak amplitude of microtremor H/V is large, so that the contrast ratio of the foundation is large.
Then, by using α of the formula (6.1), peak amplitude of microtremorH/V (A_M) and the primary peak amplitude of earthquake response due to a model (T), we define an amplitude compensation coefficient β for an average incident wave response by the following formula. That is, the peak amplitude of microtremor H/V of the site is considered to be an index indicating a gap from the average earthquake response characteristics.

$$\beta = \frac{A_M(f_p)}{T\ (f_p)} * \alpha \qquad \text{---------------------------- (6.7)}$$

The incident earthquake response spectrum of the foundation finally presumed becomes what multiplied the incident response characteristic spectrum of the two-layered model by β. Here, two kinds, an incident response (T_{in}) and an observation response (T_{obs}), can be considered in asking for β as the theoretical earthquake response characteristics of the model (T) to be used. Although since α is obtained from observation earthquake motion data, properly speaking, the observation response (T_{obs}) should be used, there is a possibility of underestimating an actual earthquake response of the site, because we used the average value of data having very large variation as coefficient α. In order to mitigate this underestimation, it can be considered it is one method to use an incident response (T_{in}) instead of an observation response (T_{obs}), or, α has comparatively large standard deviation as shown in Table 2, so, another method is to use average + standard deviation instead of α.
The examples of the estimation result of the incident earthquake wave response characteristics based on the compensation coefficient β by two kinds of method, using an incident response (T_{in}) and an observation response (T_{obs}), are shown in Figure 12. The incident earthquake wave response calculated from actual PS logging data of the site and microtremor H/V are also shown in the figure. When the incident earthquake response characteristic calculated using the borehole data of each site is compared with two presumed results, the technique proposed in this research can be said to give comparatively appropriate result. Consequently, this method may be used as the preliminary method for presuming the earthquake amplification characteristics, when we have no information about the foundation; even if the validity of this method needs to be verified for the more various kinds of foundations.

In addition, although using the spectrum intensity ratio between Horizontal transfer function and microtremor H/V is also considered as a coefficient α, it is confirmed that a presumed result becomes large too much as compared with actual amplification characteristic, because the spectral amplitude of microtremor H/V becomes very smaller than that of horizontal transfer function in higher frequency rage than predominant frequency of microtremor H/V. Moreover, it will be also possible that we use the relation between Earthquake H/V or Transfer function H/V and microtremor H/V, which reveals more stable relation, in order to estimate the incident response characteristics, if P wave velocities in a structure model can be formulated suitably. As for this, the examination is left behind as a future subject.

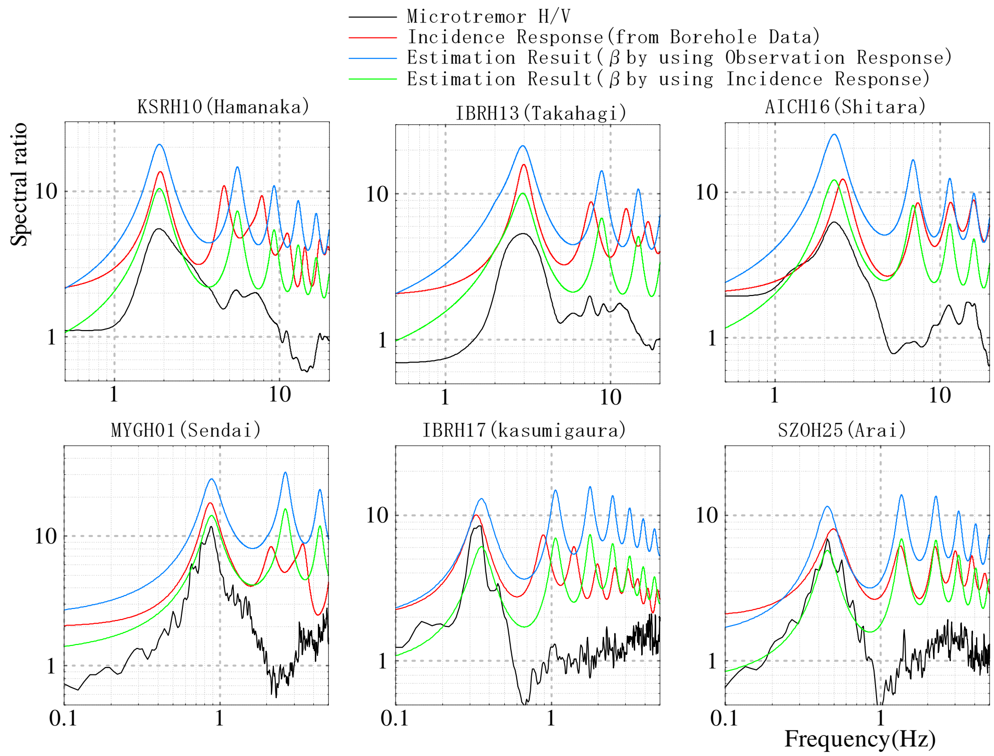


Figure 12 Example of comparison of estimation results and incidence response characteristics deduced from borehole data

CONCLUSIONS

It was clarified the microtremor H/V does not express only the response characteristics of horizontal motion but reflects the response characteristics of the both of vertical and horizontal motions in surface layer. It is possible to presume the predominant frequency of the foundation with sufficient accuracy from microtremor H/V, although it is difficult to estimate directly the horizontal incident wave response characteristics of surface layer. We formulized the relation between the average S wave velocity, depth of base rock and predominant frequency of microtremor H/V of the surface layer, and proposed an engineering technique to presume simply the earthquake incident wave response characteristics using the predominant frequency and its amplitude of microtremor H/V.

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