A Method for Dynamic Characteristics Estimation of Subsurface using Microtremor on the Ground Surface

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As methods for dynamic characteristics estimation of surface layers, investigation with boring and a method which employs microtremor are well known so far. Boring investigation, one of the most accurate methods is costly and time consuming and is not available all the time. The method that employs microtremor is handy but has not produced satisfactory result to this day.

This paper describes a new processing method that employs microtremor observation yet producing accurate estimation of characteristics of the ground motion. The method uses vertical component and horizontal components.

As a result, the spectrum ratio of the horizontal components and vertical component of microtremor bears resemblance to transfer function for horizontal motion of surface layers.

1. Introduction

A survey on the earthquake damage shows that, considering seismic intensity equal, the effects on structures vary considerably: some are free from damage almost completely while others suffer heavy damage. This phenomenon occurs due to difference in the seismic response characteristics of the structures. The surface layers carrying these structures also differ substantially in the effect of earthquake due to difference in their seismic response characteristics. The effect range is specific to the structure as far as the structural characteristics are concerned. In the case of surface layers, however, the effect covers a certain spread of the area. Consequently, understanding of characteristics of surface layers may be said to be an important review item in analysis of the earthquake disasters.

In this context, the characteristics of surface layers (particularly, the seismic response characteristics of surface layers) have been investigated positively by the administrative agencies and other authorities.

Boring exploration will surely offer highly accurate data concerning the dynamic characteristics of surface layers. To understand the surface layer characteristics over a wide area, however, lots of borings must be made in high density. Boring exploration is therefore not a ready means because it demands considerable manpower and substantial time as well as tremendous cost. From this view point, a study has been extensively made on the method to estimate the dynamic characteristics of surface layers using the microtremor (readily measurable). If large structures are not to be considered, the microtremor of a frequency range of 0.5 – 20 Hz will be measured. This frequency range tends to include tremors induced artificially, but it is necessary for investigation of characteristics of surface layers that the effect of a specific source not be large. Accordingly, measurements have to be carried out during midnight (around 3:00 a.m.) when the social activities stop almost completely in order to eliminate the effect of a tremor whose source can be identified. But this procedure will substantially detract the benefit of the micro tremor (i.e., readiness for measurement).

This paper proposes a new method to estimate the dynamic characteristics of surface layers by measuring solely the microtremor of the surface. According to this method, stable estimation of the predominant frequency and amplification factor can be made even in the presence of a certain degree of artificial tremor and there is no need any more for time restriction on microtremor measurement.

2. Effect of Surface Layers on Seismic Motion

Earthquake involves release of the strain energy accumulated in the focal region and propagation of a part of the energy thus released to the surrounding. The dynamic characteristics O (f), f means frequency, observed at a certain point include all of the wave motion radiation characteristic F(f) at the focal region, dynamic characteristic T(f) of the wave motion propagation route up to the observation point, and dynamic characteristics S(f) of the surface layers at the observation point.

Fig. 1 shows how the difference in earthquake and observation point is reflected in the tremor waveform. The acceleration waveform for 5 seconds around the maximum value is indicated vertically and horizontally, with similar earthquakes arranged vertically and same observation points horizontally. The magnitude of earthquakes rises toward the left of the figure. Evidently, the seismic acceleration waveforms at observation points are generally quite similar without much variation between different earthquakes, though there exists a trend that a high-frequency tremor prevails when the magnitude of earthquake is small and the low-frequency tremor prevails when the magnitude is large. This means that the observed seismic waveform is similar for the same observation point (i.e., the same surface layers characteristics S(f)) even when the radiation characteristic F(f) or propagation characteristic T(f) is different. In other words, it may be said that the effect of surface

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layers is most critical among the three factors influencing dynamic characteristics. This fact in turn leads to the importance of understanding the vibration characteristic of the surface layers.

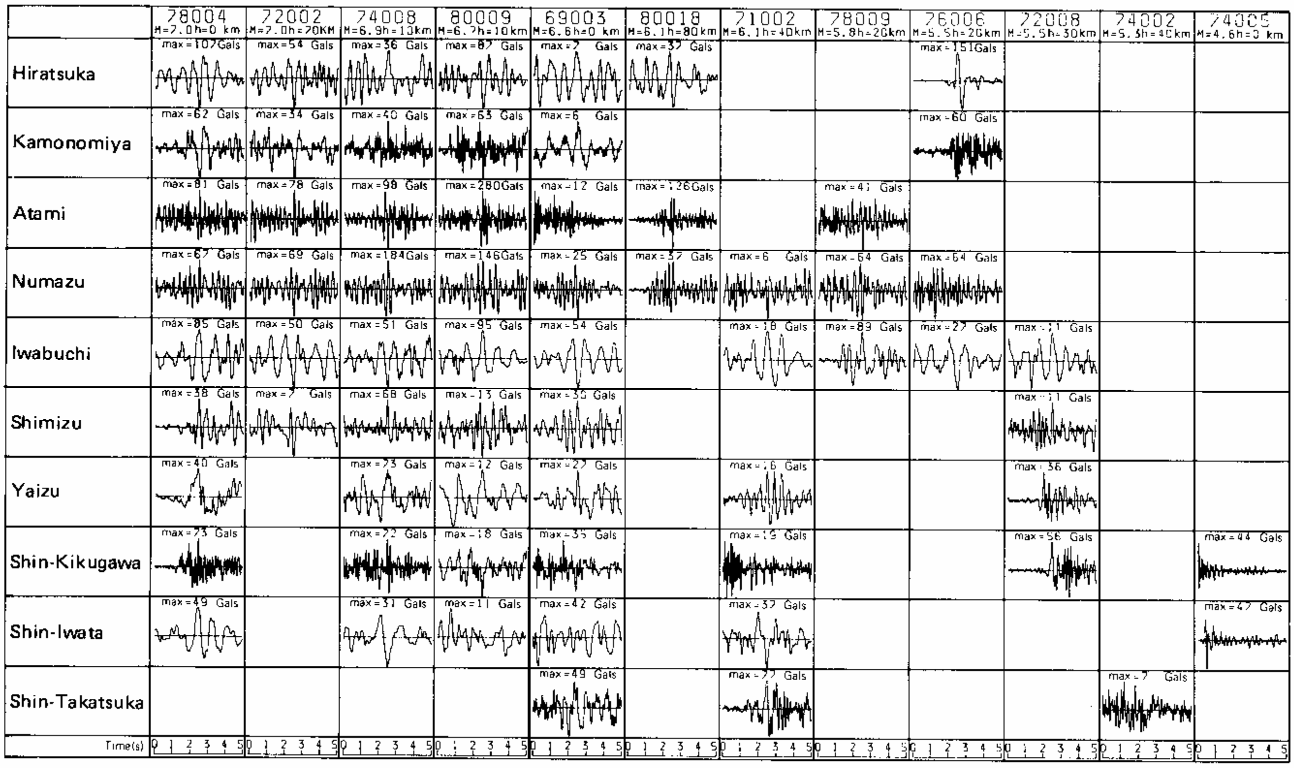

Fig. 1 Difference in seismic waveform due to difference in earthquake and observation point

3. Long-term Continuous Observation of Microtremor

The surface layers are normally exposed to tremor by natural forces (storm, sea waves) and artificial forces (plant, automobile, train and etc.). Sea waves induce a tremor of a relatively long period (2 – 3 sec. or more), the so-called microseisms, while the storm and artificial forces do a tremor of short period, the so-called microtremor.

Upon wave motion comprising the microtremor, there are two theories: the solid wave theory and the surface wave theory. Both theories have tried to prove the respective validities on the basis of measurements of microtremor, but are not yet recognized as established. The microtremor, though not known fully, has often been chosen for engineering purposes such as estimation of the prevailing frequency of surface layers with microtremor, etc.

For the purpose of utilizing the microtremor in the engineering field, an observation of microtremor was made continuously for more than 30 hours to identify the characteristics. The observation took place at the Kamonomiya substation of the Tokaido Shinkansen and the Tabata substation of the Tohoku Shinkansen. A velocity meter of specific period of 1 sec. equivalent was used for the observation. The Fourier spectrum discussed below was obtained by applying the hanning window three times to waveform data (2048 points; 20 sec.) after frequency analysis with FFT.

3.1 Observation at Kamonomiya

The N value of surface layers at this point is 15 or more and exceeds 50 at a depth of more than 35 m. The N value increases gradually while repeating an increase and decrease down to this depth. As a whole, the surface layers are silty.

Measurement of microtremor was made from the night of February 8 (Saturday) to the morning of 10 (Monday), 1986. Though this point is surrounded by plants, their principal equipment was considered to be shut down while the measurement was made. The measuring time span is considered to be cover a period with fewer artificial tremors.

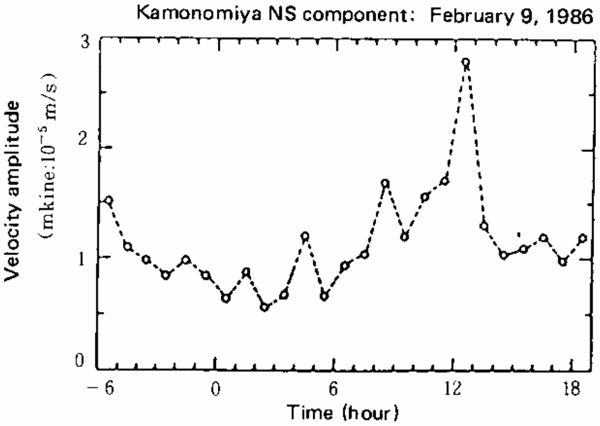

Fig. 2 Time change of the horizontal amplitude of the microtremor

Fig. 2 shows the time change of the horizontal velocity amplitude. Needless to say the tremor due to the Shinkansen train is far larger than the one shown here, but it is not include in this figure. The figure shows that the microtremor is smallest from 2:00 to 3:00 a.m. and large around noon. The extent of velocity amplitude change is around 0.5 – 2 mkine (10^{-5} m/s), with the ratio between maximum and minimum amplitudes being about 4 times. This corresponds to the quiet time at weekends, and the amplitude might be much larger during weekdays when tremors of plants are added.

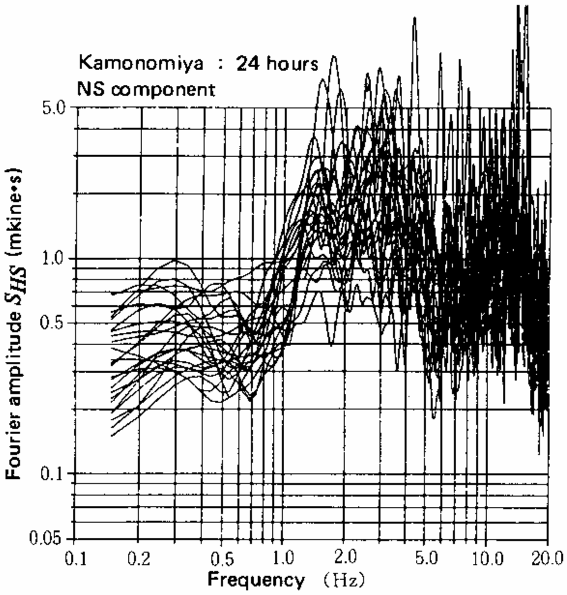

Fig. 3 Time change the horizontal spectrum of the microtremor

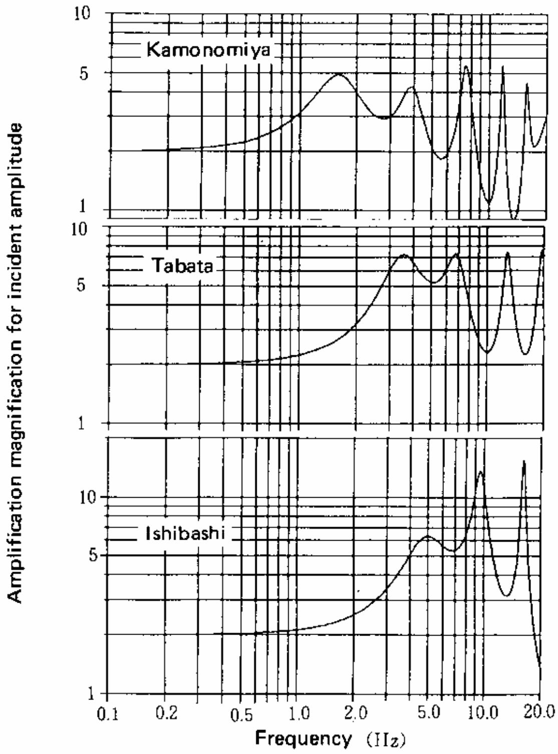

Fig. 4 Amplitude amplification characteristics for incident seismic motion on surface layers at each point, which is estimated from results of boring and PS prospecting

Fig. 3 shows spectra of hourly microtremors which are overlapped for 24 hours. Spectra indicate fluctuation according to the time and it is difficult even to read the prevailing frequency of the surface layers. Fig. 4 shows the amplitude characteristic of incident waves to surface layers estimated from boring investigation and PS velocity logging. The microtremor, which is considered to be the prevailing frequency (about 1.5 Hz) of surface layers, did not become remarkable during the time span when the amplitude becomes smallest, but it was observed during a relatively quiet time span from 20:00 p.m. of Saturday to 6:00 a.m. of Sunday.

3.2 Observation at Tabata

The surface layers at this point are 18 m in thickness and sandy as a whole. The N value to a depth of 4 m is around 3 and increases gradually as the depth increases and reaches around 50 at the depth of 18 m. Below this level, the soil has an N value of 50 or more, with the shearing wave velocity at around 500 m/s.

Measurement of microtremor was made from the night of June 24 (Thursday) to the morning of 26 (Friday), 1987. Tabata is located in a district of intense social activities and laden with microtremors. Besides, the measuring time span was one considered to be heavily laden with artificial tremors in the week.

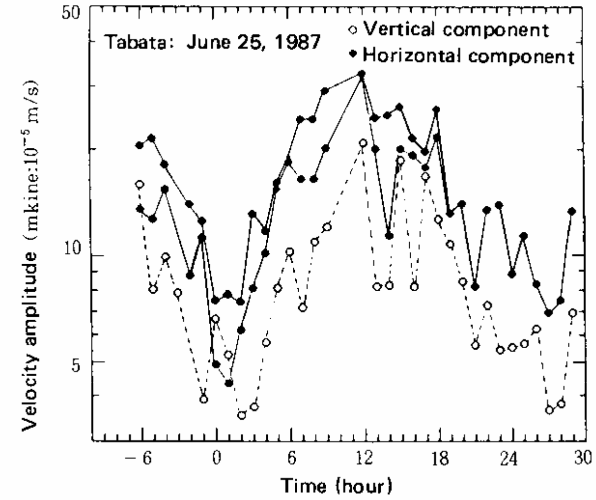

Fig. 5 Time change of microtremor amplitude

Fig. 5 shows the time change of velocity amplitude. Tabata is a place subject to substantial effect of the train-induced tremor because the Tohoku Shinkansen, Tohoku Line, Keihin-tohoku Line, Yamanote Line, and freight line run nearly. The velocity amplitude was read avoiding the train-induced tremor as much as possible.

As in the case of Kamonomiya, the velocity amplitude of microtremor was smallest from 2:00 to 3:00 a.m. and largest around noon. The horizontal velocity amplitude, on the other hand, fluctuated between 5 and 30 mkine, which is more than ten times the case of Kamonomiya (refer to Fig. 2). The ratio between maximum and minimum amplitudes is more than 6.

Fig. 6 shows spectra of hourly microtremors overlapped for 24 hours. It is known that substantial fluctuation is observed within the frequency range of 3 Hz or more. The mean prevailing frequency was read every hour on the basis of the above spectra and plotted against time as shown in Fig. 7. This figure shows that 2 to 3 Hz frequencies and 4 to 8 Hz frequencies prevail in most of the cases. The amplification characteristics of incident wave to the surface layers estimated from boring investigation and PS velocity logging are shown in Fig. 4. This indicates that 4 to 8 Hz frequencies are the specific tremor of surface layers at the Tabata point. It is also known that these frequencies did not become prevailing during the time span when the microtremor amplitude was small. Frequencies of 2 to 3 Hz prevailed during the quiet time span, but did not prevail for the estimated amplification characteristic of surface layer.

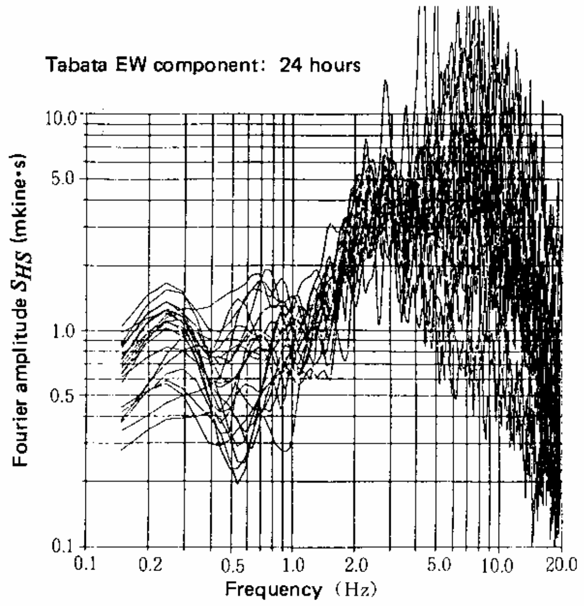

Fig. 6 Time change of Horizontal spectra of microtremor

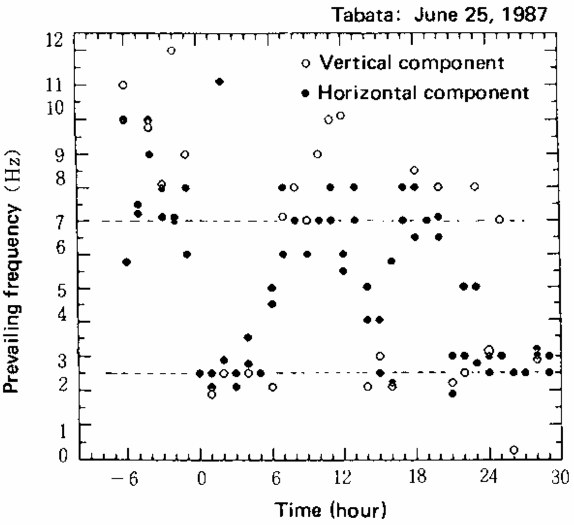

Fig. 7 Fluctuation of prevailing frequency of microtremor

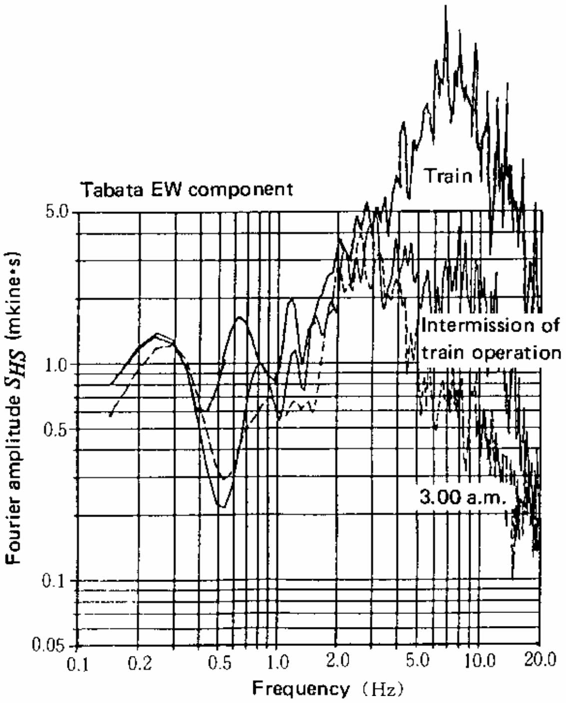

Fig. 8 Comparison of tremor spectra between train induced tremor and quiet time span (intermission of train operation and 3.00 a.m.)

Fig. 8 shows comparison of frequency analysis results between the train-induced tremor component and other components with the observation results of microtremor at Tabata. As known from this comparison, a tremor of 4 Hz or more was induced by train to cause a considerable change in the microtremor. The effect of this train-induced tremor was remarkable in the vertical component. Such fluctuation of the prevailing frequency of microtremor is considered due to a substantial effect of the artificial tremor in the vicinity.

4. Estimation Method of Dynamic Characteristic of the Surface Layers

It is said that the microtremor must be measured during the quiet time span. Indeed, the observation result at Kamonomiya shows that the tremor like a specific vibration of the surface layers prevailed during the quiet time span. At Tabata, however, what prevails during the quiet time span appears to be the tremor related to the geological structure far deeper than the soil which is considered to be the bearing soil in terms of engineering. A tremor with a frequency whose amplification magnification increases as the so-called estimated transfer function of the surface layers was not observed frequently. In this way, it often occurs that the specific frequency of the surface layers concerned cannot be found from the frequency analysis only of the microtremors during the quiet time span. It is also generally said that the prevailing frequency of microtremor fluctuates less, but the prevailing frequency of microtremor at Tabata and Kamonomiya fluctuated substantially depending on the measuring time span. Such fluctuation may be due to the tremor source in the neighborhood of the measuring point. In other words, the tremor from such source may be considered a noise from a standpoint of estimating the dynamic characteristics of the surface layers using the microtremor.

The artificial tremor source has mostly the prevailing vertical motion and tends to induce the Rayleigh waves. This may be the case of Tabata where the effect of train-induced tremor was remarkable in the vertical component. In this context, the Rayleigh wave is assumed as noise of microtremor and a method to eliminate the effect of Rayleigh wave is studied.

4.1 Basic Concept

There are various research attempts, but there is no established theory concerning what kinds of wave motions the microtremor is made up from. Namely, the microtremor can be considered to consist of various wave motions.

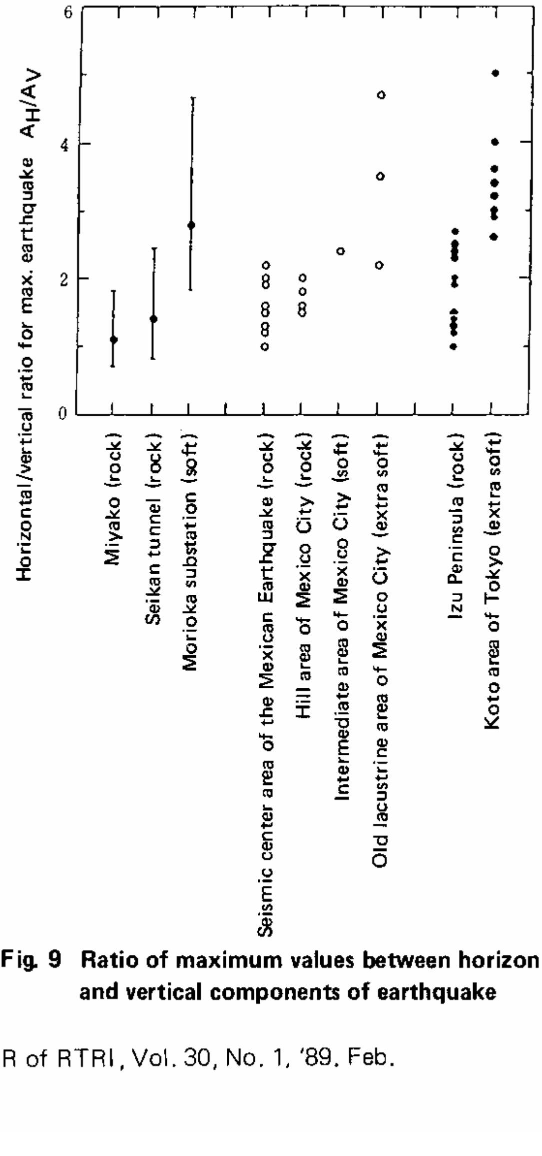

Fig. 9 Ratio of maximum values between horizontal and vertical components of earthquake

Fig. 9 shows the ratio (A_H/A_V) of maximum values between horizontal and vertical motions of earthquake for each observation point or area. Evidently, the A_H/A_V value of earthquake is related to the soil conditions of the observation point and A_H/A_V is close to "1" for the firm soil. From this viewpoint, no amplitude in a specific direction prevails on the hard soil, with the tremors even in all directions.

Dividing the tremor into horizontal and vertical directions, it is considered that horizontal and vertical tremors are similar to each other. Such tremors are amplified by the soft surface layers accumulated on the hard substrate. The horizontal tremor may be considered, to a certain accuracy, to be amplified through multi-reflection of the S wave while the vertical tremor is through multi-reflection of the P wave. The propagation velocity of the P wave is generally higher than 1000 m/s, and the tremor of around 10 Hz or less may not be amplified so much through multi-reflection within surface layers of several ten meters at most in thickness.

The effect of Rayleigh wave, on the other hand, appears remarkably in the vertical tremor. Accordingly, the degree of its effect may be known by determining the ratio of vertical tremor between the surface and substrate. Namely, the effect of Rayleigh wave is nearly zero when the ratio is approximately "1". With an increasing ratio, the effect of Rayleigh wave may become more critical. Elimination of the effect of Rayleigh wave is studied by using this ratio.

4.2 New Transfer Function Estimation Method for Surface Layers

The transfer function S_T of surface layers is generally defined as follows:

$$S_T = S_{HS}/S_{HB}$$

S_{HS} and S_{HB} are respectively the horizontal tremor spectrum on the surface and the horizontal tremor spectrum incident from the substrate to surface layers.

But S_{HS} is readily affected by the surface wave. Since the artificial noise is mostly propagated as Rayleigh wave, S_{HS} of microtremor may possibly be affected by Rayleigh wave. The effect of Rayleigh wave should be included in the vertical tremor spectrum S_{VS} on the surface, but not included in the vertical tremor spectrum S_{VB} in the base ground. Assuming that the vertical tremor is not amplified by the surface layers, the amount E_S defined below should represent the effect of Rayleigh wave on the vertical tremor:

$$E_S = E_{VS}/E_{VB}$$

If there is no Rayleigh wave, $E_S = 1$. E_S will take a value larger than "1" with increasing effect of Rayleigh wave.

Assuming that the effect of Rayleigh wave is equal for vertical and horizontal components, S_T/E_S may be considered to offer a more reliable transfer function S_{TT} after elimination of the effect of Rayleigh wave.

$$\begin{aligned} \text{Namely:}\quad & S_{TT} = S_T/E_S \\ & \phantom{S_{TT}} = R_S/R_B \\ \text{where}\quad & R_S = S_{HS}/S_{VS} \\ & R_B = S_{HB}/S_{VB} \end{aligned}$$

R_S and R_B were obtained by dividing the horizontal tremor spectrum by vertical spectrum, corresponding respectively to surface and substrate earthquake tremors. As shown in Fig. 10, R_B becomes nearly 1.0 for a relatively wide frequency range. Namely, on the firm substrate, propagation is even in all directions.

$$\begin{aligned} \text{Namely}\quad & R_B \fallingdotseq 1 \\ \text{Therefore}\quad & S_{TT} \fallingdotseq R_S \end{aligned}$$

This means that the transfer function of surface layers may be estimated from the tremor on the surface only. In other words, the vertical tremor on the surface retains the characteristics of horizontal tremor of the substrate, thereby substituting the latter. The Rayleigh wave acts to nullify such substitution. But R_S becomes more or less than "1" in the frequency range where the Rayleigh wave prevails, and thus it is not remarkable in the estimated transfer function. It may thus be presumed that R_S includes the effect to eliminate the effect of Rayleigh wave.

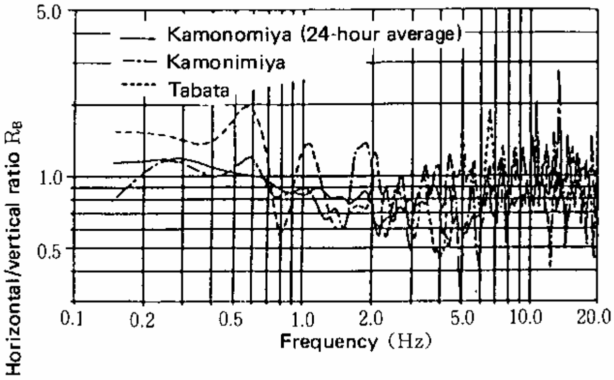

Fig. 10 Spectrum ratio of horizontal and vertical components in the substrate (Microtremor: Kamonomiya, Tabata)

Note, however, that the estimation accuracy drops when there exists a noise tremor agreeing with the prevailing frequency in the estimated transfer function.

R_B should be free from effect of Rayleigh wave and have the characteristics unique to the point (and also the characteristics unique to the earthquake when the tremor to be handled is an earthquake tremor). Consequently, a more reliable S_{TT} can be estimated by multiplying with $1/R_B$ as a compensation term when data of the ground are provided.

So far described is a discussion in terms of the frequency range. The same applies to the maximum value. Namely, the amplification magnification of the horizontal maximum value by surface layers can be estimated from the ratio of horizontal and vertical maximum values on the surface.

It is also considered that the tremor in the substrate is equal in all directions because various wave motions repeat local refraction after principal tremor of earthquake. It is therefore possible to estimate the dynamic characteristics of surface layers using the tremor observed on the surface according to the above method.

5. Verification of the Proposed Method

Figs. 11 and 12 show R_S (obtained from continuous observation results of microtremor for every hour) overlapped for 25 hours, respectively for Kamonomiya and Tabata. When compared with plottings of Figs. 4 and 7, R_S varies less with the time, and the prevailing peak position and magnitude are stable.

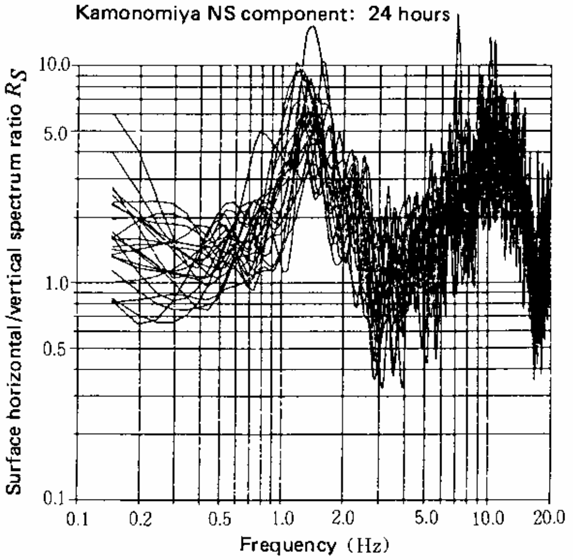

Fig. 11 Time change of horizontal/vertical spectrum ratio on the surface

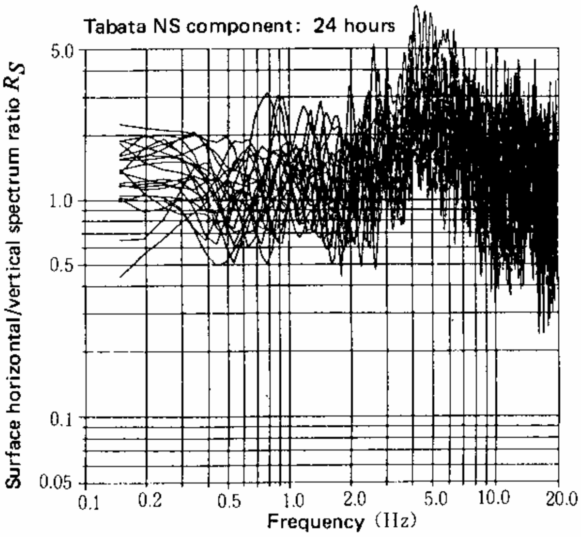

Fig. 12 Time change of horizontal/vertical spectrum ratio on the surface

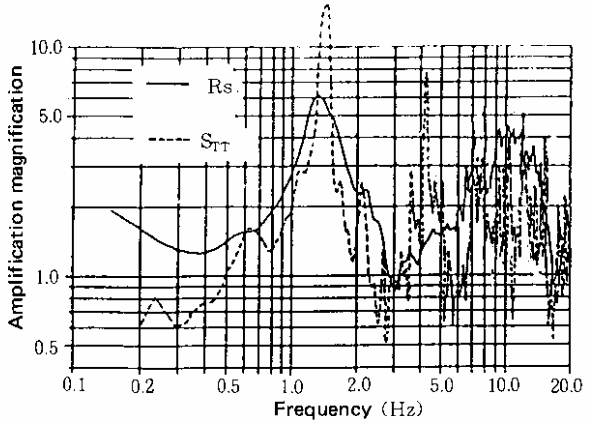

Fig. 13 **Comparison of estimated transfer function (Kamonomiya): R_S (24-hour average) and S_{TT}**

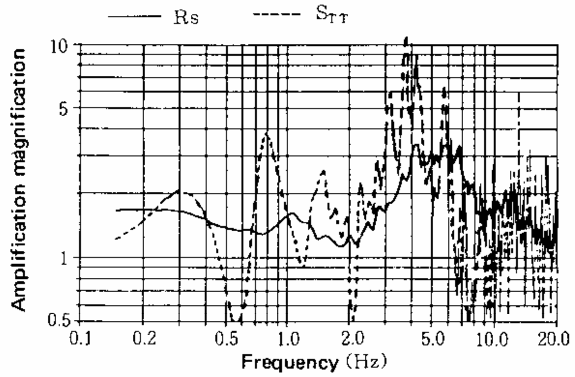

Fig. 14 **Comparison of estimated transfer function (Tabata): R_S (24-hour average) and S_{TT}**

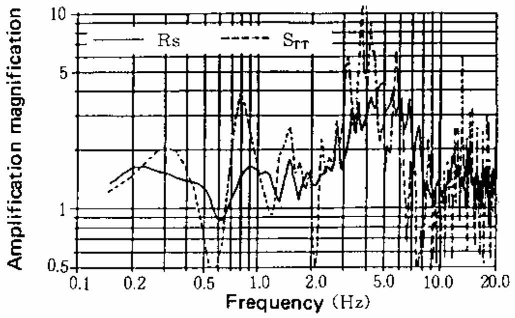

Fig. 15 **Comparison between the horizontal/vertical spectrum ratio (average) R_S of train-induced tremor and intermission tremor and the estimated transfer function S_{TT} (Tabata)**

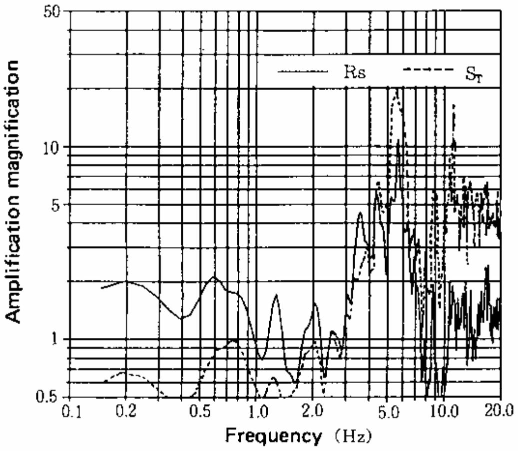

Fig. 16 **Comparison of the estimated transfer function (Ishibashi)**

Fig. 13 shows the 24-hour average of R_S at Kamonomiya as compared with the transfer function S_{TT} estimated from the seismic observation result. The figure indicates that R_S is similar to S_{TT} not only in terms of the peak position and magnitude, but also in the whole shape.

Fig. 14 shows the 24-hour average of R_S at Tabata as compared with the transfer function S_{TT} determined from another measurement data. This estimated transfer function was obtained from simultaneous observation of microtremor on the surface and at a point 25 m below the surface. In spite of variation, these are similar roughly. This fact proves validity of the proposed estimation method.

Fig. 15 shows the average of three R_S of train-induced tremor and two R_S of microtremor during intermission (measurement at Tabata) as compared with the estimated transfer function S_{TT}. S_{TT} is similar to the means R_S, which indicates that the approximate transfer function can be estimated using the train-induced tremor.

Fig. 16 shows comparison of R_S and S_T at the Ishibashi substation of the Tohoku Shinkansen. R_S was calculated from observation results of microtremor at this substation while S_T was estimated from simultaneous microtremor observation results at the surface and at a depth of 12 m. R_S and S_T are quite similar to each other. The amplification characteristic of the wave incident to surface layers as estimated from boring investigation and P_S velocity logging is shown in Fig. 4.

Fig. 17 shows comparison of R_S and S_T at four points which registered a very strong earthquake, by using seismic observation data of Mexico City.

S_T of Mexico City was estimated by assuming the tremor on the rock within the campus of UNAM (Universidad Nacional Autonoma de Mexico) to the south of the city as a substrate tremor. In all cases, R_S and S_T are quite similar to each other, indicating that the transfer function of the surface layers can be estimated with R_S also by using the seismic waveform.

Fig. 18 shows comparison between the maximum acceleration ratio of horizontal and vertical components of the tremor on the surface and the amplification magnification of maximum acceleration estimated from

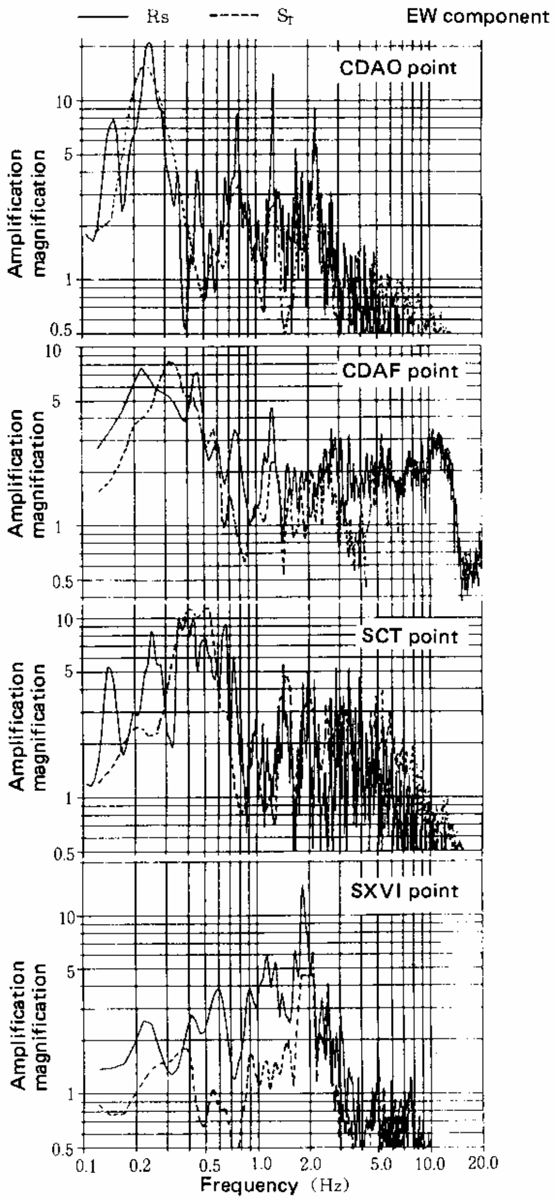

Fig. 17 Comparison of the estimated transfer function using seismic waveform (Mexico City): R_S and S_T

simultaneous observations in the ground and on the surface. Evidently, the maximum velocity amplification magnification of surface layers can be estimated roughly by using the maximum acceleration ratio of horizontal and vertical tremors on the surface although there exists a considerable variation.

6. Conclusions

Characteristics of seismic tremor and microtremor were reviewed and a new estimation method for dynamic characteristics of surface layers was proposed. This method is based on the assumption that the ratio of horizontal and vertical spectra of surface tremor as an approximate transfer function. The validity of this method was proved by using microtremor observation results at several points. It was also shown that dynamic characteristics of surface layers can be roughly understood at the seismic observation point if the seismic tremor observation waveform of 3 components, 2 horizontal components and vertical component, is available.

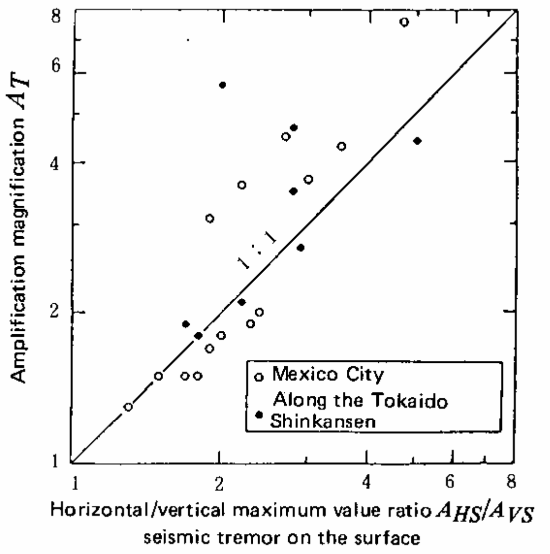

Fig. 18 Relationship between the horizontal/vertical maximum value A_{HS}/A_{VS} and amplification magnification A_T of tremor on the surface

It has generally been said that the microtremor observation should be made at midnight when the social activities are stopped nearly completely, in order to avoid effect of artificial noise. But the proposed method enables observation of microtremor at all times without restriction of the time span, thereby allowing measurements within a short period at multiple points. This method can supplement the boring investigation results for proper and minute estimation of the characteristics of surface layers and it is expected to demonstrate validity in collection of fundamental data for estimation of detailed earthquake damages.

On the basis of above results, the dynamic seismic characteristics of the soil along an about 1500 km section of the Japan Railways (JR; formar Japanese National Railways) line in the suburb of the metropolitan district have been measured by using microtremor for four years from 1987. This is a part of the research project sponsored by the Ministry of Transport and involves measurements of microtremor at an interval of about 100 m along the line. In this project, measurements were made at top and bottom of a structure in order to understand the dynamic characteristics of the structure. The results will be reported as soon as summarized.

Acknowledgment

The seismic observation waveforms in Mexico City were obtained by UNAM. The seismic observation data of the Izu Peninsula and Koto area of Tokyo Metropolitan were obtained by the Earthquake Research Institute, University of Tokyo. The author would like to express deep gratitude. He would also like to thank Mr. Y. Watanabe of Fukuyama Consultants Co., Ltd. for this cooperation in measurement and analysis.

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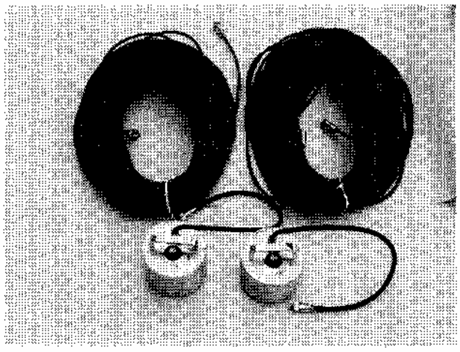
PHOTO NEWS

Portable Intelligent Collector

PIC 87

Main body of PIC87



Sensers and Extention cables for PIC87

View of the microtremor measurement along JR line using PIC87

This is a portable vibration measuring instrument for microtremor, train vibration and etc..

Dimensions and Functions

(1)	Dimension		560mm(W) x 330mm(D) x 195mm(H)
	Weight		14kg (main body)
(2)	Amp.	Channels	6 ch.
		Gain	0 – 120 dB (5 dB step)
		Freq. Char.	0.18 – 20 Hz
		L.P.F.	5 Hz/10 Hz/20 Hz
(3)	A/D	Converter	12 bit, 24 μs
		Multiplexer	16 ch.
(4)	16 bit CPU		μPD70216 (8 MHz)
	Display		640 x 400 dot Liquid Crystal
	Floppy Disk Drive		3.5 in. single drive (built-in)
	Interface		RS232C Centronics
	Power Supply		12V (2.6 AH) battery and 12V (7 AH) battery (both built-in)
	Power Consumption		10W maximum (FDD access)
(5)	Senser		3 component x 2 set
	Extention cable		50m x 2 set

Since 1987, RTRI has been measuring the microtremor along JR line in Tokyo metropolitan area (approximately 1500 km length) at every 100 m using PIC87.