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SIMULATION OF STRONG GROUND MOTIONS BASED ON SITE-SPECIFIC AMPLIFICATION AND PHASE CHARACTERISTICS

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ABSTRACT - Surface geology has important effects both on Fourier amplitude and Fourier phase of seismic ground motion. By using the method proposed by Kowada et al. (1998), both of these effects can be evaluated based on small to medium earthquake records. In this study, the method is applied to some shallow crustal and subduction-zone earthquakes in Japan to examine its validity.

1. Introduction

Evaluation of site effects is of fundamental importance for predicting strong ground motions from future large earthquakes to evaluate input motions for seismic design of structures. Although evaluation of site effects based on numerical models has greatly advanced in recent years, its applicability is still limited in many areas in Japan because of insufficient knowledge of subsurface structures. From engineering point of view, it is sometimes much more realistic and economical to evaluate site effects based on records from small to medium earthquakes obtained at the site of interest, because the site for construction of important structures is often fixed years before its design procedure begins and well-organized design program will allow us to conduct short-period (1-3 years) observation of earthquake ground motions at the site for construction before the design procedure begins. From such a point of view, it is quite important to develop a technique to evaluate time history of strong ground motions from future large earthquakes based on records from small to medium earthquakes obtained at the site of interest. From such a point of view, besides the EGF method, the method to simulate strong ground motions based on site-specific amplification and phase characteristics, which was first proposed by Kowada et al.(1998) is a very promising technique, because it can evaluate effects of surface geology both on Fourier Amplitude and Fourier phase of ground motions, although its applicability has not been fully investigated so far. In this study, strong ground motions are simulated for some shallow crustal and subduction-zone earthquakes in Japan to examine the validity of the method. We first evaluate empirical site amplification factors at strong-motion sites all over Japan including K-NET sites, KiK-net sites and sites at major ports, by using spectral inversion technique. Then, we select some several shallow crustal and subduction-zone earthquakes in Japan, for which ground motions are simulated using the present method. For subduction-zone earthquakes, simple characteristic source models are newly developed and used.

2. Evaluation of empirical site amplification factors at strong-motion sites

2.1. Data and method

Site amplification factors at strong motion sites were evaluated using spectral inversion technique (e.g., Iwata and Irikura, 1986). Figure 1 shows the strong motion sites and epicenters of the earthquakes used for the analysis. The analysis was conducted for six different regions. Medium-sized earthquakes were used, whose JMA magnitude is in the range from 4.5 to 6.0. To avoid the effects of soil nonlinearity, records with PGAs exceeding 100cm/s^2 were excluded from the analysis. The analysis is based on following equation.

$$\left| O_{ij}(f) \right| = \left| S_i(f) \right| \left| P_{ij}(f) \right| \left| G_j(f) \right| , \qquad (1)$$

where $|O_{ij}|$ is the observed Fourier spectrum (vector sum of two horizontal components), $|S_i|$ is the source spectrum, $|P_{ij}|$ is the path effect and $|G_j|$ is the site amplification factor. As for the path effect, geometrical spreading and nonelastic attenuation are considered. Q-values appropriate for each region (Kato, 2001; Satoh and Tatsumi, 2002; Petukhin et al., 2003) are used. The analysis are conducted in two steps: In the first step, $|O_{ij}|$ is calculated from portions of the records with a duration of 40 seconds including S waves. Then, based on equation (1), $|S_i|$ is estimated. In the second step, $|O_{ij}|$ is calculated from portions of the records with a duration of 160 seconds including not only S waves but also later phases. Then, based on equation (1) and using the $|S_i|$ previously determined, $|G_j|$ is estimated. $|G_j|$ thus estimated reflects the lengthening of ground motion duration due to local geology (e.g., Beauval et al., 2003) and suitable for Kowada's technique.

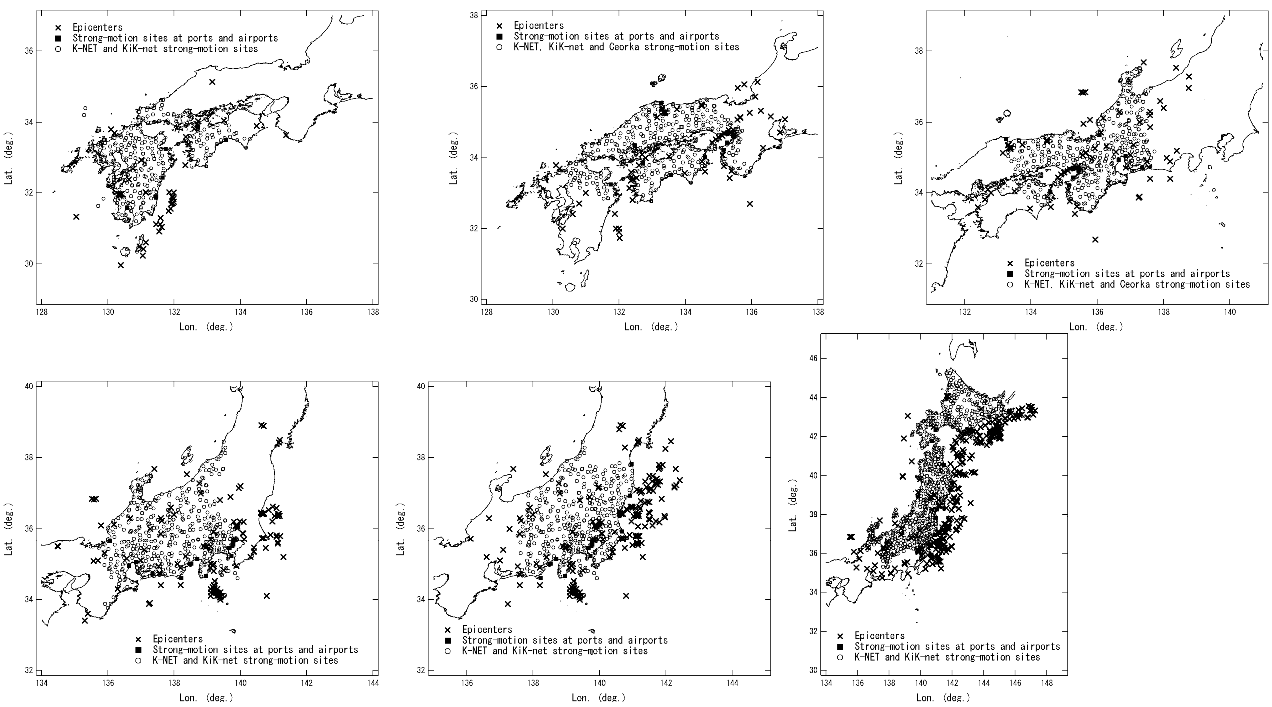


Figure 1. Location of strong motion sites and hypocenters of the earthquakes used. (Top) from left to right, Kyushu, Chugoku-Shikoku and Kinki regions. (Bottom) from left to right, Chubu, Kanto and Tohoku-Hokkaido regions.

In the first step of the analysis, trade-off between the source and the site effects is a very important issue. In the present study a new criteria was introduced to determine the reference site (a site for which $|G_j|$ is assumed to be unity in the first step): At each frequency, among all the sites except for soil sites, the site with the minimum site amplification factor is chosen as the reference site. The soil sites with the averaged shear wave velocity less than 400m/s at the top 10m were excluded from the candidates for the reference site. Validity of the reference site thus selected is discussed in the following section.

2.2. Results

Source spectra, estimated in the first step and used in the second step, have a tendency to follow ω^{-2} model. From the flat levels of the source spectra at low frequencies, seismic moments are estimated compared with those of the F-net CMT solutions (Fukuyama et al., 1996) in Figure 3. The seismic moments estimated in two different ways agree well with each other, indicating the validity of the selected reference site at least at low frequencies where flat levels are found in the source spectrum (less than 1Hz).

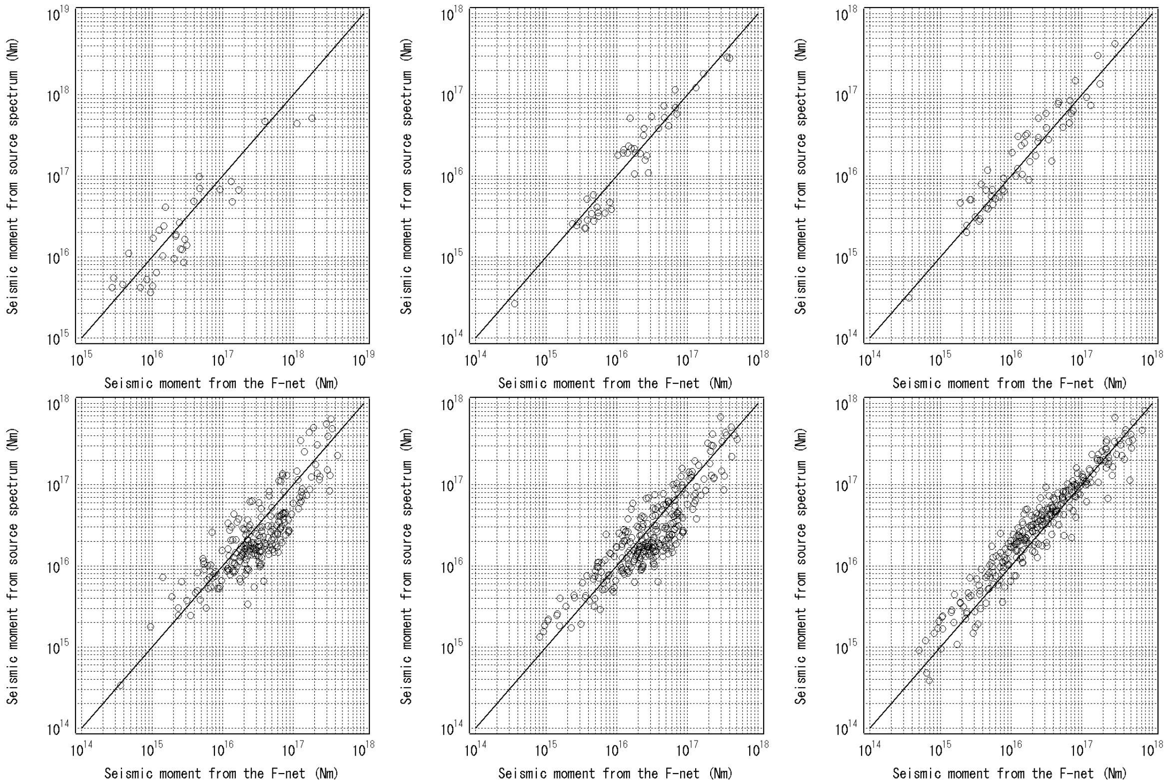


Figure 3. Seismic moment estimated from source spectra and that of the F-net CMT solutions. (Top) from left to right, Kyushu, Chugoku-Shikoku and Kinki regions. (Bottom) from left to right, Chubu, Kanto and Tohoku-Hokkaido regions.

Examples of site amplification factors in Chugoku region are shown in Figure 4. Large site amplification factors are estimated at sites located in plains, whereas small site amplification factors are estimated at sites located in mountains. Examples of site amplification factors in Kanto region are shown in Figure 5. Large site amplification factors are estimated at sites located in plains, whereas small site amplification factors are estimated at sites located in mountains. Medium site amplification factor is estimated for

Chichibu, which is in a small basin surrounded by mountains. Thus, site amplification factors obtained in this study are closely related to surface geology.

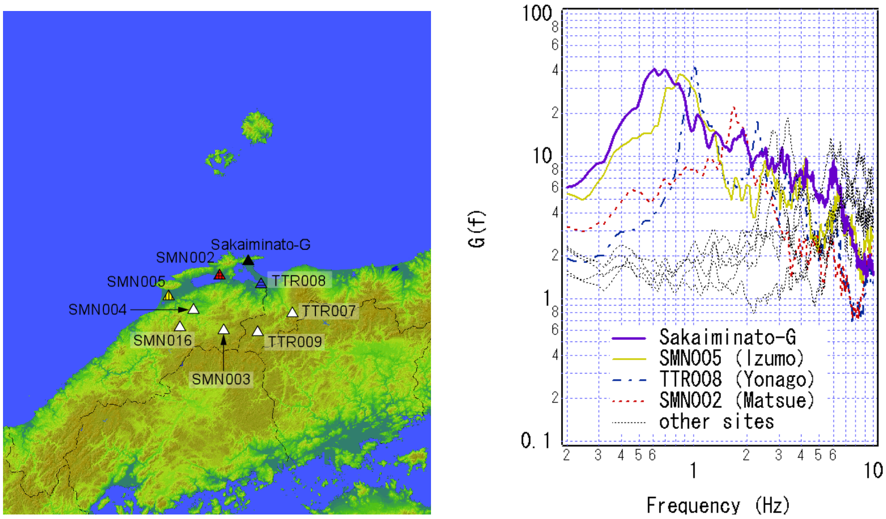


Figure 4. Examples of site amplification factors in Chugoku region. Large site amplification factors are estimated at sites located in plains (Sakaiminato-G, SMN005, TTR008 and SMN002), whereas small site amplification factors are estimated at sites located in mountains.

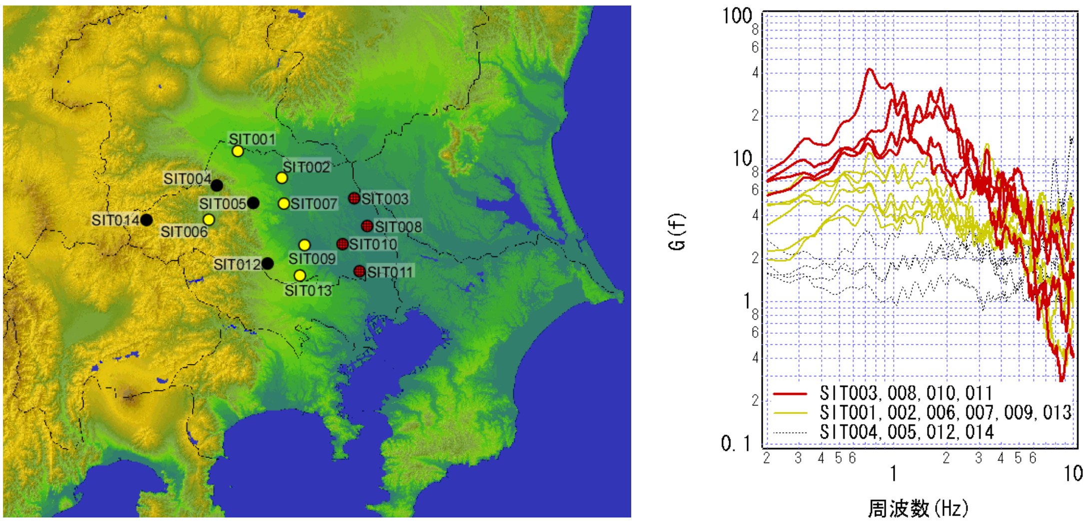


Figure 5. Examples of site amplification factors in Kanto region. Large site amplification factors are estimated at sites located in plains (SIT003, 008, 010, 011), whereas small site amplification factors are estimated at sites located in mountains (SIT004, 005, 012, 014). Medium site amplification factor is estimated for Chichibu (SIT006), which is in a small basin surrounded by mountains.

3. Simulation of strong ground motions

3.1. Method (Kowada's technique)

In general, Fourier amplitude of seismic ground motion can be expressed as a product of source, path and site effects as stated in equation (1). Similarly, group delay time of seismic ground motion, which is defined as a derivative of Fourier phase with respect to angular frequency, can be expressed as a sum of source, path and site effects (Sawada et al., 1998):

$$t_{gr}{}^{O}(f)=t_{gr}{}^{S}(f)+t_{gr}{}^{P}(f)+t_{gr}{}^{G}(f), \qquad (3)$$

where superscript 'O' represents observed ground motions, 'S' represents source effects, 'P' represents path effects and 'G' represents site effects. The method proposed by Kowada et al. (1998) assumes that, if the size of the earthquake and the hypocentral distance are both small enough, then the third term becomes predominant in equation (3), except for simple time shift due to propagation. Thus, their evaluation of site effects is based on following equation.

$$A(f)=A_b(f)\left|G(f)\right|\frac{O(f)}{\left|O(f)\right|} \qquad (4)$$

where A(f) is the Fourier transform of ground motion for a target earthquake on the ground surface (a complex number), $A_b(f)$ is the Fourier transform of ground motion for a target earthquake on bedrock (a complex number), |G(f)| is the site amplification factor (a real number) and O(f) is the Fourier transform of the record from a small earthquake (a complex number). The third term of equation (4) evaluates the effects of surface geology on Fourier phase of seismic ground motion. The record from a small event in equation (4) should be selected so that the incident angle from the small event to the sediment resemble that from the target earthquake as far as possible. |G(f)| in equation (4) should include contributions from later phases.

Ground motion for a target earthquake on bedrock can be evaluated by superposing contributions from element sources. Contributions from element sources are evaluated based on Boore's (1983) technique, except that the Fourier phase is assumed to be zero at the bedrock (Hisada, 2005). Hisada's (2005) method is helpful in avoiding underestimation of low-frequency components due to randomness. In the following simulation, $R_{\theta\varphi}$=0.63 (an averaged value) and *PRTITN*=0.71 (two equal horizontal components) are assumed. Q-values appropriate for each region (Satoh and Tatsumi, 2002; Petukhin et al., 2003) are used.

3.2. Results for a shallow crustal earthquake

First the method is applied to the 1995 Hyogo-ken Nanbu earthquake, which is a shallow crustal earthquake. Using the characteristic source model by Yamada et al. (1999) (Figure 6), ground motions at two CEORKA sites in Kobe, KBU and MOT, are simulated. Site amplification factors at these sites are shown in Figure 7. Based on the simulation of aftershock ground motions, the seismic moments of the asperities are re-evaluated as 3.4E+17Nm, 1.3E+18Nm and 2.3E+18Nm for asperities 1,2 and 4, repsctively. Rime times of the asperities are 0.4s, 0.5s and 0.6s for asperities 1,2 and 4, repsctively. The westernmost asperity was neglected in the simulation because it has little effects on ground motions in Kobe. In equation (4), the record from an aftershock (1995/2/2) was used, whose hypocenter is shown in Figure 6. Synthetic velocity waveforms and velocity Fourier spectra are compared with observed ones in Figure 8. It can be clearly seen that damaging velocity-pulses generated by asperities can be reproduced with high accuracy with the present method.

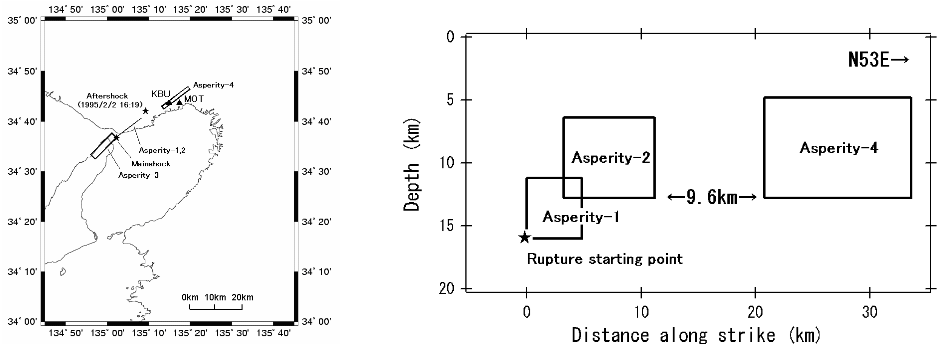


Figure 6. Characteristic source model by Yamada et al.(1999) for the 1995 Hyogo-ken Nanbu earthquake, epicenter of the aftershock used and location of CEORKA sites KBU and MOT. Cross section shows only the Kobe side of the model.

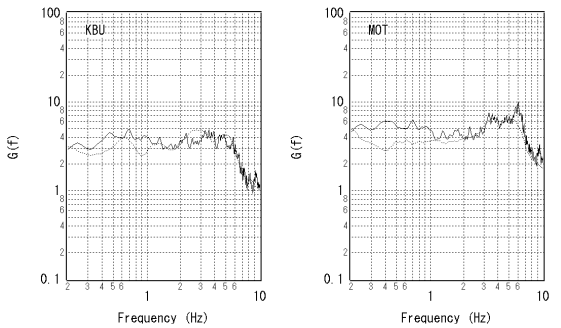


Figure 7. Site amplification factors for CEORKA strong motions sites KBU and MOT estimated in this study (thick lines) and those estimated by Tsurugi et al. (2002) (dotted lines).

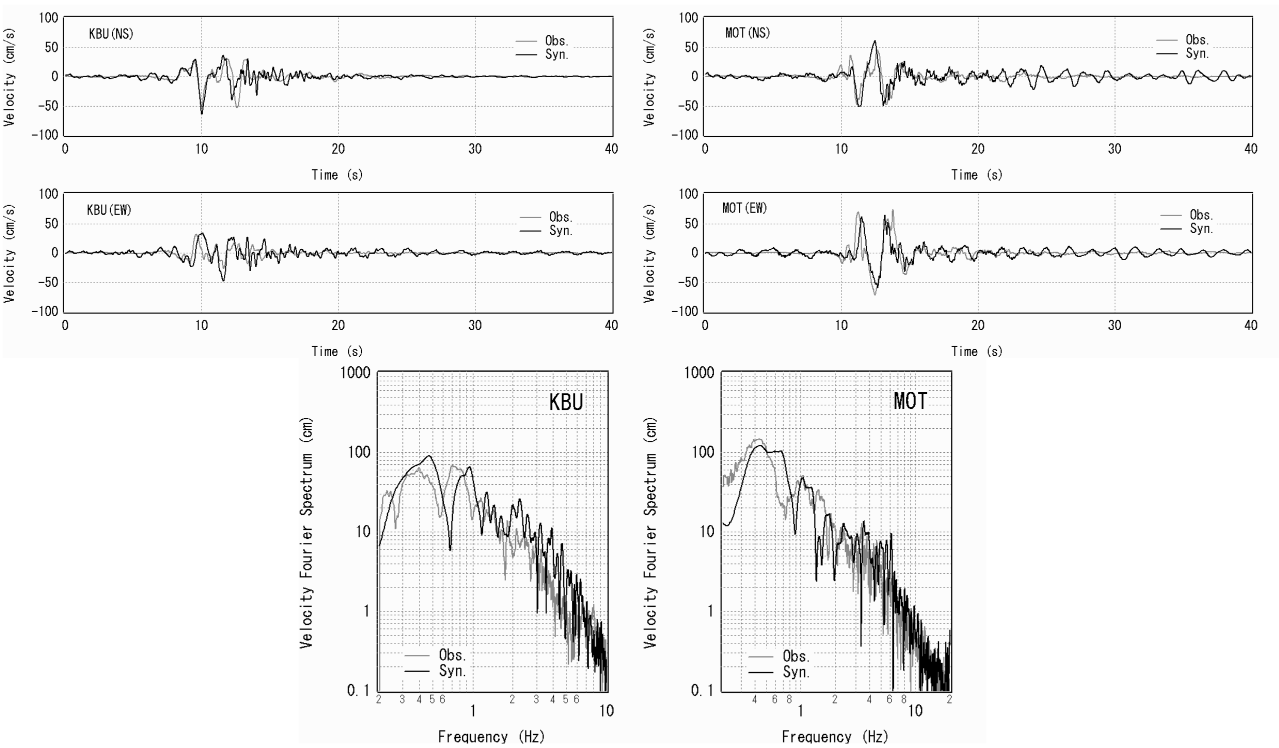
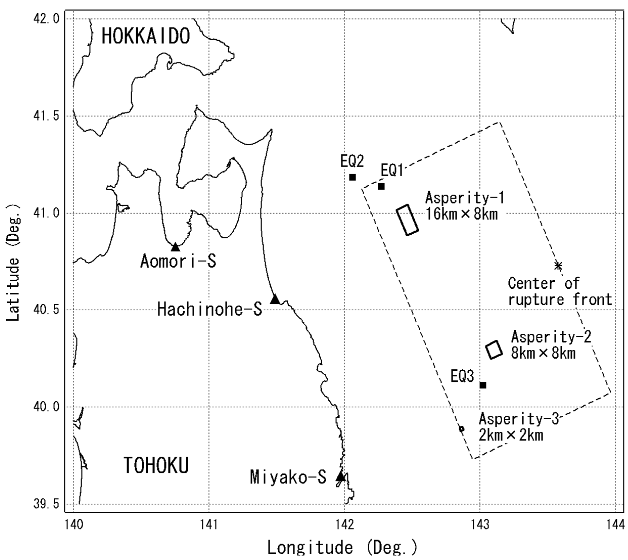


Figure 8. Observed and synthetic velocity waveforms (top) and velocity Fourier spectra (bottom) at KBU and MOT during the 1995 Hyogo-ken Nanbu, Japan, earthquake

3.3. Results for huge subduction-zone earthquakes

Then the method is applied to two huge subduction-zone earthquakes which occurred in Japan, namely, the 1968 Tokachi-oki earthquake and the 2003 Tokachi-oki earthquake. Figure 9 shows the characteristic source model newly developed for the 1968 Tokachi-oki earthquake. The model is composed of three asperities. Ground motions at three ports, namely, Aomori, Hachinohe and Miyako ports are simulated. Site amplification factors at these ports are shown in Figure 10 (At Aomori port, the site amplification factor at a K-NET site AOM020 was used). The site amplification factor at Aomori port is the largest among three. The site amplification factor at Miyako port is much smaller than other two. The record from EQ1(1995/2/6), EQ2(2003/12/8) and EQ3(1994/12/29) were used in equation (4) for Aomori, Hachinohe and Miyako ports, respectively. The hypocenters of these earthquakes are shown in Figure 9. Synthetic velocity waveforms (0.2-1Hz) are compared with observed ones in Figure 11. The observed ground velocity at Aomori port is larger than that at Hachinohe port in spite of the larger distance from the source. This phenomena can be reproduced by considering the large site amplification factor at Aomori port. At Miyako port, both observed and synthetic velocities are small and the duration is short.

Figure 12 shows the characteristic source model newly developed for the 2003 Tokachi-oki earthquake. The model is composed of three asperities. Ground motions at four KiK-net stations, namely, TKCH06, TKCH11, KSRH01 and TKCH02 are simulated. The site amplification factors at these sites are shown in Figure 13. Although the former two stations are located close to each other, their site amplification factors are quite different. Similarly, although the latter two stations are located close to each other, their site amplification factors are quite different. The records from aftershock 1 (2003/9/26 7:20) were used for the former two stations. The records from aftershock 2 (2003/9/27 17:06) were used for the latter two stations. The hypocenters of these aftershocks are



[Macroscopic parameters]
Density: 3.1g/cm^3, Shear wave velocity: 3.9km/s, Strike: 156, Dip: 20, Rupture starting point: (143.58E, 40.73N, d=9.0km), Rupture velocity: 3.0km/s

[Microscopic parameters]
[Asperity-1] Area: 16x8km^2, Seismic moment: 7.2E+26dyne-cm, Rise time: 0.67s, Discretization: 5x5x5
[Asperity-2] Area: 8x8km^2, Seismic moment: 1.8E+26dyne-cm, Rise time: 0.67s, Discretization: 5x5x5
[Asperity-3] Area: 2x2km^2, Seismic moment: 2.3E+25dyne-cm, Rise time: 0.17s, Discretization: 1x1x1

Figure 9. Characteristic source model developed for the 1968 Tokachi-oki, Japan, earthquake composed of three asperities (open rectangles). Triangles indicate strong-motion sites. Closed rectangles indicate small events whose records were used in equation (4).

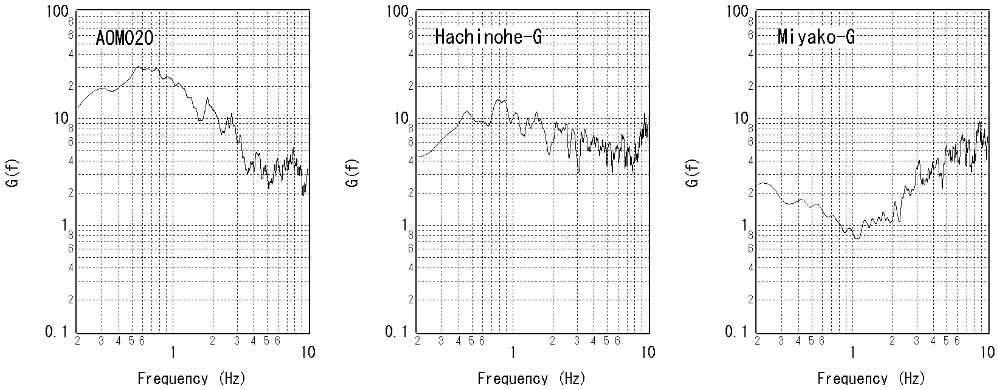


Figure 10. Site amplification factors at Aomori, Hachinohe and Miyako ports.

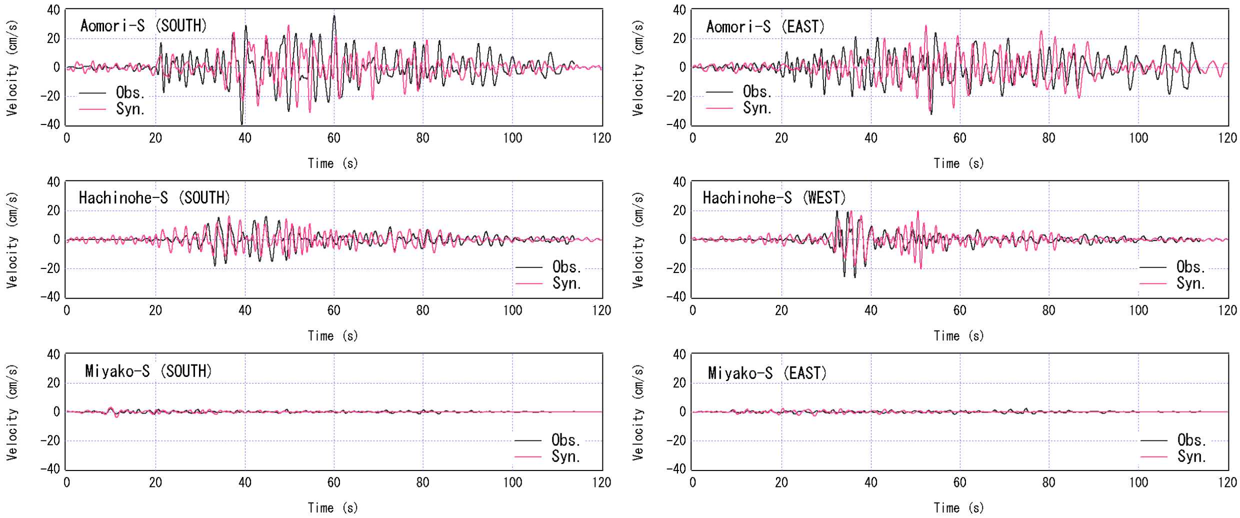
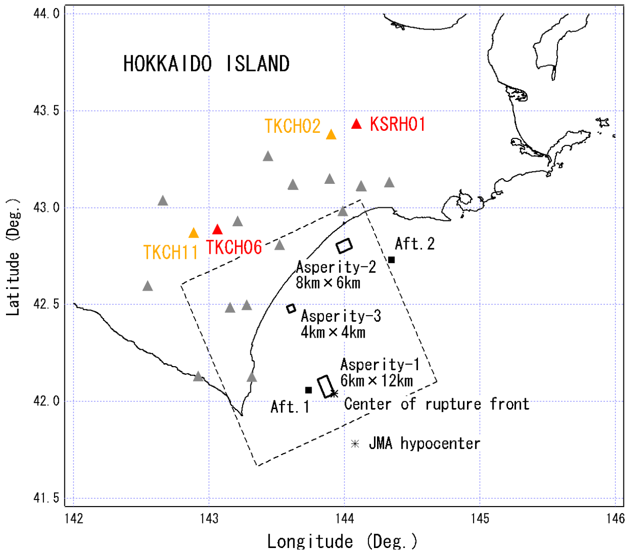


Figure 11. Observed and synthetic velocity waveforms (0.2-1Hz) at Aomori, Hachinohe and Miyako ports during the 1968 Tokachi-oki, Japan, earthquake.



[Macroscopic parameters]
Density: 3.1g/cm^3, Shear wave velocity: 3.9km/s, Strike: 246, Dip: 18, Rupture starting point: (143.925E, 42.039N, d=30.1km), Rupture velocity: 2.7km/s

[Microscopic parameters]
[Asperity-1] Area: 6x12km^2, Seismic moment: 4.2E+26dyne-cm, Rise time: 0.6s, Discretization: 5x5x5
[Asperity-2] Area: 8x6km^2, Seismic moment: 2.1E+26dyne-cm, Rise time: 0.6s, Discretization: 3x3x3
[Asperity-3] Area: 4x4km^2, Seismic moment: 2.4E+25dyne-cm, Rise time: 0.4s, Discretization: 1x1x1

Figure 12. Characteristic source model developed for the 2003 Tokachi-oki, Japan, earthquake composed of three asperities (open rectangles). Triangles indicate strong-motion sites. Closed rectangles indicate small events whose records were used in equation (4).

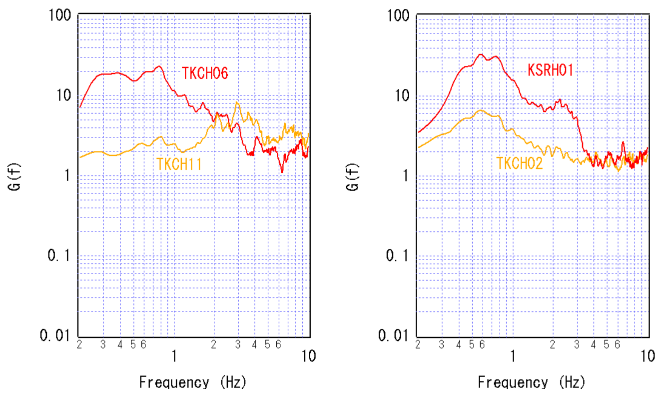


Figure 13. Site amplification factors at TKCH06, TKCH11, KSRH01 and TKCH02 used for the analysis.

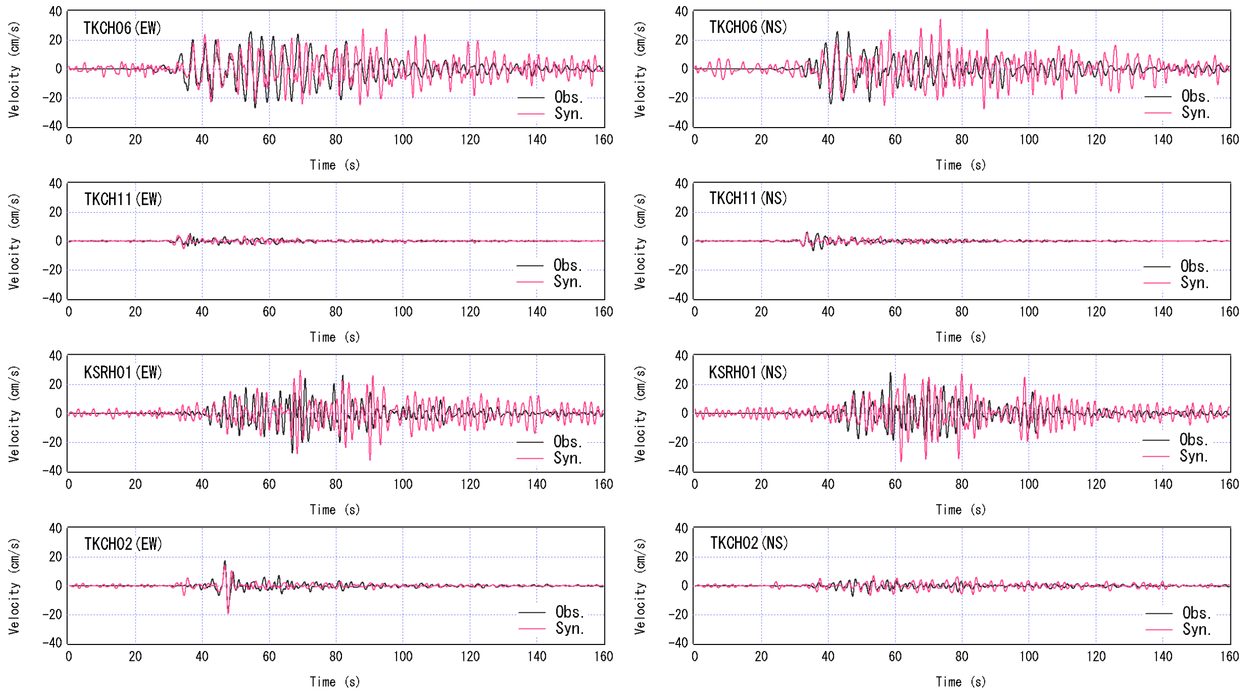


Figure 14. Observed and synthetic velocity waveforms (0.2-1Hz) at TKCH06, TKCH11, KSRH01 and TKCH02 during the 2003 Tokachi-oki, Japan, earthquake.

shown in Figure 12. Synthetic velocity waveforms (0.2-1Hz) are compared with observed ones in Figure 13. At TKCH06 and KSRH01, the observed ground velocities are larger and the duration is long. This may be one of the most dramatic example of the effects of surface geology on seismic motions. By using Kowada's method, this kind of phenomena can be reproduced fairly well.

4. Conclusions

In this article, to investigate the applicability of Kowada's method to shallow crustal and subduction-zone earthquakes, ground motion simulations are conducted for three earthquakes. From the results for the 1995 Hyogo-ken Nanbu earthquake, it can be clearly seen that damaging velocity-pulses generated by asperities can be reproduced with high accuracy with the present method. From the results for the 1968 Tokachi-oki and the 2003 Tokachi-oki eathquakes, it was confirmed that the ground motions from great sunduction-zone earthquakes in the frequency range from 0.2-1Hz, which is of great interest from engineering point of view, can be reproduced by using simple characteristic source models and the present simulation technique.

Digital data for site amplification factors obtained in this study is available on a CD-ROM attached to Nozu and Nagao (2005). The Fortran program used in this study to simulate strong ground motions is available on a CD-ROM attached to Nozu and Sugano (2006).

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