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STRONG MOTION SIMULATION FOR LARGE SUBDUCTION EARTHQUAKES

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SUMMARY

Results of strong ground motion prediction for the Nankai and Tonankai earthquakes (M~8) by a hybrid method of three dimension finite difference method (3DFDM) and the stochastic Green's function method (SGFM) are presented. Long-period strong motions simulation is performed for crustal structure model that includes 3D structures of the subducting Philippine Sea plate and the Osaka sedimentary basin. Characterized asperity model describing source heterogeneity is introduced following the source model by the Central Disaster Prevention Council. We simulated the worst case that the two earthquakes occur simultaneously and the other two cases of separate occurrence. The results indicate that the sedimentary deposits of the Osaka basin significantly affect on amplification of simulated ground motion near basin edge and that this effect depends on the direction of wave incidence. Through hybrid method of the long-period strong motion and the short-period ones that are calculated by the stochastic Green's function method (SGFM), we estimated the broad-band strong ground motions due to Nankai and Tonankai earthquakes. Our results demonstrate the possibility of practical simulation of wave propagation including basin induced surface waves, for sbuduction earthquake with large-scale source faults.

INTRODUCTION

Along the Southwest Pacific coast of Japan, large subduction earthquakes such as the Nankai and Tonankai earthquakes have occurred repeatedly for every 100 to 150 years. The earthquakes have generated heavy damage in the area. High occurring probability of the next event in 50 years is estimated by the Headquarters for Earthquake Research Promotion [1]. Results of strong ground motion prediction as seismic intensity and damage estimation during these earthquakes are also published by CDPCJ [2]. However, in large cities (such as Osaka, Nagoya and so on), where various types of buildings and structures exists, it is difficult to predict damage only from the seismic intensity. Prediction of strong ground motion waveform for future large subduction earthquakes is necessary to mitigate earthquake disaster in such area. In this study, we present results of strong ground motion prediction in the Osaka basin, Southwest Japan, for the Nankai and Tonankai earthquakes (*M*~8), by the 3D staggered-grid finite difference method (3DFDM) with variable grid sizes (Pitarka [3]), considering three-dimensional basin and subducting plate structures. Then broad-band strong ground motions of Nankai and Tonankai

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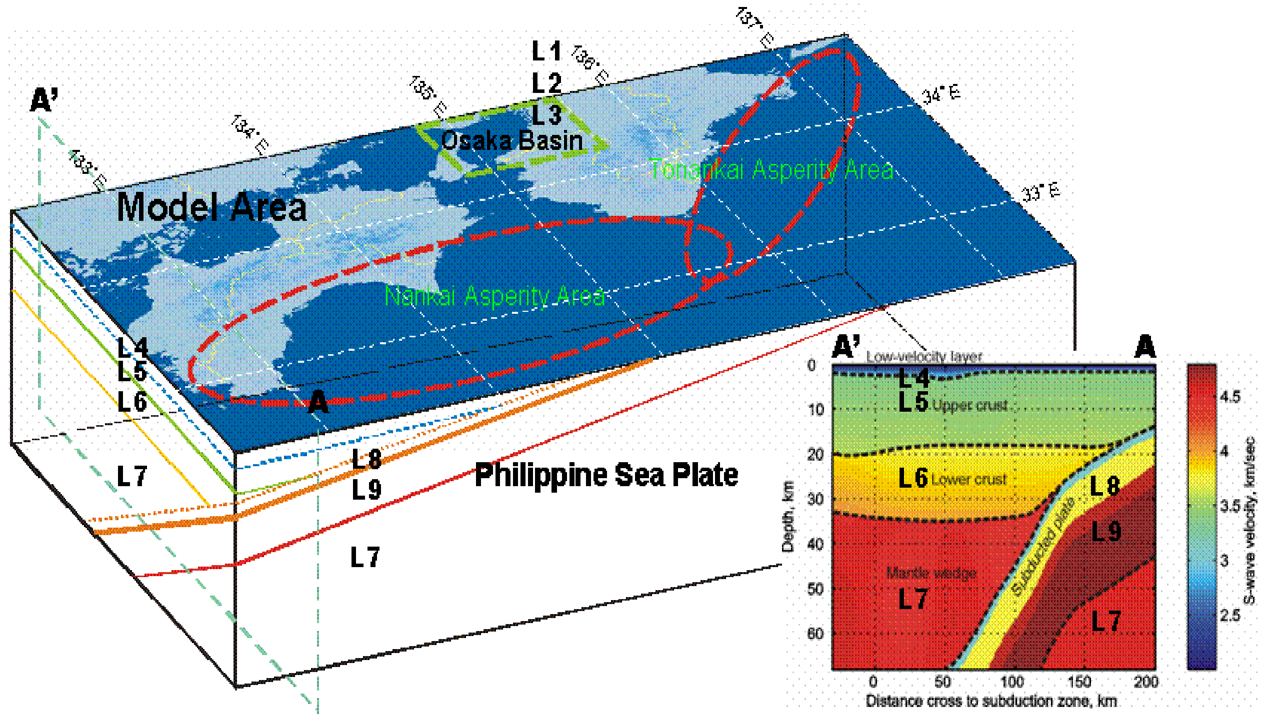

Figure 1. Simulation area for the Nankai and Tonankai earthquakes. L1-L9 marks shows layered structure in Table 1.

earthquakes are constructed using the hybrid method (Kamae [4], Irikura [5], Tsurugi [6]). Short-period strong motions are calculated using the stochastic Green's function method (SGFM) (Boore [7]). Characterized asperity model describing source heterogeneity and fault rupture parameters is introduced following the source model of the Central Disaster Prevention Council [2]. The strong ground motions are predicted in case of simultaneous occurrence of the Nankai and Tonankai earthquakes and in cases of separate occurrences of the two earthquakes.

BASIN AND CRUSTAL STRUCTURE MODEL

Figure 1 shows the modeling area for the Nankai and Tonankai earthquakes simulation. The numerical simulations were performed for velocity structure model that includes complexity of irregular subsurface structure such as the subducting Philippine Sea plate, which is sinking down beneath the Eurasian Plate, and the sedimentary basins such as the Osaka basin. For the Osaka basin, we used 3D layered basin structure model. The sedimentary basin structures (see Figure 2) are modeled based on geophysical and geological exploration data by multi-spline function technique (Kagawa [8], Zhao [9, 10]). The assumed model consists of layered sedimentary structure inside basin and rock structure without any sedimentary layers outside the basin. The latest model (Zhao [10]) includes accurate basin edge structure, additional bedrock depth estimations based on P and S wave delay time derived from strong motion records and so on.

The most important step for verification and additional refining of the basin model is the characterization of the model with higher accuracy through the 3DFD simulations of several small events (Zhao [9]). The simulation results match well observed arrival time, amplitude of main S wave portion, and generation of

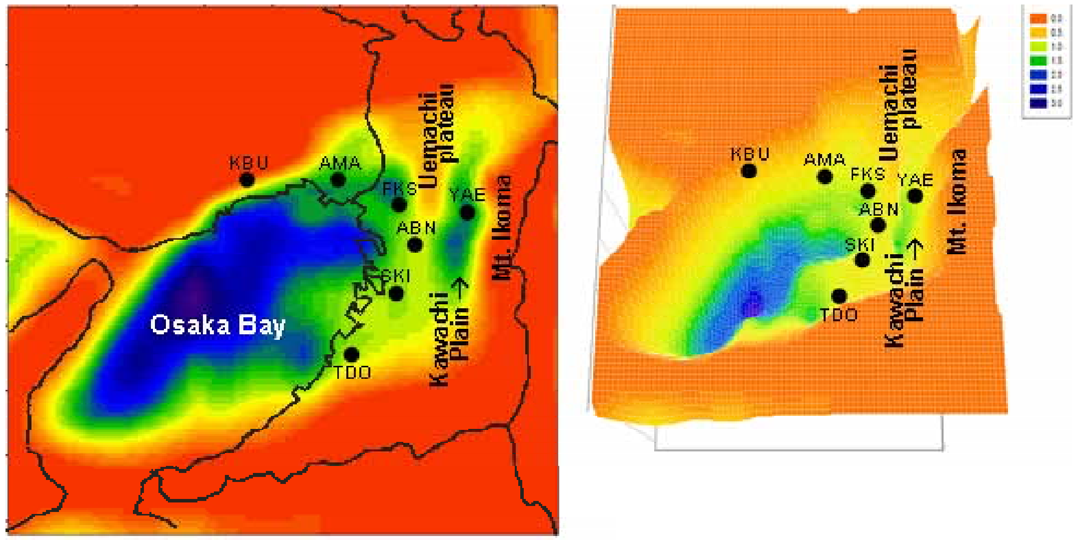

Figure 2. Three-dimensional Osaka basin structure (basement depth).

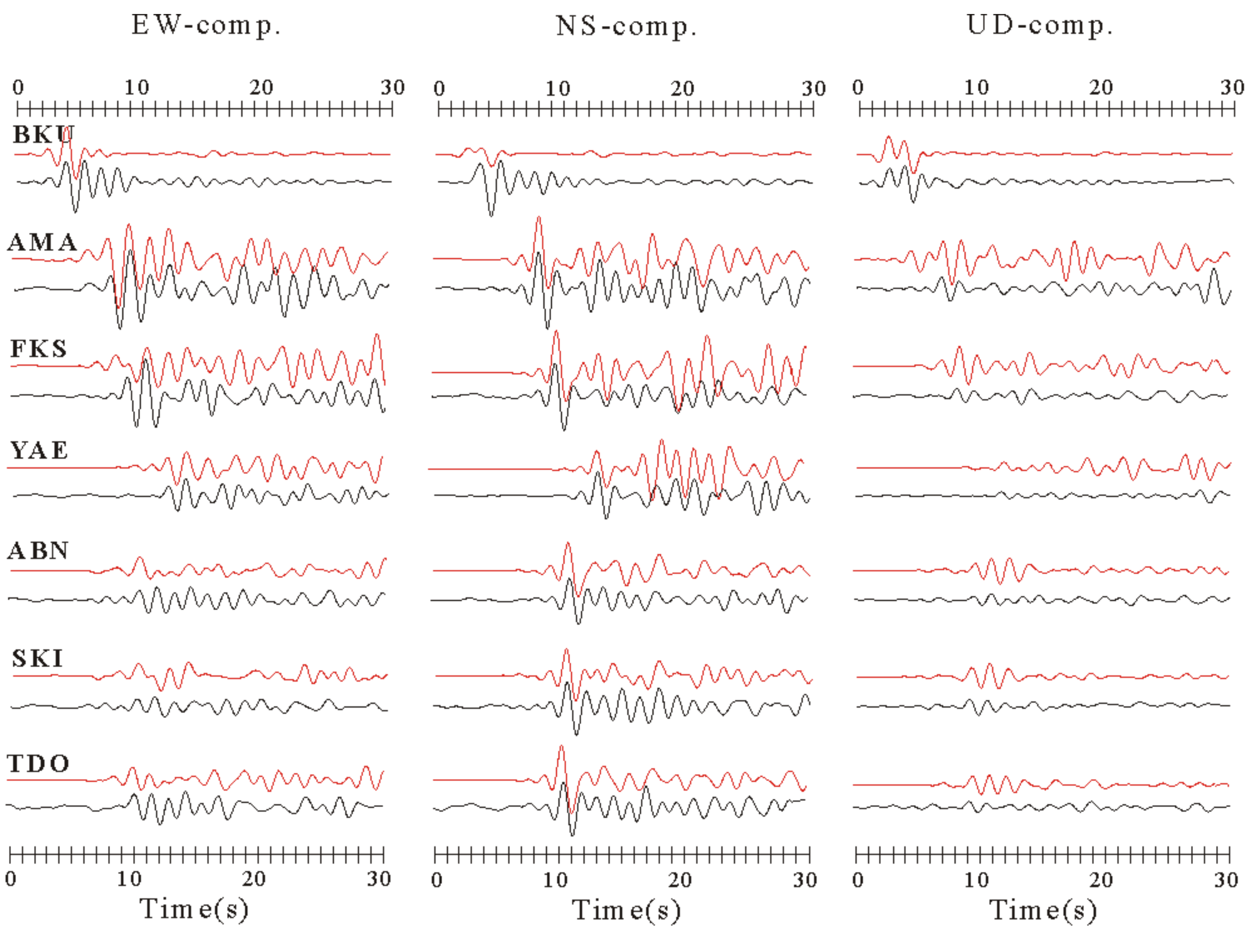

Figure 3. Comparison of three-component synthetic and observed velocity waveforms for a small earthquake. Red and black traces indicate synthesized and observed waveforms respectively. All waveforms are band-pass filtered in 0.1 - 1.0Hz.

surface waves. Figure 3 shows examples of three component synthetic velocity waveforms and compares them with observed records of small events in frequency range 0.1-1.0Hz. We found that the model provides a good agreement between synthetic waveforms and observed waveforms, everywhere all over the basin.

Shapes of deep structural interfaces are specified according to the depth distribution of the Moho and Conrad boundaries (Zhao [11]). The deep velocity structure is specified based on the crustal P-wave velocity structure used for the hypocenter determination at seismological observatories in the studied region, and on the structure estimated by inversion of dispersion curve of the Love waves in the Southwest Japan (Ito [12]). The Philippine Sea plate (Philippine slab) is built into the model. The smoothed shape of plate is specified according to the results of Hagiwara [13]. We specified the S-wave velocity in the plate according to the results of the onshore-offshore integrated seismic survey (Kodaira [14]). The plate velocity structure has a low-velocity layer on the top of the slab. The thickness of the slab is about 30 km, and the thickness of the low-velocity layer is about 5 km. This part of modeling procedure roughly is similar to the 3D velocity modeling procedure of Petukhin [15]. Figure 4 shows the Philippine slab structure model near Nankai earthquake and Tonankai earthquake fault area, and Table 1 shows the parameters of final model used for 3D-FD simulation, including Osaka basin and crustal structure.

The model space is from 31.80 N to 35.00 N, 380 km in W-E direction, and from 132.00 E to 136.00 E, 580 km in S-N direction. The modeling depth is about 100 km. The Osaka basin model occupied area about 81 km × 81 km inside the calculation model space. The deepest sedimentary layer in the Osaka basin is over 3.0 km.

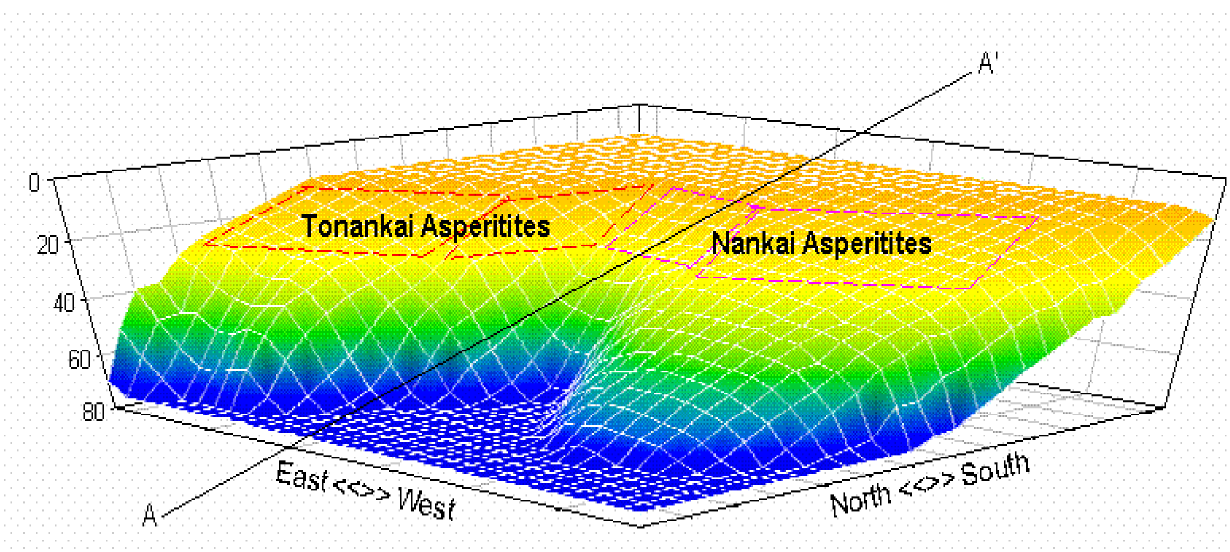

Figure 4. Shape of the Philippine slab around Nankai and Tonankai earthquakes fault area, used for 3DFD simulation (A view from Northwest).

Table 1. Parameters of the model used in 3DFD simulations including Osaka basin (red) and crustal structure (blue).

Layer	Vp (km/s)	Vs (km/s)	Density(kg/m^3)	Q-value	Depth (km)
1	1.60	0.35	1.70	50	*A/B Layer
2	1.80	0.55	1.80	80	B/C Layer
3	2.50	1.00	2.10	120	C/Bas Layer
4	5.40	3.20	2.60	300	4.0
5	6.00	3.50	2.70	350	15.2-18.0
6	6.60	3.82	2.85	500	36.9
7	8.10	4.50	3.29	1000	> 36.9
8	7.50	4.30	3.06	2000	0.0-100.0
9	7.80	4.35	3.16	2000	0.0-100.0

*Not used.

FAULT MODEL AND PARAMETERS

The CDPCJ [2] have estimated source area and asperity areas of the Nankai and Tonankai earthquakes, through comparison of damage distribution of historic earthquakes and the simulated distribution of seismic intensity. The fault macro parameters, such as seismic moment and rupture velocity are also provided. For simulation, the characterized asperity model describing the source heterogeneity was introduced following the asperity model of the CDPCJ (Tsurugi [6]). The fault surface, which has complex three-dimensional curved shape, is divided into 4 plain segments. Macro and micro fault parameters were specified according to values of parameters estimated by CDPCJ [2]. Rupture starting point is settled on the boundary of Nankai earthquake fault and Tonankai earthquake fault following CDPCJ [2]. Figure 5 shows resulting characterized fault model of the Nankai and Tonankai earthequakes. The star shows the rupture starting point, checked squares show asperity elements and open squares show off-asperity elements.

3DFD SIMULATION

The long-period ground motions were calculated by three-dimensional finite difference method (Pitarka [3]) considering 3D structure of Osaka basin and 3D shape of the Philippine slab. The smallest grid interval of the designed finite difference mesh is 220m and slowest shear wave velocity is 550 m/sec in the surface layer of the Osaka basin. In area outside Osaka basin, grid spacing vary from 440 m to 1320 m, depending on the size of fault elements and the value of surface S-wave velocity. The grid spacing also changes along the model depth. Calculations are performed for total 350-sec duration. The effective maximum frequency is about 0.5 Hz (period is 2.0 sec). We simulated the worst case that the Nankai and the Tonankai earthquakes occur simultaneously and two cases of the separate occurrence. As the source time function, we applied approximate expression of slip velocity time-function proposed for strong ground motion simulation by Nakamura [16].

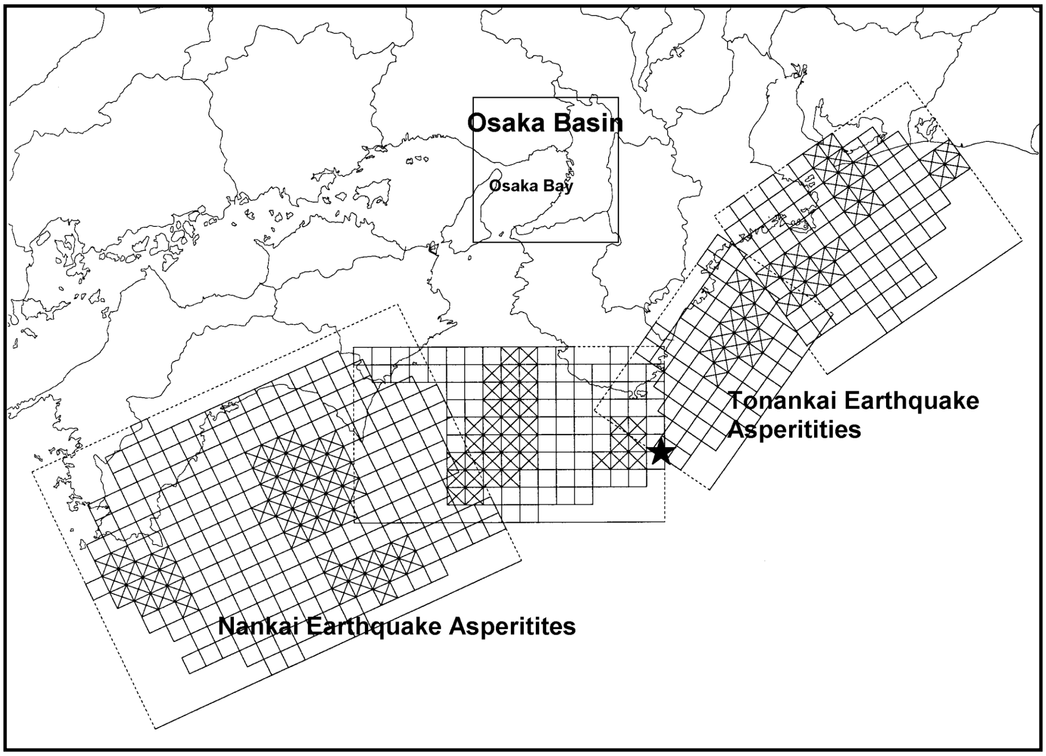

Figure 5. Characterized asperity model for the Nankai and Tonankai earthquakes. Star indicates the rupture starting point used in this study.

The target sites of analysis are observation sites of the Committee of Earthquake Observation and Research in the Kansai Area (CEORKA) in and around the Osaka prefecture, and Kyoshin Network sites (K-net, strong-motion observation network).

Figure 6 shows examples of snapshot of the earthquake wave propagation in the Osaka basin for all three cases (EW component). Amplification phenomena caused by basin edge effects can be seen clearly. Short wavelength waveforms with large amplitude are generated during the incidence of the long wavelength body waves, propagated from source region to the basin. Generation of the edge wave is clearly confirmed in the region near south edge of the Osaka basin, in case of Nankai earthquake, and near the south and east edges, in case of the Tonankai earthquake. Especially, amplification phenomenon of such waveform is remarkable in Kawachi plain (east part of Osaka Basin) that is close to the Mt. Ikoma. Moreover, it also visible that focusing/defocusing effect is strongly depended on the horizontal shape of basin edge, formed by rocks around (outside) basin. Large amplitude edge waves are intensively generated in the basin between 50 and 140 sec from the fault rupture starting. In addition, the ground motion is continued until 200 sec or more due to the effect of complex underground structure in the basin. Large shakes also exist in the bay side and area surrounding the Uemachi plateau (diluvium); it seems that these basin induced waves are generated due to the ground structure too.

Figure 7 shows the Peak Ground Velocity ***PGV*** distribution in the basin for the case of simultaneous occurring of the Nankai and Tonankai earthquakes. It is confirmed that the ***PGV*** values in the bay side are mostly the same as those in the Kawachi basin placed between the Uemachi plateau and the Mt. Ikoma. Moreover, the ***PGV*** reaches almost 30 cm/s in all regions in the basin. The ***PGV*** are small on stiff sediment and on bedrock of outside basin, that again shows good correlation with the structure.

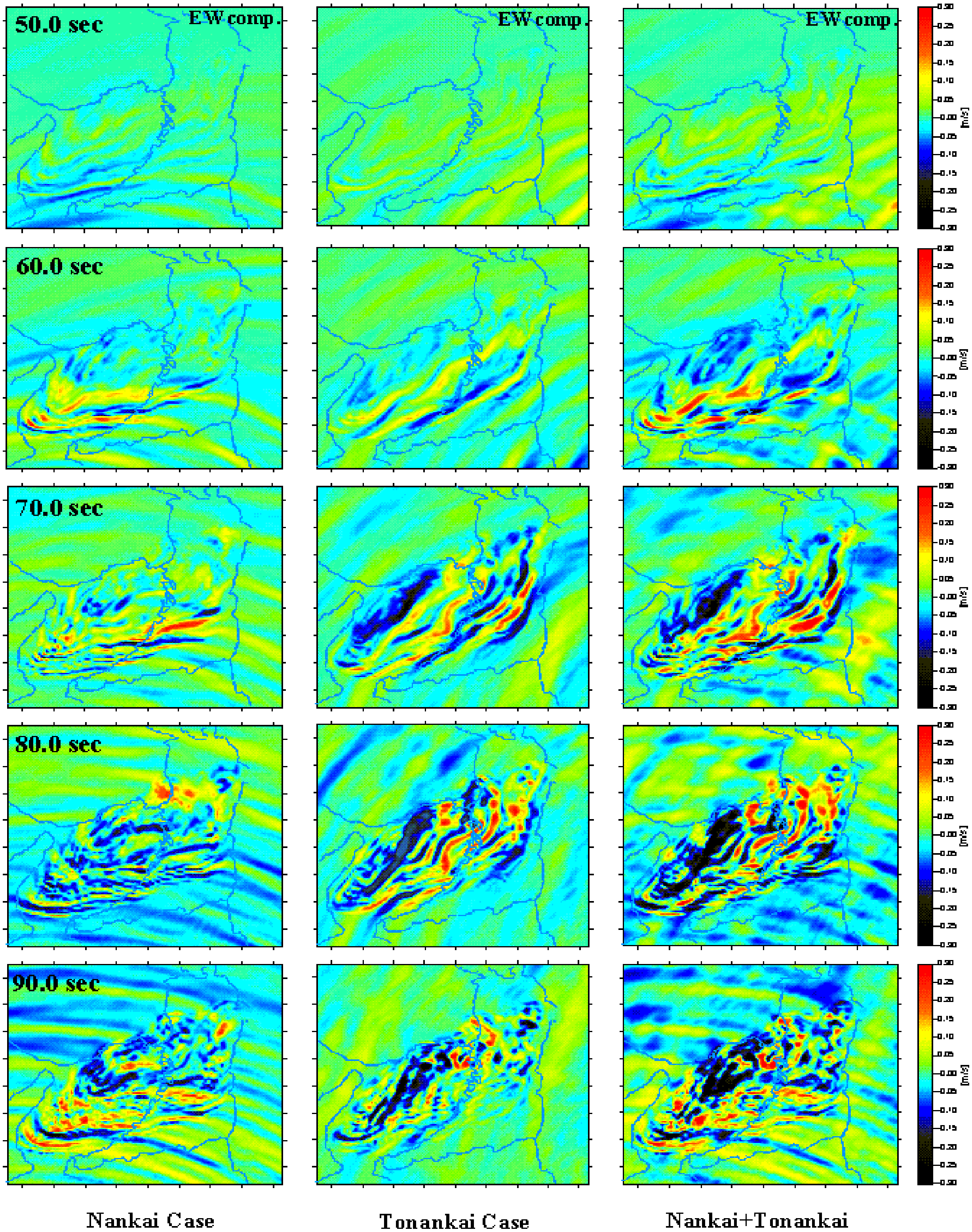

Figure 6. **Snapshots of long period wave propagation through Osaka basin for the three cases. From left to right: case of occurrence of the Nankai earthquake, case of occurrence of the Tonankai earthquake and case of occurrence of the Nankai and Tonankai earthquakes simultaneously. Note difference of the wavelengths outside and inside basin.**

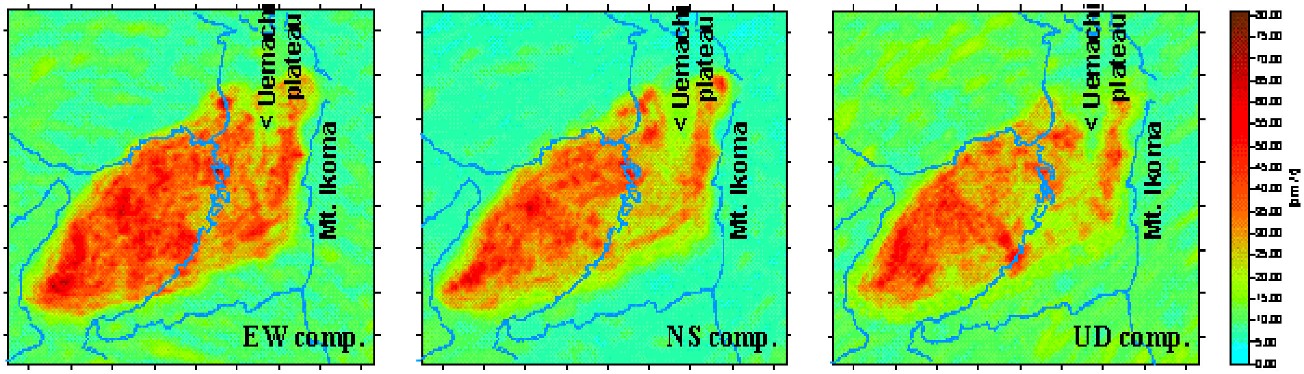

Figure 7. **Peak ground velocity (*PGV*) distribution in Osaka basin for the three cases. From left to right: the Nankai earthquake, the Tonankai earthquake and the Nankai + Tonankai earthquake.**

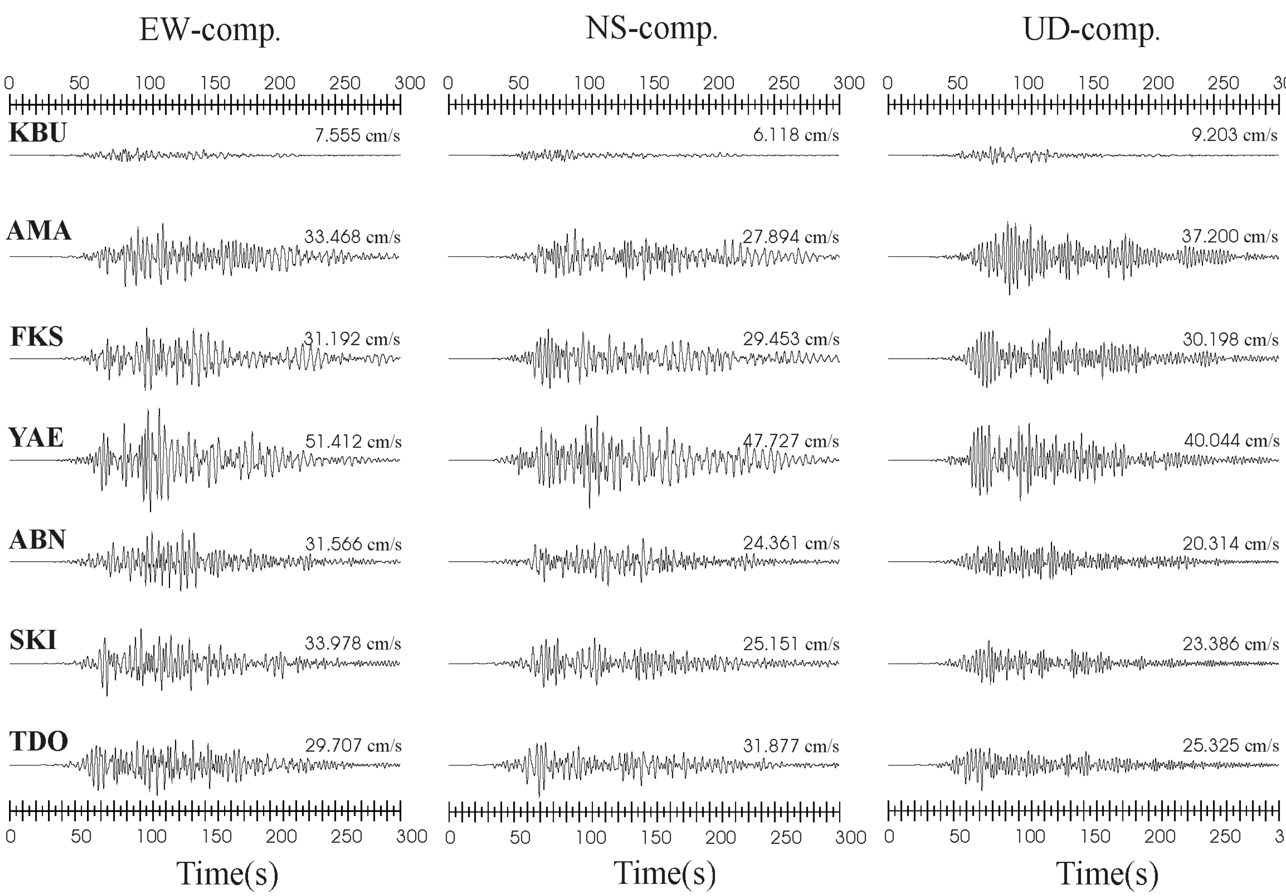

Figure 8. **An example of long-period waveforms obtained at some CEORKA sites. Location of sites is shown in Figure 2.**

Figure 8 shows examples of long-period waveforms at some CEORKA observation sites. At KBU site, located on the weathered rock, the maximum amplitude over two horizontal components is about 7.0 cm/s. However, on the soft sediments, the shakes with predominant period of 4-5 sec increase; amplitude of EW component reaches 51 cm/s in the YAE site located in the eastern part of the Kawachi basin. It is anticipated that this can be due to the interference amplification by the edges of the basin. Moreover, the ground vibrates for a long time, 200 seconds or more, at almost all sites, and the maximum amplitudes are over 70 cm/sec in several areas, in the case of occurrence of the Nankai earthquake and Tonankai earthquake simultaneously.

HYBRID BROAD-BAND STRONG GROUND MOTION

The hybrid method is adopted in the simulation to obtain reliable strong ground motion waveforms in a wide frequency range. The target sites for analysis are observation sites of CEORKA and K-net in Osaka prefecture. To get broad-band seismograms, the low-frequency records calculated by 3DFD above, were combined at the match frequency about 0.5 Hz with the high frequency records, calculated by the stochastic Green's function method. The site amplification corrections at target sites in the Osaka basin have been obtained empirically using spectral rations between observed and bedrock (theoretical) spectra (Tsurugi [17]). Figure 9 shows two examples of the site amplification characteristic.

The Figure 10a and Figure 10b show examples of ground acceleration, velocity and displacement waveforms with their response spectrum (damping constant 5%) at ABN and YAE sites, respectively. Both figures show EW components. The ABN site is an observation point located on the Uemachi plateau (diluvium), and the YAE site is an observation point located in the eastern part of Osaka basin with thick alluvium layer. The common features of both results are that the duration is very long and long-period waves (period over 1 sec) are prominent. Especially at the YAE site, the peak ground velocity is 70 cm/sec, the peak ground displacement is over 30 cm, and response spectrum in the period range between 2 and 5 sec is about 200 cm/s in the case of occurrence of both earthquakes simultaneously. This is both due to the large size of earthquake fault and due to the deep alluvium basin structure.

The distribution of JMA (Japan Meteorological Agency) seismic intensity scale, $\boldsymbol{I}_{JMA}$, that was calculated from the simulated broad-band waves, agrees well with that published by CDPCJ [2]. The intensities of ground motion in case of individual occurring of the earthquakes are about 60 or 80 % of those in case of occurrence of both earthquakes simultaneously.

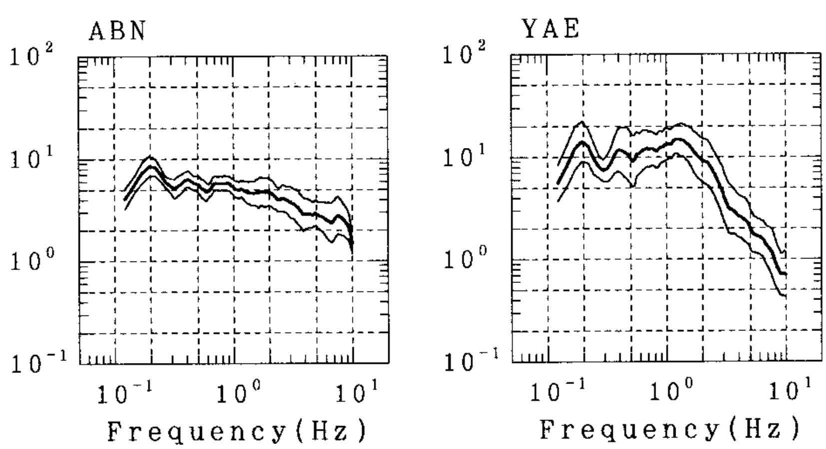

Figure 9. Examples of spectral site amplification corrections.

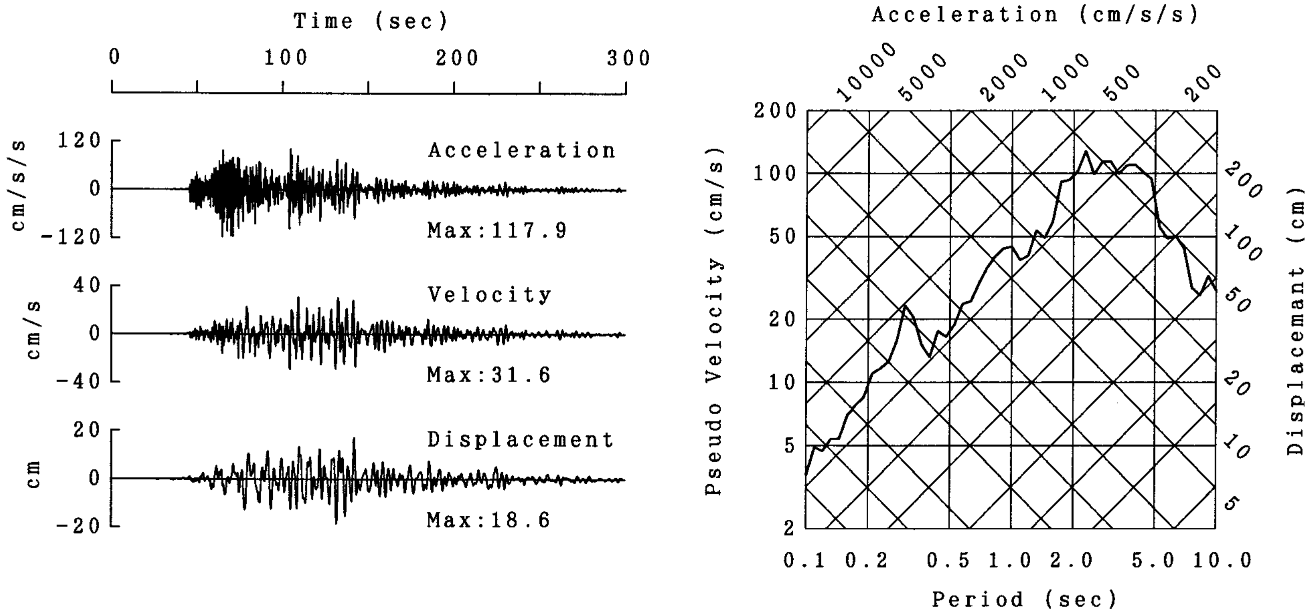

Figure 10a. The hybrid acceleration, velocity and displacement waveforms and their response spectrum (damping constant 5%) at ABN site.

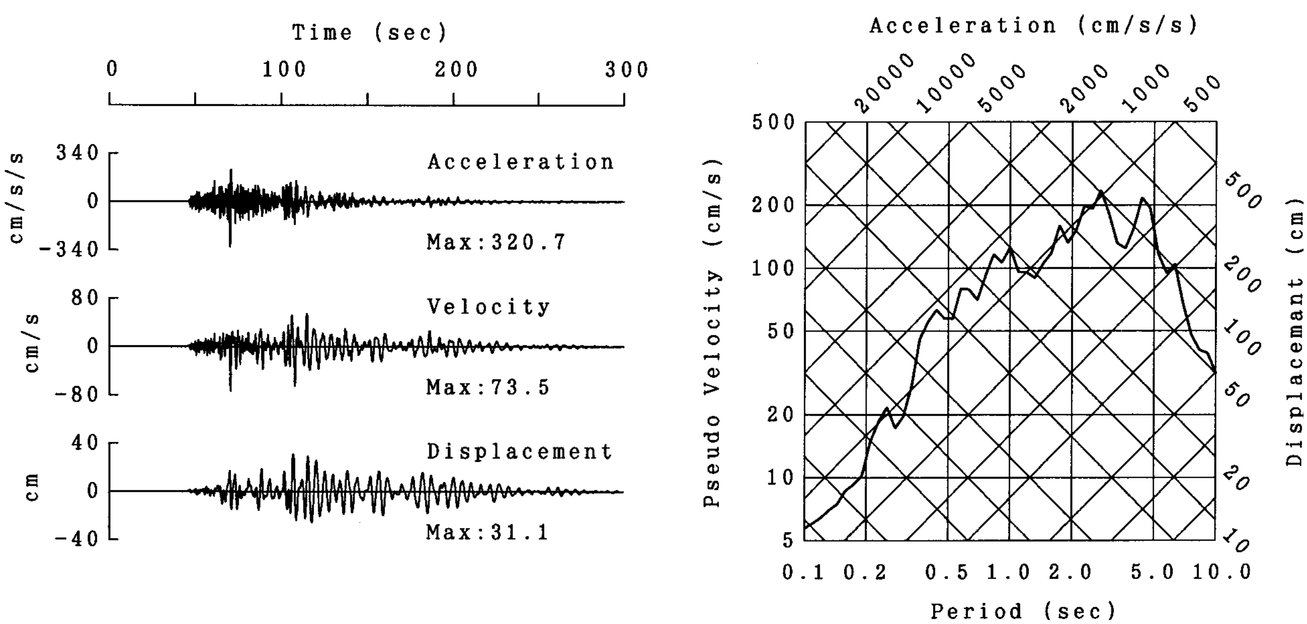

Figure 10b. The same as Figure 10a but for YAE site.

CONCLUSION

In this study, we simulated the the Nankai and Tonankai earthquakes (M~8) by combining 3DFD method with the SGF method with empirical site amplification derived from observed records. The following conclusions are obtained:

Simulated strong ground motions reflect characteristics of subduction earthquake and effects of the basin structure. The results indicate that the sedimentary deposits of the Osaka basin have significant effect on amplitude of simulated ground motion near basin edges and that this effect depends on the direction of wave incidence. Basin induced wave is confirmed mainly in the south edge region of the Osaka basin, in the case of Nankai earthquake, and near the south and the east edges, in the case of Tonankai earthquake. The peak ground velocity is especially large in eastern part of Osaka basin (Kawachi plain), where alluvium layer is thick; estimated ***PGV*** is over 70cm/sec in case that both earthquake occurs simultaneously. The duration of simulated waves is over 200 seconds at most of sites, and the predominant period is about 4-5 second. The distribution of seismic intensity $\boldsymbol{I}_{JMA}$ calculated from the simulated waveforms agrees well with that estimated by CDPCJ [2]. It also agrees well with the results based on the seismic intensity attenuation relation. Our results demonstrate the possibility of practical simulation of wave propagation including surface waves, for subduction earthquake with large-scale source faults.

Our results indicate that the edge effect in Osaka basin is very remarkable. This effect depends on the structure, especially on the shape of edge structure and on the predominant period of wave. The accuracy of 3DFD result is limited by the accuracy of three-dimensional velocity model. The key point of future study is to improve the model continuously.

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