SOURCE MODELING OF SUBDUCTION-ZONE EARTHQUAKES AND LONG-PERIOD GROUND MOTION VALIDATION IN THE TOKYO METROPOLITAN AREA

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ABSTRACT :

The national seismic hazard map of Japan indicates 30-year probability in the Tokyo metropolitan area to be controlled by megathrust earthquakes along the Nankai trough of the Philippine sea plate. This indicates that source modeling and realistic ground-motion prediction for distant subduction-zone earthquakes are quite important for disaster mitigation and hazard assessment in the Tokyo metropolitan area. We have performed long-period ground motion validation for the hypothetical Tokai (> 2 s) and Tonankai (> 4 s) earthquakes using characterized source models and integrated 3D velocity structure model. The characterized source model consists of asperities and background area. The size and slip of the asperities are constrained by the source scaling of asperities for subduction-zone earthquakes, where the scaling is based on the compilation of past slip inversion results. We adopted the 3D velocity structure models of basin, ocean, and plate constructed by integrating refraction, reflection, borehole, microtremor, and gravity data as well as ground motion spectra. The distribution of simulated long-period ground motions by the 3D finite difference method well reflects the velocity structures in the Kanto basin, and the oceanic structure with the sedimentary wedge which contributes to further propagation of the long-period ground motions. We have confirmed that long-period ground motions at a period of 7-10 s are significantly developed in the Kanto basin, indicating that the impact of damaging long-period ground motion from the future megathrust events against the Tokyo metropolitan area.

KEYWORDS: long-period ground motion, subduction-zone earthquake, characterized source model, integrated 3D velocity structure model, Tokyo metropolitan area

1. INTRODUCTION

The national seismic hazard map of Japan indicates 30-year probability in the Tokyo metropolitan area to be controlled by megathrust earthquakes along the Philippine sea plate, which are four major subduction-zone earthquakes called the Kanto (M_w 7.9), northern Tokyo-bay (M_w 7.0 or greater), Tokai (M_w 8.0), and Tonankai (M_w 8.1) earthquakes. We have experienced the 1923 Kanto and 1944 Tonankai earthquakes, however the rest of two are hypothetical earthquakes. For disaster mitigation and hazard assessment in the Tokyo metropolitan area, realistic ground-motion prediction based on the physics-based source model and 3D velocity model are quite important.

In 2004, a large offshore earthquake with an M_w of 7.4 occurred off the Kii peninsula, and excited long-period ground motions widely over the Honshu islands of Japan. The event was located at an outer rise of the Philippine sea plate neighboring the source regions of the 1944 Tonankai and 1946 Nankai earthquakes. Thanks to the installation of strong motion arrays, such as K-NET, KiK-net, SK-net, and CEORKA, more than 1,000 seismometers observed ground motions from the earthquake. Record sections indicate two types of long-period motions both by the basin surface waves and by the seismic source or propagation-path effect of the shallow and large offshore earthquake. Their combination resulted in well-developed long-period ground motions as observed within distant basins away from the 1985 Michoacan, Mexico, and 2003 Tokachi-oki, Japan, earthquakes (e.g., Anderson *et al*., 1986; Koketsu *et al*., 2005; Koketsu and Miyake, 2008). Miyake and

Koketsu (2005) pointed out that the distributions of pseudo-velocity response spectra confirmed this excitation at periods of 5-7 s in the Osaka basin, of 3-5 s in the Nobi basin, and of 7-10 s in the Kanto basin (Figure 1), which corresponds to the seismic characteristics of each basin. Ground motion simulations for the earthquake suggest that the sedimentary wedge along the Nankai trough plays a key role of development of the long-period ground motion before propagating into the basin (Furumura *et al*., 2008).

The 2004 off the Kii Peninsula earthquake provided a timely warning of damaging long-period ground motions from megathrust events such as the future Nankai, Tonankai, and Tokai earthquakes. Long-period ground motions, which will damage structures with longer natural periods like skyscrapers, wide-span bridges, and huge oil tanks in the large sedimentary basins, have been simulated for the megaturust events (e.g., Furumura *et al*., 2008; Kawabe and Kamae, 2008; Sekiguchi *et al*., 2008). We here present long-period ground motion validation for the hypothetical Tokai and Tonankai earthquakes based on the characterized source model (Miyake *et al*., 2003) and the integrated 3D velocity structure model in the Tokyo metropolitan area (Tanaka *et al*., 2005; 2006).

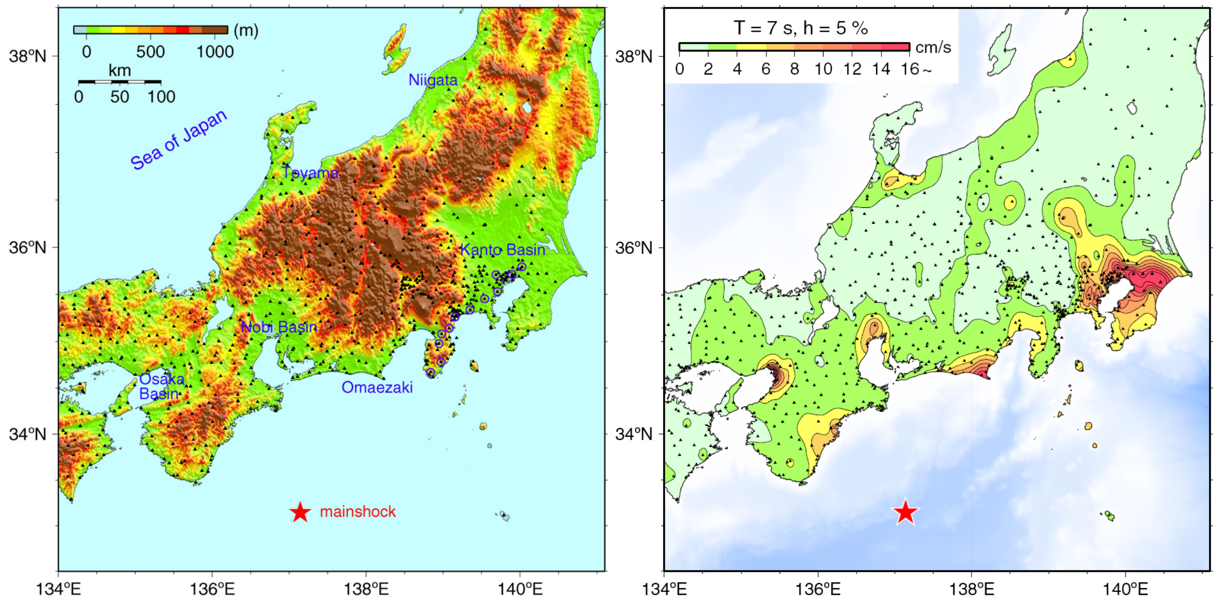

Figure 1. Index map (right) and an example of excitation of long-period ground motions (left: pseudo-velocity response spectra for a damping factor of 5% and natural period of 7 s) for of the 2004 off the Kii Peninsula earthquake along the Nankai trough (after Miyake and Koketsu, 2005). Red stars denote epicenters.

2. SOURCE MODELING OF SUBDUCTION-ZONE EARTHQUAKES

Recent studies demonstrate that most asperities of subduction-zone earthquakes in Japan rupture repeatedly (e.g., Yamanaka and Kikuchi, 2004; Wu *et al*., 2008). To quantify the size of asperities, Murotani *et al*. (2008) performed source scalings of subduction-zone earthquakes, and they found ratios of the size and slip between the asperities and rupture area are the same for subduction-zone earthquakes as for crustal earthquakes by Somerville *et al*. (1999). Considering the above, our strategy of source modeling for subduction-zone earthquakes is as follows: If source models of historical earthquakes exist, we adopt this source model for the ground motion prediction. If not, we construct a characterized source model consisting of asperities and background area (Miyake *et al*., 2003), by applying the scaling relations for rupture area and asperity. Fault parameters are obtained through the recipe for strong ground motion prediction by Irikura and Miyake (2001) and Irikura *et al*. (2006).

2.1. Hypothetical Tokai earthquake

Since the Tokai earthquake is hypothetical, there is no historical source model which can be used for strong ground motion prediction of a future event. However, the segmentation of rupture area and location of asperity have been geophysically investigated. For example, Matsumura (2002) proposed three locked zones figured out from seismicity which could be candidates for future asperities. We constructed a characterized source model that consists of asperities and background area, assuming the following geophysical constraints: (1) According to the thermal condition and geometry of the subducting Philippine Sea plate, the rupture along the dip direction extends from 5 to 25 km in depth. (2) Rocked zones estimated by the background seismicity are regarded as asperities. (3) The asperities are located not to overlap the regions of slow slip estimated by GPS measurements.

The size and slip of the asperities are constrained by the source scaling of asperities for subduction-zone earthquakes, which was derived by Murotani *et al.* (2008) based on the compilation of past slip inversion results. The stress drop was adjusted so that asperities for long-period ground motions behave as strong motion generation areas for short-period ground motions. We defined the rupture area of 9,100 km^2 with an average stress drop of 3.0 MPa as outer fault parameters, and the combined asperity area of 1,786 km^2 with a stress drop of 15.8 MPa as inner fault parameters. The moment magnitude M_w of this source model is 8.0.

2.2. Tonankai earthquake

The source process of the 1944 Tonankai earthquake was inferred from regional and teleseismic data by Ichinose *et al*. (2003) and regional data by Yamanaka (2004). Both models rupture from southwest to northeast direction with a single asperity, however the asperity location of Ichinose *et al*. (2003) is deeper, on the other hand, that of Yamanaka (2004) is shallower. We adjusted subfaults of the inverted source models to be on the plate-boundary, and tested the ability of the two source models to reproduce regional records of the 1944 Tonankai earthquake. Source model of Yamanaka (2004) worked well to reproduce the regional data. We then constructed two characterized source models to simulate the future Tonankai earthquake, where one has a shallow asperity as shown in Figure 3, and the other has a deep asperity. We modeled the rupture area of 20,475 km^2 with an average stress drop of 1.23 MPa as outer fault parameters, and the asperity area of 3,600 km^2 with a stress drop of 7.0 MPa as inner fault parameters. The moment magnitudes M_w of the characterized source models are M_w 8.1.

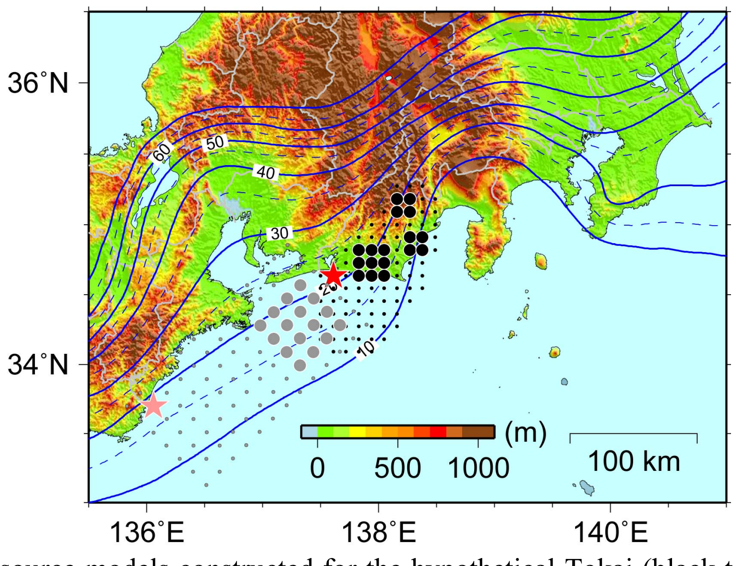

Figure 2. Characterized source models constructed for the hypothetical Tokai (black tone) and Tonankai (gray tone) earthquakes. Stars indicate epicenters. Contours show the top depth of the Philippine sea plate.

3. INTEGRATED 3D VELOCITY STRUCTURE MODEL

We adopted the 3D velocity model beneath the Tokyo metropolitan area constructed by integrating refraction, reflection, borehole, microtremor, and gravity data as well as ground motion spectra (Tanaka *et al.*, 2005). This model is upgraded into the integrated 3D velocity models of plate and oceanic structures as well as crustal structure (Tanaka *et al.*, 2006). Prior to the long-period ground motion validation for the hypothetical Tokai and Tonankai earthquakes, we have simulated ground motions of several moderate-size earthquakes to calibrate the integrated 3D velocity model. We used the integrated 3D velocity model of Tanaka et al. (2005, 2006) for the hypothetical Tokai earthquake. On the other hand, we calibrated the 3D velocity model for the Tonankai earthquake, where the *S*-wave velocity of sedimentary wedge, layering of crustal structure, basin structure of the Sagami bay, and oceanic structure of the Kii peninsula are changed into as shown in Figure 3 and Table 1. The layering of Table 1 is multiple, and the thickness of the 3D velocity model is valuable allowing zero. Consequently, shallowest *S*-wave velocities for the Osaka, Nobi, and Kanto basins are 350, 350, 500 m/s, respectively.

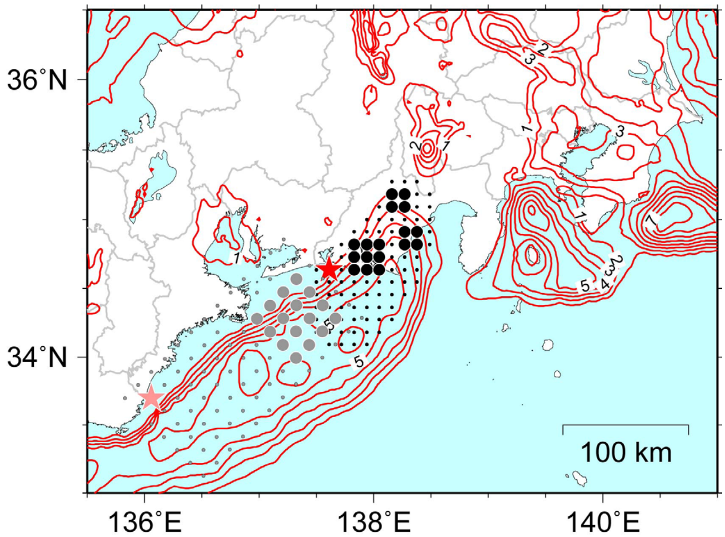

Figure 3. The basement depth of the 3D velocity structure model calibrated for the ground motion validation of the Tonankai earthquake. Note that oceanic structure above the basement consists of sedimentary wedge.

Table 1. Velocity, density, and *Q* factor for the integrated 3D velocity model calibrated for the ground motion validation of the Tonankai earthquake.

layer	V_p (km/s)	V_s (km/s)	density (10^3 kg/m^3)	Q_p	Q_s	
1	1.7	0.35	1.80	119	70	
2	1.8	0.50	1.95	170	100	*Shimosa layer in the Kanto basin*
3	2.0	0.60	2.00	204	120	
4	2.1	0.70	2.05	238	140	
5	2.2	0.80	2.07	272	160	
6	2.3	0.90	2.10	306	180	*Kazusa layer in the Kanto basin*
7	2.4	1.00	2.15	340	200	sedimentary wedge is included
8	2.7	1.30	2.20	442	260	
9	3.0	1.50	2.25	510	300	*Miura layer in the Kanto basin*
10	3.2	1.70	2.30	578	340	
11	3.5	2.00	2.35	680	400	
12	4.2	2.40	2.45	680	400	
13	5.0	2.90	2.60	680	400	
14	5.5	3.20	2.65	680	400	seismic basement
15	6.0	3.53	2.70	680	400	upper crust
16	6.7	3.94	2.80	680	400	lower crust
17	7.8	4.60	3.20	850	500	mantle
18	5.0	2.90	2.40	340	200	layer 2 of oceanic curst
19	6.8	4.00	2.90	510	300	layer 3 of oceanic crust
20	8.0	4.70	3.20	850	500	oceanic mantle

4. LONG-PERIOD GROUND MOTION VALIDATION

4.1. Hypothetical Tokai earthquake

Long-period ground motions for the hypothetical Tokai earthquake is simulated by using 3D finite difference method of Pitarka (1999). The period range of the simulation is up to 2 s with a minimum grid size of 200 m. As shown in Figure 4, the simulation shows significant excitation of long-period ground motions in the Kanto basin and the oceanic sediment as well. We have confirmed the wave front curves NW-SE into NS-EW directions when the waves enter the basin, as pointed by Koketsu and Kikuchi (2000).

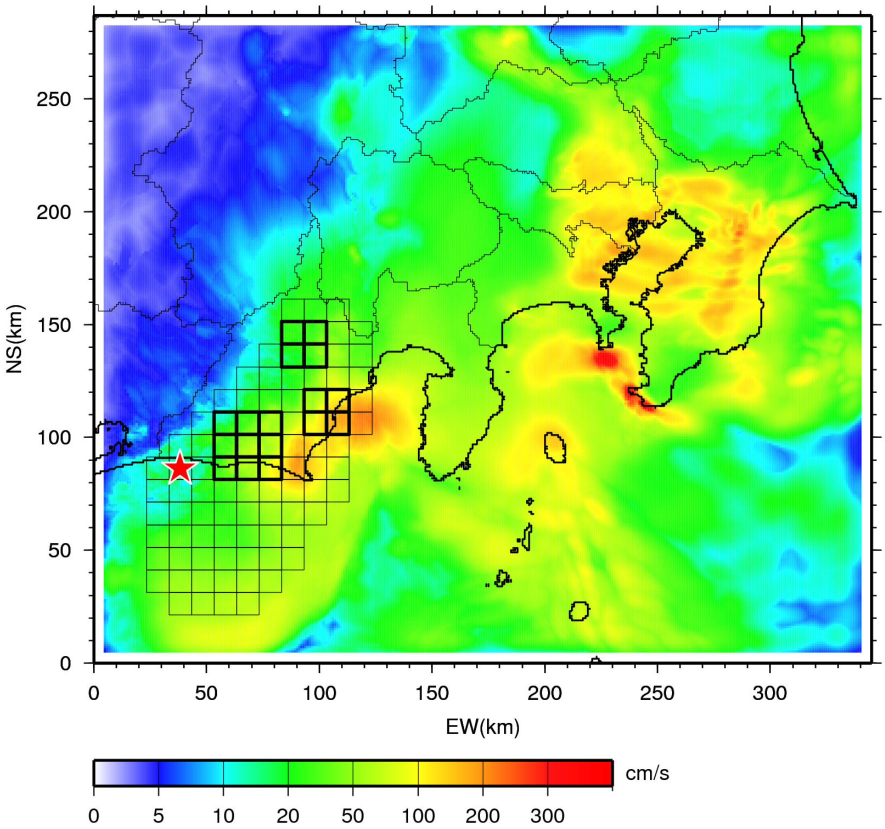

Figure 4. Distribution of pseudo-velocity response spectra for a damping factor of 5% and natural period of 7 s at the engineering bedrock based on the velocity structure for the hypothetical Tokai earthquake.

4.2. Tonankai earthquake

Long-period ground motions for the Tonankai earthquake is simulated by using 3D finite difference method of Hayashi and Hikima (2000). The period range of the simulation is up to 4 s to handle the layer of V_s = 500 m/s in the Kanto basin. We have also simulated up to 2 s to validate the layer of V_s = 350 m/s in the Nobi basin. Furumura and Nakamura (2006) recovered historical strong motion records for the 1944 Tonankai earthquake at Yokohama, Otemachi in Tokyo, and Togane in Chiba. We have compared the simulated ground motions to observed ones. The inverted source model of Yamanaka (2004) and the characterized source models reproduce similar amplitudes of long-period ground motions in Yokohama located in a distant basin from the source region (Figure 5).

The long-period ground motion validation for the Tonankai earthquake revealed that underestimates of ground motions at the backward rupture direction (e.g. Nagoya in the Nobi basin). It may suggest that the characterized source model needs to include a certain degree of heterogeneity. There are several proposal to introduce heterogeneities of slip and rupture velocity (e.g., Sekiguchi *et al*., 2008), and it is expected to overcome this underestimation.

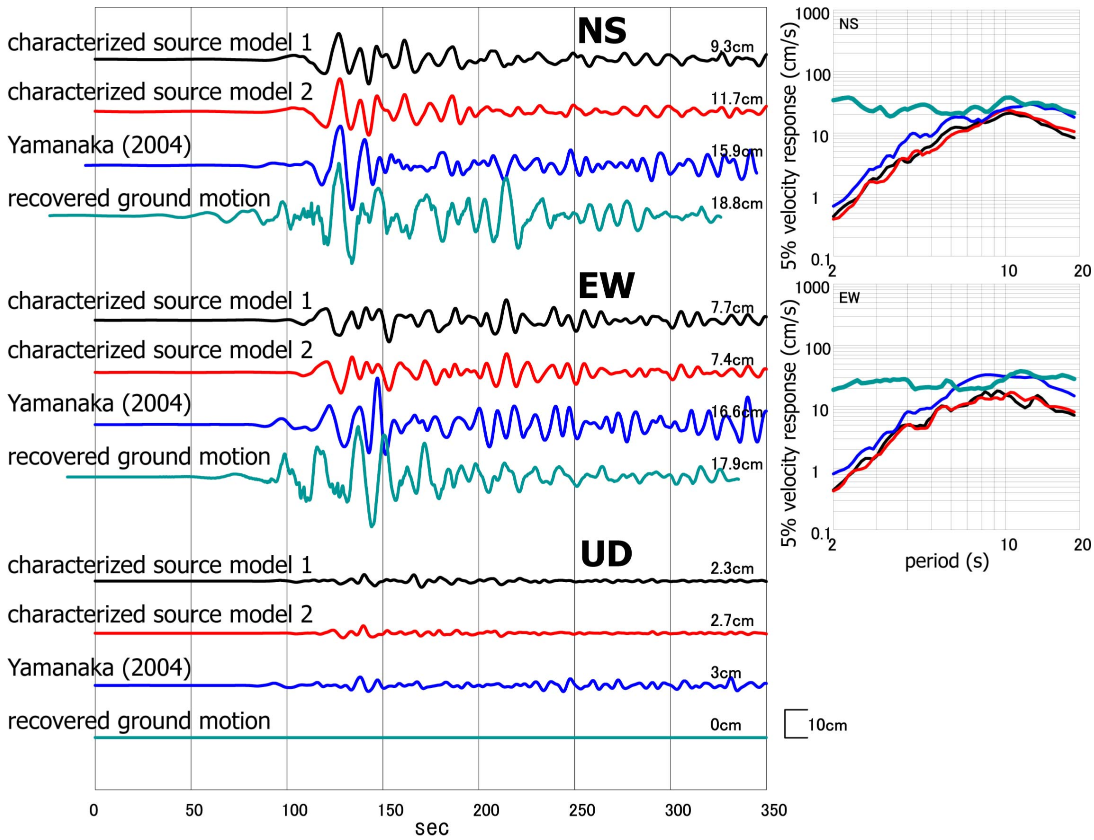

Figure 5. Left: Comparison of displacement ground motions for the Tonankai earthquake in Yokohama. From top to bottom, characterized source model 1 with a shallow asperity, characterized source model 2 with a deep asperity, 1944 Tonankai source model of Yamanaka (2004), and recovered observed ground motions by Furumura and Nakamura (2006). Right: Comparison of velocity response spectra for a damping factor of 5%.

5. CONCLUSIONS

We have performed long-period ground motion validation for the hypothetical Tokai and Tonankai earthquakes using characterized source models and integrated 3D velocity structure model. The distribution of simulated long-period ground motions by the 3D finite difference method well reflects the velocity structures in the Kanto basin, and the oceanic structure with the sedimentary wedge which contributes to further propagation of the long-period ground motions. This suggests the importance of ground motion simulation using deterministic approach with realistic 3D velocity structure model. We have confirmed that long-period ground motions at a period of 7-10 s are significantly developed in the Kanto basin, indicating that the impact of damaging long-period ground motion from the future megathrust events against the Tokyo metropolitan area.

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