Sixth International Conference on Urban Earthquake Engineering
March 3-4, 2009, Tokyo Institute of Technology, Tokyo, Japan

SOURCE MODELING OF SUBDUCTION-ZONE EARTHQUAKES FOR LONG-PERIOD GROUND MOTION VALIDATION

Hiroe Miyake[1) and **Kazuki Koketsu**[2)

1) Assistant Professor, Earthquake Research Institute, University of Tokyo, Japan
2) Professor, Earthquake Research Institute, University of Tokyo, Japan
hiroe@eri.u-tokyo.ac.jp, koketsu@eri.u-tokyo.ac.jp

Abstract: The national seismic hazard map for Japan indicates 30-year probability in the Tokyo metropolitan area to be controlled by megathrust earthquakes along the Sagami and Nankai troughs of the Philippine Sea plate. This indicates that source modeling and realistic ground motion prediction for distant subduction-zone earthquakes are quite important. We have proposed two types of source modeling for four major subduction-zone earthquakes towards long-period ground motion assessment. One type is the previous event source model, and the other type is the characterized source model. The previous event source model with kinematic or pseudo-dynamic approach is useful for ground motion simulation of the future earthquake as well as ground motion validation of the past earthquake. The characterized source model consists of asperities and a background area. The size and slip of the asperities are constrained by the source scaling for subduction-zone earthquakes, where the scaling is based on the compilation of past slip inversion results. This characterized source model is applicable to ground motion prediction for the future earthquake.

1. INTRODUCTION

The national seismic hazard map for 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 the 3-D velocity structure model are essential.

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. Record sections indicate 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). 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, which corresponds to the seismic characteristics of each basin. 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, long-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).

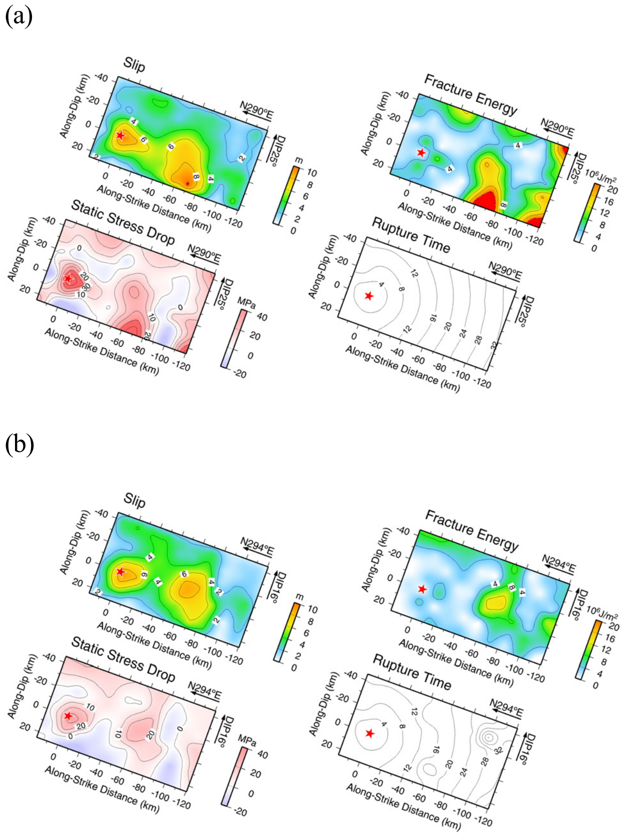
We here propose subduction-zone source modeling of the Kanto, northern Tokyo bay, Tokai, and Tonankai earthquakes, and discuss the applicability of the source models for long-period ground motion prediction in the Tokyo metropolitan area.

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 scaling of characterized source models for 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 previous event source model for the ground motion prediction. If not, we construct a characterized source model consisting of asperities and a 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 Kanto Earthquake

Several source models for the 1923 Kanto earthquake have been constructed (e.g., Kanamori, 1971). Most models provide moment magnitude of M_w 8.0. Slip distribution by Wald and Somerville (1995) is inferred from teleseismic and geodetic data, and that by Kobayashi and Koketsu, (2005) are from strong motion, teleseismic, and geodetic data. Similar slip distribution among the above analyses suggests that it is stably solved as long as the fault plane and geometry for the source inversions are the same.


(a)

(b)

Figure 1. Pseudo-dynamic source modeling for the Kanto earthquake. Distribution of slip, static stress drop, fracture energy, and rupture time are shown for the inverted source models of (a) Kobayashi and Koketsu (2005) with M_w 8.0 and (b) Sato et al. (2005) with M_w 7.9. Stars indicate the epicenters.

Recently Sato et al. (2005) discovered that the top of the Philippine Sea plate is much shallower than the previous estimates. The new estimate is based on the deep seismic reflection profiling performed by the Special Projects for Earthquake Disaster Mitigation in Urban Areas (DaiDaiToku project), and the previous one is from the distribution of seismicity by Ishida (1990). Sato et al. (2005) recalculated the finite-slip inversion for the earthquake with the new plate geometry. The shallower plate geometry changes the location and maximum slip of the asperities for the 1923 Kanto earthquake. The eastern asperity moved about 40 km northward toward Tokyo, and maximum slip was slightly decreased. Figures 1(a) and 1(b) display the slip distributions along the previous and new geometries of the Philippine Sea plate.

The past several years have seen substantial progress in physically based approaches to earthquake source modeling for the prediction of strong ground motion. Using the characteristics of the dynamic faulting based on the frictional law, the pseudo-dynamic source modeling has been proposed by Guatteri et al. (2004). As shown in Figure 1, we applied the pseudo-dynamic source modeling for the inverted slip distribution of Kobayashi and Koketsu (2005) and Sato et al. (2005). Different location of asperities results in the complex pattern of fracture energy and rupture time.

2.2 Northern Tokyo Bay Earthquake

Two characterized source models for the northern Tokyo bay earthquake are set up along the geometry of the Philippine Sea plate by Ishida (1992) and the new geometry by Sato et al. (2005). We use the same outer fault parameters of the Central Disaster Prevention Council with M_w 7.3. Using the locations of two asperities to avoid the slow slip region identified by Hirose et al. (2000) and high reflection coefficients of the seismic profiling carried out by Sato et al. (2005), we have constructed characterized source models consisting of two asperities and a background area. 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 of rupture area and asperities are 3.0 and 15.8 MPa, respectively. Figure 2 shows an example of the characterized source model for the northern Tokyo bay earthquake. This is a case that a larger asperity is located beneath the center of the Tokyo metropolitan area and a smaller asperity is beneath the Chiba prefecture.

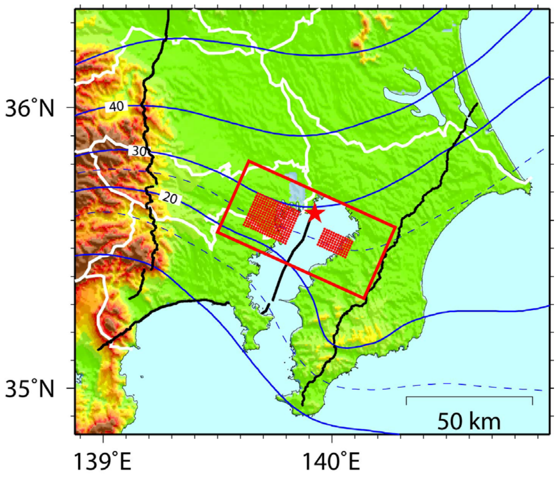


Figure 2. An example of the characterized source models constructed for the northern Tokyo bay earthquake. Star indicates the epicenter. Contours show the top depth of the new geometry of the Philippine Sea plate proposed by Sato et al. (2005).

2.3 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 three asperities and a 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) Locked 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 for subduction-zone earthquakes by Murotani et al. (2008). 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. Considering the historical evidence that the source region of the Tokai and Tonankai earthquakes ruptured together, we set the rupture starting point on the neighboring the source region of the Tonankai earthquake.

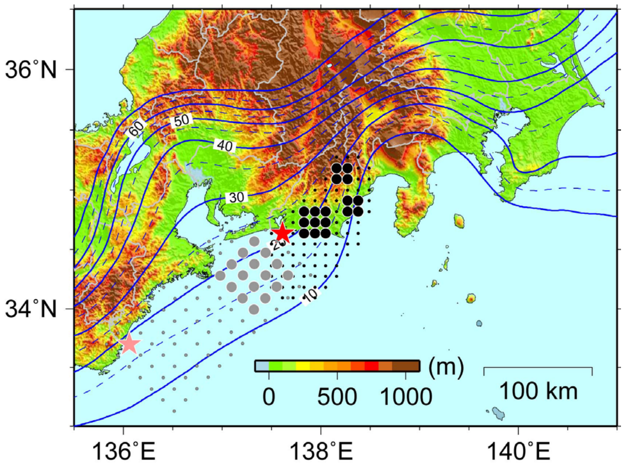


Figure 3. Characterized source models constructed for the Tokai (black tone) and Tonankai (gray tone) earthquakes. Stars indicate epicenters. Contours show the top depth of the Philippine Sea plate.

2.4 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. The heterogeneous slip model of Yamanaka (2004) worked well as the previous event source model to reproduce the regional data.

We then constructed two characterized source models to simulate the 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 8.1.

3. DISCUSSION AND CONCLUSIONS

We have proposed source modeling for four major subduction-zone earthquakes. To validate the applicability of the source modeling, long-period ground motion simulations were performed by combining the proposed source models and the integrated 3-D velocity structure model in the Tokyo metropolitan area (Tanaka et al., 2005). This geophysical-based 3-D velocity model was constructed by integrating refraction, reflection, borehole, microtremor, and gravity data as well as ground motion spectra.

For the Kanto earthquake, Miyake et al. (2006) performed waveform simulation using the FEM with a voxel mesh in a period range longer than 2 second (Figure 4). They confirmed the simulated ground motions are sensitive to the distribution of asperities in the source model along the shallower plate geometry, where the eastern major asperity is located closer toward downtown Tokyo than in the previous models. The spatial validation of ground motions is important to measure the impact of the shallower plate geometry.

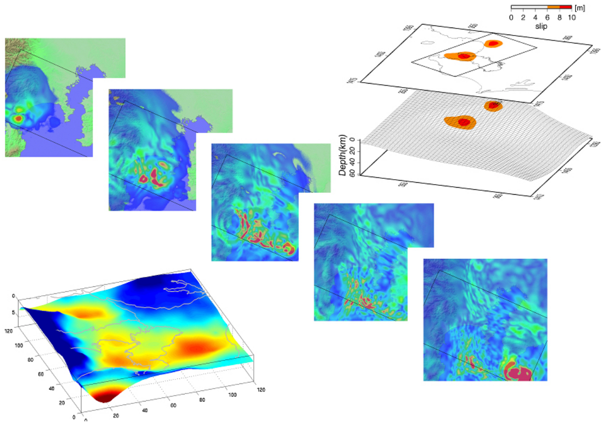


Figure 4. Long-period ground motion validation (center) for the Kanto earthquake based on the previous event source model (upper right; Sato et al., 2005) and the integrated 3-D velocity structure model (lower left; Tanaka et al., 2005).

For the northern Tokyo bay earthquake, ground motion prediction is performed by the 3-D FDM (< 1.3 Hz). The western basin edge of the Kanto basin complicated the wave propagation, as pointed by Koketsu and Kikuchi (2000). The simulated ground motion was much larger for the source model along the new geometry of the Philippine Sea plate rather than the source model along the previous geometry.

For the Tokai and Tonankai earthquakes, Miyake et al. (2008) performed long-period ground motion prediction using the characterized source models and the integrated 3-D velocity structure model. They 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.

In summary, we have confirmed that the previous event source model with kinematic or pseudo-dynamic approach is useful for ground motion simulation of the future earthquake as well as ground motion validation of the past earthquake, and the characterized source model is applicable to ground motion prediction for the future earthquake. In the future direction, it is necessary to expand ground motion simulation into short-period range to compare the detailed seismic intensity distribution. This is a challenging issues to improve realistic source modeling as well as 3-D velocity structure modeling towards broadband ground motion simulation.

Acknowledgements:

This research was supported by the Special Projects for Earthquake Disaster Mitigation in Urban Areas (2002-2006) and in Metropolitan Tokyo Area (2007-2011) from MEXT, Japan.

References:

Anderson, J.G., Bodin, P., Brune, J.N., Prince, J., Singh, S.K., Quaas, R. and Onate, M. (1986). "Strong ground motion from the Michoacan, Mexico earthquake," *Science*, **233**, 1043–1049.

Furumura, T., Hayakawa, T., Nakamura, M., Koketsu, K. and Baba T. (2008). "Development of long-period ground motions from the Nankai Trough, Japan, earthquakes: Observations and computer simulation of the 1944 Tonankai (M_w 8.1) and the 2004 SE Off-Kii Peninsula (M_w 7.4) earthquakes," *Pure Appl. Geophys*., **165**, 585–607.

Guatteri, M., Mai, P.M. and Beroza, G.C. (2004). "A pseudo-dynamic approximation to dynamic rupture models for strong ground motion prediction," *Bull. Seismol. Soc. Am*., **94**, 2051-2063.

Ichinose, G.A., Thio, H.K., Somerville, P.G., Sato, T. and Ishii, T. (2003). "Rupture process of the 1944 Tonankai earthquake (M_s 8.1) from the inversion of teleseismic and regional seismograms," *J. Geophys. Res*., **108**(B10), 2497.

Irikura, K. and Miyake, H. (2001). "Prediction of strong ground motions for scenario earthquakes," *Journal of Geography*, **110**, 849–875 (in Japanese with English abstract).

Irikura, K., Miyake, H., Iwata, T., Kamae, K., Kawabe, H. and Dalguer L.A. (2004). "Recipe for predicting strong ground motion from future large earthquake," *Proc. 13th World Conf. Earthq. Eng*., Paper No.1371.

Ishida, M. (1992). "Geometry and relative motion of the Philippine sea plate and Pacific plate beneath the Kanto-Tokai district, Japan," *J. Geophys. Res*., **97**, 489–513.

Hirose, I., Kawasaki, I., Okada, Y., Sagiya, T. and Tamura, Y. (2000). "A silent earthquake of December 9, 1989, in the Tokyo Bay, as revealed by the continuous observation of crustal movements in the southern Kanto district, central Japan," *Zisin*, **53**, 11–23, 2000 (in Japanese with English abstract).

Kanamori, H. (1971). "Faulting of the great Kanto earthquake of 1923 as revealed by seismological data," *Bull. Earthq. Res. Inst. Univ. Tokyo*, **49**, 13–18.

Kawabe, H. and Kamae, K. (2008). "Prediction of long-period ground motions from huge subduction earthquakes in Osaka, Japan," *J. Seismol*., **12**, 173–184.

Kobayashi, R., and Koketsu, K. (2005). "Source process of the 1923 Kanto earthquake inferred from historical geodetic, teleseismic, and strong motion data," *Earth, Planets and Space*, **57**, 261–270.

Koketsu, K. and Kikuchi, M. (2000). "Propagation of seismic ground motion in the Kanto basin," *Science*, **288**, 1237–1239.

Koketsu, K., Hatayama, K., Furumura, T., Ikegami Y. and Akiyama, S. (2005). "Damaging long-period ground motions from the 2003 M_w 8.3 Tokachi-oki, Japan, earthquake," *Seismol. Res. Lett*., **76**, 67–73.

Matsumura, S. (2002). "Seismicity rate changes in the inferred locked zones of the Tokai region in the latter half of the 1990's," *Zisin*, **54**, 449–463 (in Japanese with English abstract).

Miyake, H. and Koketsu, K. (2005). "Long-period ground motions from a large offshore earthquake: The case of the 2004 off the Kii peninsula earthquake, Japan," *Earth Planets Space*, **57**, 203–207.

Miyake, H., Iwata, T. and Irikura, K. (2003). "Source characterization for broadband ground-motion simulation: Kinematic heterogeneous source model and strong motion generation area," *Bull. Seismol. Soc. Am*., **93**, 2531–2545.

Miyake, H., Koketsu, K., Kobayashi, R., Tanaka, Y., and Ikegami, Y. (2006). "Ground motion validation of the great 1923 Kanto earthquake using source model along the new geometry of the Philippine sea slab and integrated 3D velocity structure model in the Tokyo metropolitan area," *Bull. Earthq. Res. Inst. Univ. Tokyo*, **81**, 267–272.

Miyake, H., Koketsu, K. and Furumura, T. (2008). "Source modeling of subduction-zone earthquakes and long-period ground motion validation in the Tokyo metropolitan area," *Proc. 14th World Conf. Earthq. Eng*, S10–012.

Murotani, S., Miyake, H. and Koketsu K. (2008). "Scaling of characterized slip models for plate-boundary earthquakes," *Earth Planets Space*, **60**, 987–991.

Sato, H., Hirata, N., Koketsu, K., Okaya, D., Abe, S., Kobayashi, R., Matsubara, M., Iwasaki, T., Ito, T., Ikawa, T., Kawanaka, T., Kasahara, K. and Harder, S. (2005). "Earthquake source fault beneath Tokyo," *Science*, **309**, 462–464.

Sekiguchi, H., Yoshimi, M., Horikawa, H., Yoshida, K., Kunimatsu, S. and Satake, K. (2008). "Prediction of ground motion in the Osaka sedimentary basin associated with the hypothetical Nankai earthquake," *J. Seismol*., **12**, 185–195.

Somerville, P., Irikura, K., Graves, R., Sawada, S., Wald, D., Abrahamson, N., Iwasaki, Y., Kagawa, T., Smith, N. and Kowada, A. (1999). "Characterizing crustal earthquake slip models for the prediction of strong ground motion," *Seismol. Res. Lett*., **70**, 59–80.

Tanaka, Y., Koketsu, K., Miyake, H., Furumura, T., Sato, H., Hirata, N., Suzuki, H. and Masuda, T. (2005). "Integrated modeling of 3D velocity structure beneath the Tokyo metropolitan area," *Eos Trans. AGU*, **86**(52), Fall Meet. Suppl., Abstract S21A–0200.

Wald, D.J. and Somerville, P.G. (1995). "Variable-slip rupture model of the great 1923 Kanto, Japan, earthquake: Geodetic and body-waveform analysis," *Bull. Seismol. Soc. Am*., **85**, 159–177.

Wu, C., Koketsu, K. and Miyake, H. (2008). "Source processes of the 1978 and 2005 Miyagi-oki, Japan, earthquakes: Repeated rupture of asperities over successive large earthquakes," *J. Geophys. Res*., **113**, B08316.

Yamanaka, Y. (2004). "Source processes of the 1944 Tonankai and 1945 Mikawa earthquakes," *Chikyu Monthly*, **29**, 739–745 (in Japanese).

Yamanaka, Y. and Kikuchi, M. (2004). "Asperity map along the subduction zone in northeastern Japan inferred from regional seismic data," *J. Geophys. Res*., **109**, B07307.