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Ground motion evaluation for intra-plate earthquake by different site amplification factors and source models

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ABSTRACT: Design earthquake ground motions should be evaluated source and site specifically. Time history acceleration is preferable for the design earthquake ground motion in order to evaluate the nonlinear response of the shallow subsurface and structure. The present paper focuses on the effect of site amplification and source characteristics on the evaluation of earthquake ground motion at the site of interest. Authors calculated the earthquake ground motions of intra-plate earthquake at Matsuyama port for the earthquake in Akinada (M_W7.4) by use of stochastic Green's function method considering two kinds of site amplification factors and two kinds of source models. Effect of the selection of those characteristics on the synthetic earthquake ground motions was discussed.

1 INTRODUCTION

Design earthquake ground motions are expressed as response acceleration spectra in many technical standards. In cases where nonlinear response of the shallow subsurface and structure are to be assessed, design earthquake ground motion as time history acceleration is preferable compared to response acceleration spectra. Stochastic Green's function method (e.g. Hisada 2008), one of the methods to compute the time history acceleration of earthquake ground motion at the site of interest, has been applied to evaluate the earthquake ground motion (Cabinet Office of Japan 2017 and technical standards for port facilities in Japan 2009).

Earthquake ground motion can be expressed as the multiplication of source, path and site amplification characteristics in the frequency domain. The point to notice is that the design earthquake ground motion should be evaluated source and site specifically. It is needless to say that adequate evaluation of the three characteristics is necessary for the strong motion simulation by the stochastic Green's function method. Of the three characteristics, path characteristic expresses geometrical spreading and inelastic attenuation of earthquake ground motion, and many studies have been made on the evaluation of the path characteristic for the region of interest.

Site amplification characteristic, amplification factor of earthquake ground motion form the seismic bedrock to the ground surface, is known to differ from site to site. The present paper deals with two methods for the evaluation of the site amplification factor: (1) conventional method based on the multiple reflection theory and (2) empirical method based on the spectral inversion technique (e.g. Iwata and Irikura 1988).

With regard to the source characteristic, characterized source model (e.g. Irikura and Miyake 2011) is often used for stochastic Green's function method. Information on the source model parameter setting method targeting plate boundary earthquake and inner-plate earthquake has been accumulated, however, few studies have been done for that targeting the intra-plate earthquake. In this study, authors applied two kinds of source model that have the possibility to be introduced to the practical design: (1) the characterized source model in accordance with the latest "recipe" for strong-motion prediction shown by the Headquarters for Earthquake Research Promotion(2017) and (2) the pseudo point-source model (Yamada et al. 2015).

Earthquake ground motions of intra-plate earthquake at Matsuyama port in Ehime prefecture for the earthquake in Akinada (M_W7.4) were calculated with the above-mentioned models. Effect of the selection of those models on the synthetic earthquake ground motions was discussed.

2 SITE AMPLIFICATION FACTOR

2.1 *Target site*

Matsuyama port is located at the Matsuyama plain, sediment from the Holocene has comparatively thick layers. Surface geology is shown in Figure 1. Figure 2 depicts the S-wave velocity profile along with the soil classification at the strong-motion observation station (Matsuyama-G) in Matsuyama port. S-wave velocity structure for shallow subsurface, namely top 33 m was obtained by the PS logging, while S-wave velocity structure for deep subsurface was evaluated according to the database "J-SHIS" (2012). Alluvial soil layer is 33 m in thickness, which is comparatively thick compared with that at sites in mountainous area.

Microtremor measurement was carried out to evaluate the predominant frequencies around the target site (see Figure 1 for the microtremor observation sites). Two of the observation sites (Matsuyama-G and outer harbor) were on the reclaimed land, while two of the sites (inner harbor and airport parking) were on the boundary between the reclaimed land and the alluvial surface ground. It is well known that horizontal to vertical spectral ratio (H/V spectrum) of microtremor is highly applicable to evaluate the predominant frequency by reading

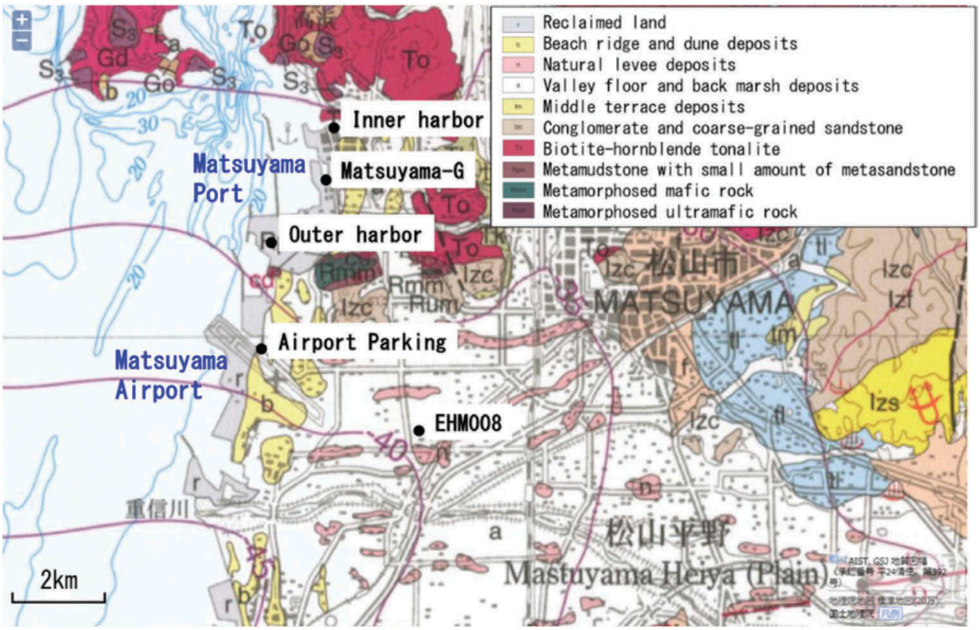


Figure 1. Geological map around Matsuyama port

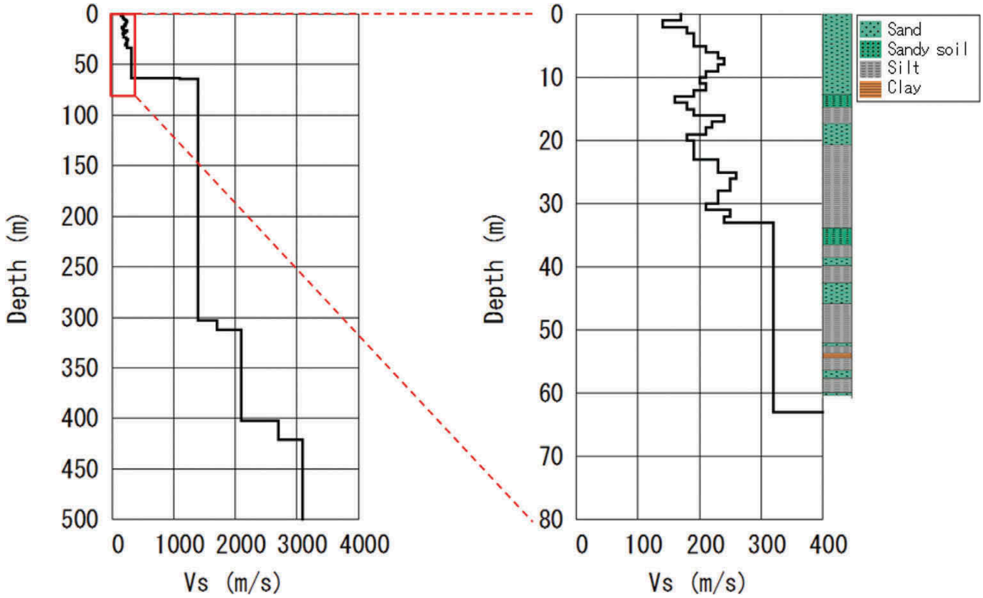


Figure 2. S-wave velocity profile along with the soil classification at Matsuyama-G

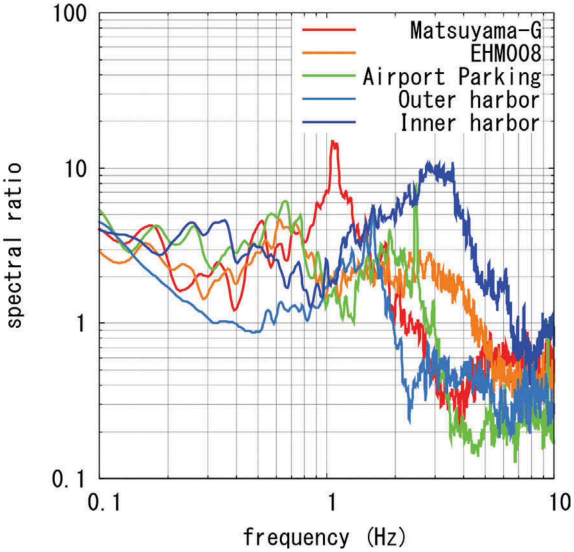


Figure 3. Microtremor H/V spectra at sites around Matsuyama port

out the peak frequency of the H/V spectrum (e.g. Konno and Ohmachi 1998). Figure 3 shows the microtremor H/V spectra at sites around Matsuyama port. EMM008 is a strong-motion observation station of K-NET (Kinoshita 1998) whose distance from the shoreline is about 3 km, while other sites are close to the shoreline. Although all the observation sites are in the Matsuyama plain, peak frequencies of H/V spectra differ from site to site. Note that even the sites that are close to Matsuyama-G, namely inner harbor site and outer harbor site, have different peak frequencies from that of Matsuyama-G. Inner harbor site has peak frequency of 3 Hz and outer harbor site has peak frequency of 1.6Hz, while Matsuyama-G has peak frequency of 1 Hz.

Table 1. Quality factors used in this study

Vs (m/s)	Q
Vs < 600	60
600 ≤ Vs < 1000	100
1000 ≤ Vs < 2000	150
2000 ≤ Vs < 3000	200
3000 ≤ Vs	300

Although outer harbor site has peak frequency comparatively close to Matsuyama-G, peak amplitude of H/V spectrum differs by a factor of 2.8. The result suggests that the peak ground acceleration as well as frequency characteristic of earthquake ground motions at those sites differ from site to site, hence the importance of the evaluation of the site specific earthquake ground motion is addressed.

2.2 *Site amplification factors at Matsuyama port*

In this study, two kinds of site amplification factors were considered: (1) theoretically obtained site amplification factor by the multiple reflection theory assuming the horizontally layered soil layers with vertically incident SH wave (1D amplification) and (2) empirically obtained site amplification factor by the spectral inversion technique according to Nozu and Nagao(2005).

Quality factor (Q) that expresses the inelastic attenuation of seismic motion is necessary for the calculation of the 1D amplification. Here, quality factor is associated with damping coefficient of the soil (h) by $Q = (2h)^{-1}$. Table 1 lists the quality factors used in this study by referring "J-SHIS" (2012).

Spectral inversion is a method that separates the source, path and site amplification charac-ter-istics from the observed earthquake ground motion data. The observed earthquake ground mo-tion can be expressed as the multiplication of source, path and site amplification characteristicsin the frequency domain as

$$O_{ij}(f) = S_i(f)P_{ij}(f)G_j(f) \tag{1}$$

where $O_{ij}(f)$ is the observed Fourier spectrum of the i-th earthquake at the j-th site, $S_i(f)$ is the source characteristic of the i-th earthquake, $P_{ij}(f)$ is the path characteristic along the source of the i-th earthquake to the seismic bedrock of the j-th site, and $G_j(f)$ is the site amplification characteristic at the j-th site.

Taking the logarithm of equation (1) yields

$$logO_{ij}(f) = logS_i(f) + logP_{ij}(f) + logG_j(f) \tag{2}$$

Combining the observed record at plural sites and applying the least squares method, one can obtain the site amplification factor at the target site.

Figure 4 compares the site amplification factors evaluated by the two methods, together with the microtremor H/V spectrum. First of all, it should be noted that 1D amplification considering only the shallow subsurface was inconsistent with other amplification and microtremor H/V spectrum, demonstrating that the 1D amplification only with the shallow subsurface greatly underestimates the site amplification factor. Therefore, it is very important to consider the deep subsurface along with the shallow subsurface in the evaluation of the earthquake ground motion. All the first-order peak frequencies of the spectra except for that of shallow subsurface amplification were 1 Hz, which means that the site amplification obtained by the spectral inversion and 1D amplification with shallow and deep subsurface were consistent

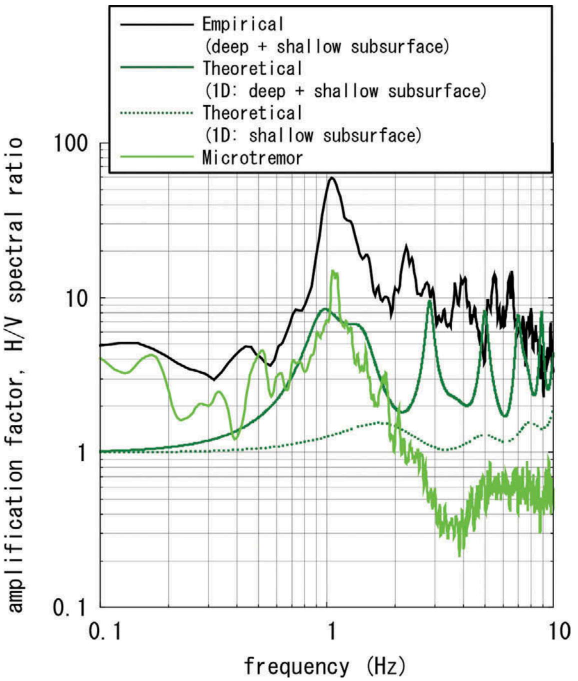


Figure 4. Site amplification factors and Microtremor H/V spectra at Matsuyama port

with the S-wave velocity structure at the site. Although the envelopes of the two amplification spectra are similar, there exists a large difference in the amplitude. Site amplification factor by the spectral inversion has much larger amplitude compared with that by 1D amplification with shallow and deep subsurface. At the first-order peak frequency, amplitude of the former was about 60 whereas that of the latter was about 8.4. One of the discrepancy was attributed to the 3D amplification characteristics caused by the basin structures at sediment sites (e.g. Furumura and Koketsu 1998), which cannot be evaluated precisely by the 1D analysis. With regard to 1D amplification, we only use that with shallow and deep subsurface hereafter.

3 SOURCE CHARACTERISTIC

3.1 *Characterized source model*

Characterized source model divides the asperities in the fault plane into subfaults and evaluates the large earthquake ground motion as the summation of the small earthquake ground motions caused by the subfaults (see left panel of Figure 5). The model can take the effect of the rupture

propagation on the earthquake ground motion into consideration. Parameter setting method for the characterized source model ("recipe") was proposed by Irikura and Miyake (2011) for crustal earthquake and the Headquarters for Earthquake Research Promotion (2017), and "J-SHIS" followed the "recipe" for the strong motion evaluation. Arai et al. (2015) and the Headquarters for Earthquake Research Promotion (2017) proposed the parameter setting method for the intra-plate earthquake, and the current study followed the method. Other parameters such as the depth of the upper boundary of the fault plane and the angles of strike, slip and dip were set by referring Koketsu et al. (2008) and "J-SHIS" (2012). Table 2 lists parameters for the characterized source model.

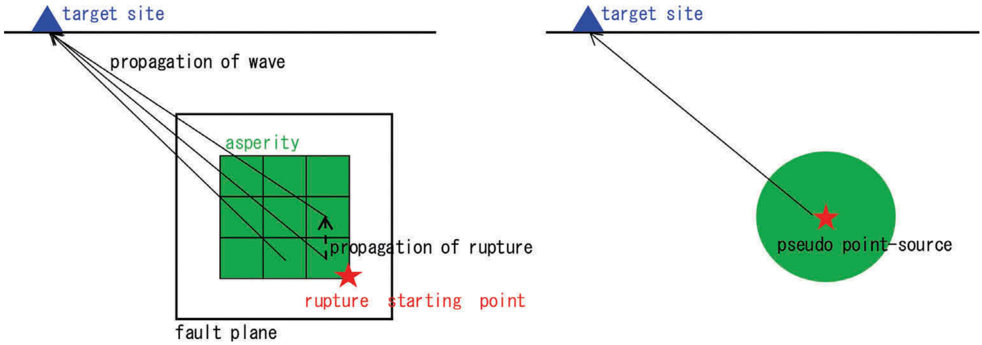


Figure 5. Concept of the characterized source model (left) and the pseudo point-source model (right)

Table 2. Parameters for the characterized source model and the pseudo point-source model

parameter	unit	characterized source model	pseudo point-source model
depth of the upper boundary of the fault plane	km	37.0	37.0
strike angle (θ)	°	180.0	—
dip angle (δ)	°	55.0	—
JMA magnitude (M)		7.4	7.4
moment magnitude (M_W)		7.4	7.4
seismic moment (M_0)	Nm	1.58E+20	1.58E+20
short-period spectral level (A)	Nm/s^2	5.74E+19	1.15E+20
density (ρ)	kg/m^3	3300	3300
S-wave velocity (β)	km/s	4.0	4.0
shear modulus (μ)	N/m^2	5.28E+10	5.28E+10
area of fault plane (S)	km^2	1715.5	—
length of fault plane (L)	km	41.4	—
width of fault plane (W)	km	41.4	—
average displacement of fault plane (D)	m	1.75	—
total area of asperities (S_a)	km^2	339.8	169.9
number of asperities		3	1
total seismic moment of asperities (M_{0a})	Nm	6.28E+19	7.08E+19
area of each asperity (S_{ai})	km^2	113.3	—
length of each asperity (L_{ai})	km	10.6	—
width of each asperity (W_{ai})	km	10.6	—
average displacement of each asperity (D_{ai})	m	3.50	—
seismic moment of each asperity (M_{0ai})	Nm	2.09E+19	—
focal depth	km	37.0, 54.0, 70.9	54.0
rupture propagation velocity (V_r)	km/s	2.88	—
rise time of each asperity (τ_{ai})	s	1.85	—
cut-off frequency (f_{max})	Hz	13.5	—
corner frequency of each asperity (f_c)	Hz	—	0.20
division number of each asperity		3×3×3	1×1×1

Number of asperities were set to three according to the "recipe", for moment magnitude (Hanks and Kanamori 1979) is 7.4. Same areas were allotted to the three asperities. Arrangement of the asperities and the rupture starting points were randomly set in order to consider all the possible combinations of those parameters. Six cases for rupture starting point and 10 cases for asperity arrangement totaled 60 cases.

3.2 *Pseudo point-source model*

Pseudo point-source model was proposed as a simplified approach for the source model (e.g. Nozu 2012, Nakano and Sakai 2017). Right panel of Figure 5 describes the concept of the pseudo point-source model. The model does not take into account of the size of the asperity and the effect of the rupture propagation on the earthquake ground motion. Owing to its simplicity, there is a limitation in the evaluation of the time-space distribution of rupture on the fault plane.

However, recent studies have shown the effectiveness of the method for the good reproduction of the strong-motion record for the past earthquakes (e.g. Nozu 2012 for inter-plate earthquake, Nakano and Sakai 2017 for crustal earthquake). Yamada et al. (2015) proposed the parameter setting method for the intra-plate earthquake of the model, which the current study followed. Parameters for the pseudo point-source model is shown in Table 2.

4 COMPARISON OF THE SYNTHETIC EARTHQUAKE GROUND MOTIONS

Earthquake ground motions at engineering bedrock (-33 m) at Matsuyama port was computed by the stochastic Green's function method. Figure 6 compares the response acceleration spectra of the synthetic waveforms with damping coefficient 0.05. Response acceleration with the empirical site amplification factor was much larger than that with 1D amplification. Response acceleration with the empirical site amplification factor in the period range of 0.7-2.0 s was larger than that with 1D amplification by a factor of 3.7. The result indicates the importance of the proper evaluation of the site amplification factor, as the conventional

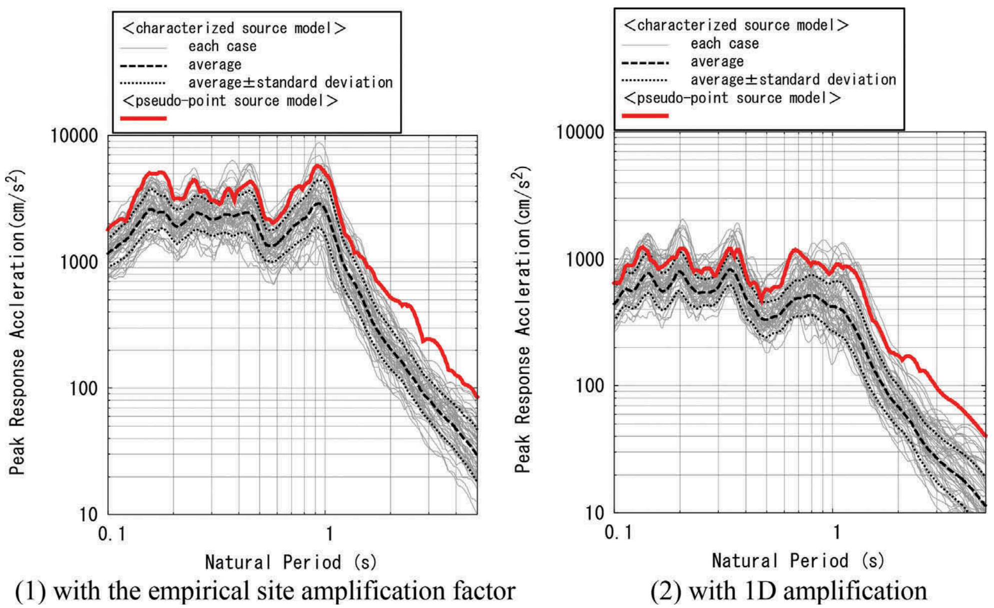
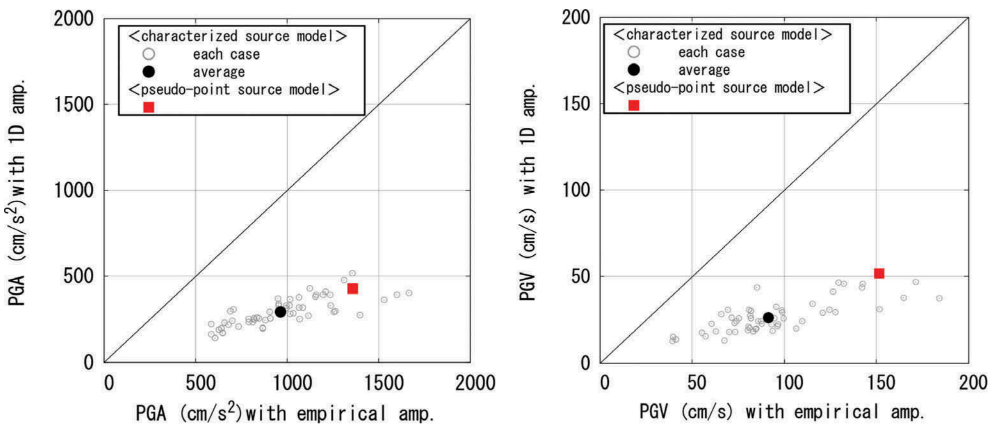


Figure 6. Response acceleration spectra of the synthetic waveforms



(1) peak ground acceleration (PGA) (2) peak ground velocity (PGV)

Figure 7. Comparison of the peak ground acceleration and peak ground velocity by the two site amplification factors

method (1D amplification) may lead to the design earthquake ground motion on the dangerous side. Variations of the response spectra with the characterized source model was large because of the variations of the asperity arrangement and the rupture starting point. Average plus standard deviation of the response spectra with the characterized source model were on a par with that with the pseudo point-source model. The reason is that the parameters for the pseudo point-source model were determined so that the earthquake ground motions were evaluated on the conservative side.

Comparison of the peak ground acceleration (PGA) and peak ground velocity (PGV) by the two site amplification factors is shown in Figure 7. Average ratios of the results with the empirical site amplification factor to that with 1D amplification were 3.3 for PGA and 3.4 for PGV, which was quantitatively similar to the difference in the response acceleration.

5 CONCLUSION

In this study, authors calculated the earthquake ground motion of intra-plate earthquake at Matsuyama port for the earthquake in Akinada (M_W7.4) considering two kinds of site amplification factors and two kinds of source models. The following findings were derived from the study.

(i) Amplification only by shallow subsurface was much smaller than that by both shallow and deep subsurface. Therefore, it is very important to consider the amplification characteristics by the deep subsurface for the evaluation of earthquake ground motion.

(ii) Response acceleration with the empirical site amplification factor was much larger than that with 1D amplification because 1D amplification ignores 3D amplification characteristics. The result indicates the importance of the proper evaluation of the site amplification factor, as the conventional method (1D amplification) may lead to the design earthquake ground motion on the dangerous side.

(iii) Variations of the response spectra with the characterized source model was large when the variation of the asperity arrangement and rupture starting point was considered. As the parameters for the pseudo point-source model were determined so that the earthquake ground motions were evaluated on the conservative side, response spectra with the pseudo point-source model was on a level with average plus standard deviation of those with the characterized source model.

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