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CURRENT STUDIES IN JAPAN ON H/V AND PHASE VELOCITY DISPERSION OF MICROTREMORS FOR SITE CHARACTERIZATION

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SUMMARY

This is a review article on the use of microtremors for site characterization or estimating site effects during an earthquake. We review mostly on recent studies on horizontal to vertical spectral ratio and array observation of microtremors carried out in Japan or by Japanese researchers. The horizontal to vertical spectral ratios correspond to the peak frequency of transfer function by 1D modeling for earthquake motion in a sediment site but disaccord with the amplification factor, except a few case studies. The method of array analysis of microtremors is a promising tool for understanding S-wave velocity structures and it has been used in determining velocity structures of large basins that include mega-cities in Japan.

INTRODUCTION

Since Kanai and his coworkers (e.g. Kanai [1]; and others; summarized in Kanai [2]), "microtremors" has been raised up over one of the tools for evaluating site effects and they have been accepted to be useful for soil classifications into four categories associated with the building code in Japan. Advantages of using microtremors or ambient ground noises for evaluating site effects during an earthquake would be invaluable, because observations of microtremors require no artificial sources and less expense, if the results are theoretically reliable and stable from observational points of view. Kanai's method, as simple as, requires only one horizontal seismometer, in principle. The interpretations by the method on the observed results are based on the experiences and assumptions: 1) dominant periods and amplitudes of microtremors in subsoil layers are similar to strong motion, 2) microtremors are resultants of multiple reflections in sedimentary layers overlying basement by vertical incidences of S-waves, 3) source spectra of microtremors or incident waves to subsoil layer are white in terms of displacements. On the other hand, criticisms were also presented related to the Kanai's assumptions on the wave-types of microtremors and the spectral shape of microtremors. Those are not direct criticisms to the Kanai's method but Aki [3], Akamatsu [4], and Nogoshi [5] commonly explained the wave-types of microtremors by surface waves.

Recent discussions on site characterizations have centered on practical use of horizontal to vertical spectral ratio of microtremors (HVSRm) and the array analysis of microtremors for determining S-wave velocity structure. The HVSRm has been a most remarkable target for estimating site amplification of

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earthquake motion, after Nakamura [6], which was paid attention in the review article by Finn [7]. The method was quickly and widely spread in the world as named 'Nakamura's technique', irrespective to his interpretations. The uniqueness of Nakamura [6] is that HVSRm correlates well with spectral site amplification of S-waves. Current discussions on use of HVSRm seem parallel to the previous debates of 40-50 years ago, in some respects. The first question or controversial subject is whether microtremors are body waves or surface waves. The second is why HVSRm correlates with the site amplification factor, which is the horizontal spectral ratio of earthquake motion (HHSRe). The third is whether HVSRm is valid for a substitution of HHSRe at everywhere. Many efforts have been paid for clarifying these issues during this decade, and we will try to introduce recent results by mostly Japanese researchers in the following.

The other pillar of microtremors utility is an array observation of microtremors and analysis for estimating S-wave velocity structure at a site. Aki [3], Toksoz [8] and Lacoss [9] will be noted as the pioneer works. Array observation of microtremors is a potentially useful method for estimating S-wave velocity structures beneath a site where a seismometer array is deployed. The method basically involves extracting surface waves from microtremors in the form of dispersion, and then inverting the dispersion data for a S-wave velocity structure. In the field of engineering seismology, the array method has again been focused on since Horike [10] and Matsushima and Okada [11].

A national project of Japan has been carried out for determining the basin structures of highly populated area, such as Kanto, Osaka, Kyoto, Nobi (Nagoya), Sendai, Ishikari (Sapporo), Kofu basins among others. The method used in the project is mostly P-wave reflection surveys using large vibrators; besides array measurements have also been included as an only method for estimating deep S-wave velocity structure. The array method seems to have established its status as one of useful tools for determining velocity structure, although it has some problems and/or difficulties for considering non-flat layering, mixing of higher modes, limitation of source-power and so on, concerned with its accuracy. We will also try to review the results by array analyses of microtremors mainly carried out in Japan or by Japanese researchers.

HORIZONTAL TO VERTICAL SPECTRAL RATIO OF MICROTREMORS

The issues of HVSRm have critically been reviewed by Horike [12], Bard [13], Kudo [14], Bard [15], Mucciarelli [16] among others from various points of view; however, there still remain controversial results and interpretations. Duplication should be kept out; however, we should make the issues clear again.

Majority of papers concerned with HVSRm may accept followings;

1) The HVSRm is very stable in terms of spectral shape with a few exceptions. It has a significant peak at soft sediment sites, while it is almost flat and a unity at rock or hard soil sites,
2) The HVSRm peak correlates well with the fundamental predominant frequency of HHSRe at soft sediment sites. However, some variations, papers to papers, are found as summarized by Bard [15].

Comparison with observed earthquake motion

Related to the second item, the observational results have shown ambiguous conclusions that some of papers (e.g., Nakamura [6]; Lermo [17]; Seekings [18]) showed good agreement with HVSRm with the HHSRe, while the HVSRm by other authors matches with HHSRe at only around the peak frequency but it is slightly smaller than HHSRe (e.g., Field [19]; Riepl [20]; LeBrun [21]), site dependent (e.g., Duval [22]) or inconsistent (e.g., Toshinawa [23]). The compiled result on HVSRm vs. HHSRe for various sites made by Bard [15] and Duval [22] shows systematically low level of HVSRm with respect to HHSRe. However, these diverse conclusions were brought by the results at various different places, whence microtremors are possibly somehow different constitution of P-, S-, Rayleigh and Love waves. We might need more verification on the correspondency between HVRSm and HHSRe. We have not discussed so strictly on 'what is a basement or a bedrock for a site amplification factor?'. Satoh [24] indicated recently importance to consider deep underground structures. Most researchers noticed that site amplification factors are determined by only knowing elastic constants of subsurface and basement materials, in a strict sense, however, the above comparisons have not explicitly defined the basement, at least its S-wave velocity (Vs) should be clarified. The ideal basement or bedrock will be a layer that underlies commonly in the target area and the velocity contrast below the base layer is very small. To incorporate the knowledge of seismology, the Vs of the basement having 3.0 km/s or the higher will be adequate, however, it is rather difficult to practically use such bedrock. A reference site method gives relative empirical amplification factors in a limited area, even if a reference site is not ideal basement. On the other hand, HVSRm requires no reference site; therefore the method must give an absolute amplification factor, if it really reflects the amplification of earthquake motion in a basin structure. Engineers in Japan, may be similar to the other countries, specify the engineering basement of which Vs is 400 m/s or higher for practical and conventional use. The basement used by Nakamura [6] is thus determined engineering one, while the others are not necessarily same and their Vs of basement may be higher than 400 m/sec. As it is well known, an amplification factor depends on the Vs of basement (impedance ratio); therefore, we are very difficult to strictly compare irrespective to Vs of basement. Recent studies by Sawada [25], and Sawada [26] may give a light for the strict comparison between HVSRm and HHSRe. They mostly used the set of earthquake motions at surface and downhole of the KiK-net and the velocity structures determined by PS-logging at 161 stations where the Vs at the downhole sensor exceed 1.5 km/sec (2.0 km/sec in average). The downhole sensors used in their analysis are mostly installed at depth of 100-199m (63 percents) and the rests are deeper than 200 m. They also included the data at 60 sites in the large basin, Nobi plain. First, they classified sites into three categories by the degree of similarity of HVSRm with the horizontal to vertical ratio of earthquake (HVSRe, like a receiver function). They excluded the data of the rank C (19 percents) in the following discussions because the peaks of HVSRm of the rank C are unclear or higher than 10 Hz, nevertheless the peaks are clearly found. Consequently the sites of the rank C are regarded as rock or hard soil.

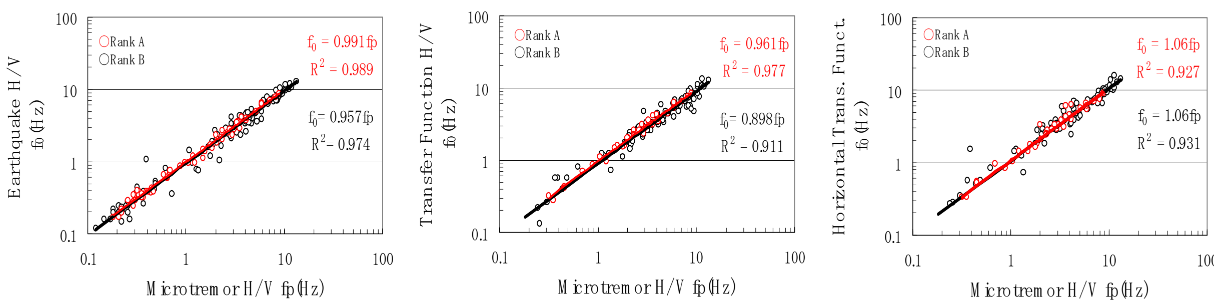

Figure 1. Correalations of peak frequencies among HVSRm, HVSRe, and HHSRe, reproduced from Sawada [26].

They found a very clear correspondency of predominant frequencies of HVSRm and earthquake data, irrespective to the rank A and B, as shown in Figure 1. In the figure, 'Transfer function H/V' means that the ratio of HVSRe at the surface to that at the downhole, while 'Horizontal Trans. Funct.' stands for the ratio of surface horizontal spectrum (square root for the product of two components) to downhole one. The peak amplitudes of HVSRm and HVSRe match fairly well, although the scattering of the rank B is rather large. On the other hand, those of HVSRm are significantly biased against the horizontal ratio of surface to downhole as shown in Figure 2. The horizontal ratios are exactly different from HHSRe; however these results are similar to Duval [22] but the amount of their bias is slightly different. Horike [27] has also suggested that HVSRm is similar to HVSRe, although the deviation is significantly large and the peak amplitudes of HVSRm are slightly smaller than HHSRe in general, but those of higher frequency than the peak frequency decrease very much at some sites, nevertheless the sites are located within small relative distances as shown in Figure 3.

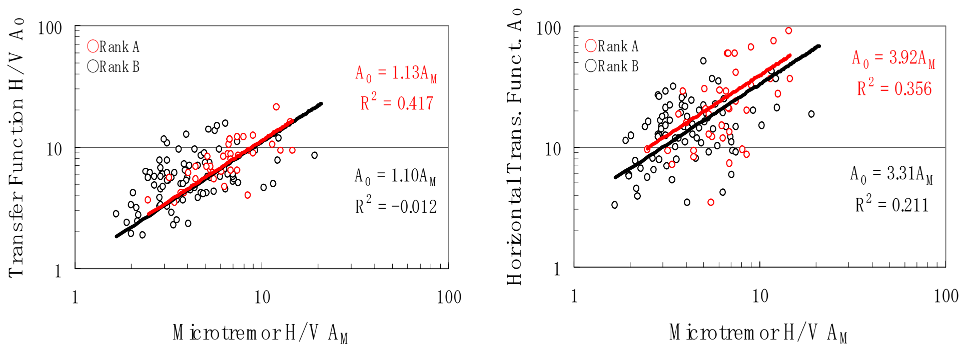

Figure 2. Comparison of amplitude ratios of HVSRe and HHSRe to HVSRm, reproduced from Sawada [26].

Sato [28] suggested the similar relation between HHSRe and HVSRm using the aftershock data from the 2000 Tottori earthquake as that the peak amplitude of HVSRm is within a factor of two around the long period peak of HHSRe; however, the HVSRm underestimates significantly the HHSRe as shown in Figure 3. On the other hand, Rodriguez [29] presented somewhat opposite results using also extensive data in Yokohama, Japan. They found a large scatter of predominant frequencies in relation between HHSRe and HVSRm, while a rather good coincidence of peak amplitudes of HVSRm with respect to those of HHSRe. Although the average of peak HVSRm is slightly smaller than that of HHSRe, the deviation is smaller than that of predominant frequency. The qualitative nature seems to contradict from the other previous results and Sawada [26]. The S-wave velocities of the basements in Rodriguez [29] are 400-600 m/sec and those in Sawada [26] are 2.0 km/sec in average. We may necessary to include the frequency range as well in the discussion on correspondency between HHSRe and HVSRm.

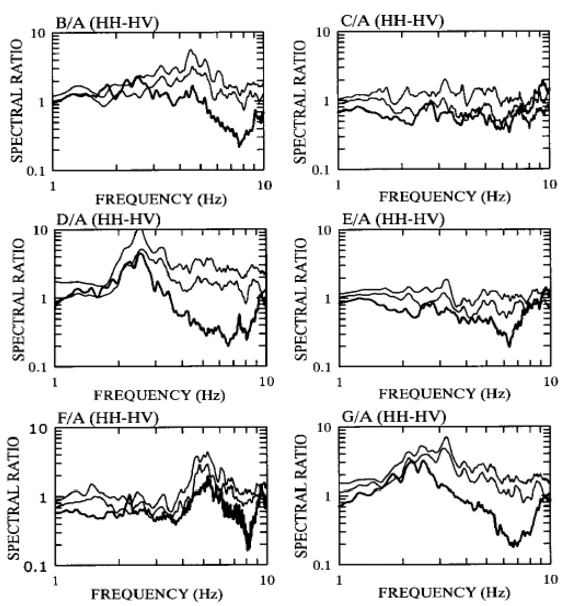

Figure 3. Comparison of HVSRm (thick line) with HHSRe (thin lines showing plus and minus on standard deviation) in relatively small area (Horike [27]).

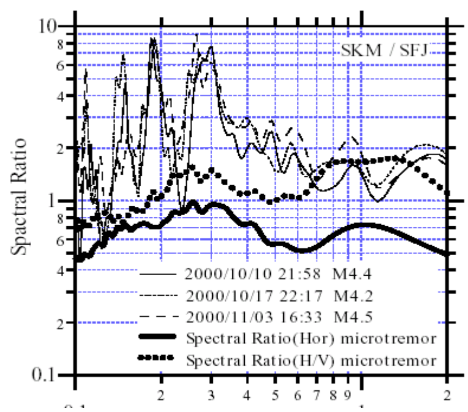

Figure 4. Comparison of HHSRe of aftershocks of from the 2000, Tottori earthquake and HVSRm, reproduced form **Sato [28]**

Satoh [24] demonstrated that HVSRm could represent neither HHSRe nor ellipticity of Rayleigh waves by only shallow underground structures; however the HVSRe correlated well with the ellipticity of fundamental mode Rayleigh waves by considering deep underground structures (down to a seismological basement), although the peak amplitudes of HHSRe and HVSRm are not coincident. They also indicated the reason why HVSRe are closely similar to HVSRm, despite it is mainly composed of Rayleigh waves, as that the S-wave portion except for its early part is primarily composed of surface waves generated by near-site inhomogeneities. Horike [27] has made a similar discussion. We may summarize the nature of HVSRm through the comparisons with observed earthquake motions as following;

1) The peak frequencies of HVSRm, HVSRe, and HHSRe are always quite similar, if we consider the seismic basement (bedrock) of higher Vs of about 1.5 km/s, except the case that the peak of HVSRm is smaller than 3 (Satoh [24]) or the impedance ratio is very low (surface is a quasi rock site) or very shallow (Sawada [26]). The peak frequency of HVSRm is well explained by the ellipticity of fundamental mode Rayleigh waves (since Nogoshi [30]; recent Satoh [24]; Horike [27])

2) The spectral shapes and amplitudes HVSRm and HVSRe are generally well correlated but the degree of the similarity depends on site conditions (Sawada [26]). Zhao [31] successfully used HVSRm for simulating vertical earthquake motion with using horizontal one.

3) The peak amplitudes of HHSRe are largely scattered and biased from those of HVSRm, therefore, a direct use of HVSRm as a substitute of HHSRe is not recommended, especially those at higher frequency than the peak one, although opposite results (Rodriguez [32]) should also be considered.

4) Vertical microtremors are mostly composed of Rayleigh waves, while horizontal microtremors are possibly ensembles of Rayleigh and Love waves (Okada [32], Arai [33]). The peak amplitudes of HVSRm are variable according to the partitions of Rayleigh and Love waves and their higher modes, if they are sufficiently included. In addition, the impedance ratio and the Poisson's ratio give also significant effects on the ellipticity of Rayleigh waves (Kudo [14]). Therefore, the peak amplitudes of HVSRm are deviated from those of HHSRe.

These conclusions are not new, however, the referred papers are based on a great deal of data and careful analyses, and then we are more confident on the interpretation and relation between HVRSm and HHSRe than the state of several years ago. Nakamura [34] claimed on the interpretation by surface wave introducing Nogoshi [30], but he might misunderstand in his Figure 3 and on energy of surface waves. The interpretation on HVSRm by body waves in Nakamura [34] has still unacceptable assumptions; why the horizontal and vertical motions at rock site or basement is unity, if the motion consists of body waves. The assumption is valid only for the P or SV-wave incidence of 45 degree. The observational results of HVSRm at rock site, which is usually unity or slightly larger, can be easily explained by Rayleigh waves. As clearly suggested by Satoh [24] and Horike [27], an interpretation on HVSRm by body waves is to be resigned.

Use of HVSRm for determining Vs structure

Once we could assume that microtremors consists mostly of surface waves, we may positively use the nature of surface waves, especially Rayleigh waves, for site characterization. Yamanaka [35] initiated the method to use the ellipticity of Rayleigh waves to estimate the deep basin structure in Kanto Plain. Tokimatsu [36], Arai [33] among others proposed simultaneous use of HVSRm and phase velocity dispersion data by array observation of microtremors (to be appeared in the later part) for estimating the Vs structure. Their method is that the velocity structures at a few representative sites are first determined applying the *f-k* method (e.g., Capon [37]; Horike [10],) to array data of microtremors and the spatial interpolation/extrapolations are carried out by HVSRm of single station method. As suggested by Scherbaum [38], we face to underdetermine due to a trade-off of depth and velocity of an underground structure without information of surface layers. Tokimatsu [39] constrained the surface layers by the data of shallow boring (SPT N-value) and then the intermediate layer between surface layers and bedrock. Arai [33] extended their method to the inversion procedure getting fulfill coincidences for not only peak frequency but also spectral amplitudes of HVSRm, including the contribution of higher modes of Rayleigh as well as Love waves. As shown in Figure 5, a very excellent matching between observations and the ellipticity of multi-modes Rayleigh waves was obtained at every site. A few questions are presented that ‘is this method applicable for the first peak of low frequency in a deep sedimentary basin?’, ‘is the partition of Rayleigh and Love waves always same in terms of time and space?’, and ‘is it sufficient to include multi-mode surface waves by spectral composition?’. The last question is that if we consider microtremors in time domain, the composition is not the same with that of spectral domain due to different dispersion and attenuation of individual modes; therefore the composition might depend on source to receiver distance. This point may be a second order, however, we need future discussion on this issue.

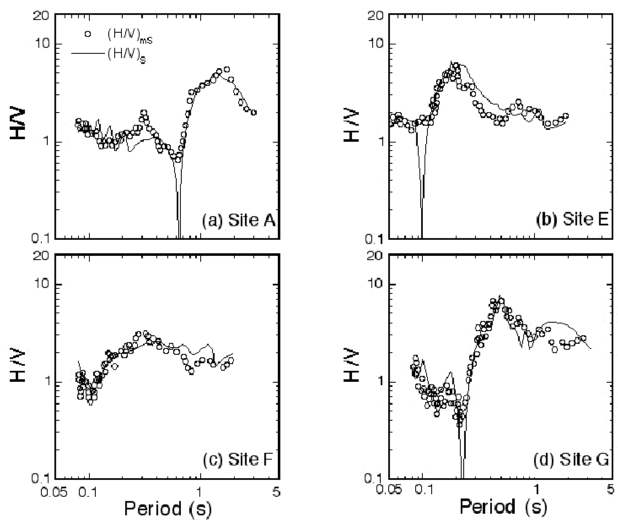

Figure 5. HVSRm compared with the ellipticity of multi modes Rayleigh waves, reproduced from Arai [33].

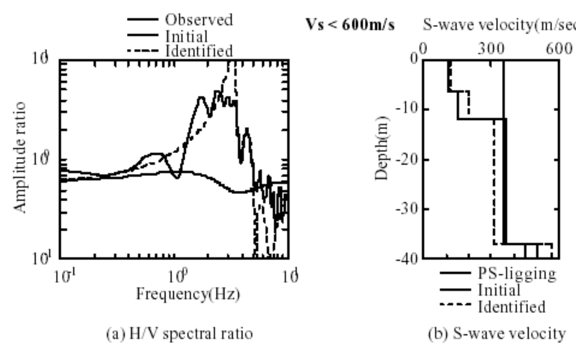

Figure 6. Inversion from HVSRm to S-wave velocity structure, reproduced from Sawada [40].

Sawada [40] proposed a more conventional method for inversion by minimizing the power of residuals between HVSRm and the ellipticity of Rayleigh waves. The dominant direction of Rayleigh waves propagation is identified using that the imaginary part of cross-power spectra of horizontal to vertical microtremors become maximum, which is correspond to the ellipticity or rotation of particle motion of Rayleigh waves. The result is fairly good as shown in Figure 6 compared with the PS logging data. They also mentioned, however, to give the initial condition is not easy and the trade-off of velocity and depth (or thickness of layer) is inevitable.

Effects of basin topography

We are obliged to assume a horizontally stratified layers at least immediately beneath the survey area for applying the elliptic particle motion of Rayleigh waves as well as the dispersion of phase velocity; however, real basin structures are more or less laterally heterogeneous, especially near basin edges. Uebayashi [41]; Uebayashi [42] carried out HVSRm measurements and analyses near the northwest edge (Hokusetsu area) of the Osaka basin, in Japan and numerical simulations of microtremors to assess the effects of 2D/3D basin structures on HVSRm. Simulations of microtremors are made by 2D-FEM [41] and 3D-FDM [42] by modeling the origins of microtremors from line sources of oceanic waves distributed at random with intervals from 1 to 5 km on the ground surface about 90 to 110 km north from the target area. The location map and the 3D basin structure are shown in Figure 7.

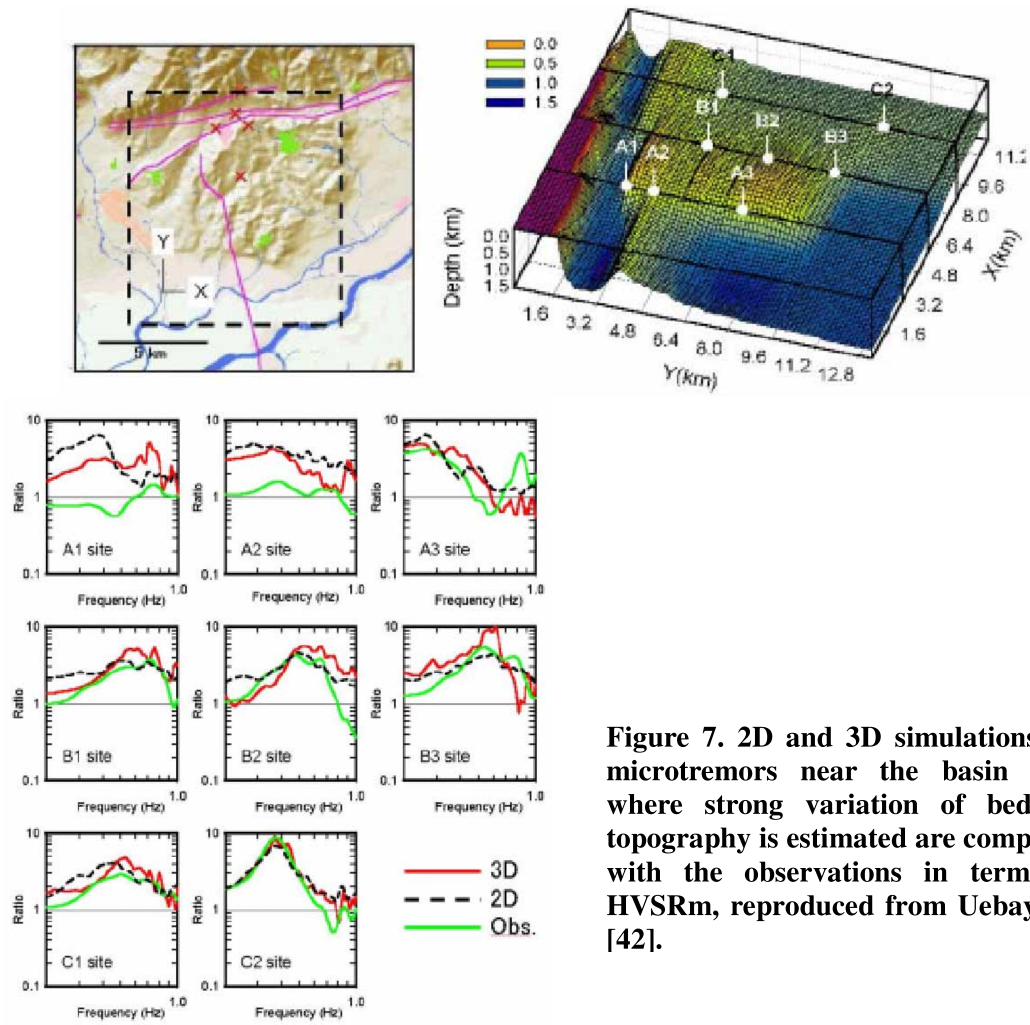

Figure 7. 2D and 3D simulations for microtremors near the basin edge where strong variation of bedrock topography is estimated are compared with the observations in terms of HVSRm, reproduced from Uebayashi [42].

Combining the results of two papers, we may summarize (1) in the areas of gentle slope of basements, HVSRm can be approximated by horizontally stratified model (peak frequencies and amplitudes match well, e.g. at C2), (2) circumference of graven structure it can also be approximated by 1D in terms of peak frequencies but agreements of amplitudes require the help of 2D/3D results, (3) in immediately above area of the graven, both peak frequencies and amplitudes of HVSRm cannot be interpreted by 1D. The simulation by 3D matches slightly similar to the observation than 2D. However, we need further study to make clear the reasons why no good agreement is obtained, despite 2D/3D effects are considered. These discussions are valuable suggestions or cautions to apply HVSRm techniques at laterally strong heterogeneous area. We generally use the gravity anomaly data for modeling a basin structure in Japan; however, Uebayashi [40] indicated a possibility that HVSRm is much better than gravity, incorporating 2D/3D wave field of microtremors.

Comparative studies with geotechnical data

Fukumoto [43] indicated a possibility using HVSRm to find engineering basements with comparing the theoretical transfer function of sediment sites (1D response) where Vs structures were determined by PS-loggings and array analysis of microtremors. They suggested that the engineering basement of higher Vs than 700 m/sec is recommended for simultaneously incorporating the peak frequency of HVSRm and the 1D response of S wave. Ishida [44] compared the peak frequencies that were estimated by Vs structures determined from empirical relation between the data of standard penetration test and Vs, with those observed HVSRm at various and many sites in Chiba Prefecture, Japan. The matching between two was a somewhat discouraging that the general trend of both peak frequencies match as increasing from bay area to inland; however, one to one correspondency is not good but effects of micro geology and topography are significant.

Miscellaneous items

Yamamoto [45] found through one year continuous observation that the peak frequency of HVSRm is quite stable but varies associated with the changes of circumstances, such as a construction of a new building near the site. The variability is more distinct in its amplitude (HVSRm). Fujimoto (2002) [46] suggested a possible nonlinear behavior of ground during the 2001 Geiyo earthquake, Japan, showing the similarity of peak frequency of HVSRm with those of weak motion and the difference with those of the mainsock.

S-WAVE VELOCITY STRUCUTURE BY ARRAY ANALYSIS OF MICROTREMORS

The array measurements of microtremors can be classified to one of a seismic prospecting. The technique has been developed to know the underground structures and has applied to many sites using the propagating nature of microtremors. Aki [3], Toksoz [8] and Lacoss [9] are noted as the pioneering works. Array observation of microtremors is a potentially useful method for estimating Vs structures beneath a site where a seismometer array is deployed. The method basically involves extracting surface waves from microtremors in the form of dispersion, and then inverting the dispersion data for a Vs structure. In practice, the vertical component of fundamental-mode Rayleigh waves is a direct object of extraction. To extract surface waves from microtremors, two methods have been presented; they are the frequency (*f*)-wavenumber (*k*) power spectral density method (*f-k* method) (e.g. Capon [37]; Lacoss [9]; Asten [47]; Horike [10]) and the spatial autocorrelation method (SPAC method) (Aki [3]; Henstridge [48]; Okada [49]). Both f-k and SPAC methods are based on the assumptions that microtremors are a spatio-temporally stationary stochastic process and propagate horizontally crossing an instruments array, as elastic waves. Details of both methods can be found in Okada [32].

Application to deep basin structures-Case study in Japan

After the 1995 Hyogo-ken Nanbu (Kobe) earthquake, the Headquarter for Earthquake Research Promotion has been established under the government of Japan. The Headquarter has promoted the development and establishment of various observation systems, projects, and planning related to earthquakes. As one of the projects, the contemporary and systematic seismic surveys started in 1998 for determining the velocity or geological structure in the basins, which include big cities or highly populated areas. The major task of surveys has mostly been reflection/refraction surveys using large vibrators or large explosions for aiming to understand deep basin structures. In addition, the array measurements of microtremors for determining Vs structures have also been included at most surveyed areas. These surveys have been conducted by mostly geotechnical consulting companies under the guidance of the committees established in the local governments. Table 1 shows the basins or areas where the array measurements of microtremors have been carried out during these five years with a brief specification of the surveys. The similar experiments conducted by mostly research groups independent to the national project are also shown in the Table1, although some experiments might be missed to allocate. Surveys of a single or a few sites and shallow profiles are not included in the Table. Thus the array measurements of microtremors seem to have saved its seat as a method for determining the deep Vs structures in a basin. It is apparent that no other method can be found for deep Vs profiling except deep borehole logging. These Vs structures will be used for 3D modeling of large basins in predicting ground motion from the anticipated future large earthquakes. The reasons why the array method of microtremors has been included in the national projects are that the method is very cheap compared with drilling a deep borehole, despite it will provide direct data of velocity structure and the validity of the method has been confirmed theoretically. In addition, the results of array microtremors method have shown satisfactory agreements with the profiles determined by the other seismic prospecting. Two examples of recent comparisons are shown in Figure 8 and 9. Figure 8 shows a part of products by Matsuoka [50] who made a geological section in Saitama Prefecture based on Vs structures determined by the SPAC method referring to the gravity data and the deep borehole data at three sites (Hidaka, Iwatsuki, Nagareyama). Numbers in the figure shows Vs in unit of km/sec. Similar systematic observations and array analyses of microtremors have been carried out aiming at large basins, such as Kanto (e.g. Yamanaka [51] and Osaka (e.g. Kagawa [52]. Almost all results are coincident with other seismic/geological data. One other example is shown in Figure 9, which compares the data of the reflection survey, sonic log, and Vs structure determined by the SPAC method (Tsuno [53]). A good coincidence is clearly found among the three kinds of data.

Some difficulties meet in surveys of deep basin structures
Both SPAC and *f-k* methods are based on the clear theoretical background; therefore, we can rely on the results by array data of microtremors. The problems are their accuracy of observed data compared with other prospecting methods and a practical complication or troublesome rather than a single station method as HVSRm. The latter leads to economical issues.

Table 1 Array measurements of microtremors conducted at deep basins in Japan.

Basin	City	Area (kmxkm)	Number of Site	Array (Max. radius/eqv)	Depth to bedrock	Bedrock Vs(km/s)	Methods	Source
Ishikari	Sapporo	15x20	11	2000m	3200m	3.2	SPAC	Okada [32]
Ishikari	Sapporo	20x25	30	1600m	3000m	3.2	SPAC	Sapporo City
Yufutsu		10x50	8	2000m	2500m	2.1-3.2	*f-k*	Okada [54]
Tokachi		40x40	18	1500m	2000m	2.8-3.2	*f-k*	Okada [32]
Sendai	Sendai	15x20	6	2500m	1000m	3.5	*f-k*	Satoh[24]
Kanto	Chiba	45x50	36	2000m	4500m	2.6-2.9	SPAC	Chiba Pref.
Kanto	Saitama	30x50	67	600m	2800m	2.7	SPAC	Matsuoka [50]
Kanto	Tokyo	15x15	6	2000m	3000m	3.2	SPAC	Tokyo Met.G
Kanto	Kawasaki	10x5	4	3000m	2800	3.0-3.2	SPAC	Kawasaki City
Kanto	Yokohama	15x15	8(L),20(S)	L:3k,S:1(km)	~4000m	3.0-3.5	SPAC	Yokohama City
Kanto	Whole	150x100	22	1500m	3200m	3	*f-k*	Yamanaka [51]
Ashigara	Odawara	5x12	11	800m	2500m	2.8	SPAC	Kanno [55]
Kofu	Kufu	15x15	10	1600	1900m	2.7-3.2	SPAC	Yamanashi Pref.
Shizuoka	Omaezaki	6x10	7	2000m	5500m	4.0	SPAC	Tsuno[56]
Nagano	Nagano	10X10	3	800m	1400m	3.0-3.2	SPAC, f-k	Tamori [57]
Okazaki	SE-Nagoya	15x15	8	1600m	240m	3.6	SPAC	Aichi Pref.
Toyohashi	Toyohashi	10x10	4	1200m	830m	3.2	SPAC	Aichi Pref.
Nobi	Nagoya	25x25	12	1500m	1700m	2.8-3.0	SPAC	Aichi Pref.
Nobi	Nagoya	25x25	12	500m	1700m		SPAC	Sawada [25]
Nobi	Nagoya	10x10	5	1500m	700m	2.8-3.05	SPAC	Feng[58]
Ise	Yokkaichi	20x45	15	2000m	2200m	2.8-3.7	SPAC	Mie Pref.
Fukui	Fukui	10x15	5	700m	1000m	3.2	*f-k*	Yamanaka [59]
Kanazawa	Kanazawa	20x25	10	2540m	3400m	3.4	SPAC	Kanno [60]
Kyoto	Kyoto	12x15	16	2000m	800m	2.6-3.5	SPAC	Kyoto City
Osaka	Osaka E-Osaka N-Osaka	20x30 5x5 5x5	18 2 3	2000m 800m 1500m	1500m 1500m 1000m	3.2 3.2 3.0	*f-k* *f-k* *f-k*	Kagawa [52] Horike[61] Horike[62]
Kobe	Kobe	35x10	45	500	1800m	2.2-2.8	SPAC	Okada[63]
Tottori	Tottori	8x8	8	500	700m	3.0-3.5	SPAC	Noguchi[64]
Tottori	Yumigahama	16x5	4	1000m	800m	3.2	SPAC	Yoshikawa [65

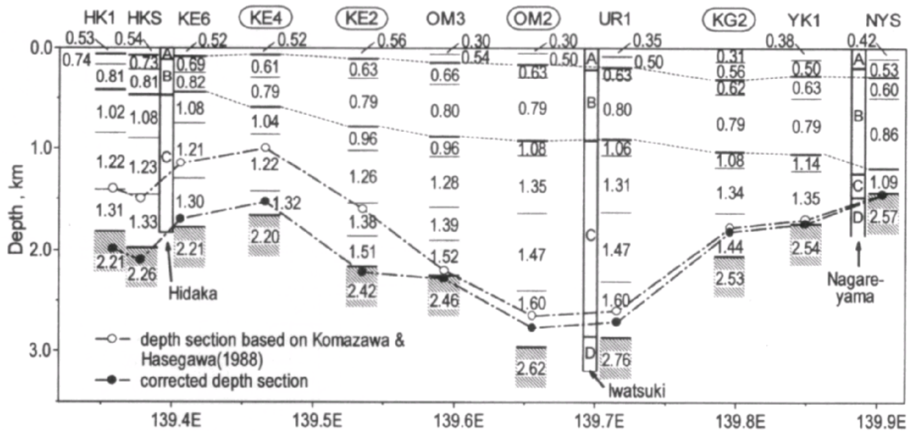

Figure 8. A geological section in Saitama Prefecture based on Vs structures determined by the SPAC method referring to the gravity data and the deep borehole data at three sites, reproduced from Matsuoka [50].

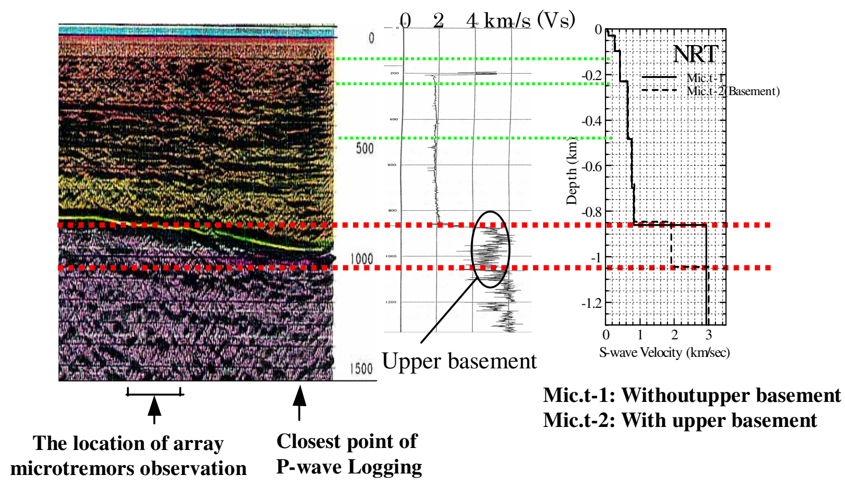

Figure 9. Comparison of geological interfaces determined by the reflection survey (left), the sonic log data (center), and the Vs structure by the SPAC method (right), (Tsuno[51]).

Spatial-Temporal variation of microtremors

We do not need any control sources in the observation of microtremors; in turn, we are obliged to follow the natural environments. As precisely described in Okada [32], the temporal variation of power of long period (> 1sec) microtremors correlates well with an inverse of atmospheric pressure change with time lag of 3-15 hours. Since Longuet-Higgins [66], the correlation between microtremors (microseisms) and ocean waves has also been indicated by many papers. Recently, Rahimian [67] observed clear correlation of long period microtremors with ocean wave height, inverse of atmospheric pressure, and wind velocity, permitting some time delays among them. The temporal variation is large enough as shown in Figure 10 (Okada [32]), which differs order of 3-4 in terms of power spectral amplitude for velocity microtremors. The spatial variation is also significant as can be seen also from Figure 10 that compares the powers of two sites by simultaneous observations. The one site in the deep basin (HKD) and the other (MIS) locates on hillside 15 km distant from HKD. Their powers of long period microtremors differ by one order. Incidentally, the power of long period microtremors at EURO- SEISTEST was 2-3 orders less than those in Tokyo (Kudo [68]). In case of low-level microtremors, we sometimes meet no good coherence and underdetermining of phase velocity at long period. Therefore, we have to be careful on some limitations in a survey of a deep basin. In addition, we should also care that the power spectra decrease rapidly at around 0.2 Hz with decreasing frequency, despite that the frequency of decreasing depends strongly on sites. However, this is the general trend as we can see in Peterson [69]. The power spectra of higher frequency than around 2 Hz (the frequency is site dependent) have a strong variation associated with the human activities. We will again face to low-level microtremors and consequently worse coherence, where no human activities exist near the site.

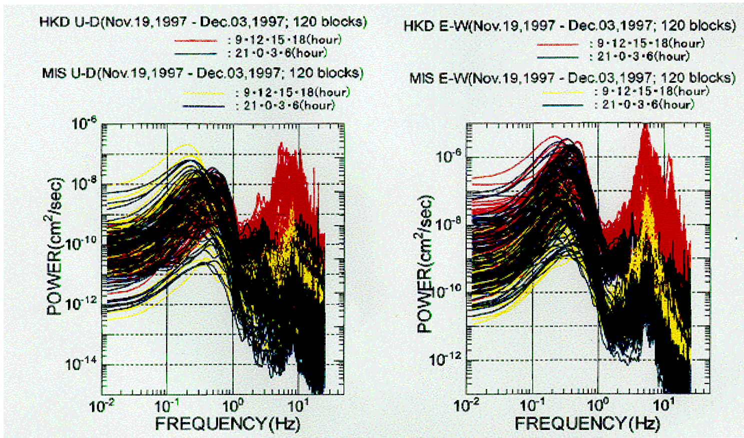

Figure 10. Power spectra of microtremors showing strong temporal and spatial variations. One site is located on hillside (left) and the other is inside basin. Reproduced from Okada [32].

Inversion of phase velocity-S-wave velocity determination

Since Yamanaka [70], the genetic algorithm has often used in the inversion of phase velocity determined by array analysis of microtremors, because it does not much depend on an initial condition and requires less computational time for getting an optimal Vs structure. Most studies represent the reasonable results by comparing with the other data, although a criticism may arise on the non-uniqueness of surface wave inversion. We will face to some difficulties in the inversion process if low velocity layers are included in the subsurface layers and if no other geological/geotechnical data is available. Arai [71] proposed a joint inversion using both phase velocity dispersion and HVSRm for confirming the validity of structure model and to extend the resolution to lower frequency range. A joint usage of array data of microtremors and peak frequency of HVSRm were successfully applied by Satoh [72] and Tokimatsu [73] among others. An inversion method is also proposed to estimate 2D/3D structure model by jointly using plural structure model (Feng [58]). The accuracy of the structure model depends on the precision of phase velocity dispersion, besides a current technology provides enough approximation for engineering purposes; however, we need much efforts to increase its accuracy for seismological or geological uses.

Difficulty for determining bedrock S-wave velocity

The amplitude function of vertical motion of Rayleigh waves decreases at lower frequency than that gives the first minim group velocity and becomes zero at a specific frequency in soft sedimentary basins due to the complex ellipticity of particle motion (in case of larger Poisson's ratio). This means that the essential difficulties exist in determining the phase velocity that closes to the bedrock Vs, if sources have not enough power at low frequency. A large power of microtremors at 3-5 sec is often observed at any site, may be due to oceanic waves; however microtremors of longer period than 5 sec have generally low power; therefore we are sometimes obliged to bring information on bedrock velocity or depth from the other data. The bedrock velocities shown in Table 1 have some-what ambiguities or they are estimated from the other data.

2D/3D effects

The array analysis of microtremors based on the assumption of horizontally stratified medium, at least immediate beneath the array space. Majority of current results are obtained, as an average of structural information. In case, the effect of dipping layer is significant, the *f-k* method has a possibility to find the effects but the SPAC method is difficult to distinguish. Although numerical examinations to the effects of irregular subsurface structures are required to understand the limitation and to stabilize a use of array observation results, Horike [62] suggested that the assumption of flat layering was applicable by comparing the result by a reflection survey conducted at the northern Osaka shown in Figure 7. A possibility of higher modes of Rayleigh waves should always be taken into account; however, it is very difficult to identify in practical measurements or to include in analyses. This is also some numerical examinations will be required.

Survey of shallow velocity structure for engineering purposes

Needs for the Vs of shallow structure have been increasing associated with the revision of building code in Japan. The array microtremors method has a potential for applying even for high frequency of shallow structure determination. Nagao[74] reported that the method of P-S logging have been regarded as the most reliable to obtain the Vs structure; however, transfer functions calculated with the Vs structures estimated by the P-S logging at the Haneda Airport are inferior to the amplification factors using structure models determined by the array microtremors, which is confirmed through comparison with the strong-motion record. Although it is not restricted for shallow structure, but we face frequently to inverting velocity of layers for shallow structures in sedimentary basins. A surface wave inversion is generally difficult to identify such inverting velocity layers without additional data, if the layers are not thick. Tsuno [53] suggested that the site amplification factors estimated by array microtremor data agree well with those by PS-logging data for the first and second peak frequencies and amplitudes in the lower frequency than 5Hz, despite the geological interfaces are not necessarily coincident. The surface wave inversion was carried out assuming only that Vs increases with depth. The reason for the validity of approximation will be that the surface wave inversion gives an equivalent Vs structure even for vertical traveling waves. In addition, interposed thin high and/or low velocity layers may not significant effects on lower frequency than around 5 Hz. If a low velocity layer has significant thickness, phase velocities do not disperse for a certain frequency range and we may estimate the existence of a low velocity layer.

CONCLUSION

We have still some controversial issues to use the amplitude of HVSRm; however, the peak frequency is very stable and valuable for site characterization with careful use considering a certain threshold of HVSRm peak larger than 3 (Horike [27]) with lower frequency than around 10 Hz (Sawada [26]). We should also be aware of subsurface irregularities near the site. In turn, if we measure HVSRm with some spatial coverage, we might have an opportunity to find the location of basin edge or steep change of geology with a help of 2D/ 3D simulation of microtremors. The amplitude of HVSR is very complicated to explain but it is necessary to define the bedrock clearly in comparing the amplitudes of HVSRm and HHSRe. The array data of microtremors have been one of key materials for 3D modeling of basin structures incorporating with the reflection data as a national project of Japan for earthquake ground motion prediction, although some issues are still unsolved. The array microtremor method is also applicable for shallow structures, which are mostly interested in engineering purposes. The accuracy is reasonable in terms of understanding the amplification factors and its peak frequencies at a site. A joint usage of array data of microtremors and peak frequency of HVSRm is recommended to cover some extents in an urban area.

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