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SITE EFFECTS IN HIROSHIMA PREFECTURE, JAPAN DURING THE 2001 GEIYO EARTHQUAKE OF MARCH 24, 2001

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SUMMARY

During the 2001 Geiyo earthquake of March 24, 2001, large shaking was observed over a wide area of Chugoku and Shikoku district, western Japan. The observed PGA during the main shock showed large differences among several sites where the focal distances were almost equal. This is considered to be due to the regional differences of site effects. In this study, first, in order to grasp site effects within Hiroshima prefecture, we estimated the predominant period of the ground in the linear condition and during the 2001 Geiyo earthquake by using various methods ever before proposed, from microtremors and seismic motion at the site of the K-NET, the KiK-net and the SIIN (Seismic Intensity Information Network) in Hiroshima prefecture. In addition, by comparing these results, we considered the nonlinearity of the soil during the main shock, and the relations between the characteristics of strong ground motion and site effects. As a result, we found that the H/V spectra were able to estimate the predominant period of the soil stably, strong nonlinear behavior of the ground that occurred at many sites during the mainshock, and a reason for the high acceleration that contains many short period waves observed at most sites during the mainshock, which is due not only to the source but also to site effects.

INTRODUCTION

During the 2001 Geiyo earthquake of March 24, 2001, large shaking was observed over a wide area of Chugoku and Shikoku district, western Japan. The magnitude (Mj) of this earthquake was 6.7 (Mw=6.9), the hypocenter was at latitude 34.129N, longitude 132.696E and 46km depth (Japan Metrological Agency; JMA), and it has been estimated that this was an intra-plate earthquake near the subduction zone in the Philippine Sea plate (see Figure 1). This earthquake caused loss of life of 2 persons, collapse of 62 buildings and half collapse of 532 buildings.

Hiroshima prefecture, which was the closest to the epicenter of the mainshock, has a Seismic Intensity Information Network (SIIN) with 99 observation sites. Earthquake motions of over 5- at a seismic intensity scale of JMA were observed at 60 sites during the mainshock. However, the main structures of few buildings suffered large damage, although large seismic intensity was measured in many sites in

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Hiroshima prefecture. Although the seismic damage was smaller than that of the Hyogo-ken Nanbu Earthquake of 1995, the importance of the earthquake disaster prevention countermeasures was re-emphasized. In addition, some researchers have indicated that western Japan has recently become an active earthquake area, and it is necessary to consider more detailed earthquake disaster prevention countermeasures. The observed peak ground acceleration (PGA) during the mainshock varied widely among several sites where the focal distances almost equal, and it was much larger than PGA estimated by a past attenuation relation. We considered the regional difference of site effects to be this reason.

In this study, first, in order to grasp the site effects within Hiroshima prefecture, we measured microtremors at the observation sites of the SIIN, the K-NET [1] and the KiK-net [2], and estimated the predominant period of the ground in the linear condition at each site using results of measurements and observed weak ground motion. Next, we estimated the predominant period during the 2001 Geiyo earthquake using strong ground motion during the main shock. In addition, by comparing these, we examined the nonlinearity of the soil during the main shock. Then, we examined the relationship between the characteristics of strong ground motions and site effects during the main shock.

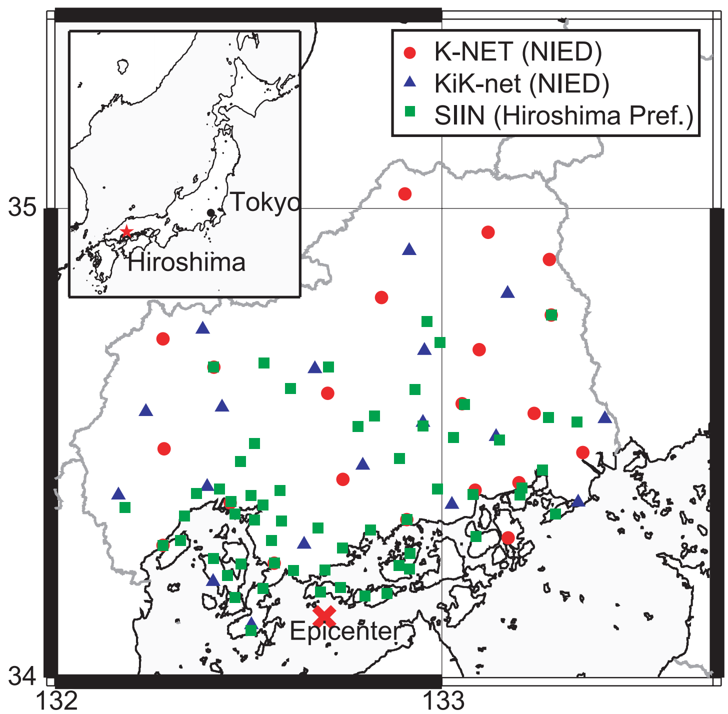

Figure 1. Location map of the epicenter of the 2001 Geiyo Earthquake, and the observation sites in Hiroshima prefecture. The circles, triangles and squares show the observation sites of the K-NET, the KiK-net and the SIIN (Seismic Intensity Information Network), respectively. Of the SIIN sites, only those where earthquake motions with JMA seismic intensities of over 5- observed during the main shock are shown.

ESTIMATION OF PREDOMINANT PERIOD OF GROUND IN LINEAR CONDITION

In this study, we used six methods to estimate the predominant period of the ground in the linear condition, as shown below.

1. Averaged Fourier Spectra of microtremors (FSP_{MT})

2. Horizontal-to-vertical spectral ratios of microtremors (H/V_{MT}) (Nakamura [3])
3. Horizontal-to-vertical spectral ratios of earthquake motion (H/V_{EQ})
4. Acceleration response spectra of earthquake motion (RESSP)
5. Spectral inversion method using earthquake motion (SPINV) (Iwata [4])
6. Transfer function based on 1-D propagation theory (SHAKE) (Schnable [5])

We applied two techniques to FSP_{MT}, H/V_{MT}, H/V_{EQ} and RESSP. One was for evaluating the period of the largest peak of the spectrum by each method as a predominant period (technique A). The other was for evaluating the common peak in the spectrum by all methods as a predominant period (technique B) (see Figure 2). For SPINV, only technique B was used. The details of each method are described in the following.

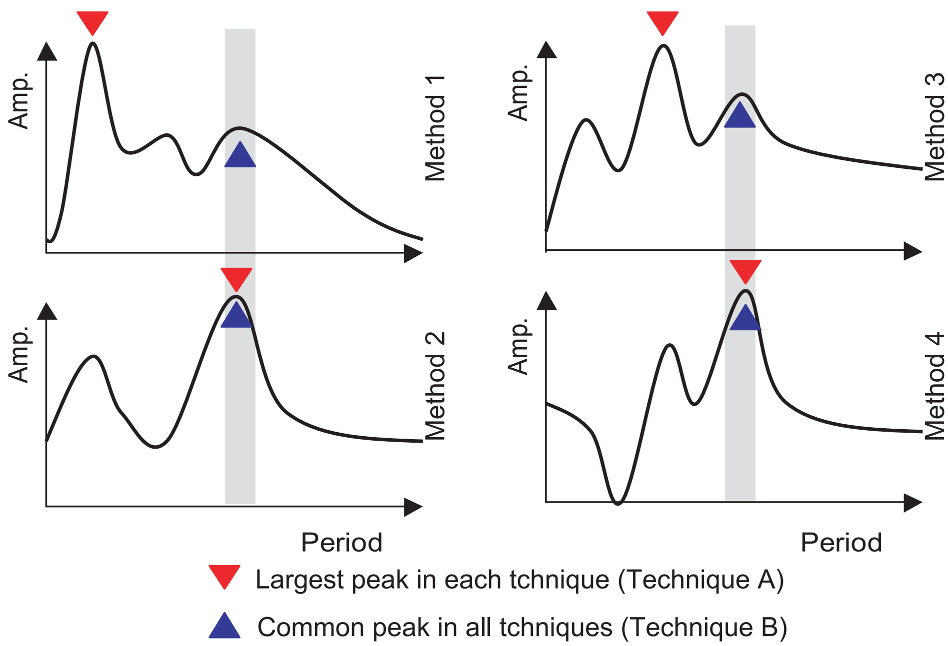

Figure 2. Conceptual scheme of decision-making procedure in predominant period of the ground. In technique A and technique B, the predominant periods of the largest peak for each technique and the common peak for all techniques, respectively, are recognized.

Estimation based on microtremors measurements

Outline of measurements

The seismic observation system of our country was reexamined in detail and greatly improved after the 1995 Hyogo-ken Nanbu earthquake. In Hiroshima prefecture, seismometers not only of the K-NET and the KiK-net but also of many seismic intensity meters have been installed by the JMA and local governments to immediately grasp of occurrence of earthquake damage.

In this study, we carried out microtremors measurements at 60 observation sites of the SIIN where earthquake motion over 5- at seismic intensity scale of the JMA was observed during the main shock, 21 sites of the K-NET and 18 sites of the KiK-net in Hiroshima prefecture. A location map of microtremors measurements sites is shown in Figure 1. We used a tri-axial velocimeter (VSE-11G、VSE-12G; Tokyo Sokushin Co. Ltd) of the servo type with a natural frequency of 1 Hz and a data logger (CV-563, 24 bits digitizer, 32 megabytes flash memory, and GPS time synchronization; Tokyo Sokushin Co. Ltd.) in this study. Sampling frequency was 100 Hz and duration was 20 or 30 minutes.

Outline of analysis

First, 20 sets of data segments with little influence of vibration from traffic noise and factory machines were selected from the measured microtremors. One segment consisted of 4096 data. Next, Fourier amplitude spectra are computed from each segment, and their spectra were averaged. FSP_{MT} is defined as

$$FSP_{MT}=(S_{NS}^{2}+S_{EW}^{2})^{1/2} \tag{1}$$

where S_{NS} and S_{EW} are averaged Fourier amplitude spectra of NS and EW components, respectively. H/V_{MT} is defined as

$$H/V_{MT}=(S_{NS}^{2}+S_{EW}^{2})^{1/2} / S_{UD} \tag{2}$$

where S_{UD} is the averaged Fourier amplitude spectra of UD component.

Estimation based on earthquake motion records

The site where the predominant period is estimated from earthquake motion records is an observation site of the K-NET and the KiK-net where weak ground motion was observed. Records that satisfied the following conditions within earthquake motion data observed from January 2000 to August 2003 were used.

1) Records observed simultaneously at 11 or more sites among 39 sites of the K-NET and the KiK-net in Hiroshima prefecture.
2) Records of 100 cm/sec^2 or less at PGA.

Earthquake motion data were analyzed using the H/V_{EQ}, RESSP and SPINV methods. In the H/V_{EQ} method, first, Fourier amplitude spectra are computed using data of 163.84 sec. from the beginning of each earthquake motion record with smoothing by Hanning window. Next, H/V spectral ratios are calculated as well as H/V_{MT}, and these ratios are averaged for every site. In the RESSP method, acceleration response spectra of 5% damping in the period ranges from 0 to 10 sec. (0.002 sec. interval) are computed by vectorial summation of two horizontal components. The predominant period in this method is the average of that of each spectrum.

Spectral inversion is a method for separating source, path and site characteristics from observed S-wave in the frequency domain. TABLE 1 shows the dataset for this analysis. When plural site amplifications are separated by the analysis, the predominant period of the ground is estimated using their averaged site amplification. In this analysis, a theoretical transfer function derived from the known underground structure is used as the constraint condition. This underground structure was reevaluated by inversion analysis (genetic algorithm; GA, Yamanaka [6]) for the ratios of earthquake motion spectra observed on the surface and in the borehole (H/H spectral ratios; H/H_{EQ}).

Estimation based on 1-D propagation theory

The predominant period of the ground at the observation site from which the underground structure data is obtained, is estimated from 1-D propagation theory. The underground structure data at the observation site of the K-NET and the KiK-net are obtained from PS-logging. S-wave structures of the SIIN site are evaluated using an empirical relation (Imai [7]) from the N value in the soil property data obtained by boring exploration. The unit weight of gravel, sand and clay is assumed to be 1.8-2.0, 1.7-1.9 and 1.4-1.8 tf/m^3, respectively. The damping factor is assumed to be 2% for the bottom layer (half space) and 5% for the other layers.

TABLE 1. Dataset used for analysis by the spectral inversion method.

Dataset No.	Site	No. of sites	No. of Earthq.
1	H01 H02 H03 H05* H06 H09 K09 K12	8	18
2	H01 H03 H07* H08 H10 K01 K03 K04 K08 K12 K21	11	11
3	H01 H02* H03 H04 H05 H06 H08 H09 H10 H11 H12 K05	12	9
4	H01 H02* H07 H08 H09 H13 H14 H16 K06 K12 K14 K19	12	6
5	H01 H02* H09 H10 H17 H18	6	5
6	H01 H02 H07* H08 H13 H14 H15 K06 K14 K19	10	6
7	H01 H03 H04 H05 H06 H07* H09 H10 K02 K03 K04 K06 K09 K11 K12 K21	16	6
8	H01 H03 H04 H05* H06 H07 H09 H10 K03 K04 K06 K08 K12 K13 K19 K20	16	7
9	H01 H02* H03 H06 H07 H09 H10 K03 K04 K07 K08 K12 K17 K21	14	7
10	H01 H03 H04 H05 H06 H07* H08 H09 H10 H11 K01 K03 K04 K10 K12 K18	16	9
11	H01 H03 H06 H07* H08 H09 H10 K01 K03 K04 K08 K12 K13 K16 K21	15	6
12	H01 H02 H03 H04 H05* H06 H07 H09 H10 K03 K04 K06 K07 K08 K11 K12 K13 K15 K17 K19 K20 K21	22	3

H and K show the site code of the KiK-net and the K-NET, respectively. * indicates the site used as condition of constraint .

Verification of accuracy of each method

In this study, the estimation accuracy of each method is verified at 18 sites of the KiK-net because the predominant period obtained from the ratios of earthquake motion spectra observed on the surface and in the borehole was assumed to be correct. As the index of the accuracy, we use the average of the relative error (ε) shown in the following, as well as the correlation coefficient (γ) of the correct values (x_i) and the estimated ones (y_i).

$$\varepsilon = (1 / n) \Sigma\{ (y_i - x_i) / x_i \} \qquad (3)$$

Figure 3 compares the predominant period of the ground in the linear condition by H/H spectral ratios and by the other methods. The correlation coefficient for FSP_{MT}(A) and RESSP(A) is small: 0.415 and 0.663, respectively. The average of their relative errors is large: 50.86% and 35.78%. The low accuracy of FSP_{MT}(A) is due to the very long predominant period of one of the sites. However, even if this site is removed, the predominant period is evaluated as too short at many sites. This is caused by microtremors, such as vibration of traffic and machines. The predominant period by RESSP(A) is estimated at 0.3 sec. or less at all sites, because it reflects the influence of the source characteristic of earthquake motion.

However, the correlation coefficient for H/V_{MT}(A) and H/V_{EQ}(A) is large: 0.941 and 0.955, respectively. The average of their relative errors is small: 19.99% and 13.90%. This is due to the offsetting of the effect of the source of microtremors by taking into account the ratio between horizontal and vertical motion. Therefore, the predominant period estimated by H/V spectra does not differ greatly from the actual one.

Because the theoretical transfer function computed using underground structures that can explain the H/H spectral ratios is used as the constraint condition, correlation between the predominant period estimated by SPINV and the correct value is very high (γ=0.965 and ε=8.79%).

With SHAKE, the correlation coefficient is not insignificant (γ=0.868), but the average relative error is large (ε=38.92%). The error tends to increase at sites where the predominant period is short. Because a short period motion is excited in a shallow underground structure, the accuracy of the shallow underground structure's modeling is important. However, it is difficult to carry out detailed modeling because such structure is complicated.

For technique B of FSP_{MT}, H/V_{MT}, H/V_{EQ}, and RESSP, the correlation coefficient is larger than 0.98, and the average relative error is less than 10%. Therefore, in order to improve the estimation accuracy of the predominant period, it is important to compare and examine results obtained from various methods.

Distribution of predominant period of ground in linear condition

In this study, the predominant period of the ground in the linear condition at the KiK-net sites is determined by using the H/H spectral ratios. For that at the K-NET and the SIIN sites, the average of results obtained from five methods where the average relative error is smaller than 10% (FSP_{MT}(B), H/V_{MT}(B), H/V_{EQ}(B), RESPSP(B) and SPINV) and the average between FSP_{MT}(B) and H/V_{MT}(B) is used. Figure 4 shows a distribution map of the predominant period of the ground in the linear condition. The predominant period at most sites in northern Hiroshima, which consists of mountains and inland valleys, is 0.1-0.3 sec. Although several sites on the sedimentary basins in southern Hiroshima have predominant periods longer than 0.6 sec., those at 80% or more of them are shorter than 0.4 sec.

PREDOMINANT PERIOD OF THE SOIL DURING THE 2001 GEIYO EARTHQUAKE

We estimate the predominant period of the ground during the 2001 Geiyo earthquake using three methods, as shown below.

1. Horizontal-to-vertical spectral ratios of strong ground motion (H/V_{EQ})
2. Acceleration response spectra of strong ground motion (RESSP)
3. Transfer function by 1-D equivalent linear method (SHAKE NS and EW) (Schnable [5])

For H/V_{EQ} and RESSP, techniques A and B are both used as well as analysis in the linear condition. The details of each method are described in the following.

Estimation based on strong ground motion during the 2001 Geiyo earthquake

The predominant period of the ground during the 2001 Geiyo earthquake is estimated from strong ground motion data observed at the K-NET, the KiK-net and the SIIN sites. The number of observation sites used for this analysis is less than the one for analysis in the linear condition because no digital seismic waveforms obtained at several sites due to the instruments troubles. (20 K-NET sites, 12 KiK-net sites and 56 SIIN sites).

In order to compute the H/V spectral ratios, first, the Fourier transform with smoothing by Hanning window is executed for a strong ground motion of 40.96 sec. from the S-wave arrival time. The H/V Spectral ratios are computed from the Fourier amplitude spectra as well as H/V_{EQ} in the linear analysis. The method for calculating the acceleration response spectra of the 2001 Geiyo earthquake is the same as that of weak ground motion.

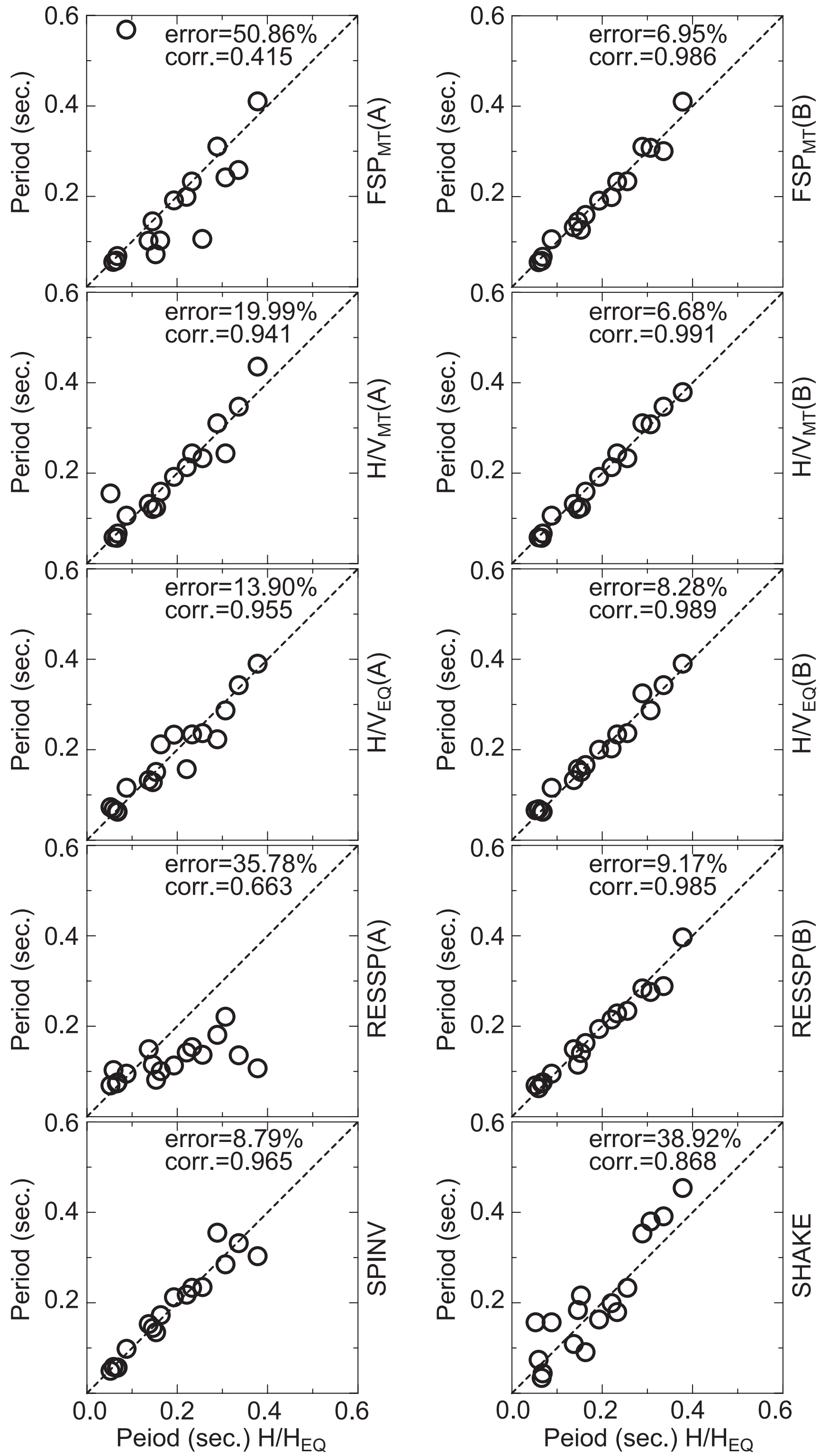

Figure 3. Comparison of predominant periods of the ground in the linear condition by H/H spectral ratios and the other methods. In the figure, error and corr. show average relative error and correlation coefficient, respectively.

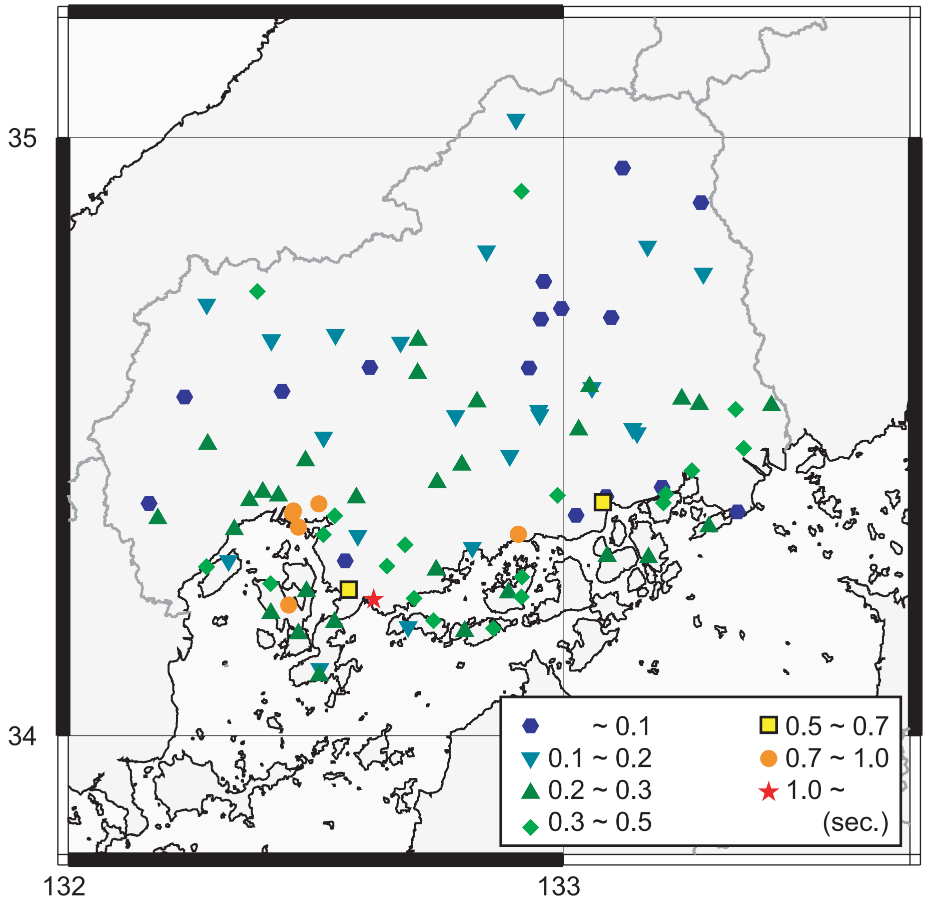

Figure 4. Distribution of predominant period of the ground in the linear condition in Hiroshima prefecture.

Estimation based on 1-D equivalent linear method

The transfer function of the ground during the 2001 Geiyo earthquake is computed by the 1-D equivalent linear method. The underground structures used for the computation are the same as those used for the linear analysis. Strong ground motion observed at a rock site (Yakiyama, Kure city) of the SIIN is corrected by focal distance, and is used for the input earthquake motion to the bedrock. Relations between shear modulus, damping factor and shear strain (G-γ and h-γ) by the past study (Koyamada [8]) are used as a nonlinear soil model.

Verification of accuracy of each method

Figure 5 compares the predominant periods of the ground during the 2001 Geiyo earthquake obtained from the H/H spectral ratios and the other methods. The average relative error of RESSP(A) (ε=26.58%) is smaller than that of H/V_{EQ}(A) (ε=28.25%). However, the correlation coefficient for RESSP(A) is small: 0.643. In addition, the predominant period obtained from RESSP(A) is estimated to be shorter than approximately 0.3 sec. These are the results of the reflecting source characteristics of the 2001 Geiyo earthquake. However, the correlation coefficient for H/V_{EQ}(A) is 0.848 and no unique point is found either.

The average relative errors of SHAKE NS and EW are large (35.19% and 38.21%, respectively). In addition to the difficulty of the modeling the shallow S wave velocity structure, this is due to the validity of the input seismic motion. Both average relative errors of H/V_{EQ}(B) and RESSP(B) are 15 % or less.

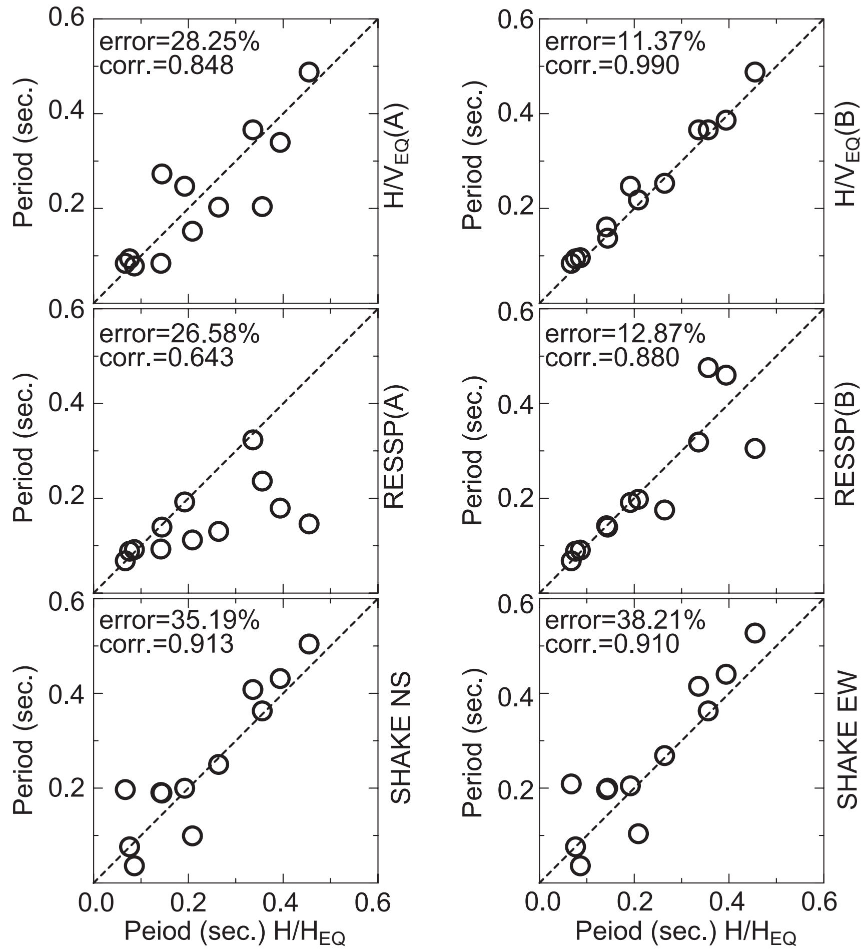

Figure 5. Comparison of predominant period of the ground during the 2001 Geiyo earthquake by H/H spectral ratios and the other methods. In the figure, error and corr. show the average relative error and correlation coefficient, respectively.

Distribution of predominant period of ground during the 2001 Geiyo earthquake

In this study, the predominant period of the ground during the 2001 Geiyo earthquake at the KiK-net sites is determined from the H/H spectral ratios. For that at both the K-NET and the SIIN sites, the average of the results obtained from two methods where the average relative error is smaller than 15% (H/V_{EQ}(B), RESPSP(B)) is used. Figure 6 shows a distribution map of the predominant period of the ground during the main shock. The predominant periods at most sites in northern Hiroshima are determined to be in the short period range from 0.1 to 0.4 sec. Those at sites in the sedimentary basins in southern Hiroshima are 0.9 sec. or more. In particular, that at the site in the central part of Hiroshima city on a thick sedimentary layer is 1 sec. or more.

NONLINEAR CHARACTERISTICS OF SOIL DURING THE 2001 GEIYO EARTHQUAKE

Figure 7 compares the predominant period of the ground in the linear condition with that during the 2001 Geiyo earthquake. During the earthquake, the period increases at all sites, and the average is 1.34 times.

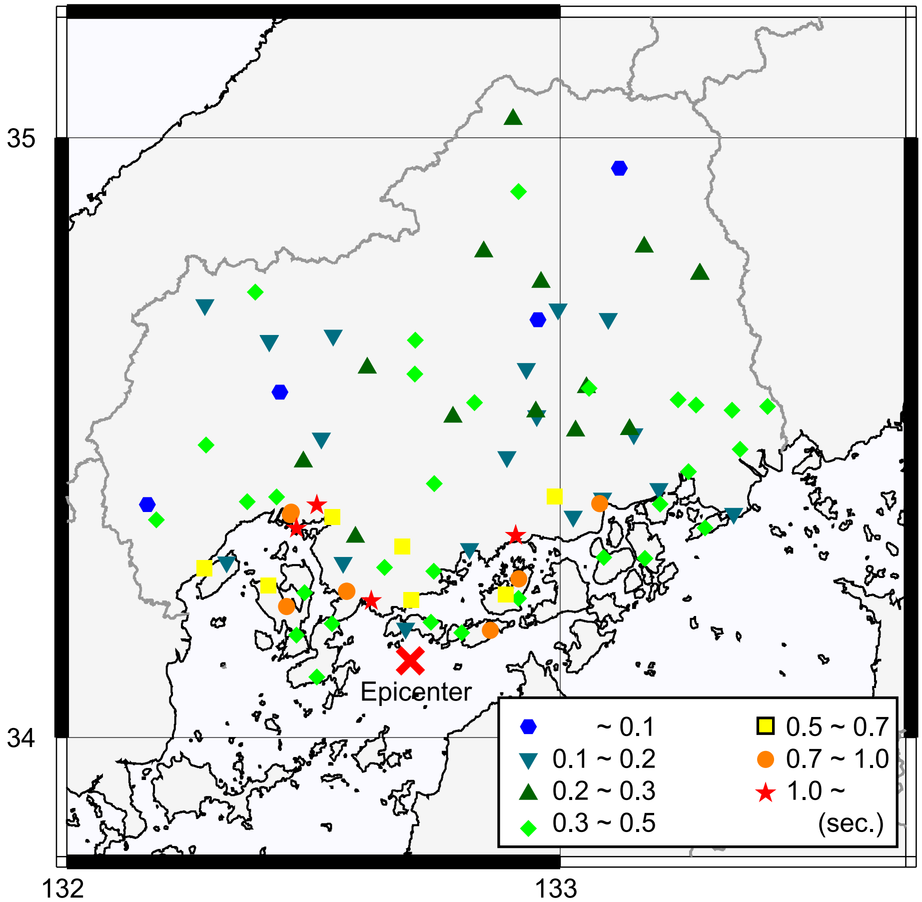

Figure 6. Distribution of predominant periods of the ground during the 2001 Geiyo earthquake in Hiroshima prefecture. The cross shows the location of the epicenter of the main shock.

The relation between the ratio of shear modulus of the soil in the nonlinearity to that in the linearity (G/G_0) and the ratio of predominant period in the linearity to that in the nonlinearity (T_0/T) (Tokimatsu [9]), is

$$G / G_0 = (T_0 / T)^2 \tag{4}$$

The relation among PGV, S-wave velocity (V_{S0}) and effective shear strain (γ_{eff}) of surface soil was formularized (Tokimatsu [10]) as

$$\gamma_{eff} = 0.4\ PGV / V_{S0} \tag{5}$$

We use these relations to compute the shear modulus of the soil from the predominant period estimated in this study and the effective shear strain during the main shock from the PGV and S-wave velocity structures. The relation between the shear modulus ratio and the effective shear strain for every soil property classification is shown in Figure 8 with the G/G_0-γ relation obtained from the in-site dynamic test of the soil property (Imazu [11]). The shear modulus ratio of clay tends to be smaller than the previous G/G_0-γ relation. However, those of sand and gravel correspond well with the results of the in-site test. Midorikawa [12] suggested that the nonlinearity of the soil becomes remarkable when the effective shear strain exceeds 3E-4. In this study, the effective shear strain exceeds 3E-4 at many sites. Moreover, the shear modulus ratio is 50% or less than that in the linear condition. Therefore, it is suggested that strong nonlinear behavior of the soil occurred at many sites during the main shock.

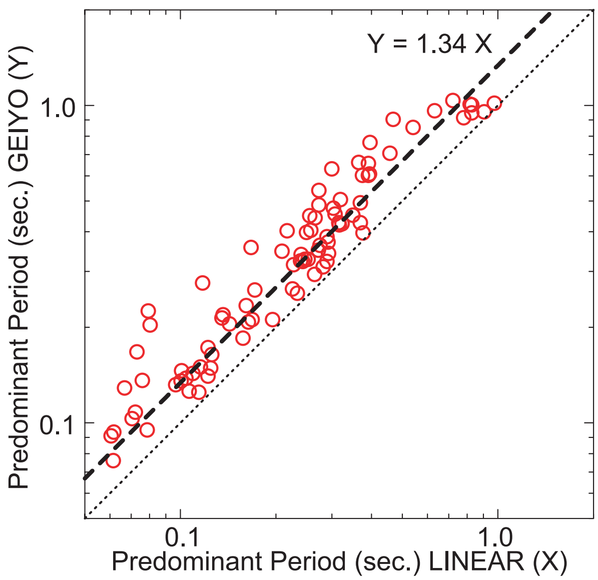

Figure 7. Comparison of predominant period of the ground in the linear condition with that during the 2001 Geiyo earthquake.

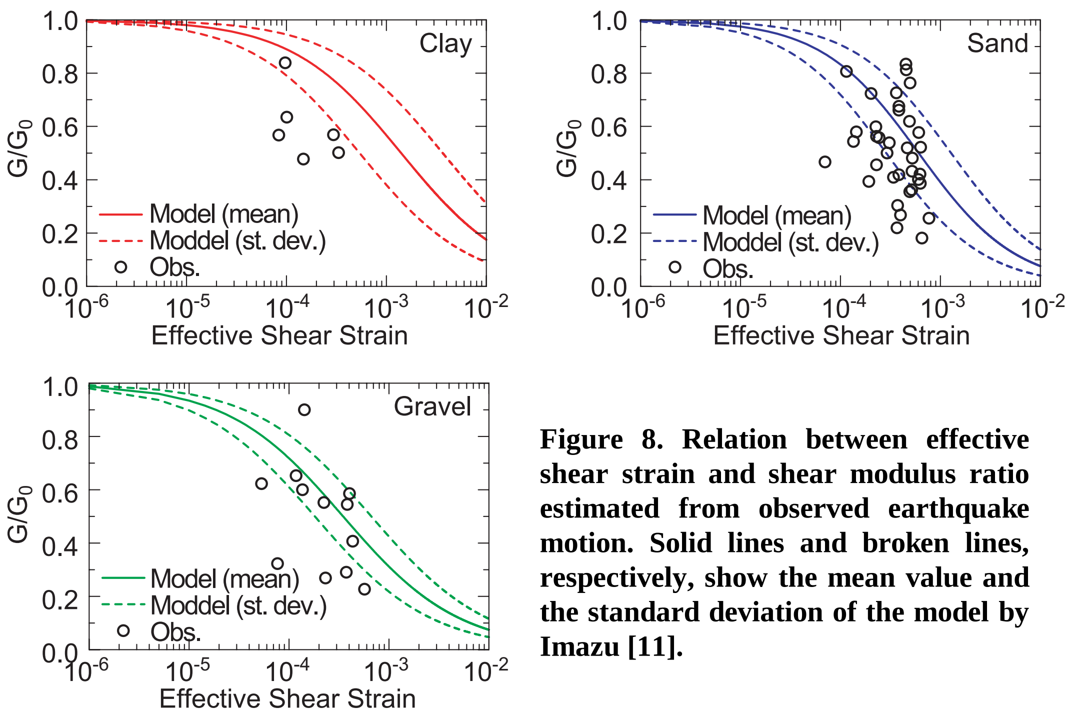

Figure 8. Relation between effective shear strain and shear modulus ratio estimated from observed earthquake motion. Solid lines and broken lines, respectively, show the mean value and the standard deviation of the model by Imazu [11].

CHARACTERISTICS OF SEISMIC MOTION DURING THE 2001 GEIYO EARTHQUAKE

Figure 9 shows the relation between peak value (PGA and PGV) of the observed strong ground motion and the attenuation relation (Si [13]). PGA and PGV in Figure 9 is the larger of two horizontal components. Since the attenuation curves in Figure 9 are for PGA and PGV on the engineering bedrock, the differences between the estimated and observed values are due to site effects on seismic motion. Therefore, the ratio between the observed and estimated peak values is considered to be the site amplification factor during the 2001 Geiyo earthquake. Figure 10 shows the relation between the predominant period of the ground during the 2001 Geiyo earthquake and site amplification factors.

The maximum site amplification factor of PGA and PGV is 6 and 3.5, respectively. The predominant period of the ground at the site with a large amplification of PGA is 0.2-0.3 sec., and that of PGV is 0.3-0.6 sec. In addition, although the amplification factor of PGA decreases remarkably as the period lengthens, that of PGV is large even at the site with a comparatively long period. It is suggested that the contribution of the predominant period of the ground to PGA is in a comparatively narrow range. However, the period range where the predominant period of the ground affects PGV is wide compared with PGA. This agrees well with the indications of the past study (Kobayashi [14]) that PGA and PGV reflect the characteristics of earthquake motion of narrow (0.1-0.3 sec.) and wide (0.5-2 sec.) period range, respectively.

Although there are several sites that have predominant periods longer than 1 second due to nonlinearity of the soil during the main shock, the predominant periods at most sites are shorter than 0.5 sec. Therefore, a reason for high acceleration that contains many short-period waves observed at most sites during the mainshock is considered to be not only the source but also site effects.

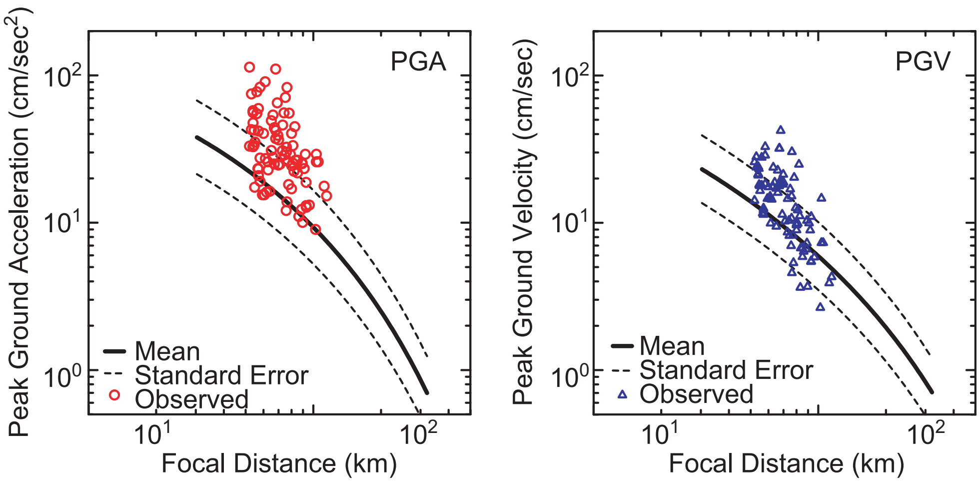

Figure 9. Relation of observed peak values of seismic motion and attenuation relation by Si [13].

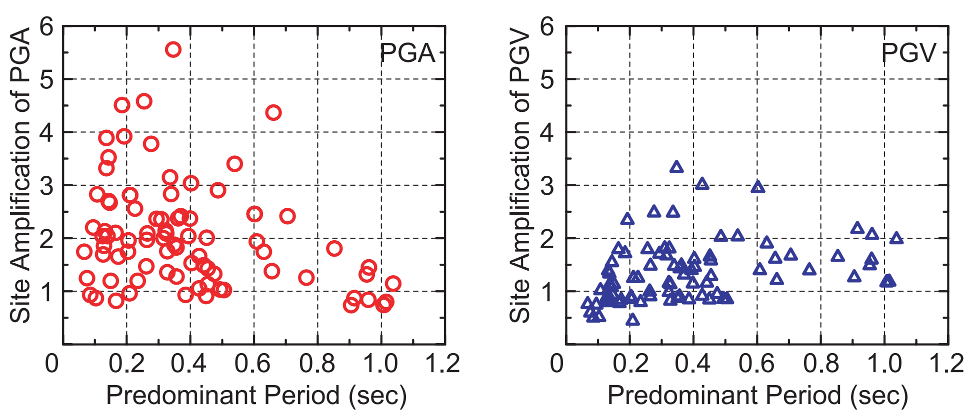

Figure 10. Relation between predominant period of the ground during the 2001 Geiyo earthquake and site amplification factors.

CONCLUSIONS

We verified the accuracy of various methods for estimation of predominant period of the ground. Moreover, we estimated the predominant period of the ground in the linear condition and during the 2001 Geiyo earthquake by using microtremors and seismic motion at sites of the K-NET, the KiK-net and the SIIN in Hiroshima prefecture. In addition, by comparing these results, we considered the nonlinearity of the soil during the 2001 Geiyo earthquake, and the relations among the characteristics of strong ground motion and the site effects. The following are our conclusions:

1) Because Fourier spectra of microtremors and response spectra of earthquake motions are influenced by the source characteristics, the accuracy of techniques for evaluating the period of the largest peak as a predominant period (technique A) is low.
2) Because the effect of the vibration source is offset by taking into account the ratio between horizontal and vertical motion, H/V spectra can estimate the predominant period of the ground stably.
3) In order to raise the estimation accuracy of the predominant period of the ground, it is important to compare and examine results obtained from various methods.
4) In the linear condition, the predominant period at most sites in northern Hiroshima, which consists of mountains and inland valleys, is 0.1-0.3 sec. Although several sites in sedimentary basins in southern Hiroshima have predominant periods longer than 0.6 sec., those at 80% or more of the sites is shorter than 0.4 sec.
5) The predominant periods of the ground during the 2001 Geiyo earthquake were increased at all sites. The predominant periods at most sites in northern Hiroshima were determined to be in the short period range of 0.1-0.4 sec., and those at sites in the sedimentary basins in southern Hiroshima were 0.9 sec. or more.
6) The effective shear strain of the soil exceeded 3E-4 at many sites during the main shock. Moreover, the shear modulus was 50% or less than that in the linear condition. This suggests that strong nonlinear behavior of the soil occurred at many sites.
7) The high accelerations that contained many short period waves observed at most sites during the main shock are considered to be due not only to the source but also to site effects.

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