Long-Period Ground Motion Simulation of Tokai-Tonankai-Nankai Coupled Earthquake Based on Large-Scale 3D FEM

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SUMMARY:
We conduct a series of long period ground motion simulation of the Tokai-Tonankai-Nankai coupled earthquake considering 3-D subsurface ground model including large-scale sedimentary basin structures, Kanto, Nobi and Osaka plain. We examine the influence of the location of rupture starting point and the contribution of each earthquake to the estimation results of the coupled earthquake. The results showed the simulated ground motions of Nankai and Tonankai earthquakes are dominant in Osaka plain. Those of Tonankai earthquake and Tokai earthquake are dominant in Nobi plain and Kanto plain, respectively. The duration time of the simulated motions of Tokai-Tonankai-Nankai coupled earthquake becomes longer than that of each earthquake. Furthermore, it is found that the Nankai earthquake amplified the long period ground motions exceeding 10 seconds in the Nobi and Kanto plains when the rupture started from the south east point of the fault plain.

Keywords: Long Period Ground Motion, Tokai-Tonankai-Nankai Coupled Earthquake, 3D-FEM

1. INTRODUCTION

Nankai Trough is the convergent boundary where Philippine Sea plate is subducting under the Southwestern part of Japanese archipelago. Historically, large thrust earthquakes of magnitude 8 have occurred repeatedly with the recurrence interval of 100 to 150 years. They are named Tokai, Tonankai and Nankai earthquake. The latest ones are 1944 Tonankai earthquake (M7.9) and 1946 Nankai earthquake (M8.0). The next large earthquake is supposed to occur in near future. The Headquarters for Earthquake Research Promotion predicts occurrence probabilities of next Tokai, Tonankai and Nankai earthquakes within 30 years are 87%, about 70% and about 60%, respectively. It is very important issue for disaster prevention in Japan.

The long period ground motions generated at the focal regions of these large earthquakes propagate long distance to large sedimentary basins such as Kanto, Nobi and Osaka plains. Those motions are amplified by these sedimentary basins and shake the long period structures such as high-rise buildings and oil tanks. Therefore, it is important to evaluate the long period ground motions considering the appropriate modeling of the long propagation path structure and sedimentary basin structures.

For this purpose, numerical simulations of earthquake ground motions of each M8 earthquake along Nankai Trough (Tokai, Tonankai and Nankai earthquake) using large-scale finite differences method (FDM) and finite elements method (FEM) have been performed. Recently, evaluation of long period ground motions of the coupled earthquake have been conducted (e.g. Central Disaster Management Council, 2003, Yoshimura et al., 2008, Furumura and Imai, 2009). Furthermore, the occurrence of the 2011 off the Pacific coast of Tohoku Earthquake makes the studies of these large earthquakes along Nankai Trough more important.

In this paper, we constructed a 3-D subsurface structure model which includes the rupture area of Tokai, Tonankai and Nankai earthquakes and Kanto, Nobi and Osaka plains. To verify the model, we simulated the M_J7.1 foreshock of the 2004 off the Kii-peninsula earthquake on September 5 at 19:07 that occurred near Nankai Trough. Finally, we perform the long period ground motion simulation of the Tokai-Tonankai-Nankai coupled earthquake. Furthermore, we examine the contribution of each earthquake to the estimation results of the coupled earthquake and the influence of the location of rupture starting point.

2. SUBSURFACE GROUND MODEL AND SOURCE MODEL

2.1. Subsurface Ground Model

We constructed the 3-D subsurface ground model for the area of 864km x 300km as shown Fig.2.1. Model depth is 50km. We newly introduced the basin structure of Osaka and Nobi plains to the subsurface structure modeled by Yoshimura et al.(2008) which included the sedimentary wedge along Nankai Trough and Kanto plain. X and Y coordinates are in the E29N and N29W direction, respectively. Fig.2.1. indicates the depth contour (1km) of seismic bedrock (Vs=3.23km/s) of the sedimentary wedge, Osaka, Nobi and Kanto plain. Table 2.1. shows material properties of the 3-D subsurface ground model. Fig.2.2. shows the vertical sections along Y direction at (a) X=375km section that cut across the sedimentary wedge and includes the hypocenter of the 2004 Off the Kii peninsula earthquake and (b) X=750 km section that cut across Kanto plain.

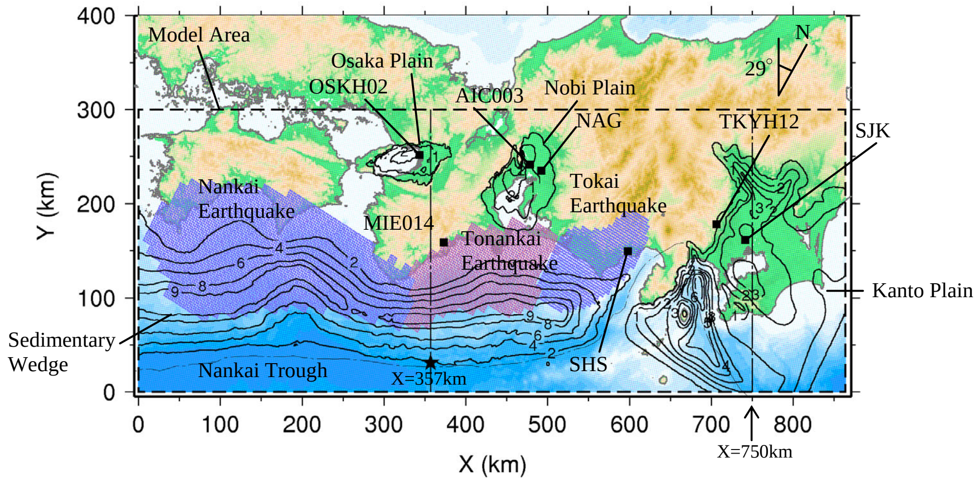


Figure 2.1. Model area for FEM calculation and rupture area of Tokai, Tonankai and Nankai earthquake

2.1.1. Propagation Path Structure

We constructed the upper surface of Philippine Sea plate (top of layer 11, see Table 2.1. and Fig.2.2.) combining the depth obtained by Nakamura(1997), Noguchi(1996), Ishida(1992), and Sato et al.(2005). Only for Nakamura(1997), we assumed 5km shallower depth because Nakamura's surface is the upper surface of seismic activities and the plate boundary is shallower than it. We modeled the depth of Moho discontinuity (top of layer 10) based on Ryoki(1999). The depth of Conrad discontinuity (top of layer 9) was set to be half of Moho discontinuity or 15 km near the Philippine Sea plate.

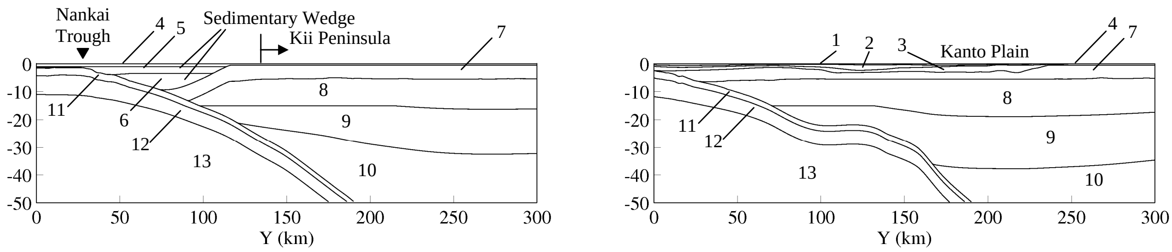
We modeled the Sedimentary wedge (layer 5,6) along Nankai Trough based on Nakanishi et al. (1998) and Nakanishi at al. (2002). The P wave velocity (Vp) obtained by Nakanishi increases along the depth. We modeled it into 2 layers. Vp of the shallower part than 3km is 2.7km/s and that of deeper part is 4.0km/s. S wave velocity and density was given based on Ludwig et al. (1970).

We set the thickness of Philippine Sea plate (layer 11,12) to be 7km. Upper 2km has low velocity. At the surface, we modeled the Vs=1.1km/s layer (layer 4) with thickness of 1km at the sea and 0.5km at

Table 2.1. Material Properties

No	Vs [km/s]	Vp [km/s]	density [g/cm^3]	Q	Q (at f=0.2)	Location	
-	Horikawa et al.(2003)			250Vs f	50Vs	Osaka Plain	
-	Hayakawa et al.(2002)			500f	100	Nobi Plain	
1	0.5	1.8	1.9	1000f	200	Kanto Plain	
2	0.9	2.3	2.1	1000f	200		
3	1.5	3.0	2.3	1500f	300		
4	1.1	2.0	2.0	1000f	200		Propagation Path
5	1.4	2.7	2.4	1000f	200	Sedimentary Wedge	
6	2.2	4.0	2.5	1250f	250		
7	3.23	5.5	2.5	1500f	300		
8	3.53	6.0	2.7	2500f	500		
9	3.94	6.7	2.8	3000f	600		
10	4.6	7.8	3.2	3500f	700		
11	2.9	5.0	2.4	1500f	300		
12	4.0	6.8	2.9	3000f	600		
13	4.7	8.0	3.2	5000f	1000		

f : frequency[Hz], Vs : S-wave Velocity[km/s]



(a) X=357km (b) X=750km

Figure 2.2. Vertical sections along Y direction (N29W)

the land. The material properties are given based on Yamada and Iwata (2005) except the sedimentary wedge.

2.1.2.Kanto Plain

We modeled Kanto plain into 3 layers (layer 1,2,3) based on Yamanaka and Yamada(2002). The depth of seismic bedrock is shown Fig.2.1. We refered to the material properties by Yamanaka and Yamada(2006) and Miyake et al.(2008).

2.1.3.Nobi Plain

We modeled Nobi plain into 2 layers, quaternary layer and tertiary layer. The depth to the bottom of tertiary layer (the top of seismic bedrock) and the bottom of quaternary layer are based on survey by Mie prefecture (2003) and Aichi prefecture (2003), respectively. The maximum depth of seismic bedrock is about 2.3km. Vs and Vp values are calculated using Vp-detph and Vs-Vp relationship based on Hayakawa et al.(2002). The lowest S-wave velocity was set to be Vs=500m/s. Density is based on Hayakawa et al.(2002). Q values are assumed to be Q=500f (f:frequency[Hz]).

2.1.4.Osaka Plain

We adopted the 3-D underground structure model based on Horikawa et al.(2003). Its maximum depth is about 2.6km. The lowest S-wave velocity is set to be Vs=500m/s as well as Kanto and Nobi plain. Q values are set to be Q=250Vsf (Vs:S-wave velocity[km], f:frequency[Hz]) so that it is equal to be Q=50Vs (Horikawa et al. 2002) at 0.2Hz.

The sea floor and land topography are modeled to be flat. The largest element size is 1km and the smallest is 0.125km. The width of elements is chosen so that more than 10 elements exist for the wavelength of S-wave in each layer. This model is effective at the period domain more than 2.5 seconds. The number of nodes is about 84,780,000 and that of elements is about 498,760,000.

2.2. Simulation of the 2004 off the Kii Peninsula Earthquake

To verify the model, we simulated the M_J 7.1 foreshock of the 2004 off the Kii-peninsula earthquake on September 5 at 19:07 that occurred near Nankai Trough. The seismic source of the earthquake is modeled by a point source based on Yamanaka(2004). Table 2.2. shows the source parameter and Fig.2.3. shows the source time function.

Table 2.2. Source parameters

Magnitude	M_J 7.1
Latitude(deg.)	33.03N
Longitude(deg.)	138.80E
Depth(km)	15
Strike(deg.)	71
Dip(deg.)	56
Rake(deg.)	75.0
Seismic Moment(Nm)	9.8×10^{19}

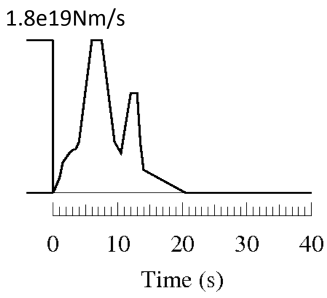


Figure 2.3. Source time function

Fig.2.4. shows the comparison of observed and calculated velocity waveforms and pseudo velocity response spectra (h=5%) at observation sites shown in Fig.2.1. All the waves are low-pass filtered components longer than 2.5 seconds. OSKH02, AIC003, TKYH12 and MIE014 are K-NET and KiK-net observation stations operated by NIED. The records of SHS were observed at the 1st floor of the Shizuoka branch office of Taisei Corporation. The records of SJK were observed in a borehole (G.L. -65m) in the firm gravel layer at Shinjuku, Tokyo.

Observed response spectra in Osaka plain have significant peaks around 5 to 6 seconds, those of Nagoya in Nobi plain have a peak with the period of 3 seconds, and those of Shinjuku in Kanto plain have a peak at around 6 to 7 seconds. Simulated velocity waveforms and pseudo velocity response spectra (h=5%) gave a good agreement with those of observation records. But simulated results at some sites overestimated observed records (e.g. AIC003, MIE014). It is necessary to adjust velocity structure to obtain a better model.

2.3. Source Model of Tokai-Tonankai-Nankai Earthquake

Tokai-Tonankai-Nankai coupled earthquake in this study consists of the source model of Tokai-Tonankai earthquake and that of Nankai earthquake proposed by Central Disaster Management Council(2003). Table 2.3. shows the source parameters. The grid of fault plain is re-sampled into about 9,500 point sources with finer grid (2.5km) than that of the original source model (5km or 10km) to eliminate the artificial peaks. Fig.2.5. shows the location of asperities. Nankai earthquake has 5 asperities (1, 2-1, 2-2, 3, 4), Tonankai earthquake has 3 asperities (5, 6, 7) and Tokai earthquake has 6 asperities (9-1, 9-2, 10-1, 10-2, 11-1, 11-2).

The source time function at each point source is described by overlapping triangles (e.g. Hisada, 2000). In this study, the number of triangles is set to be 2. Fig.2.6. shows example of source time function.

Fig.2.7. shows the source model in this study. We introduced heterogeneity into the slip distribution and rupture time using the Sekiguchi's method (Sekiguchi et al.,2006) so that the source spectra follow omega-square model. Average rupture velocity is set to be Vr=2.7km/s.

Multi-hypocenter rupture is assumed for the rupture mode of the fault. White stars in Fig.2.7. indicate the rupture starting points of each asperity.

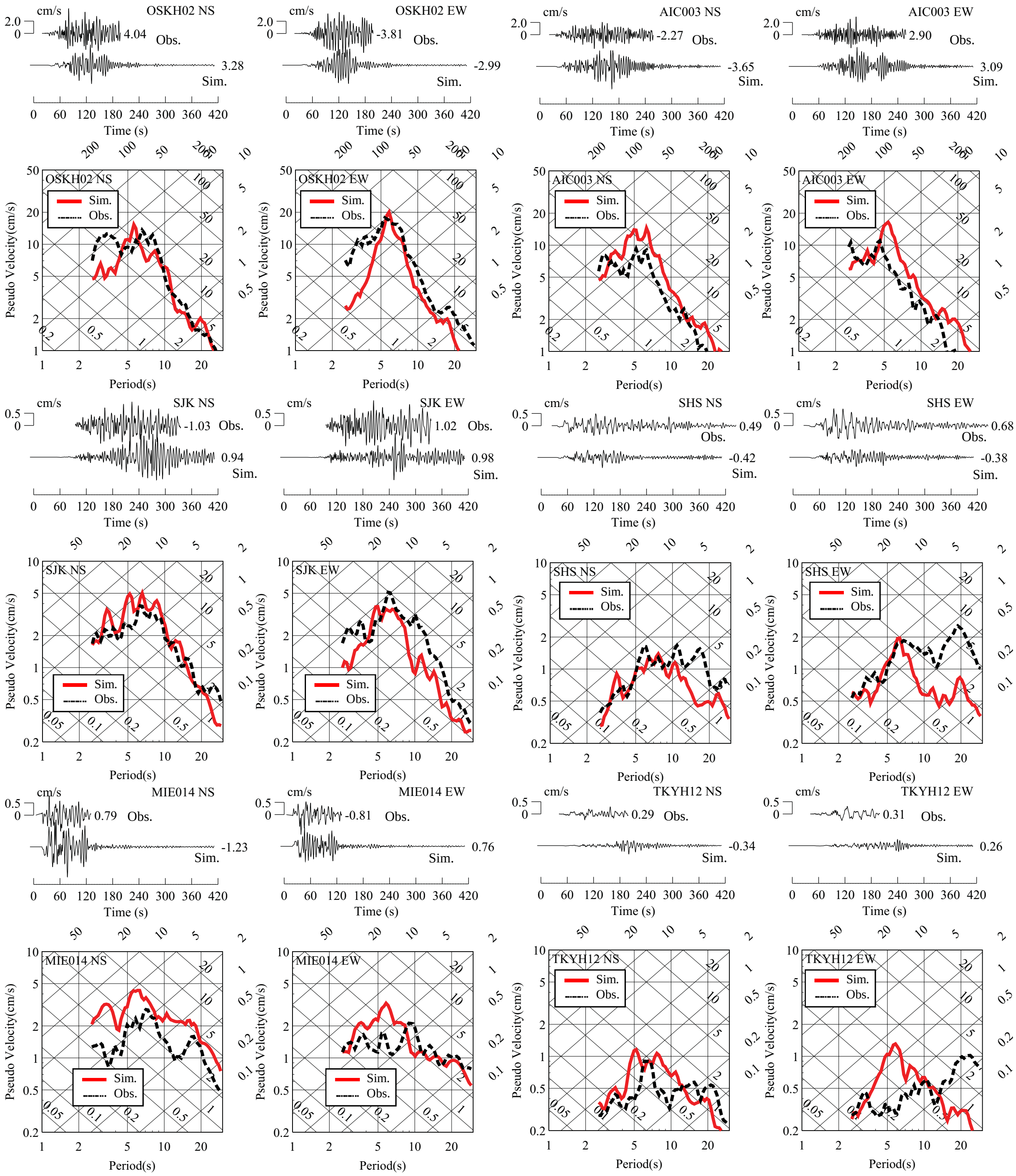


Figure 2.4. Comparison of velocity waveforms and response spectra

We considered two cases of rupture starting points as shown Fig.2.7.. Case-1 is the case that the rupture starts from Off Kii Peninsula as well as the source model of Central Disaster Management Council. The rupture propagates in the east direction on the rupture area of Nankai earthquake from Hypo-a1 and in the west direction on the rupture area of Tonankai and Tokai earthquake from Hypo-b. We assumed the rupture simultaneously starts at Hypo-a1 and Hypo-b. Case-2 is the case that the rupture starts from Off (Ashizuri misaki) at Hypo-a2 to Hypo-b and Hypo-c. In this case, the rupture directivity is the most effective to Nobi and Kanto plain.

Table 2.3. Source parameters

		Seismic Moment [Nm]	Average Slip [m]	Rise time [s]
Nankai Earthquake	1	4.32×10^{20}	8.6	5.6
	2-1	1.46×10^{21}	12.9	9.3
	2-2	4.34×10^{20}	8.6	5.6
	3	1.63×10^{21}	13.4	5.6
	4	1.93×10^{20}	6.6	3.7
	background	4.60×10^{21}	4.0	9.3
	(total)	8.76×10^{21}		
Tonankai Earthquake	5	4.26×10^{20}	7.9	5.6
	6	3.31×10^{20}	7.3	5.6
	7	3.31×10^{20}	7.3	5.6
	background	1.21×10^{21}	2.7	5.6
	(total)	2.30×10^{21}		
Tokai Earthquake	9-1	3.09×10^{20}	6.9	5.6
	9-2	1.03×10^{20}	4.8	3.7
	10-1	1.05×10^{20}	1.8	3.7
	10-2	3.49×10^{19}	3.4	2.8
	11-1	5.50×10^{19}	3.9	1.9
	11-2	2.00×10^{19}	2.8	1.9
	background	4.72×10^{20}	1.8	5.6
	(total)	1.10×10^{21}		

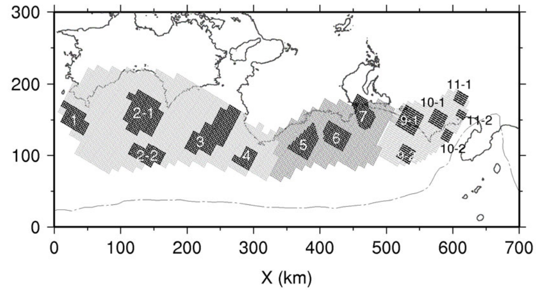


Figure 2.5. Asperity and background area

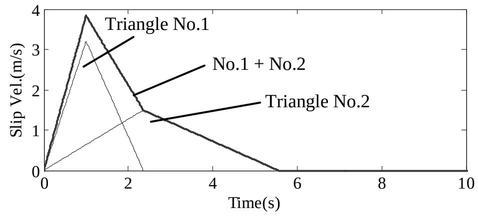
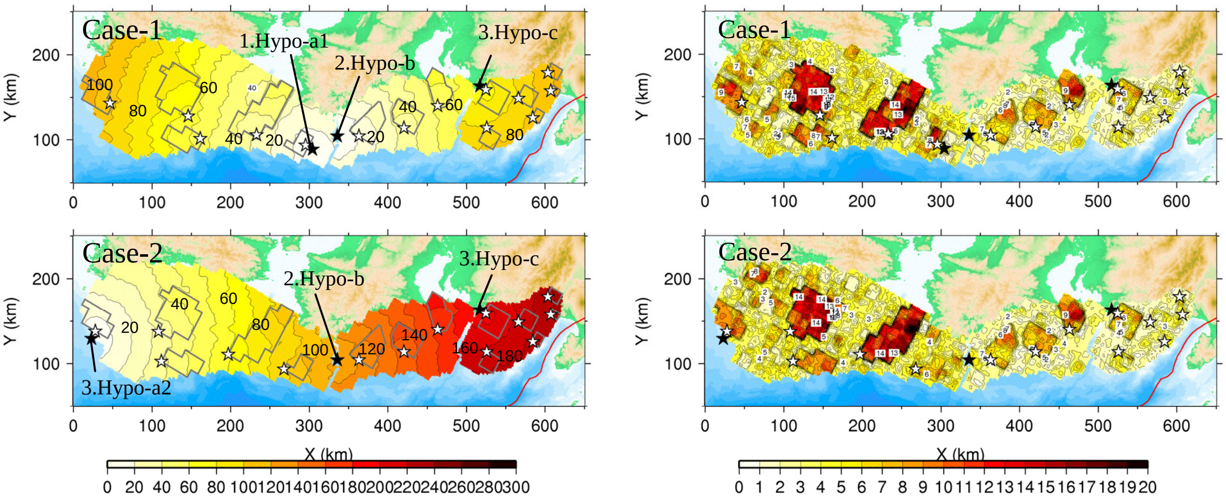


Figure 2.6. Example of source time function



(a) Rupture time[s] (b) Slip distribution[m]

Figure 2.7. Source Model for Tokai-Tonankai-Nankai earthquake

3. RESULTS

3.1. Simulation Results

Fig.3.1. shows snapshots of NS component of velocity. The seismic waves propagate from Off Kii Peninsula in the east and west directions in Case-1. On the other hand, the result of Case-2 shows the seismic waves propagate in the east direction. It is found that the seismic waves are captured in the sedimentary wedge and all plains in both cases. This causes long duration of ground motion at a site.

Fig.3.2. shows the velocity waveforms and response spectra at OSKH02 (NS, EW component) in Osaka plain, NAG (EW component) in Nobi plain and SJK (NS component) in Kanto plain. The black dotted lines in Fig.3.2. indicate the uniform design spectra regulated by Building Standard Law of Japan.

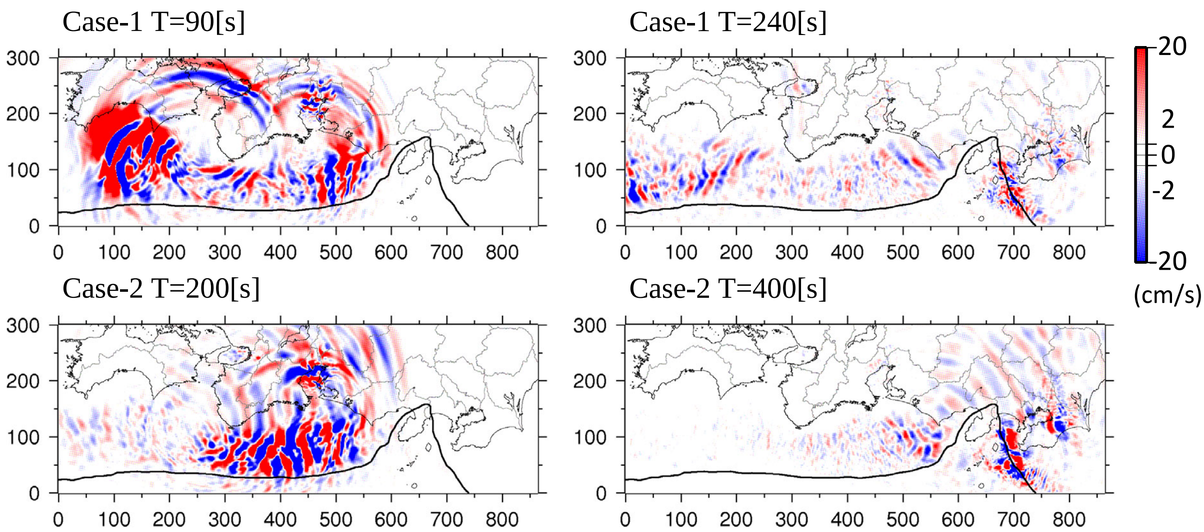
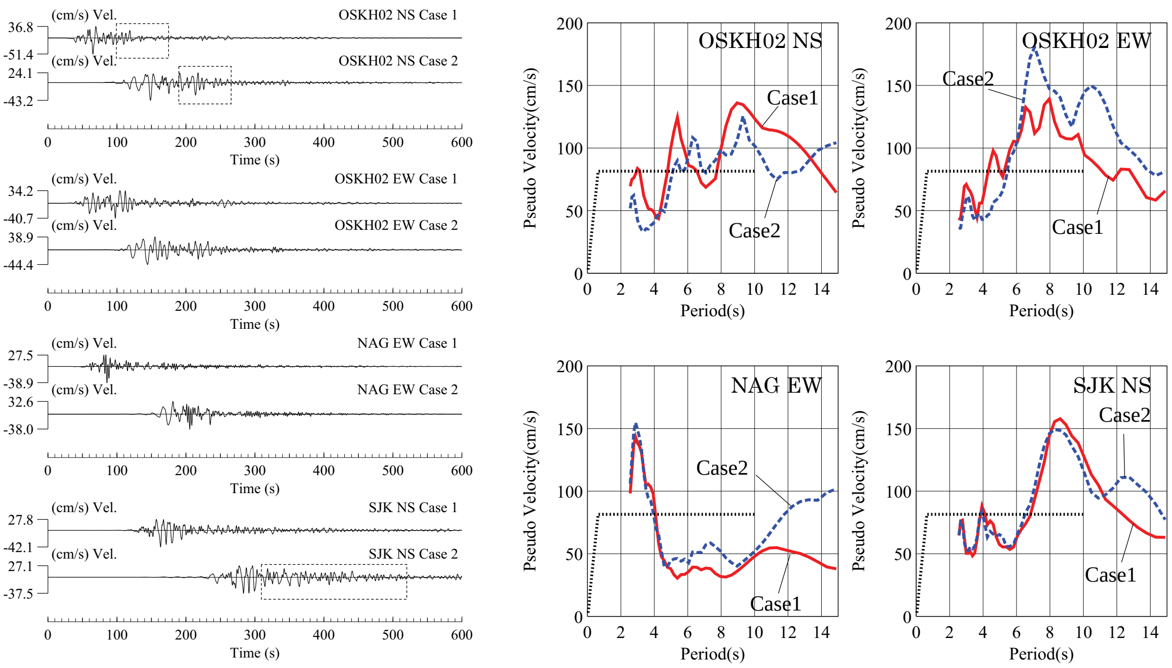


Figure 3.1. Source Model for Tokai-Tonankai-Nankai earthquake

The response spectra of EW component at OSKH02 have dominant peaks of from 7 to 8 seconds. Those dominant peaks correspond to source characteristics because it is longer than that of the peaks correspond to subsurface structure of Osaka plain. The results of NS component have dominant peaks around from 5 to 6 seconds. Those of NAG in Nobi plain have a peak with the period of 3 seconds, and those of SJK in Kanto plain have a peak at around 8 seconds. We confirmed that those dominant peaks correspond to subsurface structure of each plain. These peaks of the simulated response spectra surpassed the uniform design spectra regulated by Building Standard Law.



(a) Velocity waveforms (b) Pseudo Response Spectra(h=5%)

Figure 3.2. Calculated velocity and pseudo velocity response spectra

3.2. Contribution of each earthquake to the estimation results of the Tokai-Tonankai-Nankai earthquake

We studied the contribution of each earthquake to the estimation results of the Tokai-Tonankai-Nankai earthquake. Fig.3.3. shows the velocity waveforms and response spectra (h=5%) for

Tokai-Tonankai-Nankai earthquake ("Total" in Fig.3.3) and each earthquake (Tokai, Tonankai and Nankai single earthquake). The duration time of the simulated ground motions of Tokai-Tonankai-Nankai coupled earthquake became longer than that of each earthquake.

The simulated ground motions of Nankai and Tonankai earthquakes were dominant in Osaka plain as shown Fig.3.3.(a) and (b). Those of Tonankai earthquake were dominant in Nobi plain as shown Fig.3.3.(c) and those of Tokai earthquake were dominant in Kanto plain as shown Fig.3.3.(d).

Furthermore, we examined the influence of the location of rupture starting point. It was found that the Nankai earthquake amplified the long period ground motions exceeding 10 seconds in Nobi and Kanto plains (Fig.3.3.(c) and (d)) when the rupture started from the south east point of the fault plain (Case-2).

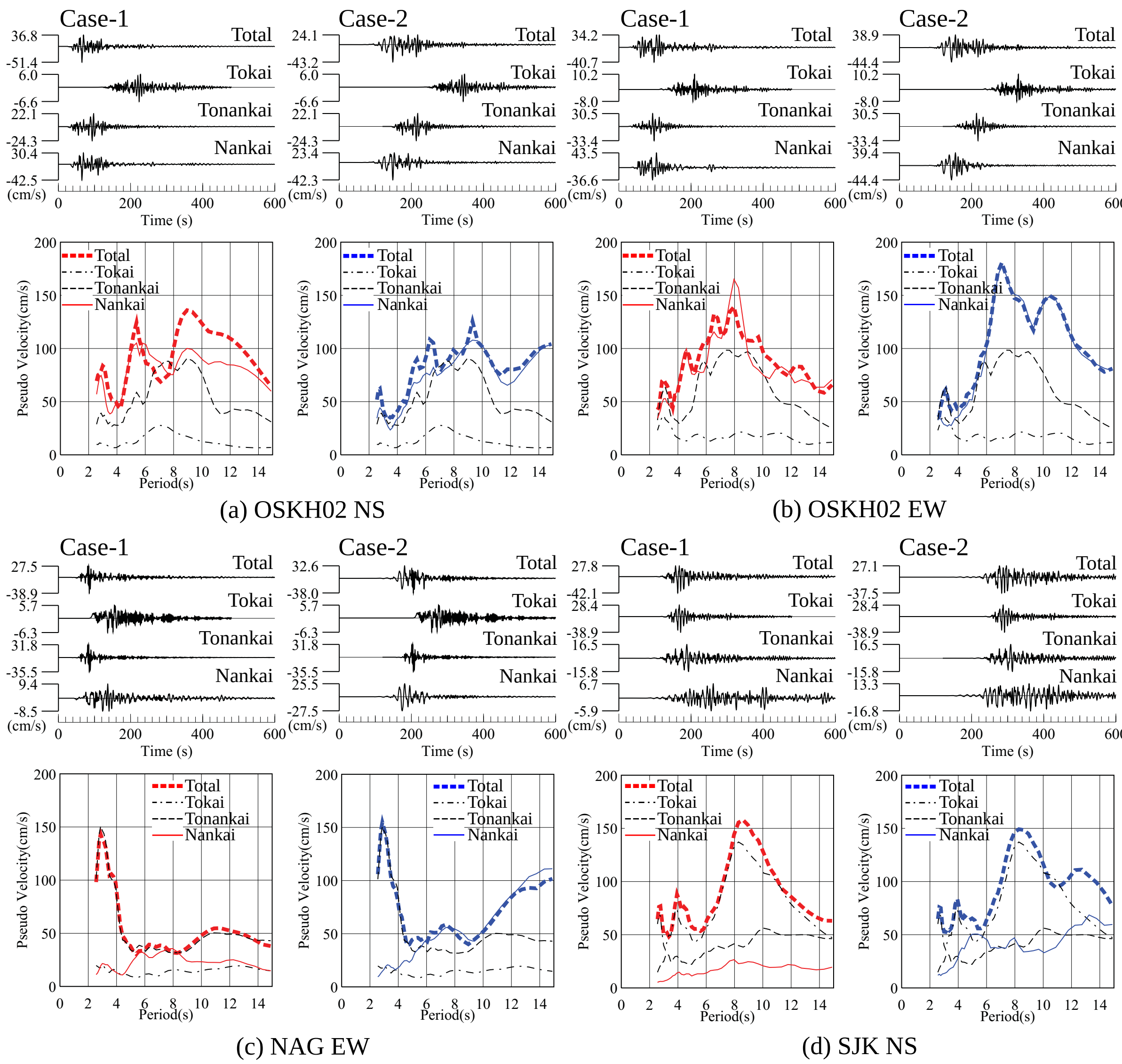


Figure 3.3. Calculated velocity and pseudo velocity response spectra

4. CONCLUSION

We constructed a 3-D subsurface structure model which includes the rupture area of Tokai, Tonankai and Nankai earthquakes and Kanto, Nobi and Osaka plains. To verify the model, we simulated the M_J7.1 foreshock of the 2004 off the Kii-peninsula earthquake on September 5 at 19:07 that occurred near Nankai Trough. Finally, we performed the long period ground motion simulation of the Tokai-Tonankai-Nankai coupled earthquake. Furthermore, we examined the contribution of each earthquake to the estimation results of the coupled earthquake and the influence of the location of rupture starting point. The results showed the simulated ground motions of Nankai and Tonankai earthquakes were dominant in Osaka plain. Those of Tonankai earthquake and Tokai earthquake were dominant in Nobi plain and Kanto plain, respectively. The duration time of the simulated motions of Tokai-Tonankai-Nankai coupled earthquake became longer than that of each earthquake. Furthermore, it was found that the Nankai earthquake amplified the long period ground motions exceeding 10 seconds in the Nobi and Kanto plains when the rupture started from the south east point of the fault plain.

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