Strong Ground Motion Evaluation in the Tokyo Metropolitan Area: The 1923 Kanto Earthquake and Future Subduction-Zone Earthquakes

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1. ABSTRACT

We proposed a method of strong ground motion evaluation for subduction-zone earthquakes, carried out the strong ground motion evaluation in the Tokyo metropolitan area for subduction-zone earthquakes along the Sagami and Nankai troughs, and examined the validity of the method. For the 1923 Kanto earthquake, we also examined the source fault model and the velocity structure model in the Tokyo metropolitan area. For a hypothetical Tokyo metropolitan earthquake, we examined the effect of the shallow surface of the Philippine Sea plate, which was estimated from large-scale seismic reflection surveys, on the result of strong ground motion prediction. For a hypothetical Tokai earthquake, appropriate source parameters and wide-range velocity structure models extended to undersea parts, the crust and the plate enable us to carry out realistic broadband strong ground motion prediction. We confirmed that distinct long-period ground motions were excited in the Tokyo metropolitan area by a giant subduction-zone earthquake along the Nankai trough. Therefore, the deterministic simulation of long-period ground motion is essential for strong ground motion prediction of a subduction-zone earthquake.

2. EVALUATION METHOD OF STRONG GROUND MOTION

Various kinds of earthquakes such as active-fault earthquakes, plate-boundary earthquakes, and in-slab earthquakes are threatening the Tokyo metropolitan area (TMA). Among them, the kind of plate-boundary earthquakes is the greatest menace as they are generally larger with higher recurrence rates than the other kinds of earthquakes. Accordingly, the strong ground motion prediction for plate-boundary earthquakes is one of the most important issues for the TMA (Figure 1).

The Headquarters for Earthquake Research Promotion published the “National Seismic Hazard Maps for Japan” (NSHMJ) in 2005. The maps for specified earthquake sources in NSHMJ were constructed by computing time histories of broadband ground motions at the engineering basement surface. The earthquake source is represented by a characterized source model consisting of asperities and a background. Broadband ground motions for an active-fault earthquake are computed with the hybrid synthesis method (hybrid combination of theoretical long-period simulation and short-period statistical Green’s function method). However, those for a subduction-zone earthquake are computed only with the statistical Green’s function method, as large-scale computation is required and we have to construct a velocity model in a large land-sea region for the theoretical long-period simulation. Only the statistical Green’s function method was mainly used even in the strong ground motion prediction for subduction-zone earthquakes by the Central Council for Disaster Prevention.

Therefore, long-period ground motions from subduction-zone (plate-boundary) earthquakes have not yet been evaluated accurately in the TMA by using the theoretical simulation method, though the damage of oil storage tanks in Tomokomai due to long-period ground motions from the 2003 Tokachi-oki earthquake validated the necessity of their accurate simulation (Koketsu et al., 2005; Hatayama et al., 2004). Since a source model, a velocity structure model, and a computational scheme are the key components of the theoretical long-period simulation, we here upgrade the source and velocity structure models, and then evaluate long-period ground motions in the TMA for subduction-zone (plate-boundary) earthquakes. These will lead to the prediction of strong ground motions from subduction-zone (plate-boundary) earthquakes by the hybrid synthesis method.

For constructing a source model used in strong ground motion prediction of a subduction-zone earthquake, the slip distributions obtained by waveform inversions can provide basic information. Murotani et al. (2005) and Miyake et al. (2006) compiled the results of waveform inversions for Japanese subduction-zone earthquakes, and extracted asperities from them. They then calculated regression relationships between rupture area or combined asperity area and seismic moment. These relationships are similar to those for crustal earthquakes, though the areas are a little (1.3 times) larger than those for crustal earthquakes with the same moment. However, there is a possibility that these asperities do not equally correspond to strong motion generation areas as for crustal earthquakes. Hata et al. (2006) examined this possibility and suggested that asperities almost correspond to strong motion generation areas if asperities are extracted from the result of a waveform inversion carried out with a minimum rupture area.

In addition, the asperity model has been studied extensively (e.g., Nagai et al., 2001; Okada et al., 2003; Yamanaka and Kikuchi, 2004; Wu and Koketsu, 2006), claiming that the same asperities are ruptured repeatedly and their combination is responsible for the magnitude of an earthquake. As shallow plate-boundary earthquakes have shorter recurrence intervals (100 – 200 years) than those of other subduction-zone earthquakes, we can know the shaking by a previous event for most of them. If this sort of plate-boundary earthquake repeats similar rupture, similar shaking should be repeated in a next event. Therefore, it is essential for strong ground motion prediction of a future plate-boundary earthquake to investigate the shaking by a past event in detail and examine its strong ground motions.

We here propose two procedures for source modeling of a subduction-zone earthquake as follows:

(1) If we know the rupture process of a previous event, we take this process as a source model of a future event based on the hypothesis of repeated asperity rupture (Nagai et al., 2001). As the source time functions derived by waveform inversion for a large subduction-zone earthquake are often short of medium-period components, we introduce a pseudo-dynamic source model (Guatteri et al., 2004). (e.g., Kanto earthquake, Tonankai earthquake).

(2) If we do not know the rupture process of a previous event, we take a characterized source model (Irikura and Miyake, 2001; Miyake et al., 2003) based on the scaling of asperity size from the compilation of rupture process models. We empirically assume a stress drop of around 3 MPa and the ratio of a combined asperity and fault areas to be about 20% such that asperities appropriately correspond to strong motion generation areas. The characterized source model is constructed using these assumptions and the recipe of strong ground motion prediction (Irikura and Miyake, 2001; Irikura et al., 2003). (e.g., Tokyo metropolitan (Northern Tokyo Bay) earthquake, Tokai earthquake)

3. STRONG GROUND MOTION VALIDATION FOR THE KANTO EARTHQUAKE

The 1923 Kanto earthquake, which caused the great Kanto earthquake disaster, is a typical subduction-zone earthquake around the TMA. The fault plane of this earthquake is located on a shallow part of the Philippine Sea plate subducting from the Sagami trough. As the 1703 Genroku earthquake occurred in the combined region of the fault plane and a neighboring area in the east, the recurrence interval of the earthquake is about 220 years. It is only 82 years after the Kanto earthquake, so that the Earthquake Research Committee (ERC) (2005) obtained a 30-year probability as small as 0.065%. However, since the recurrence interval is not so long, a 50-year probability will reach 0.85%. We here perform strong ground motion validation for the 1923 Kanto earthquake in order to examine its source model and the velocity structure model in the TMA.

The large-scale seismic reflection surveys in 2002 and 2003 revealed the upper surface of the Philippine Sea plate to be shallower than the previous estimates (e.g., Ishida, 1992). Kobayashi and Koketsu (2005) carried out a rupture process inversion only with a fault plane at the previous depth, and so Sato et al. (2005) performed another inversion with a new fault plane on the shallow surface. We use the results of these inversions as source models for the 1923 Kanto earthquake (Figure 2). In the result for the new fault geometry, the second asperity in the east was relocated northward approaching the downtown Yokohama and Tokyo. Its depth was changed from 10 km to 15 km.

For the velocity structure, we adopted the DaiDaiToku integrated model (Tanaka et al., 2005, 2006; Miyake et al., 2006; Table 1 and Figure 3), which was being constructed using exploration data. Figure 4 shows a cross section of the deep part of this model with three-dimensional extensions to the crust and the subducting Philippine Sea plate. We note that the shallow subsurface structure derived from borehole data is already built in the DaiDaiToku integrated model.

For ground motions from a giant subduction-zone earthquake, it is pointed out that long-period ground motions effective on long and large structures can be threatening the TMA in addition to short-period ground motions relating to seismic intensities and damage to houses and ordinary structures. Therefore, it is preferable for this strong ground motion evaluation to compare synthetic seismograms with observed ground motions besides comparisons of attenuation relations and intensities distributions.

We carried out simulations of long-period ground motions using the result of the waveform inversion as a source model, the DaiDaiToku integrated model as a velocity structure model, and the voxel finite element method (Koketsu et al., 2004) as a computational scheme. The obtained waveform well simulates the seismogram observed at Hongo, Tokyo during the 1923 Kanto earthquake. Figure 5 shows this agreement with the seismogram restored by Yokota et al. (1984). The original record was observed by an Imamura seismograph oriented N77°E at the Department of Seismology, the University of Tokyo in Hongo. The agreement in the time histories looks excellent, but the agreement in the response spectra is not so good at periods longer than 5 s, though good in a band from 2 s to 4s. In order to solve this problem, we have to revise the source and velocity structure models considering the excitation of surface waves.

The short-period ground motions were computed with the statistical Green's function method and a pseudo-dynamic source model derived from the slip distribution of the inversion result. Their instrumental intensities at Hongo, Shinjuku and Yokohama are almost equal to or a little larger than the intensities estimated from the damage (Moroi and Takemura, 2002).

We computed long-period and short-period ground motions for the previous and new source models (Models A and B in Figure 2). The long-period ground motions of Model A are almost similar to those by Sato et al. (1999). The peak response spectra of the long-period ground motions for Model B are about halves of those for Model A, as the second asperity of Model B is located at a deeper part than that of Model A (Tanaka et al., 2005). In contrast, the short-period ground motions for Model B are a little larger than those for Model A, because the second asperity approached the TMA in Model B.

4. CONCLUSIONS

We proposed a method of strong ground motion evaluation for subduction-zone earthquakes using the information on the location and areas of asperities, which were greatly improved in recent years, and carried out the strong ground motion evaluation and prediction of subduction-zone earthquakes assumed along the Sagami or Nankai trough. We found that the modeling of an earthquake source has been improved, since the location and areas of asperities can be estimated not only by a source process inversion but also by exploration, analysis of seismicity, tomography and others.

We also proposed a method for the modeling of a velocity structure using the results of explorations and seismic records, and constructed the DaiDaiToku integrated model of the velocity structure beneath the TMA. We further improved this model by building in the shallow subsurface structure and three-dimensionally extending to the structures of the crust and Philippine Sea plate.

For the 1923 Kanto earthquake, the source and velocity structure models were reconstructed, as large-scale seismic reflection surveys provided us with the shallower estimate of the upper surface of the Philippine Sea plate than the previous depth. Since the eastern asperity approached Tokyo with a deeper depth, the excitation of long-period ground motions has been halved, and the short-period ground motions and seismic intensities have increased.

For the hypothetical Tokyo metropolitan earthquake, we carried out strong ground motion predictions with the deep and shallow source models on the previous and new geometry of the Philippine Sea plate, respectively. We confirmed that the strong ground motion for the shallow source model is a little larger than that for the deep source model. We also found the effects of the complex velocity structure in the TMA such as the reflection of surface waves at the western end of the Kanto basin and propagation of seismic wave along the northwestern corridor. This implies the importance of deterministic ground motion simulation.

For the hypothetical Tokai earthquake, we confirmed that a characterized source model and the hybrid synthesis method could work for broadband strong ground motion prediction if we could assume appropriate source parameters and a wide-range accurate velocity structure model three-dimensionally extended to undersea parts, the crust and Philippine Sea plate. We also confirmed the distinct excitation of long-period ground motion in the TMA by a giant subduction-zone earthquake along the Nankai trough. For a further improvement, we have to tune the velocity structure model and its details such as an accretionary prism, by using observed records of small- or medium-size earthquakes.

We constructed source and velocity structure models for subduction-zone earthquakes threatening the TMA and applied the method of strong ground motion prediction to them. We then confirmed the advancement of the strong ground motion prediction method, and in particular the usefulness of the deterministic method for evaluating long-period ground motions. As problems to be solved in a future, we should clarify the relation between asperities and strong motion generation areas on a plate boundary, and introduce heterogeneity based on a dynamic physics model into the source model. We should develop a method of efficiently tuning a velocity structure model with observed records and extend it to larger ranges.

Acknowledgements:

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References:

1) Earthquake Research Committee (ERC) (2005), "National Seismic Hazard Maps for Japan", Separate Volume **1**, 213pp. (in Japanese).

2) Hata, N., Miyake, H. and Koketsu, K. (2006), "Strong motion generation area and asperity of subduction-zone earthquakes," *Abstracts of the Japan Geoscience Union Meeting 2006,* Paper No. S204-008.

3) Hatayama, K., Zama, S., Nishi, H., Yamada, M., Hirokawa, M., Inoue, R. (2004), "Long-period strong ground motion and damage to oil storage tanks due to the 2003 Tokachi-oki earthquake," *Zisin*, **57**, 83-103 (in Japanese).

4) Irikura, K. and Miyake, H. (2001), "Prediction of strong ground motions for scenario earthquakes, J. Geography, **110**, 849-875.

5) Irikura, K., Miyake, H., Iwata, T., Kamae, K., Kawabe, K. and Dalguer L.A. (2003), "Recipe for predicting strong ground motion from future large earthquake," *Anuuals Disas. Prev. Res. Inst. Kyoto Univ.*, **46B**, 105-120 (in Japanese).

6) 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.

7) 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. Seism. Soc. Am.*, **93**, 2531-2545.

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

9) Koketsu, K., Fujiwara, H. and Ikegami, Y. (2004), "Finite-element simulation of seismic ground motion with a voxel mesh", *Pure Appl. Geophys.*, **161**, 2463-2478.

10) Koketsu, K., Hatayama, K., Furumura, T., Ikegami, Y. and Akiyama, S. (2005), "Damaging long-period ground motions from the 2003 Mw 8.3 Tokachi-oki, Japan, earthquake," *Seismological Research Letters*, **76**(1), 67-73.

11) Miyake, H., Koketsu, K., Furumura, T., Inagaki, Y., Masuda, T. and Midorikawa, S. (2006), "Integration of the shallow subsurface -structure model for strong ground motion prediction in the Tokyo metropolitan area," *Proc. 12th Jpn. Earthq. Eng. Symp.*, 214-217.

12) Miyake, H., Murotani, S. and Koketsu, K. (2006), "Scaling of asperity size for plate-boundary earthquakes," *Chikyu Monthly*, extra issue No.55, 86-91 (in Japanese).

13) Moroi, T. and Takemura, M. (2002), "Re-evaluation on the damage statistics of wooden houses for the 1923 Kanto earthquake and its seismic intensity distribution in and around southern Kanto district," *J. Jpn. Assoc. Earthq. Eng.*, **2**, 35-71 (in Japanese).

14) Murotani, S., Miyake, H., Koketsu, K. (2005), "Source scaling of heterogeneous slip models for subduction-zone earthquakes," *Abstracts of the 2005 Japan Earth and Planetary Science Joint Meeting,* Paper No. S052-006.

15) Nagai, R., Kikuchi, M. and Yamanaka, Y. (2001), "Comparative study on the source processes of recurrent large earthquakes in Sanriku-oki Region: the 1968 Tokachi-oki earthquake and the 1994 Sanriku-oki earthquake," *Zisin*, **54**, 281-298.

16) Okada, T., Matsuzawa, T. and Hasegawa, A.(2003), "Comparison of source areas of M4.8 +/- 0.1 repeating earthquakes off Kamaishi, NE Japan: Are asperities persistent features?," *Earth Planet. Sci. Lett.*, **213**, 361-374.

17) Sato, T., Graves, R.W., and Somerville, P.G. (1999), "Three-dimensional finite difference simulation of long-period strong motion in the Tokyo metropolitan area during the 1990 Odawara earthquake (MJ 5.1) and the great 1923 Kanto earthquake (Ms 8.2) in Japan," *Bull. Seism. Soc. Am.*, **89**, 579-607.

18) 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.

19) 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.

20) Tanaka, Y., Koketsu, K., Miyake, H., Furumura, T., Sato, H., Hirata, N., Suzuki, H., Masuda, T. (2005), "The Daidaitoku community model of the velocity structure beneath the Tokyo metropolitan area (1)," 2005 Japan Earth and Planetary Science Joint Meeting, S079-P010.

21) Tanaka, Y., Miyake, H., Koketsu, K., Furumura, T., Hayakawa, T. Baba, T., Suzuki, H. and Masuda, T. (2006), "The DaiDaiToku Integrated Model of the Velocity Structure beneath the Tokyo Metropolitan Area (2)," Japan Geoscience Union Meeting 2006, S116-P14.

22) Yamanaka, Y. and Kikuchi, M. (2004), “Asperity map along the subduction zone in northeastern Japan inferred from regional seismic data,” *J. Geophys. Res.*, **109**(B7), Art.No.B07307.
23) Yokota, H., Kataoka, S., Tanaka, T. and Yoshizawa, S. (1989), "Estimation of long-period ground motion of the 1923 great Kanto earthquake," J. Struct. Const. Eng. Trans. Arch. Inst. Jpn., 401, 35-45.
24) Wu, C. and Koketsu, K. (2006), “Complicated repeating earthquakes on the convergent plate boundary: Rupture processes of the 1978 and 2005 Miyagi-ken oki earthquakes,” *Report of the Grant-in-Aid for Special Purposes No. 178000022005,”* 31-36.

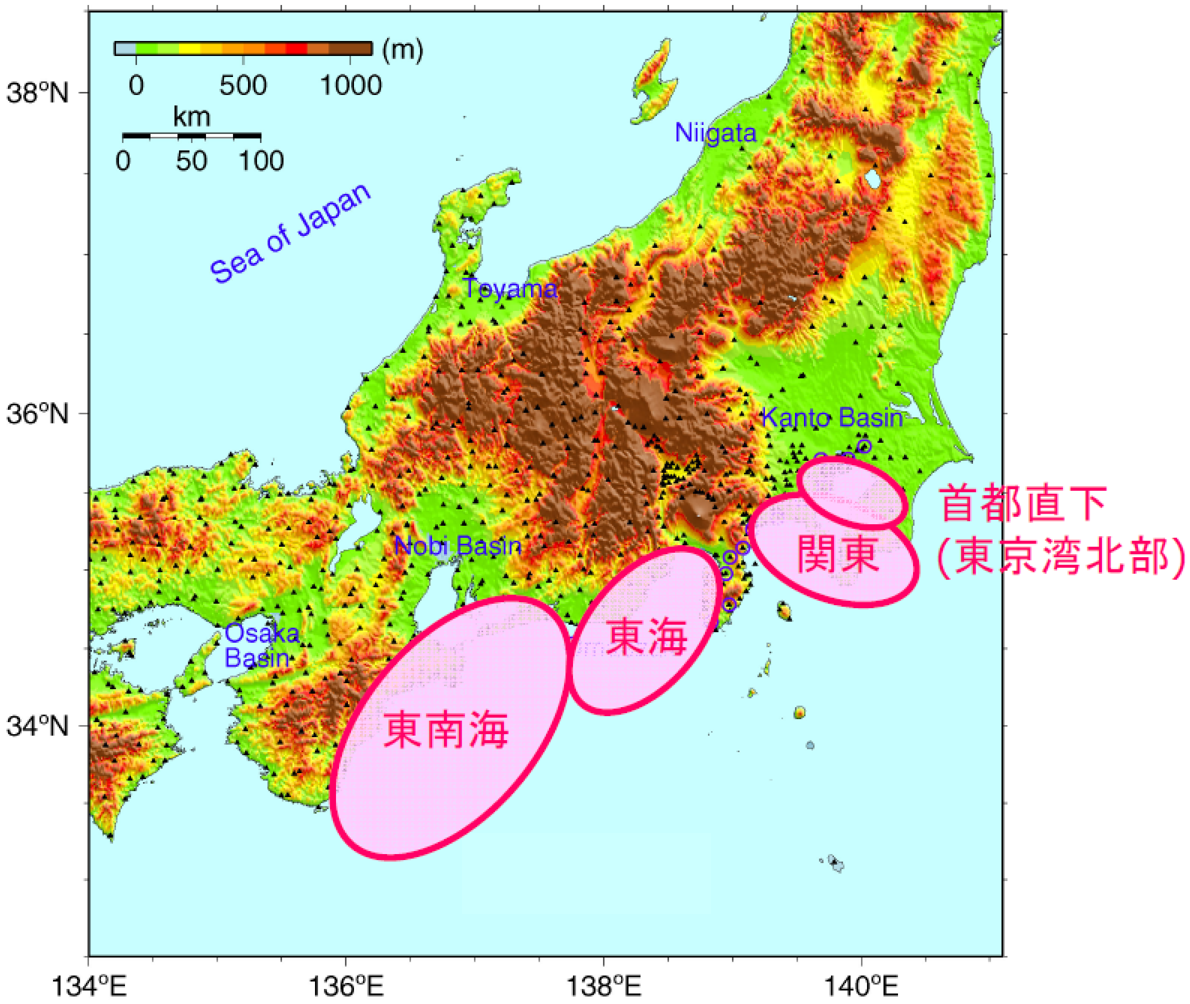
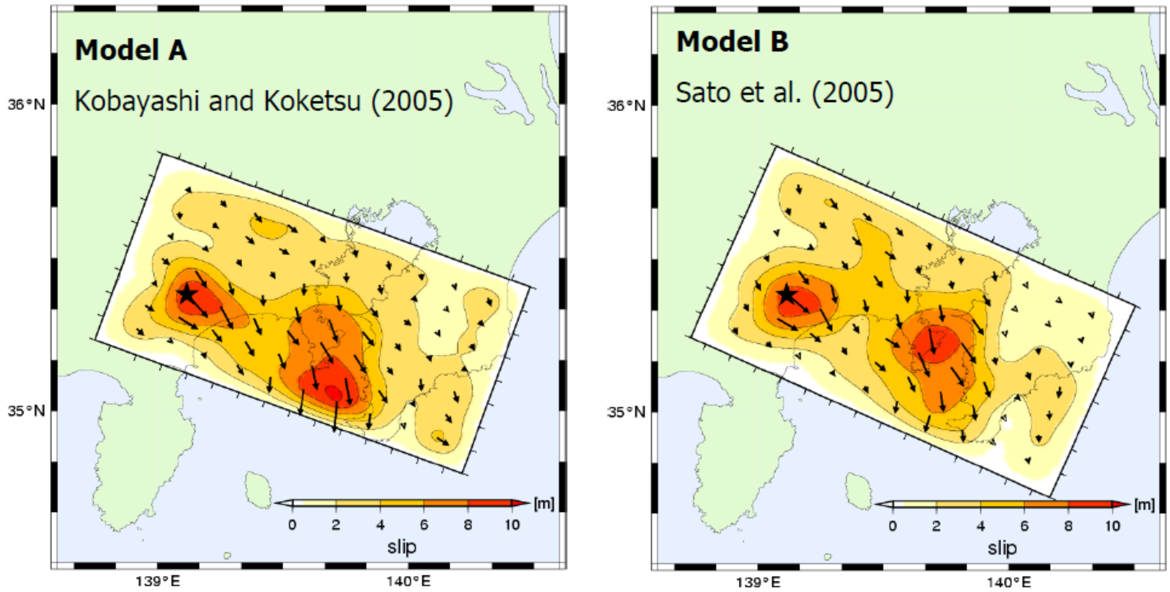


Figure 1. Subduction-zone earthquakes along the Sagami and Nankai troughs to be considered for the strong ground motion evaluation in the Tokyo metropolitan area. 首都直下, 関東, 東海, and 東南海 indicate the Tokyo metropolitan, Kanto, Tokai, and Tonankai earthquakes, respectively.



	Strike	Dip	Depth of Hypocenter (km)	M_0 (Nm)	M_w	Max Slip (m)	Reference
Model A	290	25	14.6	1.1×10^{21}	8.0	10.0 (2nd asperity)	Kobayashi and Koketsu (2005)
Model B	294	16	12.0	1.0×10^{21}	7.9	9.0 (1st asperity)	Sato *et al.* (2005)

Figure2. The results of the source process inversions with the fault models in the previous (left: Kobayashi and Koketsu, 2005) and new fault geometry (right: Sato et al., 2005).

Table 1. Property parameters in the DaiDaiToku integrated model in the Tokyo metropolitan area.

	V_p (m/s)	V_s (m/s)	Density (kg/m^3)
Layer 1		350	
Layer 2		450	
Shimosa	1800	500	1850
Kazusa	2400	900	2080
Miura	3200	1500	2280
Bedrock	4800 ~ 5700	3200	$0.319V_p + 700$

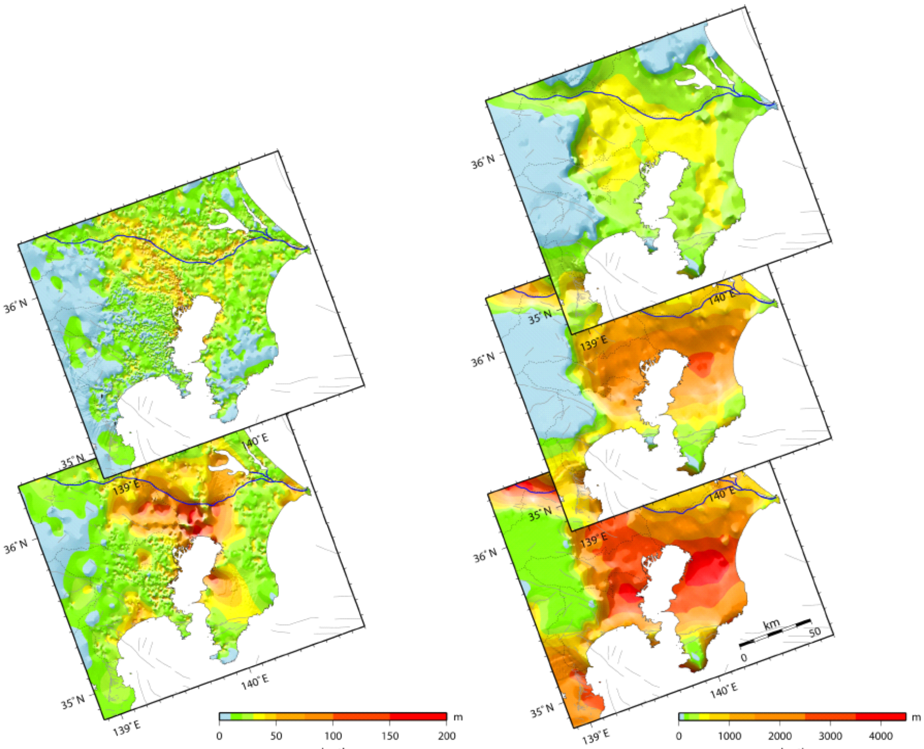


Figure 3. The DaiDaiToku integrated model for the velocity structure in the TMA. (Upper Left) Depth distribution of N values equal to 50. (Lower Left) Depth distribution of Vs equal to 500 m/s corresponding to the surface of the Shimosa layer. (Upper Right) Surface of the Kazusa layer. (Middle Right) Surface of the Miura layer. (Lower Right) Surface of the basement.

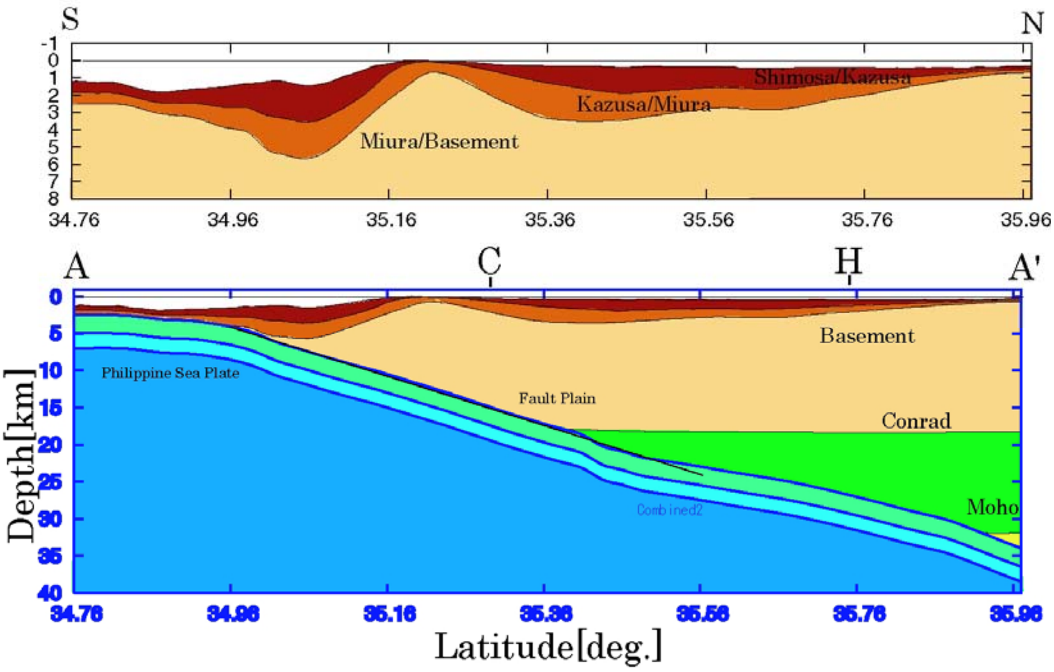


Figure 4. Cross section of the DaiDaiToku integrated model for the velocity structure in the TMA including three-dimensional extensions to the undersea parts, the crust, and the Philippine Sea plate (Tanaka et al., 2006).

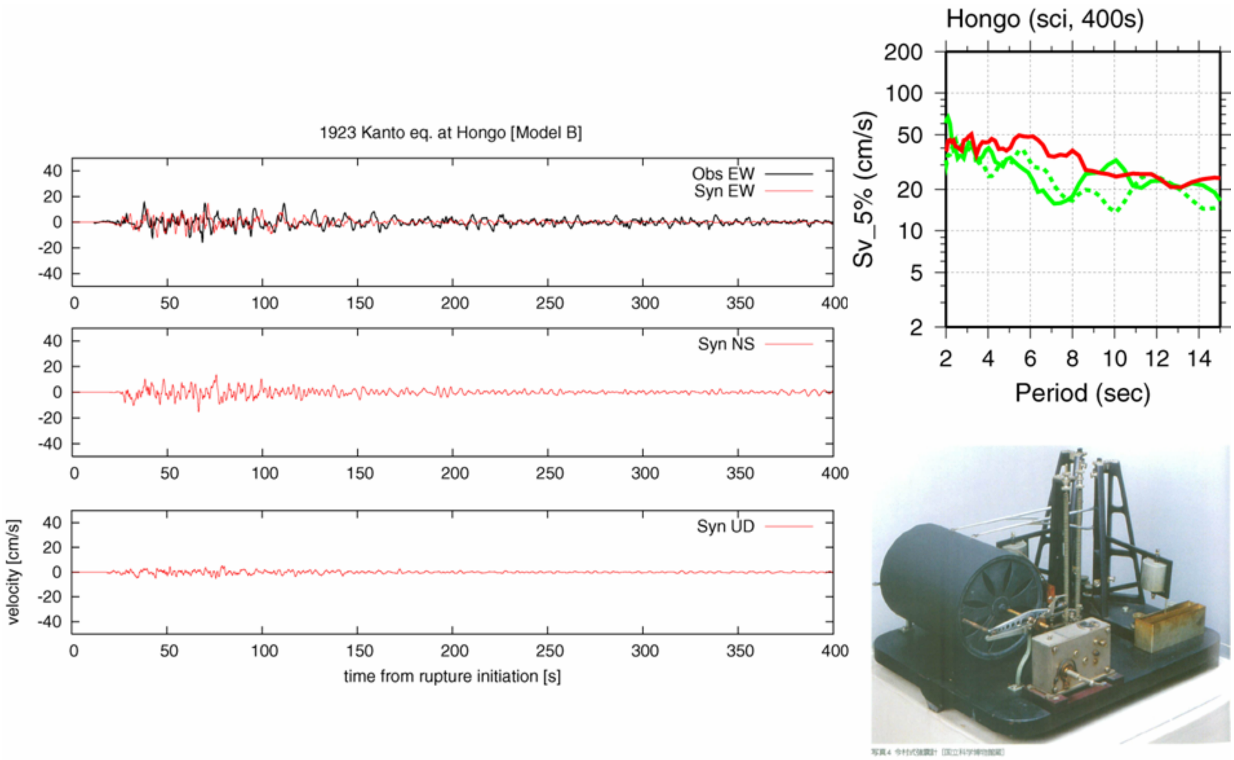


Figure 5. Comparison of the simulated (red) and observed seismograms (black) at Hongo, Tokyo. Only the east-west component was restored and the misplacement of the seismograph (rotated counterclockwise by 13°) was already taken into the simulations. The upper right panel shows velocity response spectra (red: observed east-west component, green solid: simulated east-west component, green dashed: simulated north-south component). The Imamura seismograph in the lower right panel obtained the observed record.