



## USEFULNESS OF HIGH DENSITY MICROTREMOR OBSERVATION FOR UNDERSTANDING OF GROUND SHAKING CHARACTERISTICS OF SUBSURFACE SOIL LAYER

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### ABSTRACT

The ground shaking characteristics, predominant period and amplification, due to subsurface soil layer are very important for damage estimation for buildings before the earthquake occurrence. We are performing high density microtremor observation in order to understand the usefulness for understanding of microtremor characteristics and also to check the utilization for seismic microzoning study. So, we performed high density microtremor observation in several cities and towns located plains and low land areas in Kanagawa Prefecture, observed sites were about 10,000 sites. Then we could understand the differences of ground shaking characteristics caused by subsurface soil layer. And also we investigated the predominant period distribution by performing the dense microtremor observation in Yokohama City, the capital city of Kanagawa Prefecture, Japan about 6,500 sites dividing 250m interval and calculated H/V spectra at each site. And the result is significantly good agreement between the predominant period obtained from H/V spectra and the general information of subsurface soil structure. In this paper, we summarized the observed H/V spectral ratio in order to understand of ground shaking characteristics in Kanagawa Prefecture. And also, according to the calculated results in Yokohama City, we investigated about the relationship between predominant period and depth of unconsolidated soil layer considering the history of landform development.

### INTRODUCTION

In Japan, there are so many large scale earthquakes occurred along the tectonic situation, as like as the 2011 Tohoku Earthquake (Mw9.0) which is explained by The Plate Tectonics Theory. Kanagawa Prefecture is located at central part of Japan Island, just south of Tokyo Metropolis, and the location is just close to the tectonic boundary, named Sagami Trough. This tectonic boundary is generated large scale earthquakes which were about Mw8.0 with 100 to 200 years interval. Actually, Kanagawa Prefecture was affected the 1923 Great Kanto Earthquake (Mw7.9) and devastating damages were occurred in many cities and towns located in southern part of Kanto District including Tokyo Metropolis, Chiba Prefecture. In general, the structural damages due to the strong motions or liquefaction phenomena are deeply related to the subsurface soil condition. In the 1923 Great Kanto Earthquake, the devastating damages were generated in the areas located soft soil condition distributed in low land in several plains in Kanagawa Prefecture, Ashigara Plain, Sagami Plain and areas around Tokyo Bay including the eastern part of Yokohama City.

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According to these reasons, it's very important to understand the ground shaking characteristics, predominant period and amplification named site effect, due to the condition of subsurface soil layer and also to understand the risk for the earthquake damage potential (Kuriyama T. et al. 2012). So, we performed the high density microtremor observation in many cities and towns existed in Kanagawa Prefecture, basically using 250mx250m distance interval in the geomorphological low land areas. And then we evaluated the predominant period by using H/V spectral ratio technique at each microtremor observation sites. The number of observation sites was about 10,000, shown in Figure 1. Using these results, we could clearly understand the distribution of predominant period due to the subsurface soil layer and also the relationship between the predominant period and soil condition. According to this relationship, we could estimate the velocity structure. In Yokohama city, we have many boring data and detailed soil structure identified the geologically classified soil layer along to the several cross sections. So, we have tried to investigate the relationship between the predominant period and the depth of subsurface soil layer sediment in Quaternary Period considering landform history.

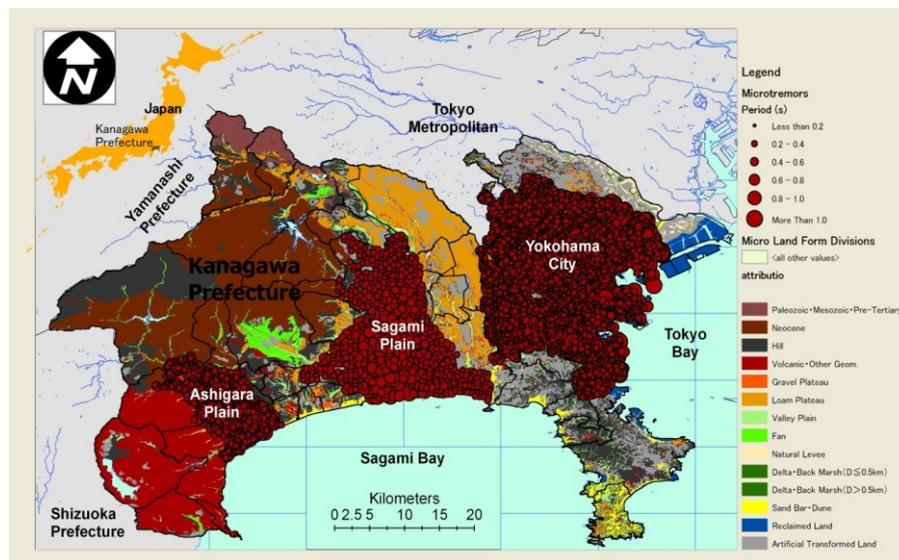


Figure 1 Distribution of Predominant Period Obtained From High Density Microtremor Observation in Kanagawa Prefecture

The ground shaking characteristics, predominant period and amplification, due to surface soil structure are very important for damage estimation for buildings before the earthquake occurrence (Navarro M. et al. 2004 and 2013). These shaking characteristics, especially predominant period, are able to calculate by soil structure with shear wave velocity obtained from SPT information and PS logging Test (Enomoto T. et al. 2000). A simple method for estimation of predominant period of surface soil structure is to use the H/V spectra based on microtremor measurement and it's very useful and popular in the world (Yamamoto T. et al., 2007). Up to now, we are using microtremor observation in order to check the purpose of microtremor utilization for seismic microzoning study (Enomoto T. et al. 2002, Rahimian et al. 2002, Yamamoto et al. T. 2007 and Navarro M. et al. 1999, 2001 and 2008). And, in this study, we investigated the predominant period distribution by performing the dense microtremor observation in Yokohama City, the capital city of Kanagawa Prefecture, about 6,500 sites dividing 250m interval and analysed H/V spectra at each site. And the result is very significantly good agreement between the predominant period obtained from H/V spectra and the general information of surface soil structure. By the way, the deposit soil materials accumulated on engineering basement, namely bearing soil layer for buildings, are constituted the geographical settlement, hill, table land and low land, and the history of landform development is influenced by the change of sea water level due to glacial period according to the meteorological change of earth and also the influence of ascent and descent due to crust movement in the geological history. In this paper, we summarized the H/V spectra observed in Yokohama City and made a database of predominant period and landform classification, lowland and table land according to the history of landform

development in Yokohama City shown in Figure 2 (Yokohama City 2003), and we performed the investigation about the relationship between predominant period and depth of unconsolidated soil layer.

We picked up and summarized the H/V spectral ratios of microtremors obtained in the Tamagawa, Tsurumigawa and Kanazawa lowlands and also Shimosueyoshi and Sagamino Table Land, respectively. The relationship between their predominant periods and the total thickness of the latest Pleistocene and Holocene deposits was explained by the equation  $Y=A*X+B$ . In this equation, X and Y mean the total thickness and the predominant period, respectively. The values of A and B as well as the correlation coefficients reflect historical development of landforms and soils. We have obtained the clear relationship under consideration of history of landform development and we would like to present the results in this paper. We think that this result brings us that more effective use of microtremor observations is possible for seismic microzoning.

## MICROTREMOR MEASUREMENTS AND DATA ANALYSIS

Despite there exists the numerous amount of boreholes in urbanized areas in Kanagawa Prefecture, Japan, many of them were dug very short and do not reach the stiff layers. Microtremors measurement is a very useful method to obtain ground characteristics, by applying the predominant period and the site amplification factor (Enomoto et al, 2000). A three components velocimeter, were used for the measurements (Tokyo Sokushin Model SPC 51) as shown in Figure 2. Three components aligned along North-South, East-West and Up-Down (Vertical) direction respectively. Velocity amplitudes of microtremors at a sampling frequency of 100Hz were recorded for 300 seconds. We analyzed the recorded microtremors data by a software that have been developed (SAMR) to automatically trace, identify and eliminate the short period transient noises and then identify the possible numbers of segments with any length of data (2048 data points used in this case). All the procedure is summarized in Figure 3. As shown in this figure the possible numbers of samples (in this example two samples) have chosen automatically by the software then the Fourier Spectra of identified records are calculated and smoothed by a log window with 15% bandwidth. Horizontal vector component calculated using the formula,

$$H(\omega)=[NS(\omega)*EW(\omega)]^{0.5} \quad (1)$$

$$H/V= H(\omega) / UD(\omega) =[NS(\omega)*EW(\omega)]^{0.5}/UD(\omega) \quad (2)$$

The mean spectrum for all components, NS( $\omega$ ), EW( $\omega$ ) and UD( $\omega$ ) as well as H( $\omega$ ), were calculated assuming the waves remain stationary during three minutes of recording. The mean spectrum of H/V also calculated with no assumption since non-stationary condition will not affect the H/V since the H amplitudes has been normalized by V (Rahimian and Seo 2002, Yamanaka et al. 2007). H/V spectral ratio is used to estimate the site predominant periods and corresponding amplitudes as shown in Figure 4. There are many discussions (e.g. Field and Jacob 1995) over the application of H/V ration first introduced by Nakamura (1989) but recent researchers (Lachet et al. 1994 and 1996) shown very good confident on the results of this method. It was confirmed that the predominant period of H/V spectra and corresponding amplitude of H/V spectrum shows very good correlation with characteristics of surface geology such as amplification factors (Enomoto et al. 2000). Also, it as confirmed the same for soft sediments by comparison with strong motion site to reference spectra ratio (Rahimian et al. 2000). In general, we can use the following formula for a rough estimate of the effective soil layers with an average shear wave velocity,

$$h=T*Vs/4 \quad (3)$$

Where h is the estimated depth of the effective layer, T is the predominant period of resonant period and Vs is the average shear wave velocity.



Figure 2 Measurement Equipment for Microtremors Observation (Tokyo Sokushin Model SPC 51)

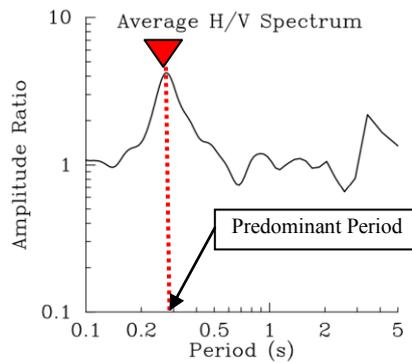


Figure 4 Calculated H/V Spectral Ratio and Evaluated Predominant Period

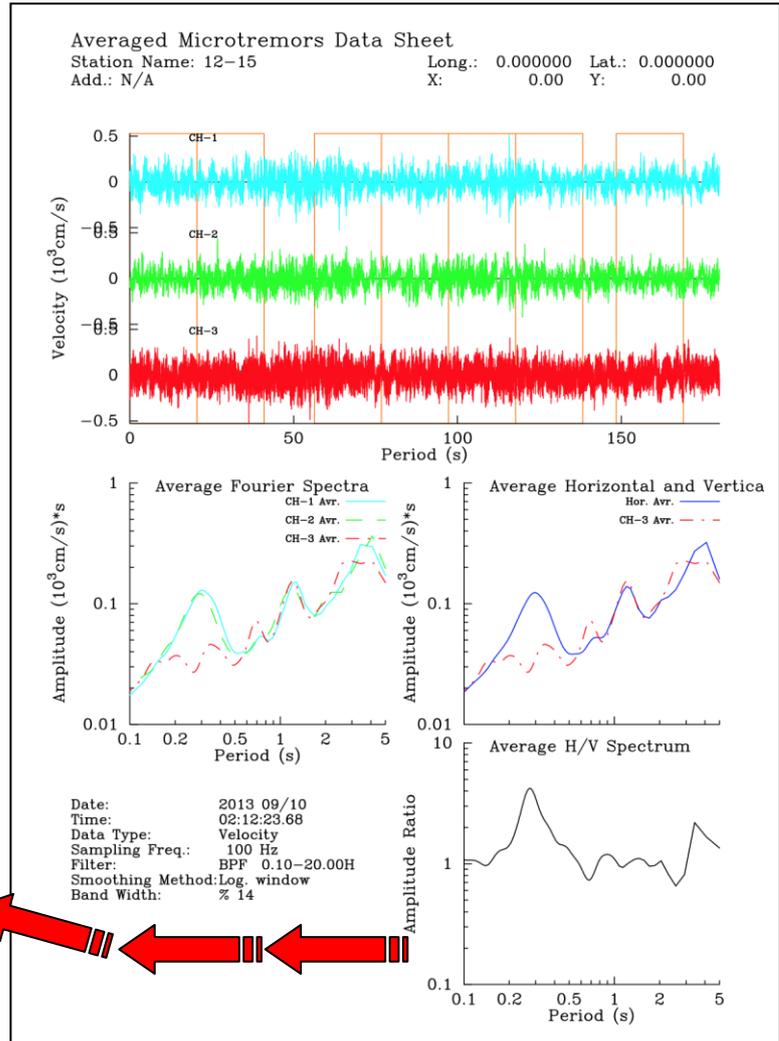


Figure 3 Automatically Analytical Result of Microtremor Observation Data used the Software, SAMR.

## INTERPRETATION OF H/V SPECTRAL RATIOS FOR MICROTREMORS

Considering observations that have been made herewith and using a logical approach, it is thought that ground specific predominant periods can be estimated using H/V spectral ratios based on Rayleigh wave characteristics in ground structures built on sedimentation layers that are particularly relatively soft where surface wave components of microtremors are dominant. As a result of these findings, observation of microtremors has been attracting attention as it allows ground shaking characteristics to be determined easily, with a number of research projects being conducted to further investigate these conditions. As discussed above, although it is expected that disaster prediction studies for damages from earthquakes will be conducted even on a village, town, or city scale, it can be seen from experience that ground characteristics can vary quite dramatically from point to point, even for locations separated by distances of only several tens of meters. As a result, it is imperative that high-density observations be conducted to obtain more accurate results.

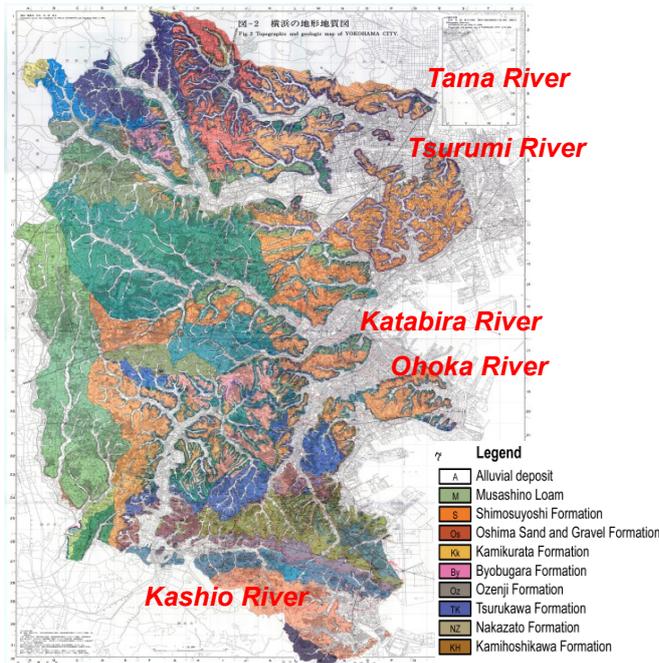


Figure 5 Geological and Geographical Map of Yokohama City

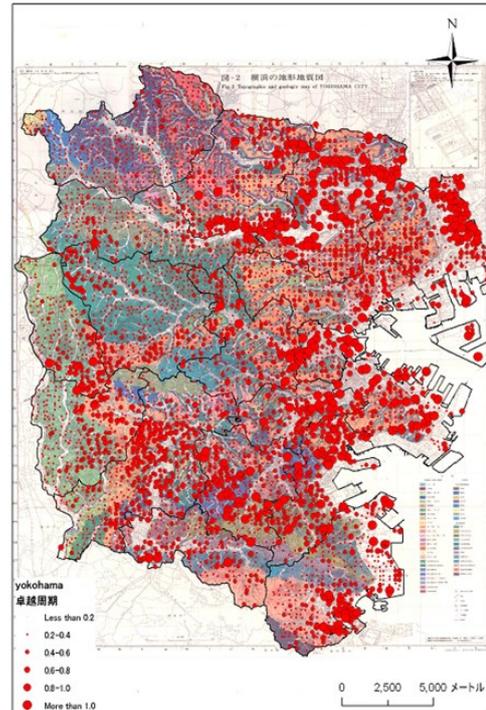


Figure 6 Distribution Map for Predominant Periods

## OBSERVATIONS OF HIGH-DENSITY MICROTREMORS IN YOKOHAMA CITY

### High-Density Microtremors Observation

The author began to conduct observations of high-density microtremors in Yokohama starting in 2005 with the purpose of clarifying details on ground shaking characteristics. Dividing the entire city of Yokohama up into sections defined using 250-m-wide meshes, the author observed approximately 6500 different points of those identified, not including those that were unobservable, near the center of each specified mesh. A servo velocimeter was used to measure velocities, with the sampling frequency set to 100 Hz and the observation time to 180 seconds. Figure 5 shows the geological and geographical map of Yokohama City and Figure 6 shows a distribution map for predominant periods. The figure displays results for predominant periods corresponding to topography and geology as well as the ground for the city of Yokohama.

### Relationship between H/V Spectra for Microtremors and Land/Ground Features

Geological classifications for different regions specified based on formation logs for topographical features are shown in Figure 6. Deposits on so-called engineering bedrock make up landforms such as hills, plateaus, and lowlands. The historical development of these landforms is greatly influenced by rises and falls in sea surface height due to climate change and accompanying glacial eustasy, as well as uplift and subsidence due to crustal movement. “In other words, ground conditions differ according to how the rivers that created the landforms responded to these external conditions.”

The author created a database for data from observations and analysis of constant microtremors for alluvial lowlands and plateaus in Yokohama, a city with complicated topography, and classified land features based on logs of when land features were formed in order to evaluate ground shaking characteristics in land features, with the evaluation being used to validate the correlativity between ground shaking characteristics and topographic effects.

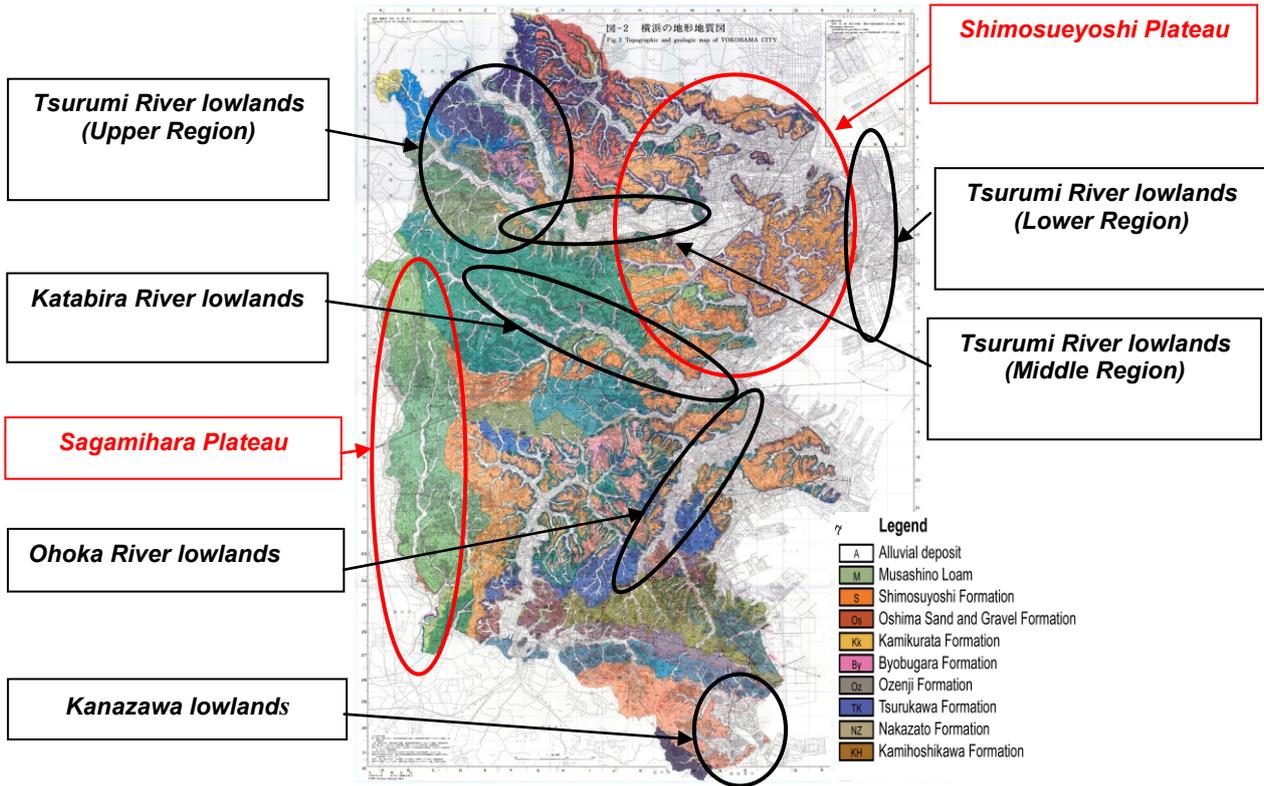


Figure 7 Geological Map of Yokohama Land

### Types of H/V Spectra

As shown in Table 1, there are two broad types of H/V spectra, the first one used to classify spectra where there is only one clearly defined peak (Type 1, where predominant periods can be identified easily) and the other one used to classify spectra where there are two or more peaks (Type 2, which require predominant periods to be identified using specialized knowledge). The number of observation points used for each type is shown in Table 2. As listed in Table 2, there were 1670 observation points (approx. 26% of the total) from which the predominant periods could be determined easily, 4476 observation points (approx. 69% of the total) for which predominant periods could be estimated and determined using specialized knowledge (boring logs for specific points and surrounding areas, information on geological and topographical features, etc.), and 318 observation points (approx. 5% of the total) for which predominant periods could not be determined using H/V spectra.

Table 1 Types of H/V Spectra

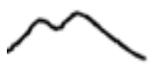
|   |  |
|---|--|
|  | Type 1 :<br>Predominant period can be determined easily                      |
|  | Type 2 :<br>Predominant period can be determined using specialized knowledge |

Table 2 Relationship Between Topography Distribution and Number of Observation Points in Classified Types

| Land Feature  | Composition Layer   | No. of points | No. of Type 1 points | Percentage |
|---------------|---|---------------|----------------------|------------|
| Hill Region 1 | Tsuchiya/Tsuchihashi Loam Layer,<br>Totsuka/Terao Layer<br><br>Souda/Maioka Layer, Tsurumi/Maioka Layer                                     | 241           | 94                   | 39%        |
| Hill Region 2 | Tama 2 Loam Layer, Oshinuma Sand Gravel Layer<br><br>Sanodai Loam Layer, Kami-kurata Layer, Sanodai Sand Dune                               | 704           | 203                  | 29%        |
| Hill Region 3 | Byobugaura Layer, Naganuma Layer  | 227           | 21                   | 9%         |
| Hill Region 4 | Kazusa Layer Group  | 1232          | 207                  | 17%        |
| Plateau 1     | Tachikawa Loam Layer, Tachikawa gravel Layer  | 31            | 14                   | 45%        |
| Plateau 2     | Upper/middle/lower sections of Musashino Loam Layer<br><br>Nakadai Terrace Gravel Layer, Musashino Gravel Layer, Obaradai Sand Gravel Layer | 581           | 196                  | 34%        |
| Plateau 3     | Shimosueyoshi Loam Layer, Shimosueyoshi Layer   | 816           | 227                  | 28%        |
| Lowland       | Lowlands  | 2314          | 708                  | 31%        |
|               | Total   | 6146          | 1670                 | 27%        |

### Correspondence to Topographic Classifications

From comparisons of the distribution patterns for Type 1 and Type 2, it can be seen that Type 2 features are present locally in dominant regions whereas Type 1 features cannot be identified in dominant regions. The ratio of Type 1 observation points was calculated for land features in Yokohama, which were classified as hills, plateaus, or alluvial lowlands, and it was found that there was a relatively high rate of Type 1 observation points for Hill Region 1 and Plateau 1, but not, for example, for Hill Region 3, which had few Type 1 observation points compared to other hill regions.

The percentage of observation points in Yokohama for which the ground predominant periods could be identified easily using H/V spectra was almost 30%. Including the observation points for which the predominant periods could be determined using boring logs as well as geological information, topographical information and ground information for surrounding areas around observation points, predominant periods can be estimated for approximately 95% of all observation points, which demonstrates that observation of constant microtremors is an effective method to use to find ground predominant periods when used in conjunction with classification of regions.

## APPROACH FROM HISTORICAL DEVELOPMENT OF LANDFORMS AND SOILS

### Methodology

In recent estimations of earthquake damage, velocity and acceleration at the ground surface are found based on AVS30, which is the average S-wave velocity from the ground to 30 m below the ground surface. It is extremely costly to measure AVS30 densely with identical accuracy, and so it is corrected for altitude and distance to rivers, etc. but it is found for each accessible microrelief. However, there are serious disadvantages in determining AVS30 for each microrelief.

In seismic microzoning targeting the buildings that exist everywhere in cities, deposits on so-called engineering bedrock is the target on so-called engineering bedrock. These deposits make up landforms such as hills, plateaus, and lowlands. The historical development of these landforms is greatly influenced by rises and falls in sea surface height due to climate change and accompanying glacial eustasy, as well as uplift and subsidence due to crustal movement. In other words, ground conditions differ according to how the rivers that created the landforms responded to these external conditions. Specifically, the type of deposit and its distribution, or the distribution of the ground, is determined according to the sediment transportation ability of the respective river. Therefore, seismic microzoning must be performed for each plain formed by the respective river and, in terms of microrelief, it is unreasonable to treat areas in between different plains in the same way. Also, even within the same plain, the microrelief does not represent the deposits to 30 m below the ground. The microrelief is the topography forming the ground surface, and it only represents the final stage in the historical development of the landforms. It does not reflect the state of the ground (deposits) to 30 m below the surface.

The authors of this paper investigated the practical use of microtremors in seismic microzoning. Here, considering historical development of landforms, we show that more effective use of microtremor observations is possible and that microtremor observations are valuable data for seismic microzoning.

### Alluvium thickness and predominant period

Unlike carrying out seismic observation by installing seismometers, it is possible to measure microtremors at any time in any place and so a large volume of spatially-close data can be obtained. Predominant periods of approximately 2 seconds and below, which are important in earthquake damage to the low- and medium-rise buildings common in cities, are considered to be dependent on the nature (primarily, lithofacies and hardness) and thickness of the deposits in the surface layer. Therefore, taking alluvium thickness as  $X$  (m) and predominant period of microtremor as  $Y$  (sec.), the two are related using the following regression equation:

$$X=A*Y+B \quad (4)$$

$A$  indicates the contribution ratio of each 1 m of alluvium to the predominant period and is inversely proportional to S-wave velocity of the alluvium. Also, if  $B=0$ , the average S-wave velocity of the alluvium is  $4/A$ .  $B$  indicates the contribution to the predominant period of deposits lower than the alluvium.

Figure 8(a) shows a geological cross-section of the area downstream of the Tama River lowlands prepared using boring data measured during the construction of the Yokohama/Haneda route of the Metropolitan Expressway. The vertical lines show the locations of the borings and they are numbered. Some numbers are omitted because it would complicate the diagram if all of the data were entered. Also, it must be kept in mind that the horizontal and vertical scales differ, so gradients are emphasized. From number 74 (hereafter, the word “number” will be omitted) to 87, a sandy gravel layer with its top face at from -47 to -53 m forms the basal gravel of the alluvium. It appears that the bottom face reaches -60 m. This deep valley is named the Paleo-Tama River Valley. From 108 to 132 is a buried wave-cut platform formed during the Jomon Transgression. Here, the alluvium is thin and the Kazusa Group that forms the bedrock is thickly covered by the Middle/Late Pleistocene Series

(called the intermediate layer). From Figure 8, the ground subject to seismic microzoning is divided into three; bedrock, intermediate layer, and alluvium.

Figure 8(b) shows a geological longitudinal section along the Paleo-Tama River Valley, and changes in the ground from the alluvial fan of the lowlands to the end of the delta can be seen. The Paleo-Tama River Valley was deeply eroded until the Last Glacial Maximum, so an intermediate layer is not distributed in this section. Figure 8(c) shows a geological cross-section of the Tsurumi River lowlands. Characteristics are that the mud layer is thick with a humid soil layer distributed close to the uppermost layer, and there is no intermediate layer. Figure 8(d) shows a geological longitudinal section of the Kanazawa lowlands, which is a small valley plain located at the southern end of the city of Yokohama. The bay entrance is blocked by a sandbar, and a mud layer is thickly distributed. The mud layer is divided into a lower continental layer and an upper marine layer, but there is no intermediate layer

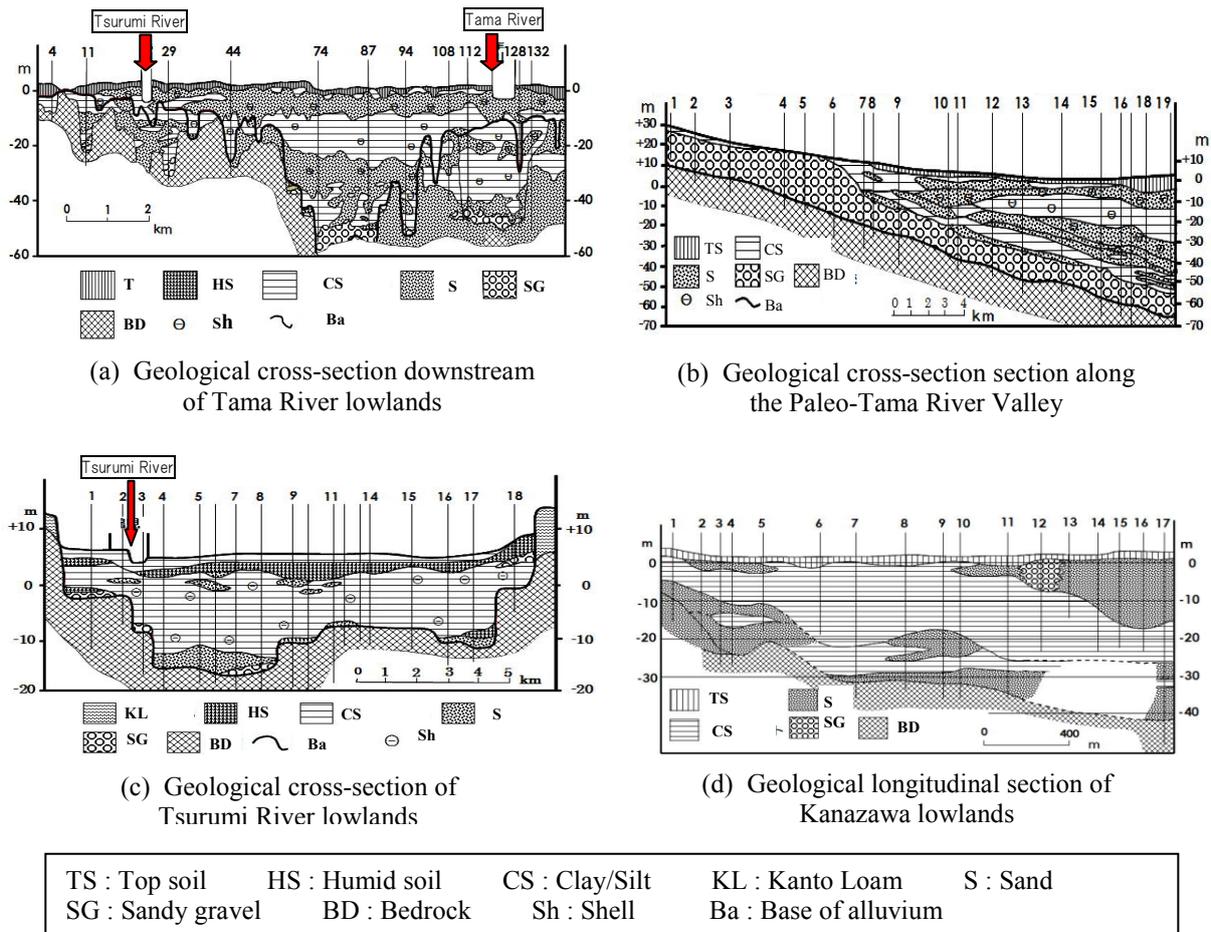


Figure 8 Geological cross-section of several areas located in Yokohama City, the locations are indicated in Figure 7.

Figure 9(a)-(e) show the relationship between alluvium thickness and predominant period of microtremors observed in several areas indicated in Figure 7. For example, Figure 9(a) shows the relationship between thickness of deposit and predominant period observed in areas where the intermediate layer is thick on the left bank of the Paleo-Tama River Valley. The predominant period is taken to be the period at which the H/V spectral ratio reaches its greatest peak. Figures 9(b) and (c) show the same relationship obtained from above the Paleo-Tama River Valley, the Tsurumi River lowlands, where there is no intermediate layer. The linearly regressed equations and correlation coefficients (R) are as follows:

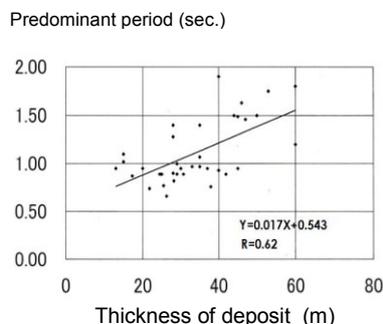
|                              |                  |          |     |
|------------------------------|------------------|----------|-----|
| Tama River lowlands,         |                  |          |     |
| With intermediate layer :    | $Y=0.017X+0.543$ | $R=0.62$ | (5) |
| Without intermediate layer : | $Y=0.012X+0.190$ | $R=0.86$ | (6) |
| Tsurumi River :              | $Y=0.026X+0.209$ | $R=0.75$ | (7) |
| Kanazawa lowlands :          | $Y=0.021X+0.052$ | $R=0.80$ | (8) |

Figures 9(d) and (e) show the same results obtained from the Sagamino Plateau and Shimosueyoshi Plateau in the city of Yokohama in order to make a comparison with alluvial lowland. With regard to the Shimosueyoshi Plateau, which is a marine-built platform, the layer at which the N-value exceeds 50 is taken as the bedrock, and the relationship between the predominant period and thickness of the deposit (primarily, Shimosueyoshi Formation and Kanto Loam Formation) covering the bedrock is found. While with regard to the Sagamino Plateau, which is a fluvial terrace, the relationship between the predominant period and the thickness of the Kanto Loam Formation covering the terrace gravel is found. The results obtained are as follows:

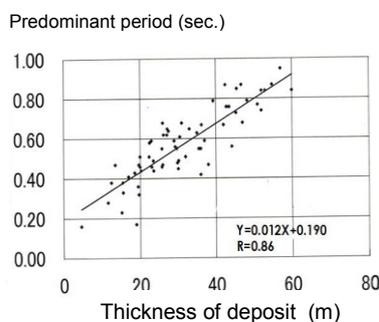
|                         |                  |          |      |
|-------------------------|------------------|----------|------|
| Shimosueyoshi Plateau : | $Y=0.006X+0.244$ | $R=0.56$ | (9)  |
| Sagamino Plateau :      | $Y=0.004X+0.232$ | $R=0.34$ | (10) |

In these figures, Figures 8(a)–(e), the thickness of the deposit is alluvium thickness in case of lowlands, and deposits up to N-value 50 in case of plateaus. The above results are summarized in Figure 10. The following can be understood from Figure 10.

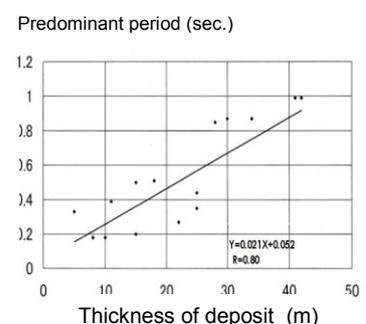
- 1) When there is no intermediate layer in lowlands, the correlation coefficient is high and the value of B is small. When there is an intermediate layer, the correlation coefficient is small and the value of B is large. The influence of the intermediate layer is obvious here.
- 2) The fact that the value of A in the Kanazawa lowlands and Tsurumi River lowlands is larger than in the Tama River lowlands indicates that the average S-wave velocity in the alluvium of the Kanazawa and Tsurumi River lowlands is slower than in the Tama River lowlands. In other words, the alluvium is soft.
- 3) The fact that the value of B in the Kanazawa lowlands is smaller than in the Tama River lowlands without an intermediate layer and smaller than in the Tsurumi River lowlands indicates that the predominant period is more dependent on the alluvium in the Kanazawa lowlands. In other words, in the Kanazawa lowlands, there is a large contrast between the bedrock and the alluvium. This result is consistent with the fact that the bedrock of the Kanazawa lowlands is made up of older deposits.
- 4) In the plateaus, the value of A is small. This is consistent with the fact that deposits in the surface layer of plateaus are more consolidated than in alluvial lowlands.
- 5) In the plateaus, the correlation coefficient is small. This shows that the deposits in the surface layer of the plateaus are non-uniform.



(a) Tama River lowlands  
(With intermediate layer)



(b) Tama River lowlands  
(Without intermediate layer)



(c) Kanazawa lowlands  
(Without intermediate layer)

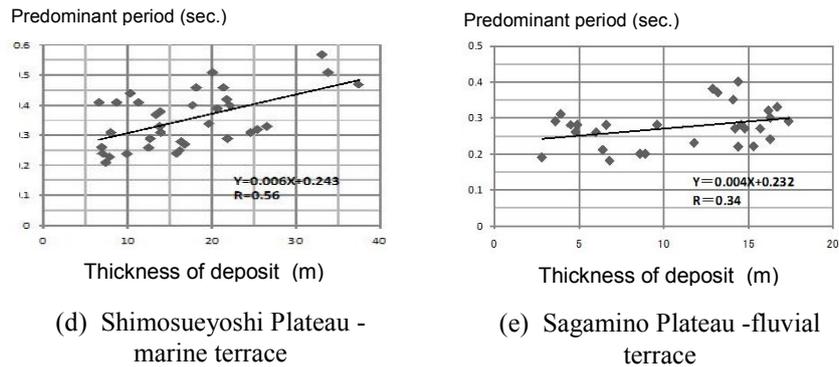


Figure 9 Relationship between the thickness of alluvium deposit and predominant period obtained from H/V of observed microtremors

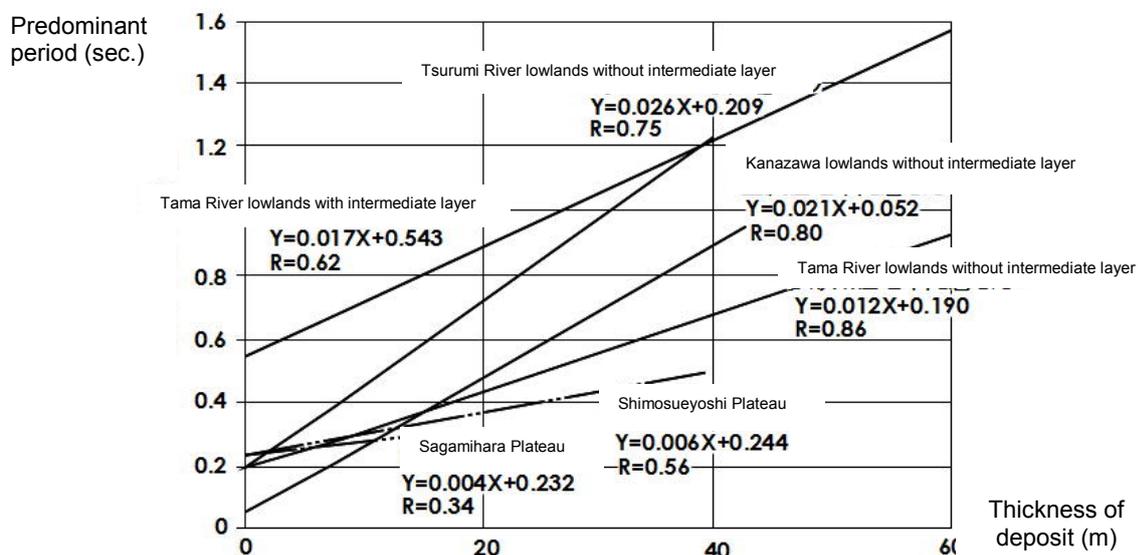


Figure 10 Relationship between predominant period and sedimentary layer thickness (In case of lowlands, alluvium thickness; In case of plateaus, deposits up to N-value 50)

## CONCLUSIONS

In order to investigate the usefulness of microtremor observations for seismic microzoning and damage prediction, we are performing the high density microtremor observations in Kanagawa Prefecture, especially in lowlands developing in Ashigara, Sagami and Yokohama City. In the 1923 Great Kanto Earthquake (Mw7.9), the huge devastating structural damages occurred in these areas and it's also very vulnerable areas for future expected big earthquake. We could derive several concluding remarks which are very important for seismic microzoning study in target areas. The suitable and important process is summarized as follows.

The nature of the bedrock and ground is reflected in the predominant period of microtremors, and so analysis of the historical development of landforms and ground is essential in seismic microzoning. As an example, the zoning procedure shall be as follows: Landform classification maps will be created from field surveys and interpretation of aerial photographs, and if possible, geographical sections will be created by collecting boring data. Next, with reference to these maps and sections, the historical development of the landforms will be compiled. Based on these results, deposits will be classified, and units will be established for conducting area classification from their combinations. Furthermore, microtremors will be measured and area classification will be conducted

by confirming consistency with distribution of predominant periods of the microtremors. Response calculations will be carried out for each area-classified unit, and seismic motion characteristics will be assigned to each zone.

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