A STRONG MOTION SIMULATION METHOD SUITABLE FOR AREAS WITH LESS INFORMATION ON SUBSURFACE STRUCTURE
- KOWADA'S METHOD AND ITS APPLICATION TO SHALLOW CRUSTAL EARTHQUAKES IN JAPAN -

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ABSTRACT :

In this article, a procedure is presented for strong motion prediction which is suitable for the areas with high seismicity but less information on subsurface structures. The procedure begins with temporal earthquake observation at a construction site for important structures and then proceeds to the evaluation of the site effect based on the records. The validity of the method is demonstrated for shallow crustal earthquakes in Japan.

KEYWORDS: Strong ground motion, Site effect, Shallow crustal earthquake, Fault

1. INTRODUCTION – IMPORTANCE OF SITE EFFECTS

Prediction of strong ground motions from a future large earthquake is of fundamental importance for disaster mitigation and earthquake-resistant design of structures. Generally speaking, strong ground motions are determined by three effects, namely, the source effect, the path effect and the site effect as shown in Fig.1. Among these, the site effect can be defined as the influence of sediments on strong ground motions and it includes amplification of body waves, propagation of basin-induced surface waves and so on. Study on the site effect has a long history in the field of engineering seismology. Recent development of the nation-wide strong motion networks in Japan has greatly contributed to our understanding of the importance of the site effect. Fig.2 shows a typical example. The left panel of Fig.2 shows the topography around the Port of Sakai, western Japan. Two seismometers, namely, Sakaiminato-G (Strong Motion Earthquake Observation in Japanese Ports) and JMA (the Japan Meteorological Agency) are located in the plains of Yumigahama Peninsula. Other two seismometers, namely, SMN001 of K-NET (Kinoshita, 1998) and SMNH10 of KiK-net (Aoi *et al.*, 2000) are located in mountainous Shimane Peninsula. Observed peak ground velocities during the 2000 Tottori-ken Seibu earthquake (M_J7.3) were approximately four times larger for the plains of Yumigahama Peninsula than for mountainous Shimane Peninsula (Fig.2). Thus, evaluation of the site effect is fundamentally important to predict strong ground motions from future large earthquakes and to determine design ground motions.

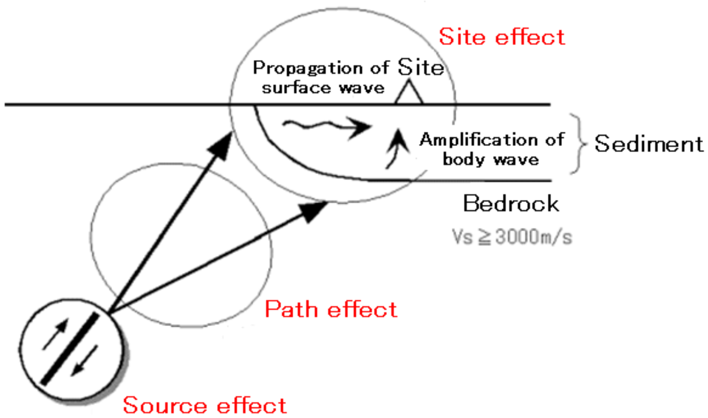

Figure 1 The source, path and site effects.

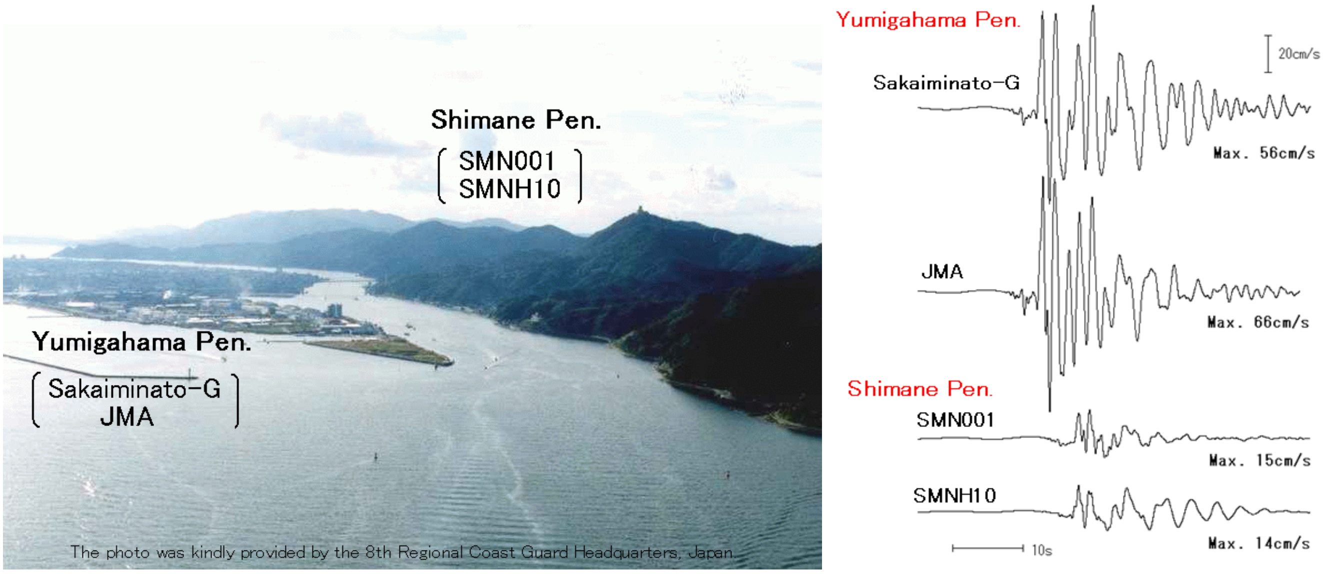

Figure 2 The topography around the Port of Sakai, western Japan (left) and the velocity waveforms for the fault-normal component recorded around the port during the 2000 Tottori-ken Seibu earthquake (M_J7.3). The peak ground velocities observed in the plains of Yumigahama Peninsula were approximately four times larger than those observed in mountainous Shimane Peninsula.

In principle, there are two ways to evaluate the site effect: one is the numerical evaluation based on the information on subsurface structures and the other is the empirical evaluation based on earthquake observation at the site of interest. For the former type of evaluation, precise information on subsurface structure down to the bedrock (Vs≥3000 m/s) is required. It should be noted that one-dimensional profile beneath the site down to the bedrock is not sufficient in many cases: two or three dimensional nature of the subsurface structure is also important. Investigations to reveal the subsurface structure are often costly and beyond the scope of engineers.

In this article, a strong motion prediction method is presented based on the empirical evaluation of the site effect. The procedure begins with temporal earthquake observation at a construction site. Because the site for the construction of important structures is often fixed years before its design procedure begins, well-organized design program will allow us to conduct temporal (typically 1-3 years) observation of earthquake ground motions at the site before the design procedure begins. Roughly speaking, the cost for earthquake observation is almost as small as that for the standard penetration test with a depth of 20-30 m (at least in Japan) and within the scope of engineers. Thus, the procedure is suitable for strong motions prediction in the areas with high seismicity but less information on subsurface structures.

In this procedure, once records are obtained at the site of interest, methods are required to evaluate site amplification factors and ground motions from future large earthquakes based on the records. These methods are described in this article. In particular, Kowada's method (Kowada *et al.*, 1998; Nozu *et al.*, 2006), which can take into account the effect of sediments both on Fourier amplitude and Fourier phase of strong ground motions, is described as a method to synthesize ground motions from large earthquakes and its applicability is demonstrated for recent damaging shallow crustal earthquakes in Japan.

2. OUTLINE OF STRONG MOTION PREDICTION BASED ON EARTHQUAKE OBSERVATION

2.1. Temporal Earthquake Observation at Construction Site for Important Structures

The term for the temporal observation should be determined taking into account the seismicity of the area. Typically, in Japan's case, a term of 1-3 years would be required. The seismometers used for the observation should cover all the frequency range for which strong ground motions should be predicted. The trigger level should be chosen very carefully. In general, a very small trigger level should be chosen to obtain as many records as possible in a limited term. It might be useful to adopt a mechanism in which the seismometer is triggered when the velocity, instead of the acceleration, exceeds certain value. The location of the observation should also be determined carefully. When it is difficult to install the seismometer just at the construction site, then microtremor observation should be conducted in and around the construction site and the seismometer should be installed within an area in which the characteristics of microtremor can be regarded uniform.

2.2. Evaluation of Site Amplification Factors

One way to evaluate site amplification factors (the ratio of Fourier amplitude spectrum at the surface with respect to the bedrock outcrop) at the observation site is to use spectral inversion (e.g., Iwata and Irikura, 1986). Nozu and Nagao (2005) and Nozu *et al.*(2006) used the method to evaluate site amplification factors for strong-motion sites all over Japan including K-NET sites, KiK-net sites and sites at major ports. 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 100 cm/s^2 were excluded from the analysis. The analysis was based on the following linear equations:

$$\log|O_{ij}| = \log|S_i| + \log|P_{ij}| + \log|G_j|, \tag{2.1}$$

where $|O_{ij}|$ is the observed Fourier spectrum (vector sum of two horizontal components), $|S_i|$ is the source effect for the i^{th} earthquake , $|P_{ij}|$ is the path effect and $|G_j|$ is the site amplification factor for the j^{th} site. As for the path effect, geometrical spreading and nonelastic attenuation were considered. The analysis was conducted in two steps: In the first step, $|O_{ij}|$ is calculated from portions of the records with duration of 40 seconds including S waves. Then, based on Eqn. 2.1, $|S_i|$ is estimated. In this step, $|G_j|$ is assumed to be unity for the reference site, *i.e.*, the site with the smallest site amplification factor for each frequency among all the sites with averaged shear wave velocity over 400 m/s at top 10 m. In the second step, $|O_{ij}|$ is calculated from portions of the records with duration of 160 seconds including not only S waves but also later phases. Then, based on Eqn. 2.1 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 strong motion simulation technique described in the next chapter. Fig.3 (left) shows the location of strong motion sites and hypocenters of the earthquakes used in the spectral inversion analysis for Kanto region. In Fig.3 (right) the seismic moments estimated from the analysis for Kanto region is compared with those of the F-net CMT solutions. F-net CMT solutions are based on very long period (0.01-0.1 Hz) surface waves. The agreement between the two seismic moments indicates that the reference

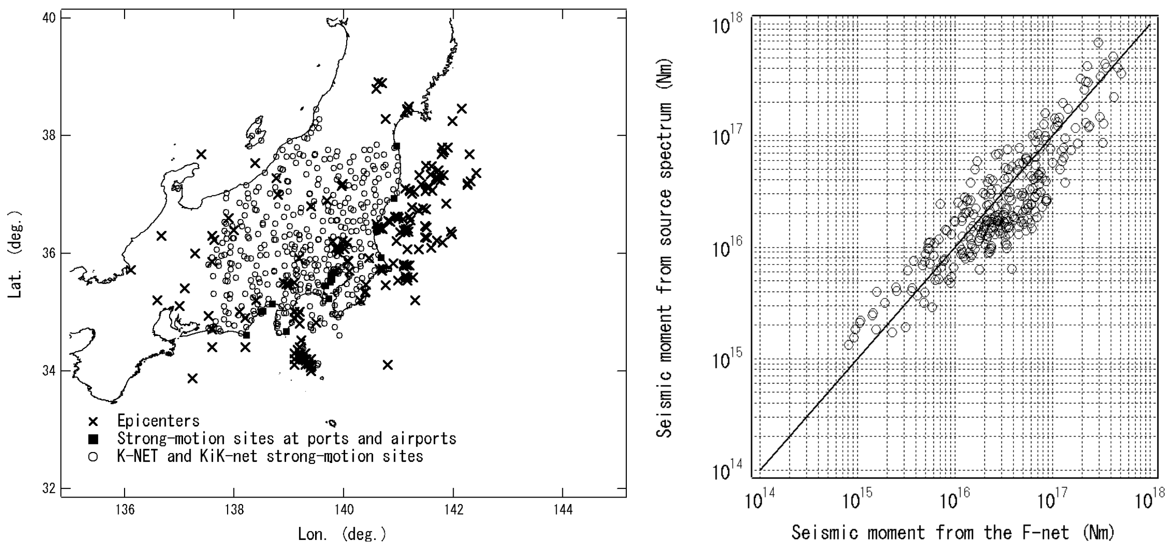

Figure 3 (left) Location of strong motion sites and hypocenters of the earthquakes used in the spectral inversion analysis for Kanto region. (right) Comparison between the seismic moments estimated from the analysis for Kanto region and those of the F-net CMT solutions.

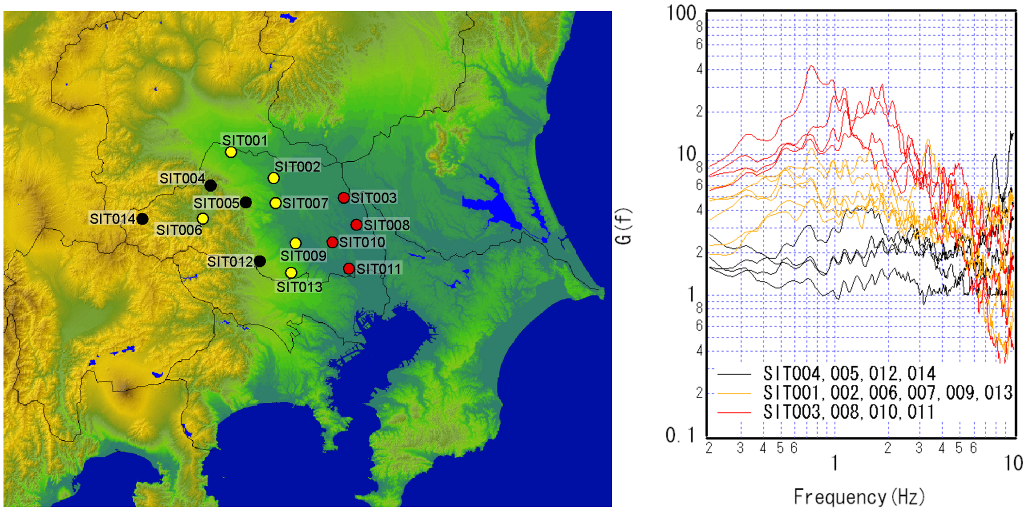

Figure 4 Examples of site amplification factors in Kanto region. Large site amplification factors are estimated at sites located in plains (SIT003, 008, 010, 011), whereas small site amplification factors are estimated at sites located in mountains (SIT004, 005, 012, 014). Medium site amplification factor is estimated for Chichibu (SIT006), which is in a small basin surrounded by mountains (after Nozu and Nagao, 2005).

site is adequately chosen and there is no serious overestimation or underestimation of the source effect. Fig.4 shows examples of site amplification factors in Kanto region. Once site amplification factors are established for permanent observation sites, then the site amplification factor at a temporal site can be estimated simply by, for example, taking the ratio of the Fourier spectrum at the temporal site with respect to a nearby permanent site.

2.3. Prediction of Strong Ground Motions from Scenario Earthquakes

For the prediction of strong ground motions from a scenario earthquake, a rupture scenario for the earthquake should be prescribed. The rupture scenario should be in accordance with seismological, geological and geomorphological knowledge. Details of the prescription are out of the scope of this article. Once a rupture scenario is prescribed, strong ground motions at the site of interest can be simulated using Kowada's method (Kowada *et al.*, 1998; Nozu *et al.*, 2006), which can take into account the effect of sediments both on Fourier amplitude and Fourier phase of strong ground motions. Details of the method are described in the next chapter.

3.KOWADA'S METHOD

3.1. Outline of the Method

At first, the ground motion for a small earthquake (Green's function) is evaluated. The Fourier amplitude of the Green's function is evaluated as a product of the source spectrum $|S(f)|$, path effect $|P(f)|$ and the site amplification factor $|G(f)|$. The source spectrum is assumed to follow the ω^{-2} model (Aki, 1967). As for the path effect, geometrical spreading and nonelastic attenuation are considered. As for the site amplification factor, the empirical site amplification factor (***2.2***) is used. Then, as for its Fourier phase, the Fourier phase of an actual record is used. Thus, we can obtain a time domain Green's function which incorporates the effects of sediments both on Fourier amplitude and Fourier phase. The Green's function in the frequency domain can be written as follows:

$$|S(f)|\,|P(f)|\,|G(f)|\,O_s(f)\,/\,|\,O_s(f)|_p, \tag{3.1}$$

where $O_s(f)$ is the Fourier transform of an actual record at the site and $|\,O_s(f)|_p$ is its Parzen-windowed amplitude (band width of 0.05 Hz is used). If several records are available at the site, it is recommended to choose an event which has a similar incident angle and a similar backazimuth with the target event. Finally, the Green's function is superposed just like in the EGF method. In the following chapters, strong ground motions are simulated with the method for some shallow crustal earthquakes in Japan and compared with the observed ones.

3.2. Application to the 1995 Hyogo-ken Nanbu, Japan, earthquake (M_J7.3)

The method is applied to the 1995 Hyogo-ken Nanbu earthquake, which was a shallow crustal earthquake and killed more than 6000 people in and around Kobe City. Using the characteristic source model by Yamada et al.

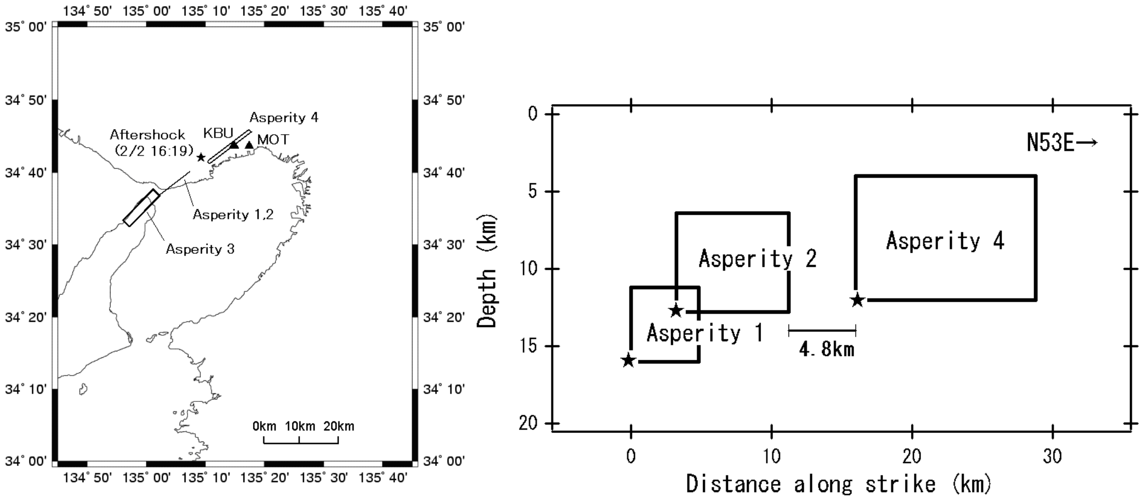

Figure 5 (left) The characteristic source model by Yamada et al. (1999) for the 1995 Hyogo-ken Nanbu earthquake, the epicenter of the aftershock used and the CEORKA strong motion sites KBU and MOT. (right) Its cross section for the Kobe side. The source model has three asperities in the Kobe side. The stars indicate the rupture starting point for each asperity.

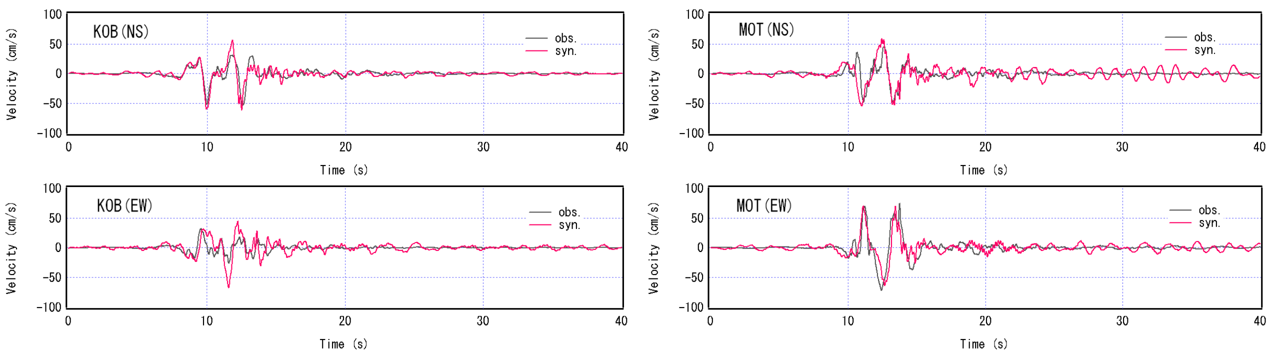

Figure 6 The recorded (black) and simulated (red) velocity waveforms at KBU and MOT for the 1995 Hyogo-ken Nanbu earthquake.

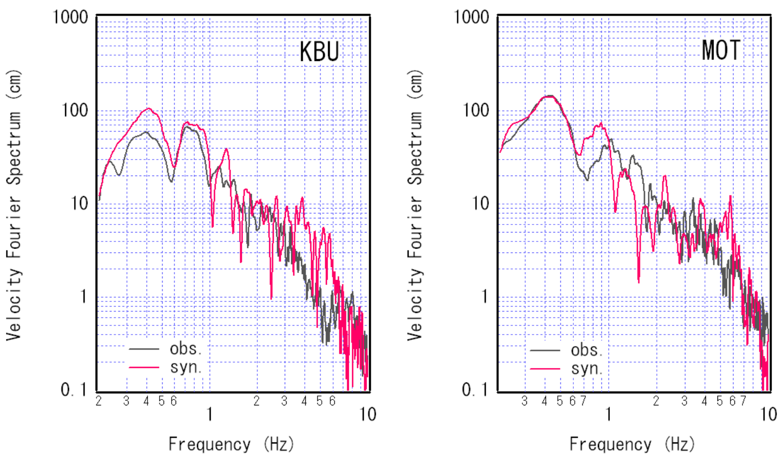

Figure 7 The recorded (black) and simulated (red) velocity Fourier spectra at KBU and MOT for the 1995 Hyogo-ken Nanbu earthquake.

(1999) (Fig.5), ground motions at two CEORKA sites in Kobe, KBU and MOT, are simulated. Site amplification factors estimated by Nozu and Nagao (2005) for these sites were used. Based on the simulation of aftershock ground motions, the seismic moments of the asperities are re-evaluated by Nozu *et al.* (2006) as 3.4E+17Nm, 1.3E+18Nm and 2.3E+18Nm for the asperities 1,2 and 4, respectively. Relative rupture times are 0.0s, 1.8s and 6.9s for the asperities 1,2 and 4, respectively. Rise times are 0.4s, 0.5s and 0.6s for the asperities 1,2 and 4, respectively. The Awaji-side asperity was neglected in the simulation because it has little effects on ground motions in Kobe. In Eqn. 3.1, the record from an aftershock (1995/2/2) was used, whose hypocenter is shown in Fig.5. The coefficient *PRTITN* (Boore, 1983) was assumed to be 0.71. Synthetic velocity waveforms and velocity Fourier spectra are compared with observed ones in Figs.6 and 7. It can be clearly seen that damaging velocity-pulses generated by the asperities can be reproduced with high accuracy with the present method.

3.3. Application to the 2007 Off Mid Niigata Prefecture, Japan, earthquake (M_J6.8)

Finally the method is applied to the 2007 Off Mid Niigata Prefecture earthquake. Based on the final slip distribution estimated from a waveform inversion (color contours in Fig.9), the characteristic source model (red rectangles) was developed. The seismic moments of the asperities are 0.4E+18Nm, 1.0E+18Nm and 1.0E+18Nm for the asperities 1,2 and 3, respectively. Relative rupture times are 1.3s, 2.4s and 6.4s for the asperities 1,2 and 3, respectively. Rise times are 0.17s, 0.33s and 0.25s for the asperities 1,2 and 3, respectively. Based on this source model, ground motions at three observation sites, namely, KKZ1R2 (TEPCO), NIG016 (K-NET) and NIG018 (K-NET) were simulated. Locations of the sites are shown in Fig.9. As for site amplification factors for NIG016 and NIG018, those obtained by spectral inversion (Nozu and Nagao, 2005) were used. The site amplification factor for KKZ1R2 was obtained as follows. First, six aftershocks were selected for which records were obtained at all of the four sites KKZ1R2, NIG016, NIG017 and NIG018. Then the source spectra for these aftershocks were estimated by using site amplification factors for NIG016, NIG017 and NIG018 (Nozu and Nagao, 2005) and by fitting the observed and synthetic Fourier spectra at these sites. Finally, from the observed Fourier spectra at KKZ1R2 and the source spectra for the aftershocks, the site amplification factor for KKZ1R2 was obtained for six aftershocks and averaged. To determine the Fourier phase of the Green's function, the records of the aftershocks a (7/16 15:37), b (7/16 21:08) and c (7/18 16:53) (Fig.9) were used for NIG016, KKZ1R2 and NIG018, respectively. As for the coefficients *PRTITN* (Boore, 1983), values in the range from 0.63-0.77 were selected so that the observations can be explained well. For NIG018, nonlinear behavior of the soil in and around the site during the mainshock was considered as follows.

1. The Green's function at the outcrop of the firm ground (V_s=500m/s) was evaluated.
2. The Green's function was corrected for the multiple nonlinear effects (*e.g.*, Nozu and Morikawa, 2004) with

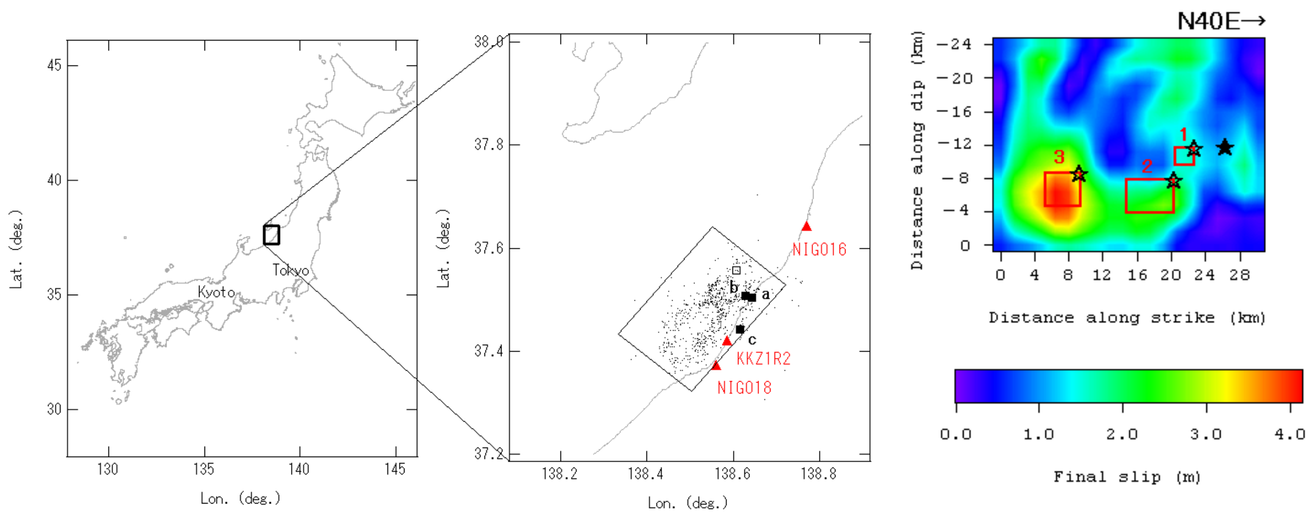

Figure 9 The source model of the 2007 earthquake. The map in the central panel shows the location of the fault (black rectangle) with the sites (red triangles) and the aftershocks (black squares) used for the analysis. The dip angle is 36 degrees. The right panel shows the final slip distribution for the 2007 earthquake estimated from a waveform inversion (color contours) and the characteristic source model based on the inversion results (red rectangles). The open stars indicate the rupture starting point for each asperity.

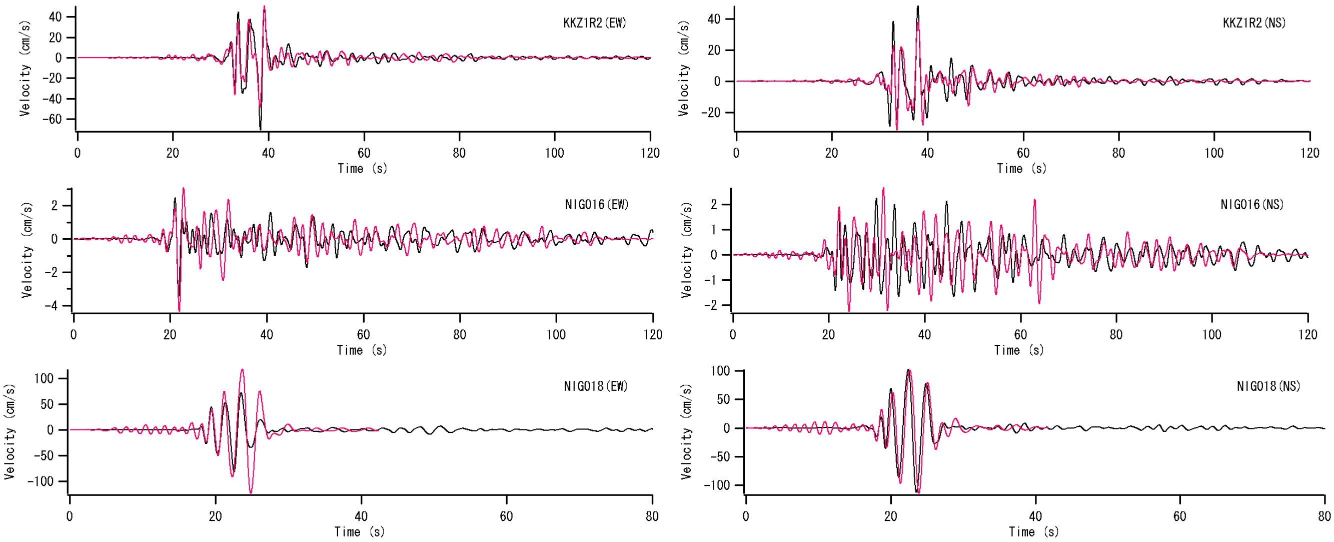

Figure 10 The recorded (black) and simulated (red) velocity waveforms (0.2-1Hz) at KKZ1R2, NIG016 and NIG018 for the 2007 Off Mid Niigata Prefecture earthquake.

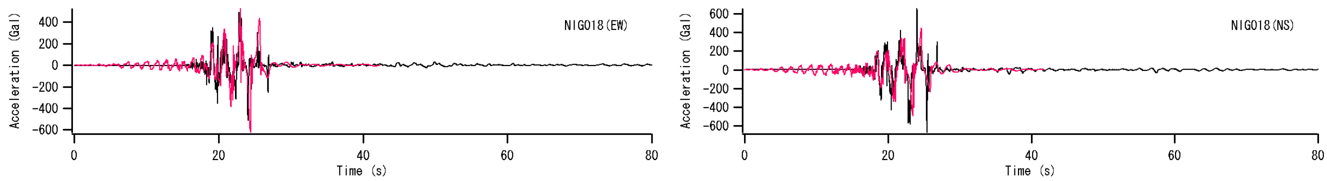

Figure 11 The recorded (black) and simulated (red) acceleration waveforms at NIG018 for the 2007 Off Mid Niigata Prefecture earthquake.

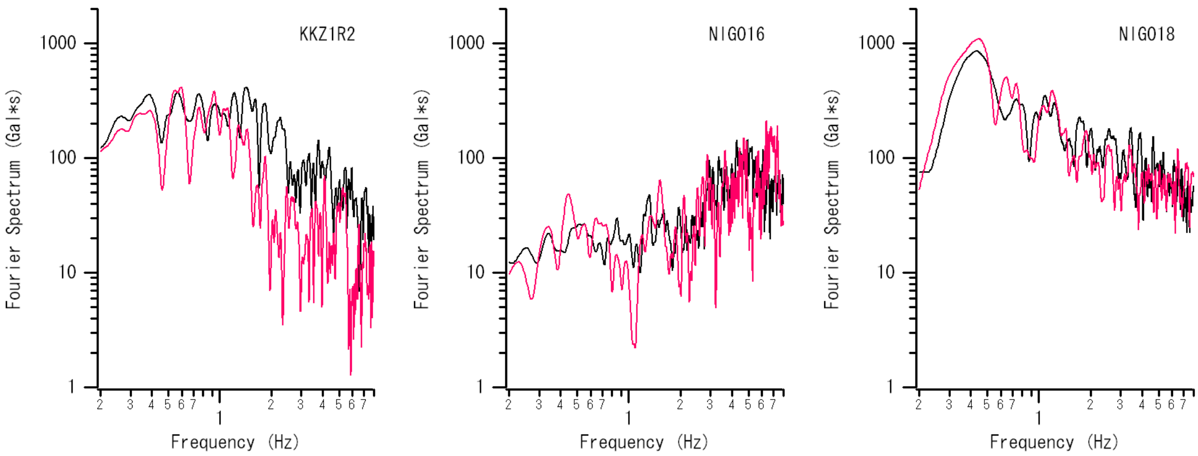

Figure 12 The recorded (black) and simulated (red) Fourier spectra at KKZ1R2, NIG016 and NIG018 for the 2007 Off Mid Niigata Prefecture earthquake.

nonlinear parameters ν_1=0.8 and ν_2=0.06 and then superposed.

3. One dimensional effective stress analysis was conducted using a computer program FLIP (Iai *et al.*, 1992), which is a finite element code equipped with the multiple mechanism model.

As for KKZ1R2, only multiple nonlinear effects were considered and local soil nonlinearity was neglected. The Green's function at the observation site was corrected with nonlinear parameters ν_1=0.85 and ν_2=0.01. The results are compared with the observations in terms of velocity waveforms (0.2-1Hz), acceleration waveforms and acceleration Fourier spectra. The results are quite reasonable. Note the significant difference of the observed Fourier amplitude spectra between NIG016 and NIG018. These characteristics were accurately reproduced in the simulation mainly because realistic empirical site amplification factors were incorporated in the analysis. At NIG018, spiky acceleration time histories due to cyclic mobility were reproduced by the effective stress analysis.

4. CONCLUDING REMARKS

In this article, a procedure is presented for strong motion prediction which is suitable for the areas with high seismicity but less information on subsurface structures. The procedure begins with temporal earthquake observation at a construction site for important structures and then proceeds to the evaluation of the site effect based on the records. It was demonstrated that, once appropriate source models are given, the procedure generates very realistic ground motions for shallow crustal earthquakes in Japan. The authors hope the procedure will contribute to earthquake disaster mitigation in the areas with high seismicity all over the world.

The digital data of the site amplification factors and the computer program used to generate synthetics in this article including FORTRAN source code are open to the public (Nozu and Nagao, 2005; Nozu and Sugano, 2008).

ACKNOWLEDGEMENTS：The authors would like to thank the National Research Institute for Earth Science and Disaster Prevention (NIED), the Japan Meteorological Agency (JMA), the Committee of Earthquake Observation and Research in the Kansai Area (CEORKA) and the Tokyo Electric Power Company, Inc. (TEPCO) for providing important strong motion data.

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