# Analysis of ground motion based on microtremor characteristics in Kagawa Prefecture, Japan

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**Abstract:** The Japanese Government anticipates the occurrence of the Nankai earthquake in Shikoku Island in the near future. Takamatsu, the capital city of Kagawa Prefecture, has been seriously damaged by Nankai earthquakes at intervals from 90 to 150 years. The seismic damage is closely related to the ground structure. It is very important to clarify the geological structure of the region, when designing earthquake-proof buildings and structures and in drawing up an earthquake disaster prevention plan for the region. Microtremor measurement is effective as a method for conveniently and cheaply understanding the ground properties.

Previously, the authors had determined that the horizontal and vertical spectrum (H/V spectrum) of the short cycle tremor was effective for analysis of the ground motion characteristics and for evaluation of the earthquake motion. Further, the authors have performed advance research of the ground properties of the Takamatsu Plain and Marugame-Sakaide Plain in Kagawa Prefecture. In addition, the research group of authors have developed a ground information database for the main plain in Kagawa Prefecture.

In this context, microtremor measurement are carried out in the Takamatsu and Marugame-Sakaide plains and the estimation of ground motion characteristics based on the H/V spectrum are carried out, which are discussed in this paper. It is noticed that the predominant period and amplification factor required for the microtremor has effective consistency with land summary classification. Similarly, it is possible to clearly demonstrate that the ultra long-period component is large in reclaimed land and delta, whereas the short period element is large in the tableland and hilly areas.

**Résumé:** Le gouvernement japonais prévoit occurrence du tremblement de terre de Nankai en île de Shikoku dans un proche avenir. Takamatsu, la ville capitale de la préfecture de Kagawa, a été sérieusement endommagé par Nankai tremblements de terre à des intervalles de 90 à 150 ans. Les dommages séismiques sont étroitement relié à la structure au sol. Il est très important de clarifier le géologique structure de la région, en concevant des bâtiments de tremblement de terre-preuve et les structures et en élaborant un empêchement de désastre de tremblement de terre projettent pour région. La mesure de Microtremor est efficace comme méthode pour commodément et à bon marché arrangement les propriétés au sol.

Précédemment, les auteurs avaient déterminé que le spectre horizontal et vertical (spectre de H/V) du tremblement court de cycle était efficace pour l'analyse des caractéristiques au sol de mouvement et pour l'évaluation du mouvement de tremblement de terre. De plus, les auteurs ont effectué la recherche anticipée des propriétés au sol de la plaine de Takamatsu et de la plaine de Marugame-Sakaide en préfecture de Kagawa. En outre, le groupe de recherche d'auteurs ont développé une terre base de données de l'information pour la plaine de force en préfecture de Kagawa.

Dans ce contexte, la mesure de microtremor sont effectué dans les plaines de Takamatsu et de Marugame-Sakaide et l'évaluation de des caractéristiques au sol de mouvement basées sur le spectre de H/V sont effectuées, qui sont discutés en cet article. On le note que la période prédominante et le facteur d'amplification exigé pour le microtremor a l'uniformité efficace avec la classification de sommaire de terre. De même, il est possible à clairement démontrez qu'ultra le composant de long-période est grand dans la terre reprise et delta, tandis que l'élément court de période est grand dans le plateau et accidenté secteurs.

**Keywords:** alluvium, earthquakes, geodata, geology of cities, liquefaction, seismic risk

## INTRODUCTION

The Japanese Government anticipates the occurrence of the Nankai earthquake in Shikoku Island in the near future. Takamatsu, the capital city of Kagawa Prefecture, has been seriously damaged by Nankai earthquakes at intervals from 90 to 150 years. The severity of past earthquake damage is considered to be closely related to ground structure (Shimbo et al. 2002). Thus, it is important to clarify the geological structure of the region and to understand the vibration characteristics of the ground to enable appropriate seismic design of structures and to devise effective earthquake disaster prevention systems in the region.

A number of methods to determine the ground structure exist; these include boreholes with PS logging and in-situ tests (standard penetration tests etc) as well as use of strong motion observation and microtremor measurement. The evaluation of ground characteristics based on the borehole data is common, however relatively few boreholes are advanced to bedrock. Therefore, it is necessary to accumulate the geological data from many different methods.

 

Therefore, microtremor observation methods have been developed as a simple and cost effective method to determine the characteristic of the ground (Nakamura 1988, Tokimatsu et al. 1994). Among various kinds of geological explorations by using microtremor records, the horizontal to vertical spectrum ratio (H/V spectrum) is considered most effective (Nakamura 1988). The H/V spectrum only requires observation at single point, which is much easier than the array observation for the F-K spectrum and the SPAC methods.

In this study the potential effectiveness of the H/V spectrum for the investigation of deep and shallow soil structure on alluvial lowland sites is discussed with reference to microtremor observations at over 400 sites in the Takamatsu Plain and at about 80 sites in the Marugame-Sakaide Plain.

## OUTLINE OF TOPOGRAPY AND GEOLOGY

### *Topographical features in Takamatsu Plain*

Takamatsu is the capital city of Kagawa Prefecture on Shikoku island of Japan. It is located on the northern border of Shikoku and bordered to the Inland Sea (Figure 1). Takamatsu city is situated on the north side of Sanuki mountain and in the alluvial plain formed by Shin, Kasuga Tsumeta, Koto, and Honzu rivers. The area of the Takamatsu Plain is about 100 square kilometres. The Takamatsu Plain is mainly composed of the alluvial fan of the Koto River and the subordinate flood plains of the Shin, Kasuga and Honzu rivers as well as deltas of these rivers and reclaimed land along the shore (Figure 2). At present, the Koto River flows on the west side of Mt.Shiun, however, previous studies indicate that the Koto River had flowed on the east side of the Mt.Shiun during Holocene period. Close to the coast the salt farms areas and areas of former shallow sea have reclaimed. Similarly, several terraces of the Pleistocene are distributed in the southern part of the plain.

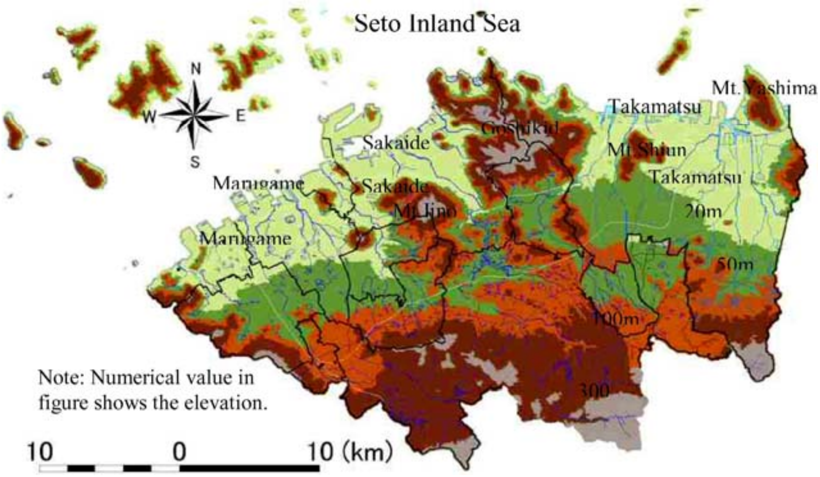


**Figure 1.** Topological map of centre Kagawa Prefecture

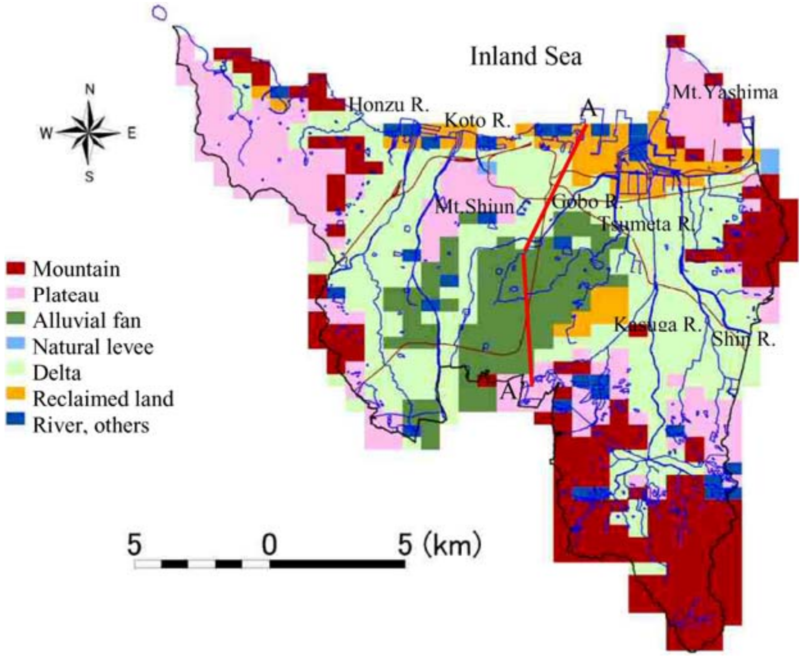


**Figure 2.** Topographical map of Takamatsu Plain (Kubo et al. 2003)

## *Geological features in Takamatsu Plain*

In the Takamatsu Plain, the Mitoyo Group has thickness of up to 200m overlies granite bedrock. The terrace deposits and the alluvial deposits cover the Mitoyo Group. The surface geology of the Takamatsu Plain is closely related to topography. In the alluvial fan deposits of the Koto River, soil of 2-3 m from the surface consists of gravels where as muddy deposits are found in flood plain of Kasuga and Shin rivers. Deltas at the mouth of all of these rivers consist of sandy deposits. Similarly, granite bedrock appears at depths of 100 – 200 m in these river deposit areas.

The thickness of the alluvium has been assumed to be about 30m or less up to now, but recent research clarified that the thickness of the alluvium is about 10m in the coastal zone. In the inland area also, the thickness of the alluvium is in the order of several meters (Kawamura, 2000).

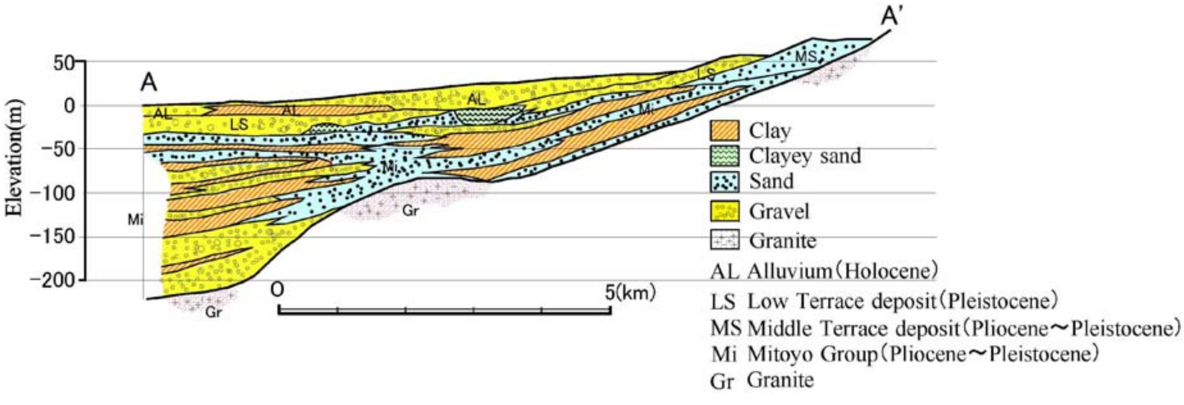


**Figure 3.** Typical geological profile of Takamatsu Plain (RGGA, 1984)

## *Topographical features in Marugame-Sakaide Plain*

The Marugame-Sakaide Plain is almost located on the centre part of Kagawa Prefecture and faces towards the Seto Inland Sea. The Marugame Plain is mainly composed of the alluvial fans dissected by the Doki River and the coastal plain is composed of delta and sandbar deposits. Similarly, back march is formed along the coast as shown in Figure 4.

The Sakaide Plain is formed by the Aya River, which is situated in a bay coast facing toward the Inland Sea.

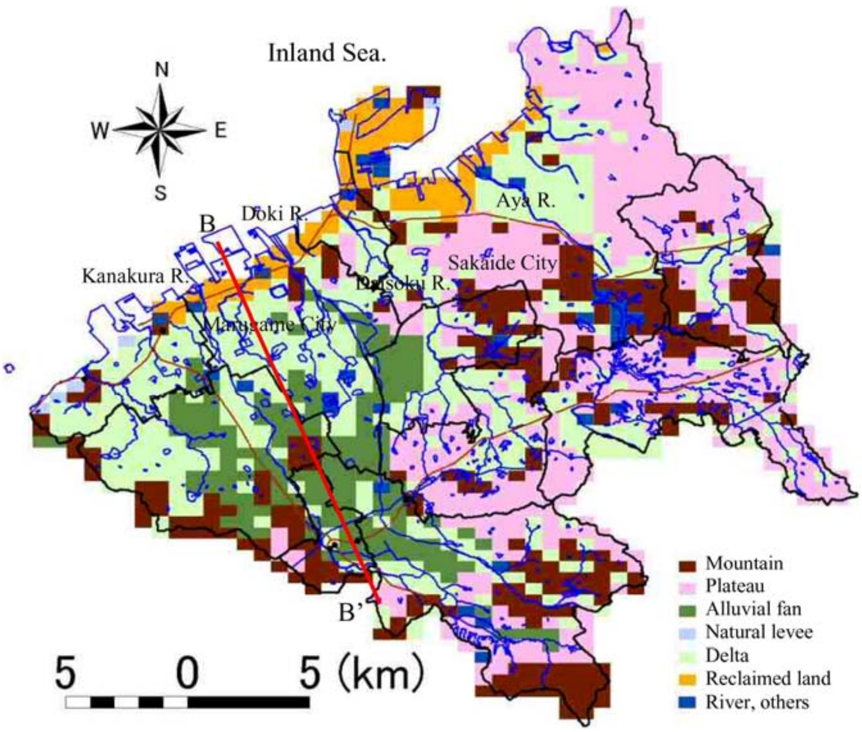


**Figure 4.** Topographical map of Marugame-Sakaide plain (Kubo et al, 2003)

## *Geological features in the Marugame-Sakaide Plain*

In the Marugame Plain, the alternation of layers of gravel, sand, silt, and clay of Mitoyo Group are found. These sediments are deposited over the granite (bedrock) and covered by terrace deposits (LS) and alluvium (AL) as shown in Figure 5. The alluvial fan is mainly composed of gravel beds. Patches of clay are also found in the Marugame Plain that are considered to be an old river channel deposit or back swamp deposit. In the delta, the upper part consists of finer gravel beds, the middle part consists of marine deposits containing shell fragments and the lower part is mainly composed of gravel beds. The thickness of the alluvium is approximately 20m.

The geological features of the Sakaide Plain differ from the other alluvial fan seen in the Kagawa Prefecture. Near surface materials of the Sakaide Plain are mainly composed of very soft colloidal sediment deposited in the small bay, whereas the Mitoyo Group (Diluvium) is of greater thickness.

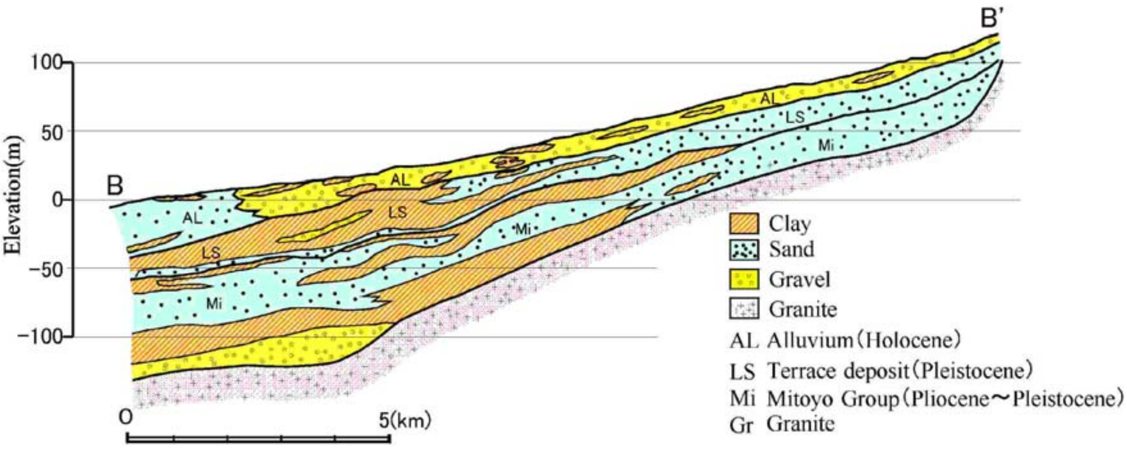


**Figure 5.** Typical geological profile of Marugame-Sakaide Plain (RGGA,1984)

## MICROTREMOR MEASUREMENT AND DATA ANALYSIS

### *Instrument set-up*

In this study, microtremor measurements were performed using portable microtremor equipment (SPC-35N), manufactured by Tokyo Sokushin Co.,Ltd. (Japan). The sampling frequency for all the measurements was set at 100Hz with a high-pass filter of 0.1Hz. The velocity sensor (VSE-15D) used in this investigation is able to measure three components of vibration: two horizontal and one vertical. The natural period of the sensor is 1 second. The available frequency response range for the sensor is 0.3-30Hz. A global positioning system (GPS) was used for recording the coordinates of measuring points. Figure 6 shows a map of microtremor observation points in Takamatsu Plain, which includes about 400 sites.

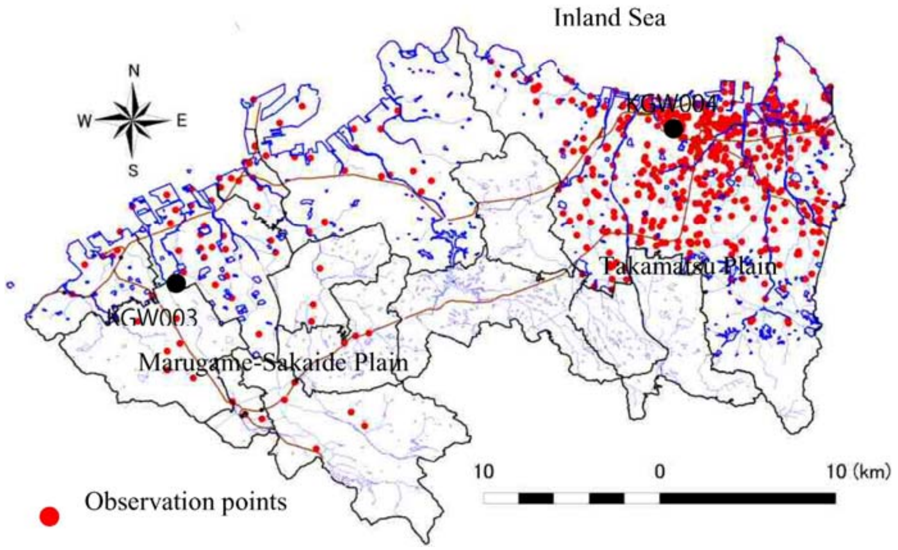


**Figure 6.** Microtremor observation points in Takamatsu Plain and Marugame-Sakaide Plain

### *Data acquisition and processing*

Microtremor measurement was carried out at more than 500 points in the Takamatsu Plain and the Marugame-Sakaide Plain (Figure 6). At each site, data was recorded for 300 seconds (i.e. 30000 data points at the sampling rate of 100Hz). The recorded time series data were divided into various segments each of 20.48s duration. For each site, ten segments of the data were chosen by omitting the segments that are influenced from very-near noise sources. These ten segments were used for the calculations. The Fourier spectra were calculated for the selected ten segments using the Fast Fourier Transform (FFT) algorithm and the Fourier spectrum was smoothed by the Parzen window of bandwidth 0.3Hz. The Fourier amplitude ratio of the two horizontal Fourier spectra and one vertical Fourier spectrum were obtained using Equation (1):

$$r(f) = \frac{\sqrt{S_{NS}(f) \times S_{EW}(f)}}{S_{UD}(f)} \qquad (1)$$

where r(f) is the horizontal to vertical (H/V) spectrum ratio, and $S_{NS}$, $S_{EW}$, and $S_{UD}$ are the Fourier amplitude spectra in the NS, EW and UD directions, respectively.

After obtaining the H/V spectra for the 10 segments, the average of the spectra were obtained as the H/V spectrum for a particular site. The peak period of the H/V spectrum plot shows the “predominant period” of the site. The H/V spectra were obtained for all the observation sites and the predominant periods of ground motion for all the sites were identified.

### *Microtremor measurement at strong motion station*

Before use of the H/V spectrum in the Takamatsu Plain, microtremor was measured at the K-NET Takamatsu station (KGW004) where the ground structure was assessed by logged boreholes as shown in Figure 7. This enabled confirmation that the peak of the H/V spectrum showed a good correlation with ground properties.

Comparison with the H/V spectrum of the strong motion recorded at the K-NET Takamatsu station and the H/V spectrum obtained from the microtremor measurement are shown in Figure 8. Two peaks are seen in these spectra. The predominant period, which is seen at about 0.25 and 0.8 second shows good correlation.

The peak of the microtremor reflects the layer by which alluvial deposit and the bedrock can be differentiated. It is also presumed that the plainer peak of about 0.8 second corresponds to the depth of the bedrock (diluvium) and the peak of about 0.25 second corresponds to the depth of the alluvium.

From the above results, it is felt that use of the H/V spectrum for the analysis of the microtremor record in the Takamatsu Plain is very appropriate.

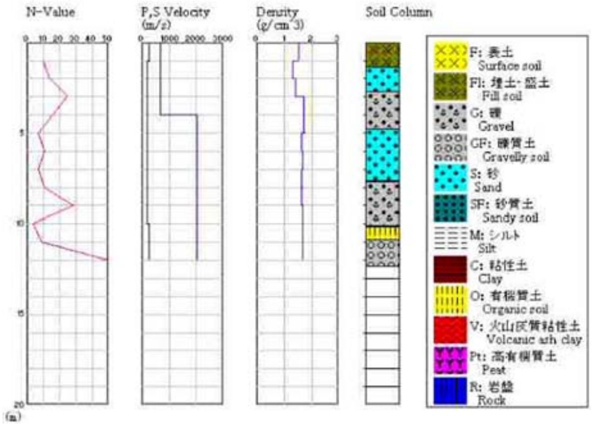


**Figure 7.** Soil conditions at K-NET Takamatsu station(KGW004)

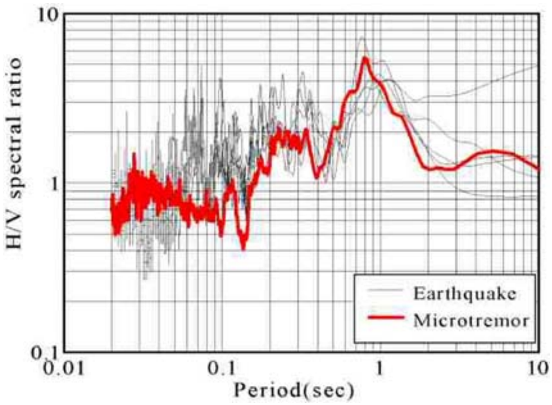


**Figure 8.** H/V spectrum for observed earthquake and microtremor observation at K-NET Takamatsu station(KGW004)

In the Marugame-Sakaide plain, K-NET Marugame station (KGW003) was set up. Comparison of the H/V spectrum in the strong motion can be recorded at the K-NET Marugame station and the H/V spectrum obtained from the microtremor measurement is shown in Figure 10. Both show a relatively good correlation. This can be clearly seen as peak at a point where the contrast of the surface and bedrock is clear. It is presumed that the clearly visible peak of about 0.7 second reflects the deep ground structure, and the peak of about 0.1 second reflects the shallow ground structure. According to soil data, gravel layer of 6 m depth has N-values more than 50 and it can be considered that the predominant period of about 0.1 second reflects this layer.

Though details are uncertain because there is no deep soil data of 10m or more, the peak of about 0.7 second is corresponding to the alluvium or the diluvium layer (for example LS layer shown in Figure 5).

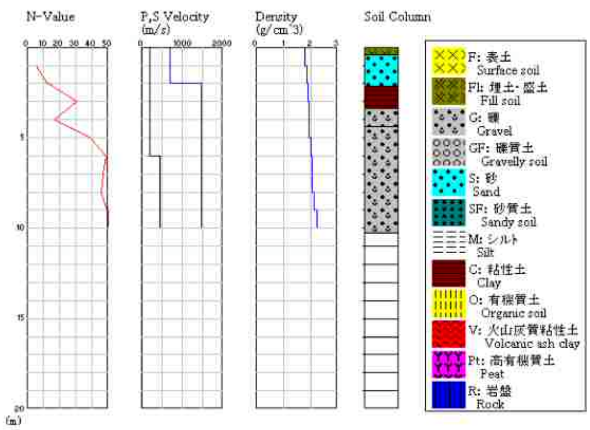


**Figure 9.** Soil conditions at K-NET Marugame station (KGW003)

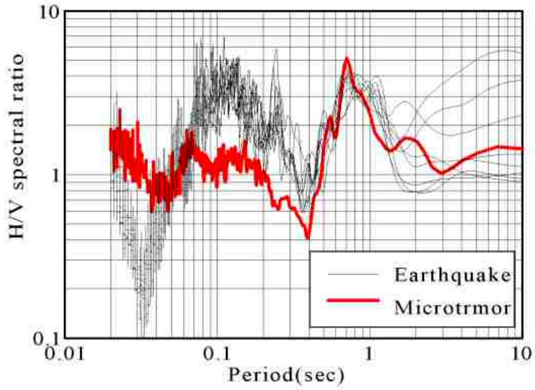


**Figure 10.** H/V spectrum for observed earthquake and microtremor observation at K-NET Marugame station (KGW003)

## *Distribution of predominant period and amplification factor*

The distribution of the predominant period and the amplification rate obtained by all measuring point data are shown in Figures 11 and 12. The contour of the predominant period is also shown. When the entire Takamatsu Plain is analysed, following features can be noted.

In the Koto River alluvial fan, the ground is comparatively good, because the predominant period is about 0.5 second or less and amplification factor is also small. However, at the mouth of Shine and Kasuga rivers, river flows in the eastern part of plain and present urban area are developed in this delta zone. This zone has predominant period about 0.5 second or more. This result shows that thick soft sediments are deposited in this area. Similarly, predominant period of about 0.6 second or more is noted in reclaimed land along the coast. In the centre of the plain, which is located in the alluvial fan, the predominant period is ranged between 1.0 second and more and this value reflects a deep ground structure. On the terraces and mountains and hills of southern part of the plain, the predominant period is about 0.4 second or less. Therefore, this indicates that the ground is hard.

The geomorphological features are determined as per the data. Figure 13 shows the relationship between the predominant period and amplification factor obtained from the H/V spectra at the microtremor observation sites of various geomorphological terrains. Results are arranged in Figure 13 for each geomorphological terrain. Each geomorphological terrain is classified as group-I, group-II, and group-III (ground group) and it is realized that the ground group usually based on the characteristics value (natural period) of specification for highway bridges (JRA, 2002). The following points can be acertained.

1) For reclaimed land (N-value : 0-10) along the coastline, it is evident that the old landfill is the ground group-II, and the new landfill is group-III. The recent reclamation gives longer predominant period. Bedrock is deep and a thick soft sediment layer is present above it. Likewise, artificially modified ground (N-value : 0~20) has long predominant period and it is considered as group-III.

2) Delta zone (N-value : 0-15) is classified as group-II or group-III. Among these, in the mouth of the Koto River where the sandy gravel exists at relatively shallow depth, the ground is relatively good, because the predominant period is about 0.5 second or less and amplification factor is small and this ground is considered to be group-II.

Similarly, Takamatsu urban area has predominant period 0.5 second or more and it is classified as group-III. This area has thick sediment layer and it belongs to mouth or delta of Shin and Kasuga rivers.

3) In the alluvial fan (N-value : 10~), which is mainly composed of sandy gravel, the predominant period is greatly varies as per the sites. Likewise, there are some sites that have values of more than 1.0 second. There are some sites where ground group II and group III are adjacent and detailed examinations are necessary in the future. Perhaps, this resembles to a deep ground structure in the sites, which has predominant period more than 1.0 second.

4) In the terrace and hill area of southern part of plain, the predominant period is about 0.4 second or less. Therefore, it is considered that the ground is good and majority of ground belongs to group-I.

5) In the basin of the Koto River, the ground is hard, because gravel and rounded pebble had been transported from the mountains by the repeated flood in the past, and has been deposited in the plains over many years. However, the basin of Shin and Kasuga rivers has relatively soft ground because of sand and clay deposits. These rivers are smaller than the Koto River and have a raised river bed.

Thus, it is understood that the ground vibration properties presumed from the microtremor have good correspondence with the surface geology and the microtopography.

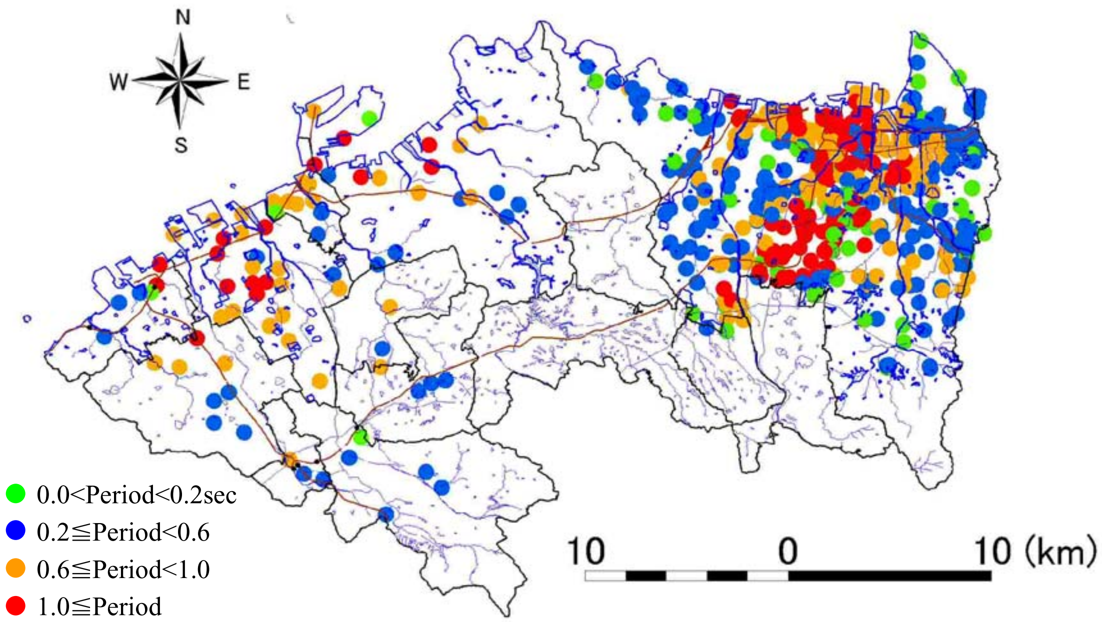


**Figure 11.** Distribution of predominant period in Takamatsu & Marugame-Sakaide Plain

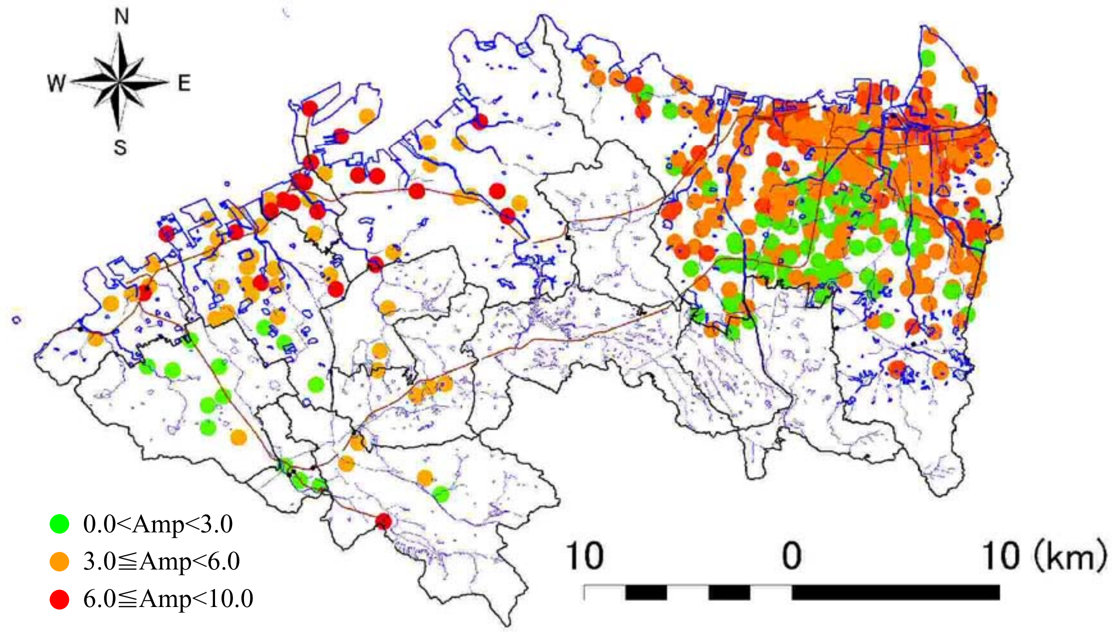


**Figure 12.** Distribution of amplification factor in Takamatsu & Marugame-Sakaide Plain

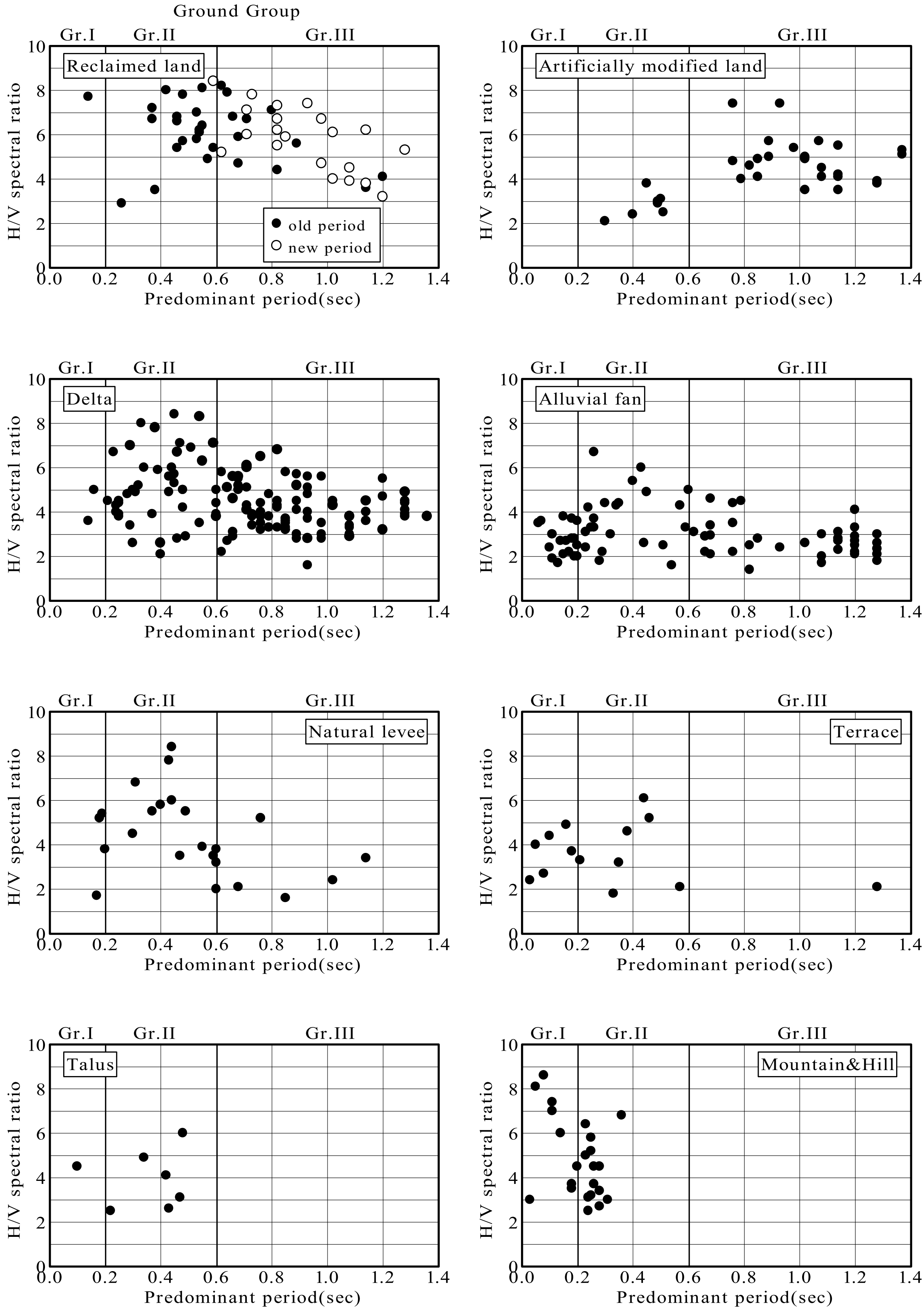


**Figure 13.** Relation between geomorphological classification, predominant period and amplification factor

## *Geomorphological classification and shape of H/V spectrum*

An investigation of the depth of bedrock and a seismic zoning etc. in addition to use of the H/V spectrum by microtremor to enables the ground amplification properties to be understood.

The first order peak seen in H/V spectrum is considered to be an accurate indication of the natural period of the ground. There is a good correlation between the bedrock depth and period. This allows the distribution of bedrock depth in the sedimentary basin to be determined accurately with high density observations.

In addition to a relative value of the predominant period and the amplification factor, the H/V spectrum by microtremor is used to group the ground type by the shape of spectrum for a seismic zoning. The H/V spectrum can be classified into five types for the surface geological features as shown in Figure 14. Likewise, when the contrast of the S-wave velocity of the surface and the bedrock is high, a visible peak appears in H/V spectrum. Conversely, when the contrast of the S-wave velocity of the surface and the bedrock is low, it becomes difficult to determine a clearly visible peak (Tokimatsu et al, 1994, Ohmachi et al, 1994, and Wakamatsu et al, 1996).

Type-A: On a bedrock site, H/V spectral ratio is almost 1.0 during all period and spectrum shape is flat.

Type-B: On the mountain and hill site, the weathered surface possesses the peak on the short period side, even if the surface is a diluvium, it has a clear peak on the short period side.

Type-C: On the alluvial fan site, it has two visible peaks. It gives the peak that reflects the influence of the amplifying characteristic of the alluvium in the short period side but the peak value is relatively small. The peak that reflects influence of deep layers appears on the long period side.

Type-D: On the delta site, it gives the peak that reflects the influence of the amplifying characteristic of the alluvium in the short period side but the peak value is relatively small. However, the peak that reflects the influence of the deep layer is usually larger than Type-C.

Type E: On the reclaimed site, it gives the peak that reflects the influence of the deep layer in the long period side. The peak on the short period side could not disclose. It is seen that the amplification factor cuts 1.0.

This indicates effectiveness of H/V spectrum of microtremor for natural period estimation of deep soil structures in case of clear S-wave velocity if contrast exists between bedrock and upper layers.

Similarly, clear peaks are also evident in relatively short range of periods as in Type-B. This peak may correspond to the second higher mode of Rayleigh wave. The natural period for surface layer above the upper boundary of stiff diluvial gravel layer is also analysed. It is understood that the relatively shallow soil structures can be detected from H/V spectrum of short period microtremor when the clear layer boundary with high impedance ratio is existed.

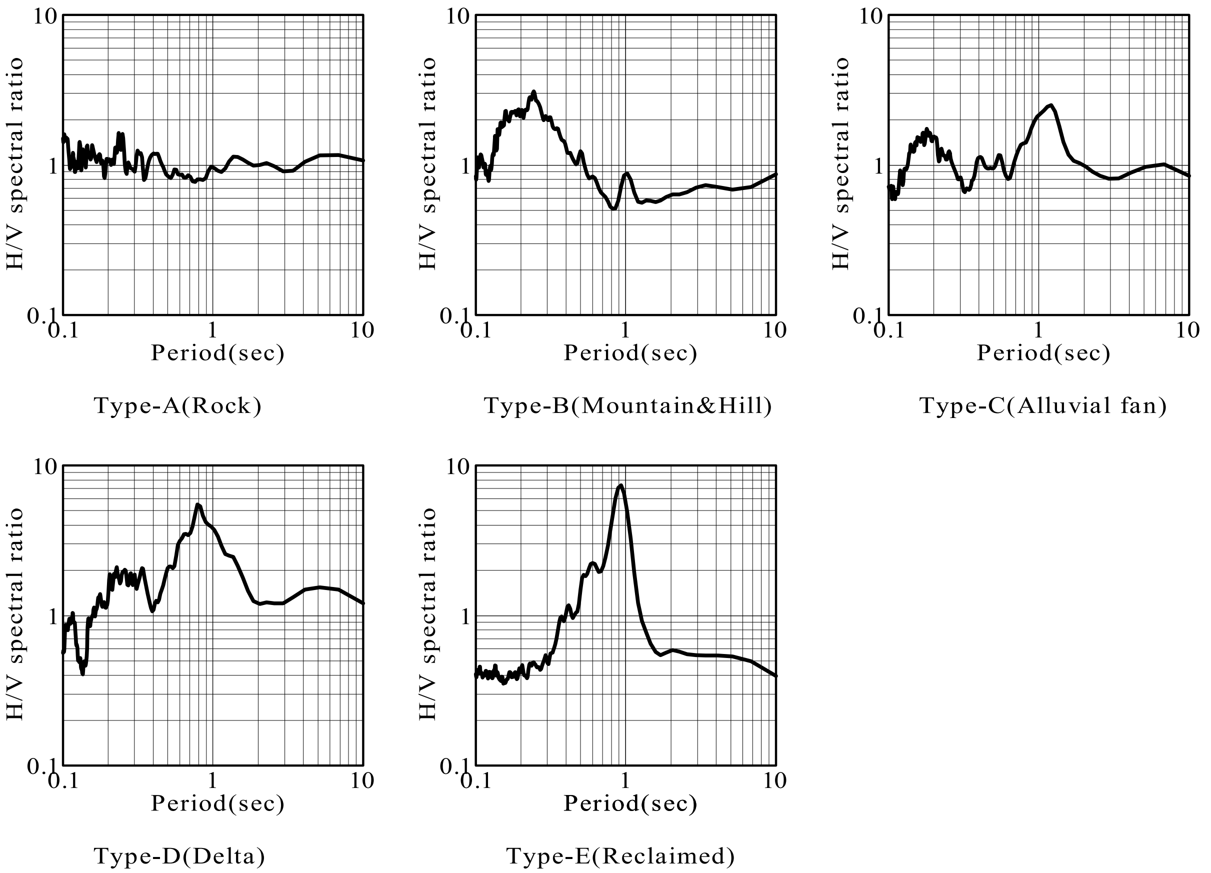


**Figure 14.** Surface geological feature and typical shape of H/V spectrum

The various shapes of H/V spectrum are considered to show varieties of shallow soil conditions. Clear peaks are observed at sites where a high contrast is present at the engineering bedrock and upper alluvial layer. The peak period corresponds the amplification period of the S-wave for the layers above the boundary (e.g. alluvial layer). Figure 14 shows the period for some sites with clear H/V peak.

# CONCLUSIONS

In conclusion, the shape of H/V spectrum shows good correspondence with geological conditions in the Takamatsu Plain and the Marugame-Sakaide Plain. It implies that the long period element of 0.6 second or more is superior and amplification factor is greater in delta and reclaimed land. The short period element of 0.4 second or less is superior and amplification is lesser in terrace, mountain and hill.

The depth of engineering bedrock is estimated from predominant period in the longer period range of H/V spectra of microtremor records. Average S-wave velocity is roughly estimated for each soil layers. The depth of upper boundary of engineering bedrock is estimated from second predominant period. The higher predominant period exists when clear impedance ratio is detected.

The collection of data concerning the bedrock structure and the S-wave velocity profile is necessary for more accuracy.

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