地 震 研 究 所 彙 報
Bull. Earthq. Res. Inst.
Univ. Tokyo
Vol. 81 (2006) pp. 267-272

Ground Motion Validation of the 1923 Kanto Earthquake Using the New Geometry of the Philippine Sea Slab and Integrated 3D Velocity-Structure Model

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Abstract

The Tokyo metropolitan area is under constant threat of strong ground motions from future plate-boundary earthquakes along the subducting Philippine sea slab. Here, we upgrade a ground motion simulation of the 1923 Kanto earthquake using a source model along the new geometry of the Philippine sea slab, geophysical-based velocity model, and efficient computational tool. The source process was inferred from strong-motion, teleseismic, and geodetic data with the new geometry of the slab. The 3D velocity-structure model beneath the Tokyo metropolitan area has been constructed using integrating refraction, reflection, borehole, microtremor, and gravity data, as well as ground motion spectra. We introduce a low-frequency ground motion simulation using these models and the finite element method with a voxel mesh. The western basin edge complicated wave propagation, and excited long-period motions were found within the basin. We confirmed that the simulated ground motions are sensitive to the distribution of asperities of the source model along the shallower plate geometry where the eastern major asperity is located closer to downtown Tokyo than in previous models. Because high-frequency components are essential for seismic intensity measurements, source modeling using the pseudo-dynamic approach and ground-motion simulation using the hybrid method combining deterministic and stochastic approaches are strong candidates to complete a broadband ground motion simulation.

Key words: 1923 Kanto earthquake, Tokyo metropolitan area, Philippine sea slab, Integrated 3D velocity-structure model, ground motion simulation

1. Introduction

The 1923 Kanto earthquake was one of the most disastrous earthquakes in the last century, killing about 105,000 people. The Tokyo metropolitan area is under constant threat from strong ground motions generated by future plate-boundary earthquakes along the subducting Philippine sea slab. Ground motion validation of past large earthquakes in the large basin is important for assessing quantitative source, propagation path, and site amplification effects, as well as basin effects and long-period ground motion due to the development of surface waves. The validation is expected to improve the accuracy of strong ground-motion predictions and hazard assessments.

Regional records during the 1923 Kanto earthquake are ground motion time histories at Hongo, University of Tokyo, geodetic data, and seismic intensities inferred from damage. Based on the slip model of Wald and Somerville (1995), ground motion validations were performed by Sato *et al.* (1999) in the low-frequency range using FDM, and by Dan *et al.* (1998, 2000) in the broadband frequency range using empirical and stochastic Green's function methods.

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Takeo and Kanamori (1997) estimated the possible range of long-period ground motions during the 1923 Kanto earthquake, and compared them to two types of seismograms, Ewing- and Imamura-type, recorded at Hongo, University of Tokyo.

Recently, Sato *et al.* (2005) discovered the new geometry of the Philippine sea slab. Here, we upgrade the ground motion simulation of the 1923 event using a source model along the new geometry of the slab, geophysical-based 3D velocity model beneath the Tokyo metropolitan area, and an efficient computational tool. We then discuss the impact on ground motions in the Tokyo metropolitan area from differences in fault geometry.

2. Source Model of the 1923 Kanto Earthquake Using the New Geometry of the Philippine Sea Slab

Several source models for the 1923 Kanto earthquake have been constructed using geodetic, teleseismic, and strong motion data (e.g., Kanamori, 1971; Matsu'ura *et al.,* 1980; Matsu'ura and Iwasaki, 1983; Wald and Somerville, 1995; Kobayashi and Koketsu, 2005). Most models provide moment magnitude of *Mw* 8.0. Slip distribution of Wald and Somerville (1995) is inferred from teleseismic and geoedetic data, and that of Kobayashi and Koketsu, (2005) are from strong motion, teleseismic, and geoedetic data. Their similar slip distributions with two asperities suggest that it is stably solved as long as fault plane and geometry for the source inversions are the same.

Recently, Sato *et al.* (2005) discovered that the depth of the upper surface of the Philippine sea plate is much shallower than previously estimated. The new estimate is based on deep seismic reflection profiling performed by the DaiDaiToku project, and the previous one is from the distribution of seismicity by Ishida (1990). Sato *et al.* (2005) recalculated 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 decreased slightly. Figures 1 (a) and 1 (b) show the slip distributions along the previous and new geometries of the Philippine sea slab. The differences between fault parameters for Models A and B are summarized in Table 1.

The asperities greatly affect the generation of strong ground motions during an earthquake. Ground motion validation using the new plate geometry is a crucial issue for the Tokyo metropolitan area.

3. Integrated 3D Velocity-Structure Model in the Tokyo Metropolitan Area

The Tokyo metropolitan area is located in the Kanto basin, which is the largest basin in Japan. 3D velocity structure as well as basement shape are of central importance to validate ground motions. Several 3D structural models have been proposed for the Kanto basin using refraction/reflection, geology, borehole, microtremor measurement, and gravity data (e. g., Koketsu and Higashi, 1992; Suzuki, 1996; Sato *et al.,* 1999; Yamanaka and Yamada, 2002; Afnimar *et al.,* 2003). Most models adopt three sediment layers (Shimosa, Kazusa, and Miura layers) above the basement. Afnimar *et al.* (2003) determined the interfaces jointly inverted using refraction/reflection, borehole, and gravity data. The refraction survey lineswere distributed mainly in the central part of the Kanto basin, but there were a few stations in areas such as the southwestern part of the basin and the Boso peninsula.

The DaiDaiToku project conducted large-scale reflection surveys along the Boso, Tokyo bay, Sagami, and Kanto west lines (e.g., Sato *et al.*, 2005). Most areas in the Kanto basin are now covered by survey lines. Based on the structural model of Afnimar *et al.* (2003), Tanaka *et al.* (2005) constructed an integrated velocity structure model of the Tokyo metropolitan area by the refraction/gravity joint inversion method (Afnimar *et al.*, 2002) with refraction data, as well as the large-scale refraction data mentioned above (Figure 2), and gravity data for the whole Kanto basin. They estimated the depth of Kazusa/Miura and sediment/basement interfaces and the resulting basement *P*-wave velocity distribution with minimum residuals of travel times and gravity data. The structural model of Suzuki (1996) is used as the initial model, then Shimosa/Kazusa interfaces estimated by Yamanaka and Yamada (2002) and borehole information are used as depth constraints in the inversion. The deepest point of the basement in the Boso peninsula is estimated at a depth of over 4.5 km.

Tanaka *et al.* (2005) also adjusted the velocity structure to reproduce the dominant periods of the observed R/V spectra. The depth of the basement was fixed, and the ratios of the layer thicknesses

Table 1. Fault parameters of two source models for the 1923 Kanto earthquake.

	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)

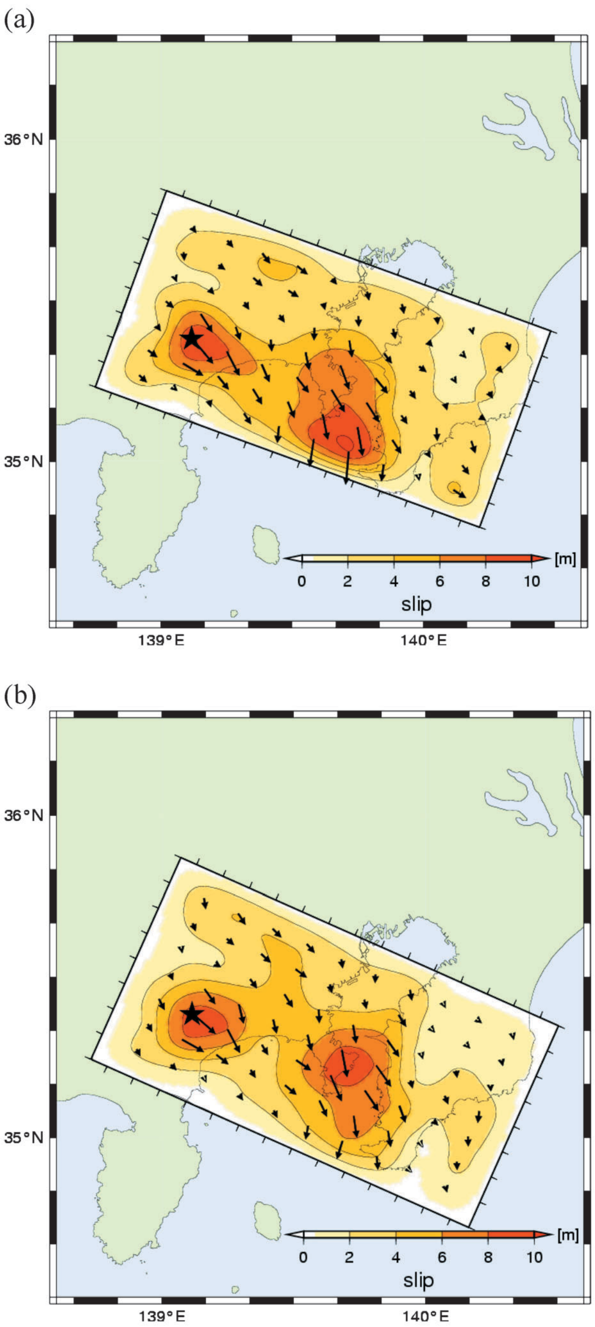

Fig. 1. Slip distribution of the 1923 Kanto earthquake from joint inversions of the strong motion, teleseismic, and geodetic data. (a) Model A by Kobayashi and Koketsu (2005) along the previous geometry of the Philippine sea slab. (b) Model B shown in Sato *et al.* (2005) along the new geometry of the slab.

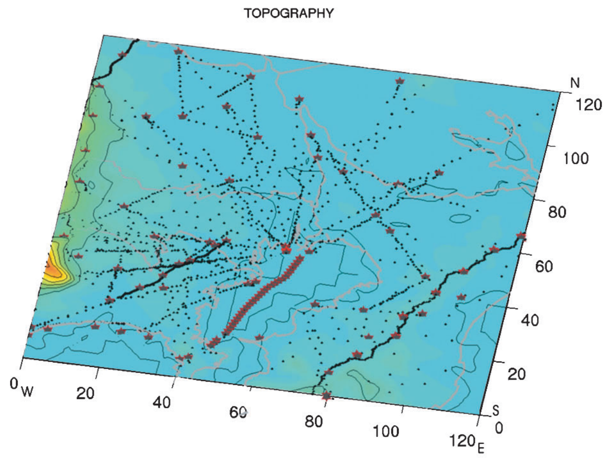

Fig. 2. Refraction/reflection survey used for integrating velocity model. The Boso peninsula, Tokyo bay, Sagami, and Kanto West lines with dense points are performed by the DaiDaiToku project.

Table 2. Velocity structure of integrated model.

	V_p (m/s)	V_s (m/s)	Density (kg/m^3)
Shimosa	1800	450	1850
Kazusa	2400	900	2080
Miura	3200	1500	2280
Bedrock	4800 ~ 5700	3000	$0.319\,V_p + 700$

were preserved during the adjustments. The velocity structure after the turning off the R/V spectra is summarized in Table 2 and Figures 3(a)–3(c).

4. Ground Motion Simulation

We performed a ground motion simulation for the 1923 Kanto earthquake to validate two source models with the integrated 3D velocity-structure model. The FEM with a voxel mesh developed by Koketsu *et al.* (2004) is applied to the ground motion simulation for a period longer than 2 seconds. Here, we use moment rate functions by source inversion as input sources.

During the 1923 Kanto earthquake, ground-motion time histories were recorded by an Imamura-type seismograph at the University of Tokyo in Hongo. The period range of the restored waveforms in the N

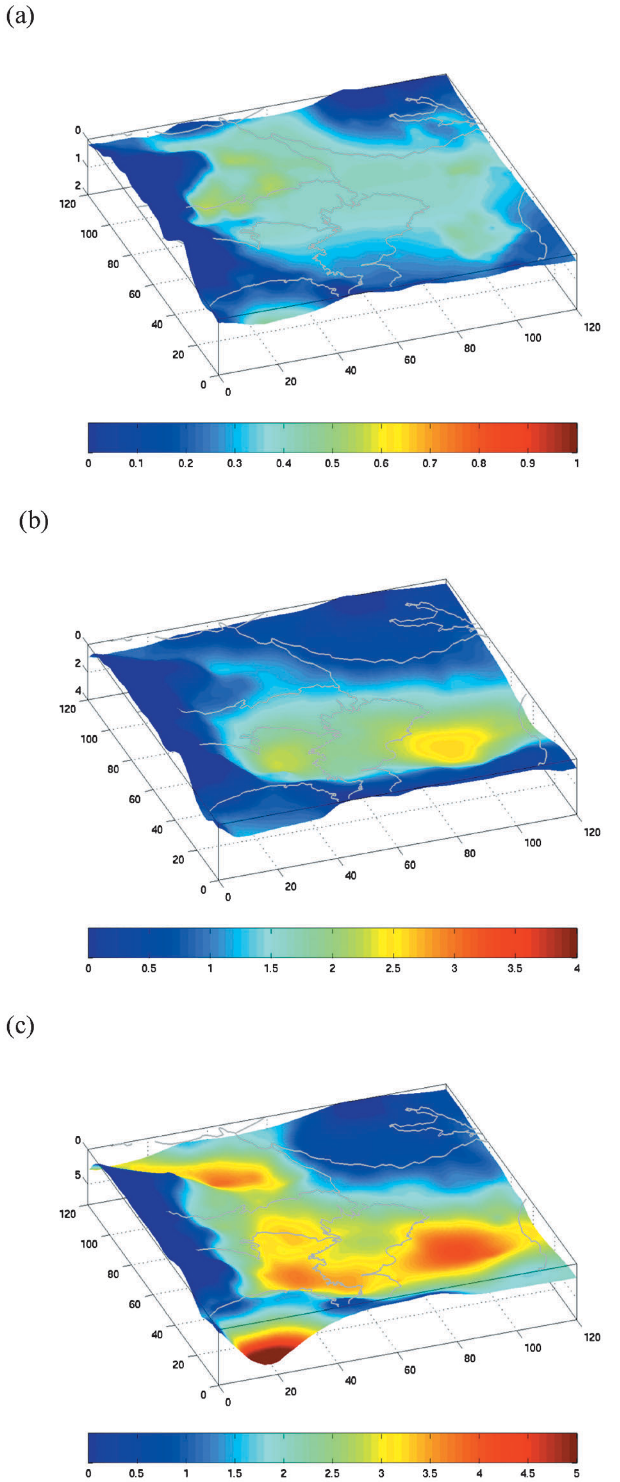

Fig. 3. The depth of (a) Shimsa/Kazusa, (b) Kazusa/Miura, and (c) Miura/Bedrock interfaces for the integrated 3D velocity-structure model (after Tanaka *et al.*, 2005). Contour bars indicate kilometers in depth.

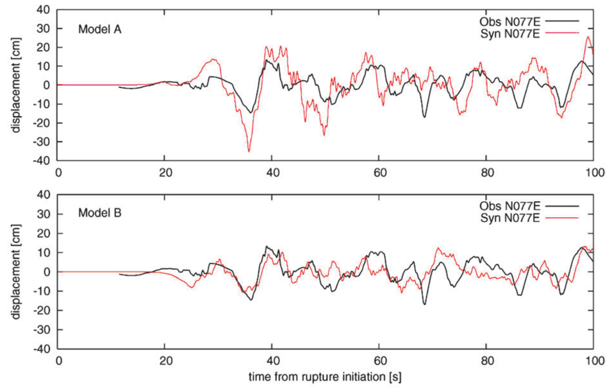

Fig. 4. Observed and synthetic displacement waveforms for Models A (upper) and B (lower) at University of Tokyo in Hongo.

077E component of Yokota *et al.* (1989) is 2-15 seconds. We compare the simulated ground motion with the observed one (Figure 4). Model A generated a larger ground displacement than Model B, both for the integrated velocity model. Both source models are inverted using the waveforms at Hongo with a 1 D velocity structure based on Sato *et al.* (1999). The effects of the discrepancy between 1D and 3D Green's functions on the waveform inversion have been discussed (e.g., Graves and Wald, 2001; Wald and Graves, 2001). Further investigation of the relationships between the source models and the integrated velocity model, as well as the velocity structure outside the basin, is important to quantify the mechanisms of the ground motion generation in the Tokyo metropolitan area.

Figures 5 (a)–(c) are snapshots of the ground velocities simulated by Model B. After waveform generation from the two asperities, excitation of long-period ground motions inside the basin was confirmed even when the *S*-wave was propagated. The FEM simulations have the advantage of reproducing a permanent displacement at the ground surface. The simulated ground-motion time histories help us to understand strong ground motions, long-period ground motions, and crustal deformation during the earthquake.

5. Conclusions

We introduce two source models for the 1923 Kanto earthquake along the different plate geometries and geophysical-based integrated velocity model beneath the Tokyo metropolitan area. By combining

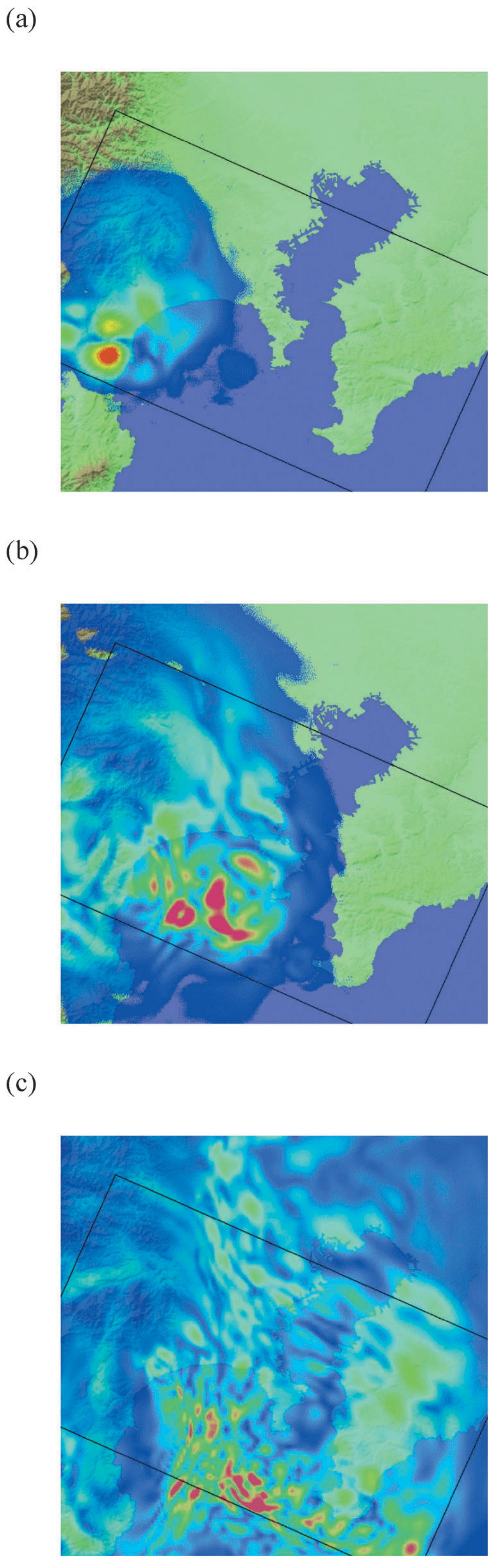

Fig. 5. Snapshots of simulated ground velocities for source model B of the 1923 Kanto earthquake with the integrated velocity model in the Tokyo metropolitan area. (a), (b), and (c) are 10, 20, and 40 seconds after rupture initiation.

source and velocity models, a waveform simulation using the FEM with a voxel mesh was performed for a period longer than 2 seconds. We confirmed that 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 to downtown Tokyo than in previous models. The simulated displacement at Hongo from Model B along the shallower plate model is smaller than Model A along the previous plate model. The spatial validation of ground motion is important to measure the impact of the shallower plate geometry.

In the future, we will expand the ground motion simulation to a shorter-period range to compare the detailed seismic-intensity distribution (e.g., Moroi and Takemura, 2002). Source modeling using the pseudo-dynamic approach (Guatteri *et al.,* 2003; 2004) and ground-motion simulation using the hybrid method (Kamae *et al.,* 1998) combining the deterministic and stochastic approaches are strong candidates to complete a broadband ground motion simulation.

Acknowledgments

We thank Shunichi Kataoka for providing waveforms of Hongo, University of Tokyo.

References

Afnimar, K. Koketsu, and M. Komazawa, 2003, 3-D structure of the Kanto basin, Japan from joint inversion of refraction and gravity data, *IUGG 2003 Scientific Program and Abstracts,* SS04/07A/A03-002, B.487.

Dan, K. and T. Sato, 1998, Strong-motion prediction by semi-empirical method based on variable-slip rupture model of earthquake fault, *J. Struct. Constr. Eng., Architectural Inst. Japan,* **509**, 49–60 (in Japanese with English abstract).

Dan, K., M. Watanabe, T. Sato, J. Miyakoshi, and T. Satoh, 2000, Isoseismal map of strong motions for the 1923 Kanto earthquake (M_{JMA} 7.9) by stochastic Green's function method, *J. Struct. Constr. Eng., Architectural Inst. Japan,* **530**, 53–62 (in Japanese with English abstract).

Graves, R. W. and D. J. Wald, 2001, Resolution analysis of finite fault source inversion using one- and three-dimensional Green's functions 1. Strong motions, *J. Geophys. Res.*, **106**, 8745–8766.

Guatteri, M., P. M. Mai, G. C. Beroza, and J. Boatwright, 2003, Strong ground-motion prediction from stochastic-dynamic source models, *Bull. Seism. Soc. Am.,* **93**, 301–313.

Guatteri, M., P. M. Mai, and G. C. Beroza, 2004, A pseudo-dynamic approximation to dynamic rupture models for strong ground motion prediction, *Bull. Seism. Soc. Am.,*

94, 2051–2063.

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.

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

Kamae, K., A. Pitarka, and K. Irikura, 1998, A technique for simulating strong ground motion using hybrid Green's function, *Bull. Seism. Soc. Am.,* **88**, 357–367.

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

Koketsu, K. and S. Higashi, 1992, Three-dimensional topography of the sediment/basement interface in the Tokyo metropolitan area, central Japan, *Bull. Seism. Soc. Am.*, **82**, 2328–2349.

Matsu'ura, M., T. Iwasaki, Y. Suzuki, and R. Sato, 1980, Statical and dynamical study on faulting mechanism of the 1923 Kanto earthquake, *J. Phys. Earth,* **28**, 119–143.

Matsu' ura, M. and T. Iwasaki, 1983, Study on coseismic and postseismic crustal movements associated with the 1923 Kanto Earthquake, *Tectonophysics,* **97**, 201–215.

Moroi, T. and M. Takemura, 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, *Japan Assoc. Earthq. Eng.*, **2**, 35–71 (in Japanese with English abstract).

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

Sato, T., R. W. Graves, and P. G. Somerville, 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.

Suzuki, H., 1996, Geology of the Koto deep borehole observatory and geological structure beneath the metropolitan area, Japan, *Rept. Natl. Res. Inst. Earth Sci. Disas. Prev.*, **56**, 77–123 (in Japanese with English abstract).

Takeo, M. and H. Kanamori, 1997, Simulation of long-period ground motion near a large earthquake, *Bull. Seism. Soc. Am.*, **87**, 140–156.

Tanaka, Y., K. Koketsu, H. Miyake, T. Furumura, H. Sato, N. Hirata, H. Suzuki, and T. Masuda, 2005, The Daidaitoku community model of the velocity structure beneath Tokyo metropolitan area, *2005 Joint Meeting for Earth and Planetary Science,* s079p–010.

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

Wald, D. J. and R. W. Graves, 2001, Resolution analysis of finite fault source inversion using one- and three-dimensional Green's functions 2. Combining seismic and geodetic data, *J. Geophys. Res.*, **106**, 8767–8788, 2001.

Yamanaka, H. and N. Yamada, 2002, Estimation of 3D S-wave velocity model of deep sedimentary layers in Kanto plain, Japan, using microtremor array measurements, *Butsuri-Tansa,* **55**, 53–65.

Yokota, H., S. Kataoka, T. Tanaka, and S. Yoshizawa, 1989, Estimation of long-period ground motion of the 1923 Great Kanto earthquake, *J. Struct. Constr. Eng., Architectural Inst. Japan,* **401**, 35–45 (in Japanese with English abstract).

(Received November 30, 2005)
(Accepted January 29, 2007)