STRONG GROUND MOTION PREDICTION BY USING NEW ANALYSIS METHOD NAMED "PSEUDO EMPIRICAL GREEN'S FUNCTION PROCEDURE"

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ABSTRACT :

In order to apply the empirical Green's function method to predict wide area strong ground motion practically, the pseudo empirical Green's function procedure is introduced and verified and an application for an earthquake in the Tokai area of Japan is also presented. For the validation of the proposed procedure, a number of transfer functions between two arbitrary recording sites estimated by the proposed procedure are compared with those of observed ground motions. The proposed procedure is shown to be able to estimate ground motions of a specific site, which has no appropriate records, better than conventional estimation methods such as the 3D-finite difference method or the stochastic simulation method. Using the proposed procedure, strong ground motions are simulated for the hypothetical Tonankai earthquake. The distribution of the simulated seismic intensity in the Nagoya area shows good agreement with that of observed building damage due to the Tonankai earthquake of 1944.

KEYWORDS: Strong motion prediction, Ground motion records, Transfer function, 3D-finite difference method, Stochastic simulation method, Soil model

1. INTORODUCTION

In recent years, numerical simulation in which waveforms are calculated has been used in seismic zoning. In Japan, the mesh size that divides an area in seismic zoning has become as small as 50 m × 50 m. Therefore, the accurate strong motion prediction technique is needed. The empirical Green's function method (e.g., Hertzell, 1978; Irikura, 1986; Dan and Sato, 1998), which was proposed to calculate a record of an earthquake by summing records of smaller events near the large event, is a most effective method for application at the recording site.

In Japan, the number of earthquake observation sites has been increased since the Hyogo-ken Nanbu earthquake of 1995. Moreover, mutually connected systems have been developed using existing earthquake observation networks of local governments, enterprises, and universities, for example, and the uniform collection systems of the earthquake observation records have been developed (e.g., Tobita et al., 2001). However, the distribution density of the earthquake observation point is not higher than the size of the mesh of a seismic zoning. Thus, strong motion prediction for a wide area is not possible using the empirical Green's function method.

On the other hand, a great deal of data and knowledge on the modeling of subsurface structure and surface layer has been accumulated. In Japan, a number of investigations have examined sedimentary basins, and subsurface structures have been modeled based on these investigation results. The theoretical waveforms of a small event obtained by the 3D-finite difference method (3D-F.D.M.) (e.g., Graves, 1996) using the subsurface structural model almost fit the predominant period, amplitude, and duration time of observed waveforms (e.g., Suzuki et al., 2005). Moreover, methods of accurate surface layer modeling based on drilling data has been examined (e.g., Takahashi and Fukuwa, 2006; Eto et al., 2007).

In the present paper, we propose a new procedure to estimate ground motion at a site using the observed motion at a nearby site and theoretically evaluated the transfer functions calculated between the two sites based on soil models. The theoretical transfer function is calculated by dividing a spectrum of the synthetic ground motion of the recording site into that of the specific site. Synthetic long period ground motions are obtained by the 3D-F.D.M., and synthetic short period ground motions are obtained by the stochastic simulation method (S.S.M.) (Boore, 1983). Thus, the ground motion at the specific site is calculated from both the transfer function and the ground motion observed at the recording site. Using the procedure, strong motions are simulated for the hypothetical Tonankai earthquake.

2. FORMULATION FOR ESTIMATION GROUND MOTION

Ground motion records of event A are assumed to be obtained at two sites, namely, X and Y. Under this condition, spectra of the observed records at two sites are expressed as follows:

$$O_{XA}(\omega) = S_A(\omega) \cdot PG_{XA}(\omega) \tag{1}$$

$$O_{YA}(\omega) = S_A(\omega) \cdot PG_{YA}(\omega) \tag{2}$$

In the above equations, $S_A(\omega)$ is the source effect, $PG_{XA}(\omega)$ is the path effect from the hypocenter to site X, including site effect, and $PG_{YA}(\omega)$ is the path effect from the hypocenter to site Y, including site effect. The observed record contains the surface wave. Therefore, the path effect and site effect in Eqs. (1) and (2) are matched. The transfer function $R_{XYA}(\omega)$ between site X and site Y is expressed as follows:

$$R_{XYA}(\omega) = PG_{XA}(\omega) / PG_{YA}(\omega) = O_{XA}(\omega) / O_{YA}(\omega) \tag{3}$$

Small event B is assumed to be located near small event A. The transfer function of small event B between site X and site Y may be approximated by $R_{XYA}(\omega)$, and the spectrum of the ground motion at site X due to small event B is expressed as follows:

$$\begin{aligned} O_{XB}(\omega) &= S_B(\omega) \cdot PG_{XB}(\omega) = S_B(\omega) \cdot R_{XYB}(\omega) \cdot PG_{YB}(\omega) \\ &\cong R_{XYA}(\omega) \cdot O_{YB}(\omega) = O_{YB}(\omega) \cdot O_{XA}(\omega) / O_{YA}(\omega) \end{aligned} \tag{4}$$

It is assumed that the observed record due to small event B is obtained at site Y and that waves of small event A are theoretical waves, which simulated small event B. Theoretical waves are obtained at arbitrary sites. Therefore, if $O_{XA}(\omega)/O_{YA}(\omega)$ calculated by theoretical waves is equivalent to that calculated by observed waves, the waveform of site X due to small event B can be calculated using Eq. (4).

3. VALIDATION OF THE PROCEDURE

3.1 Data and Analysis

In order to improve the accuracy of the theoretical transfer function, in simulation, it is important to improve the accuracy of the modeling of the source, the propagation path, and the site. However, complete modeling is very difficult. In the following sections, we describe the influence on the transfer function of the three parameters, namely, the source location, the distance between sites that are influential to the transfer function, and the hypocentral distance. Figure 3.1a shows the epicenters of the small events used in the present study.

We used ground motion records obtained by the on-line strong motion data acquisition system (Tobita et al., 2001).

In order to determine the influence on the transfer function of the source location, we used Evt.1, Evt.2, and Evt.3. We compare two cases. In one case, the hypocentral distances are the same (Evt.1 and Evt.2), and in the other case, the hypocentral distances are different (Evt.1 and Evt.3). Figure 3.1b shows the distribution of the locations of seismic observation sites used in the present study.

In order to determine the influence on the transfer function of the distance between two points, we use the recording sites shown in Figure 3.1b.

In order to determine the influence of hypocentral distance, we used Evt.4 and Evt.5. Figure 3.1c shows the locations of the seismic observation sites used herein. We compare two cases. In one case, the stations are far from epicenter (Evt.4), and in the other case, the stations are near the epicenter (Evt.5).

Four events are simulated by the 3D-F.D.M.: Evt.1, Evt.3, Evt.4, and Evt.5. The source models of these events are shown in Table 3.1. We use a finite difference scheme based on the velocity-stress staggered grid (Robertsson et al., 1994). As a source time function, we use the smoothed ramp function.

We use the subsurface structural model of the Tokai district (Aichi Prefecture, 2004). This model is modified to be fit to the predominant period based on the H/V spectra at seismic observation sites. As the model under the seismic bedrock, we use the model estimated by Zhao et al. (1994). We set the smallest grid size to 200 m, and the effective range of period is longer than 2 seconds.

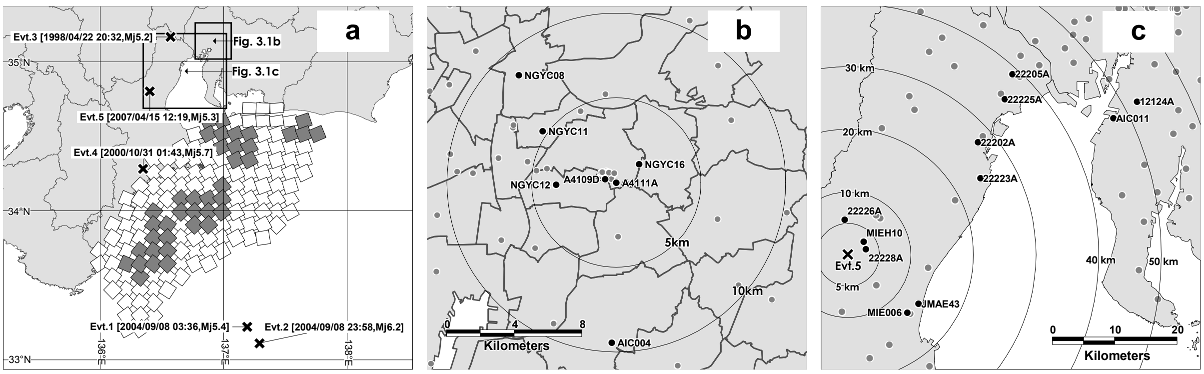

Fig. 3.1 Map showing the locations of the epicenters and the source model of the hypothetical Tonankai earthquake (a), and the seismic observation sites used in the present study (b and c).

Table 3.1 Source parameters for calculation by the 3D-F.D.M.

	Lat (d)	Lon (d)	Depth (km)	Mj	Strike (d)	Dip (d)	Rake (d)	Mo (Nm)	Rise time (s)
Evt.1	33.2	137.2	39	5.4	254	34	75	2.06×10^{17}	1.0
Evt.3	35.2	136.6	10	5.2	163	29	53	6.74×10^{16}	0.6
Evt.4	34.2	136.4	38	5.7	302	72	130	1.70×10^{17}	0.8
Evt.5	34.8	136.4	10	5.3	148	45	77	3.94×10^{16}	0.6

3.2 Results

Figure 3.2 shows Evt.4 and Evt.5 with a comparison of the calculated wave using the 3D-F.D.M. and the EW component of observed records. In this figure, in the case of Evt.4, the amplitude of the theoretical wave is slightly smaller than that of the observed record, and the travel time of the theoretical wave is slower than that of the observed wave. In the case of Evt.5, seismic observation sites do not correspond well between the observed record and theoretical wave. Because of the low dimensional accuracy of the focal depth in the case of Evt.4 and the low dimensional accuracy of the source model in the case of Evt.5, the correspondence between the observed and the theoretical wave is not good.

Figure 3.3 shows the transfer function calculated from the record of three small events (Evt.1, Evt.2, and Evt.3) and that calculated from the theoretical wave, which is calculated by the 3D-F.D.M. In this figure, these events reveal the same tendency of the transfer function of Evt.1, whereby the amplitude ratio and phase lag of the transfer function are calculated by ground motion records of Evt.2 near the epicenter of Evt.1. However, the transfer function of Evt.3, which is far from the epicenter of Evt.1, reveals a tendency of the transfer function of Evt.1 that is different, especially with respect to phase lag. The larger the difference between two sites, the greater the difference. Moreover, the greater the distance from the A4111A site, the greater the difference between the transfer function calculated from the theoretical wave and the transfer function calculated from observed records.

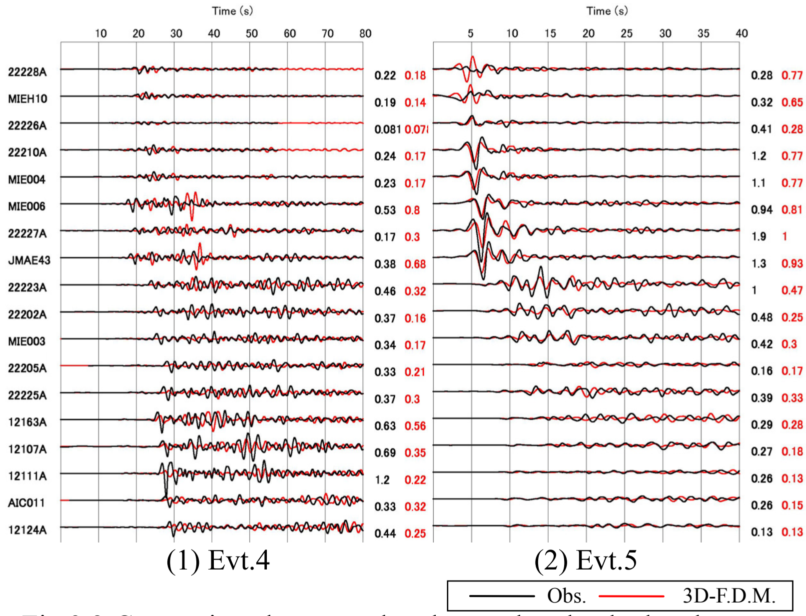

Fig.3.2 Comparison between the observed and calculated waves using the 3D-F.D.M. with the EW components of Evt.4 and Evt.5.

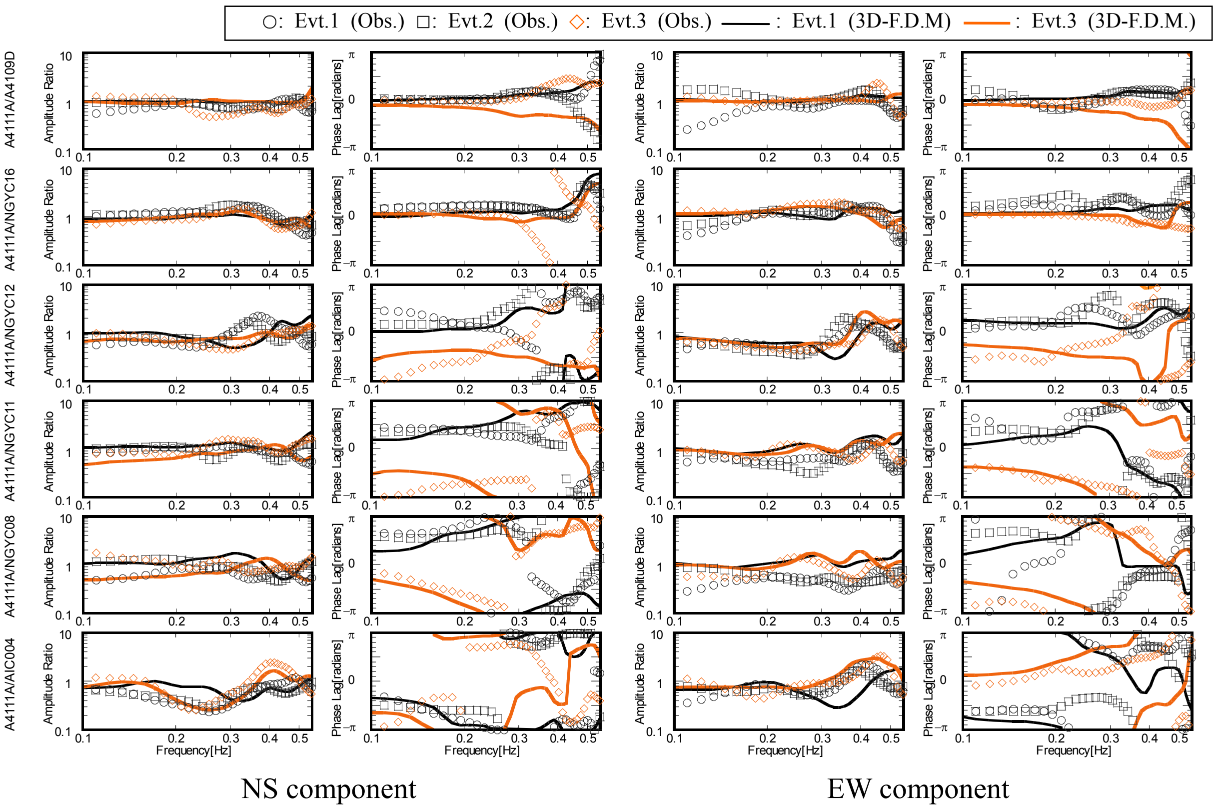

Fig.3.3 Comparison between the transfer functions calculated from the observed records of three small events (Evt.1, Evt.2, and Evt.3) and one small event calculated from the theoretical wave by the 3D-F.D.M.

Figure 3.4 shows the transfer function calculated for the observed records and theoretical waves of Evt.4 and Evt.5. In this figure, in the case of Evt.4, the transfer function calculated from the observed wave and the one calculated from theoretical wave are in approximate correspondence. On the other hand, in the case of Evt.5, the nearer the transfer function calculated from theoretical wave is to the epicenter, the worse the correspondence between the transfer function calculated from the observed wave and the one calculated from theoretical wave.

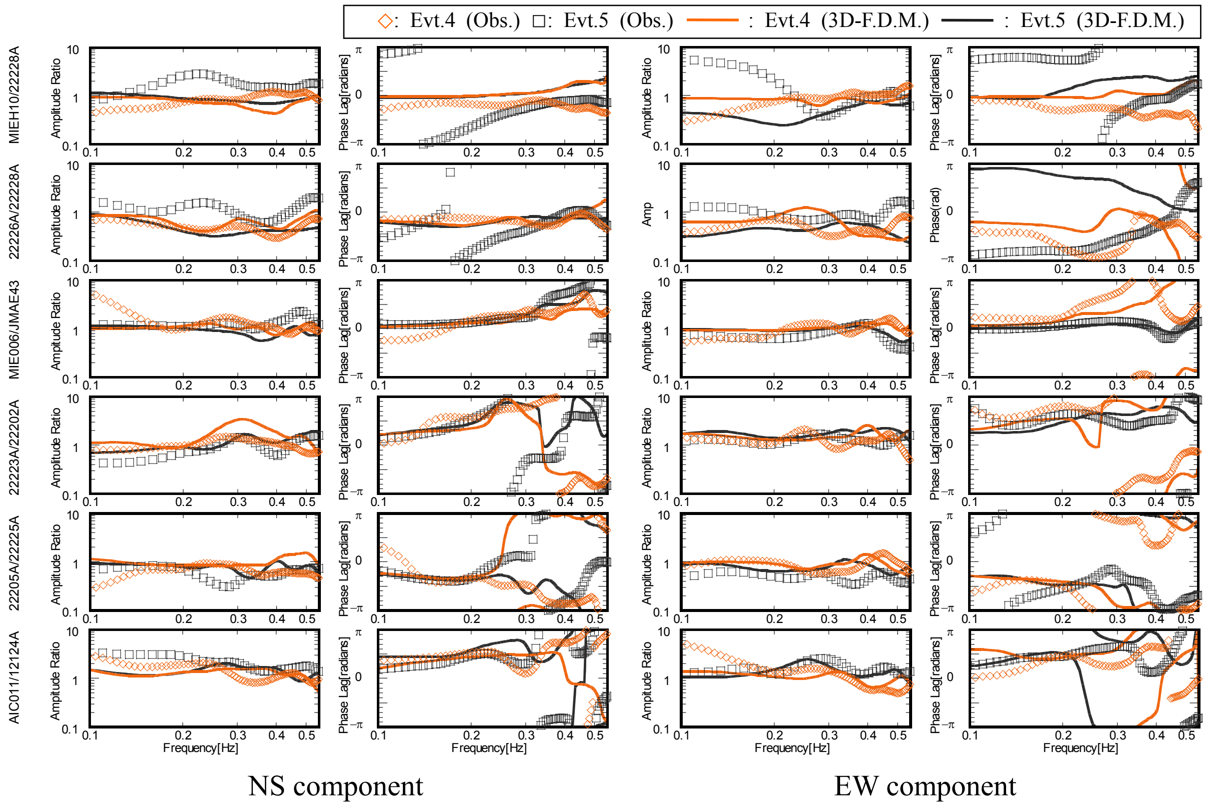

Fig.3.4 Comparison between the transfer functions calculated from the observed records of two small events (Evt.4 and Evt.5) and one small event calculated from the theoretical wave by the 3D-F.D.M.

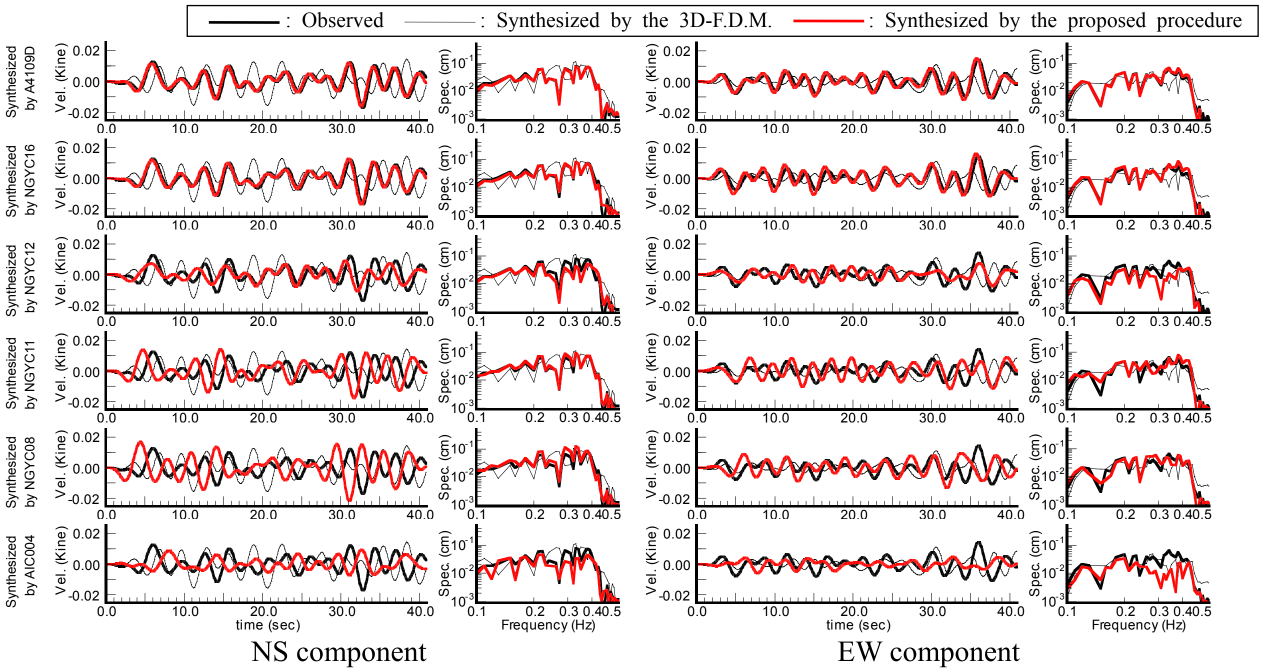

Figure 3.5 Comparison of velocity waveforms and velocity spectra observed at A4111A, those calculated by the 3D-F.D.M., and those calculated by the proposed procedure.

3.3 Discussion

In this section, the influences on the transfer function calculated from the theoretical wave of the source location, the distance between sites that are influential to the transfer function, and the hypocentral distance are described. If following three conditions are fulfilled through this discussion, agreement between transfer function calculated from theoretical waves and transfer function calculated from observed waves assumes to be better. However, this requires that the soil model has been modified to correspond to the predominant period.

1) The hypocentral distance from the objective site is great.
2) The distance between two sites used for the transfer function is small.
3) The hypocentral distance between the simulated earthquake and the real earthquake is small.

Multiplying the above transfer function, shown in Figure 3.3, by the observed wave, the A4111A waveform is estimated. In addition, Figure 3.5 shows the estimated waveforms and their spectra. In this figure, the estimated waveforms show a better correspondence to the observed wave than the wave calculated by the 3D-F.D.M.

The proposed procedure is used for waveform estimation of short period ground motion. The S.S.M. (Boore, 1983; Sato, 2006) is applied for waveform estimation of short period ground motion instead of the 3D-F.D.M. During the application of the S.S.M., the radiation pattern of three components (P wave, SV wave, and SH wave) are considered, and the site amplification is applied considering the incident angle for the seismic bedrock based on ray-tracing. The surface layer model is applied using the Nagoya City model proposed by Takahashi and Fukuwa (2006). Then, according to Eq. (4), the waveform at the A4111 site is estimated. Figure 3.6 shows the synthetic waveforms and their spectra. In this figure, the estimated waveforms correspond more closely to the recorded waveform than to the waveform calculated by the S.S.M.

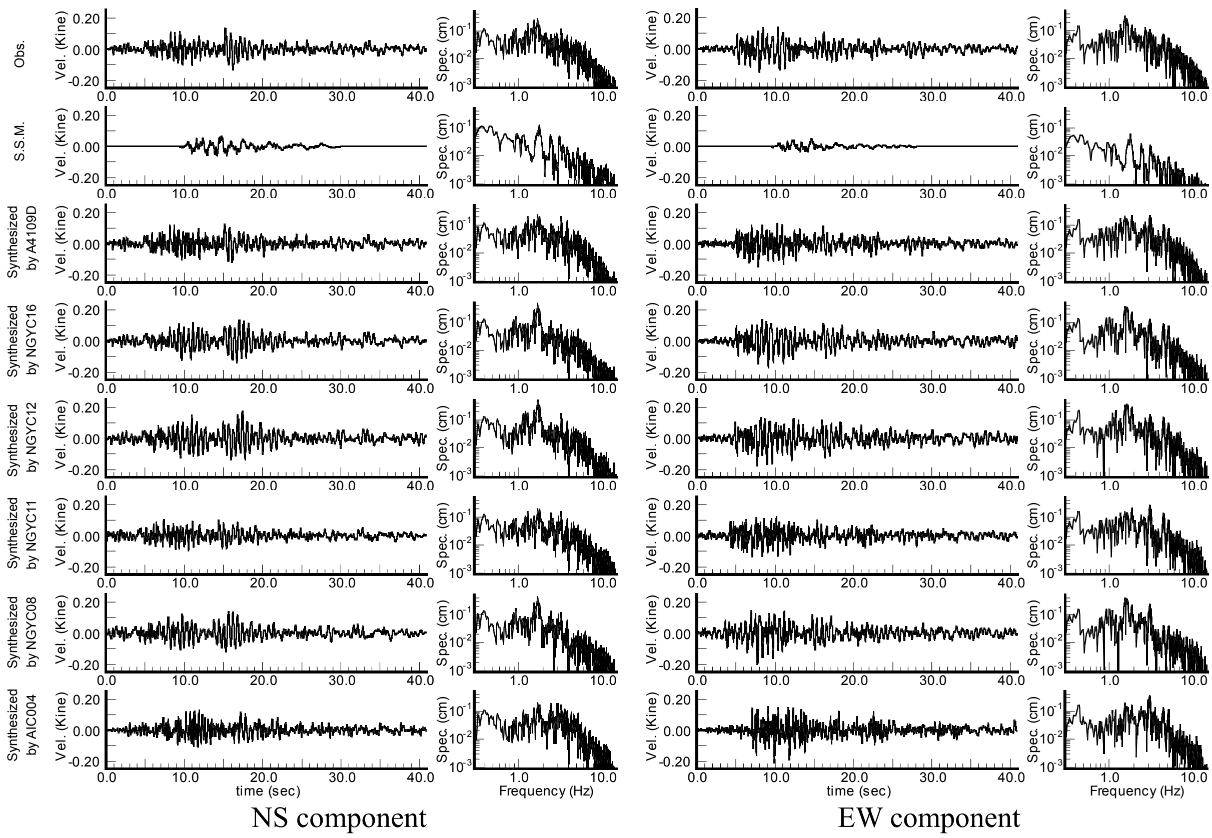

Figure 3.6 Comparison of velocity waveforms and velocity spectra observed at A4111A, those calculated by the S.S.M., and those calculated by the proposed procedure.

4. STRONG MOTION PREDICTION OF THE HYPOTHETICAL TONANKAI EARTHQUAKE

4.1 Data and Analysis

Using the proposed procedure, we simulate the strong motion of the hypothetical Tonankai earthquake in the Nagoya City district. There are 48 seismic observation sites used for calculating waveforms at arbitrary sites in the Nagoya City district, where the seismograph data of Evt.1 were recorded. Figure 4.1 shows the location of the seismic observation sites. A total of 4,290 observation sites were used for calculating the waveforms. These sites are distributed at 400-m intervals to the north, south, east, and west in Nagoya City. We use the subsurface structural model of the Tokai district (Aichi Prefecture, 2004) and use the surface layer model of Nagoya City proposed by Takahashi and Fukuwa (2006). Using the proposed procedure, waveforms of Evt.1 at seismic observation sites are created. The created waveforms are applied as the empirical Green's function method to be simulated. We followed the source model used by the Central Disaster Prevention Council (2003). The source model of the hypothetical Tonankai earthquake is shown in Figure 3.1. We calculated the synthetic waveforms according to the empirical Green's function method proposed by Dan and Sato (1998). We use 3.3 MPa as the stress drop of Evt.1, as estimated by Suzuki et al. (2005).

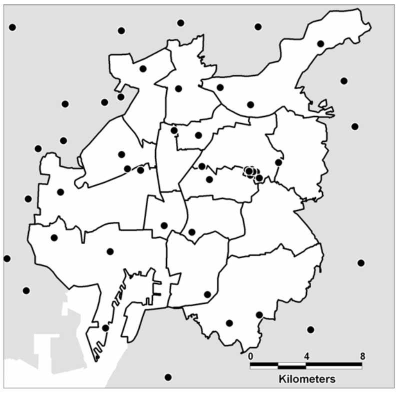

Fig.4.1 Location of seismic observation sites used in this section.

4.2 Results and Discussion

Figure 4.2 shows the distribution of the JMA seismic intensity of the hypothetical Tonankai earthquake simulated using the proposed procedure and that using the stochastic Green's function method and the distribution of building damage caused by the Tonankai earthquake of 1944 (Iida, 1977). The areas subjected to the seismic intensity of 6.5 calculated by the proposed procedure exceed 30% of the damages. On the other hand, the distribution of the seismic intensity calculated by the stochastic Green's function method does not show such large seismic intensity in these areas.

According to the above discussion, strong motion prediction with good accuracy is expected using the proposed procedure.

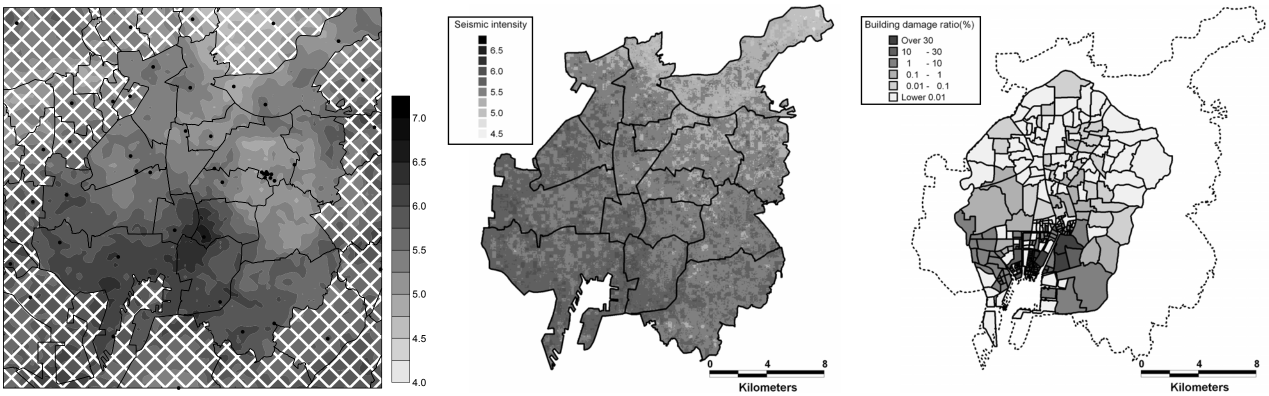

Fig.4.2 Distribution of the JMA seismic intensity calculated by the proposed procedure (left) and that calculated by the stochastic Green’s function method (center) and distribution of observed building damage due to the Tonankai earthquake of 1944 (right).

5. CONCLUSION

In the present paper, in order to apply the empirical Green’s function method to strong ground motion prediction over a wide area, we proposed a procedure for small-event ground motion estimation at an arbitrary site. Using this procedure, under the following conditions, even if theoretical waveforms have poor

accuracy, the waveform can be created with good accuracy.
1) The hypocentral distance from objective site is great.
2) The distance between two sites used for the transfer function is small.
3) The hypocentral distance between the simulated earthquake and the real earthquake is small.

Furthermore, using the proposed procedure, strong ground motions are simulated for the hypothetical Tonankai earthquake. The distribution of the simulated seismic intensity in the Nagoya area shows good agreement with that of the building damage caused by the Tonankai earthquake of 1944.

REFERENCES

Aichi Prefecture. (2005). Report of the investigation of subsurface structure about the Mikawa basin. (in Japanese)

Boore, D. M. (1983). Stochastic simulation of high frequency ground motions based on seismological models of the radiated spectra, *Bull. Seism. Soc. Am.*, **73**, 1865-1894.

Central Disaster Prevention Council. (2003). Materials of the 16th "Special investigation committee such as Tonankai and Nankai earthquakes" (in Japanese)

Dan, K., and Sato, T. (1998). Strong-motion prediction by semi-empirical method based on variable-slip rupture model of earthquake fault, *J. Struct. Constr. Eng. AIJ.*, **509**, 49-60. (in Japanese with English abstract)

Eto, C., Ishihara, Y., Tanabe, S., Kimura, K., and Nakayama, T. (2007). Three-dimensional models of lithofacies and N-values of alluvial deposits obtained using borehole logs: An example of the latest Pleistocene to Holocene incised-valley fills in northern part of the Tokyo lowland, central Japan, *Jour. Sediment. Soc. Japan*, **64**, 9-13.

Graves, R. W. (1996) Simulating seismic wave propagation in 3D elastic media using staggered-grid finite differences, *Bull. Seism. Soc. Am.*, **86**, 1091-1106.

Hertzel, S. H. (1978). Earthquake aftershock as Green's functions, *Geophys. Res. Lett.*, **5**, 1-4.

Iida, K. (1977). Distribution of the earthquake damage and seismic intensity caused by the Tonankai earthquake of December 7, 1944, Report of the Earthquake Section of Disaster Prevention Committee of Aichi Prefecture. (in Japanese)

Irikura, K. (1986). Prediction of acceleration motions using empirical Green's function, *Proc. 7th Japan Earthq. Eng. Symp.*, 151-156.

Sato, T. (2006). Envelope model of short-period ground motions for earthquakes caused by subductiing philippine sea plate based on scattering theory, *J. Struct. Constr. Eng. AIJ.*, **601**, 75-82. (in Japanese with English abstract)

Rovertsson, J. O. A., Blanch, J. O., and Symes, W. W. (1994). Viscoelastic finite-diffrence modeling, *Geophysics*, **59**, 1444-1456.

Suzuki, H., Morino, M., Iwamoto, K., Liu, Y., Fujiwara, H. and Hayakawa, Y. (2005). 3D subsurface structural model for strong motion simulation around lake Biwa, southwest Japan. *Zisin*, **58**, 91-106. (in Japanese with English abstract)

Suzuki, W., Iwata, T., Asano, K., and Yamada, N. (2005). Estimation of the source model for the foreshock of the 2004 off Kii peninsula earthquakes and strong ground motion simulation of the hypothetical Tonankai earthquake using the empirical Green's function method, *Earth Planets Space*, **57**, 345-350.

Takahashi, H., and Fukuwa, N. (2006). Proposal and verification of modeling of the surface layers for strong motion prediction, *J. Struct. Constr. Eng. AIJ.*, **599**, 51-59. (in Japanese with English abstract)

Tobita, J., Fukuwa, N., Nakano, M., and Yamaoka, K., (2001). Development of on-line data acquisition system for strong moton seismic records and its application to existent observation systems, *J. Technol. Des. AIJ.*, **13**, 49-52.(in Japanese with English abstract)

Zhao, D., Hasegawa, A. and Kanamori, H., (1994). Deep structure of Japan subduction zone as derived from local, regional, and teleseismic events, *J. Geophys. Res.*, **99**, 313-329.