Proceedings of the International Symposium on Engineering Lessons Learned from
the 2011 Great East Japan Earthquake, March 1-4, 2012, Tokyo, Japan

GROUND MOTION SIMULATIONS FOR GREAT INTERPLATE EARTHQUAKES AROUND JAPAN: VARIABILITY OF GROUND MOTION RESULTED FROM COMPREXITY IN SOURCE MODELS

Masayuki YOSHIMI[1], Haruko SEKIGUCHI[2] and Haruo HORIKAWA[3]

[1]Researcher, Geological Survey of Japan, AIST,
Tsukuba, Ibaraki, Japan, yoshimi.m@aist.go.jp
[2]Associate Professor, Disaster Prevention Research Institute, Kyoto University,
Uji, Kyoto, Japan, sekiguchi.haruko.6u@kyoto-u.ac.jp
[3]Senior Researcher, Geological Survey of Japan, AIST,
Tsukuba, Ibaraki, Japan, h.horikawa@aist.go.jp

ABSTRACT: We numerically simulate ground motions in sedimentary basins for anticipated great interplate earthquakes along the plate boundaries surrounding Japan. Possible multi-scale heterogeneous rupture scenarios have been modeled combining characteristic properties of the source area and adequate variation in source parameters. Ground motions for anticipated Nankai and Tonankai earthquakes to the Osaka basin, and those for Kanto earthquakes and Off Boso Peninsula earthquakes to the Kanto basin have been simulated and variations been investigated.

Key Words: Ground motion prediction, Nankai and Tonankai earthquakes, Kanto earthquakes, Off Boso Peninsula earthquake, variability analysis

INTRODUCTION

Ground motion prediction is one of the most important issues to be tackled in order to assure seismic design against earthquakes that might come near future. Uncertainty in the ground motion prediction depends on how well we know about the future source process and subsurface structure. Thanks to rigorous efforts in modeling subsurface velocity structure all over the Japan, reliable subsurface structure models have become available in wider areas for ground motion computations. On the contrary, large uncertainty still exists about the future source process. Appropriate modeling of complex source process and its variation is, thus, a key factor especially in ground motion prediction where the variation of the estimation is of great concern as well as the estimation itself.

After the 2011 huge Tohoku Earthquake with horrible tsunami disaster and nuclear crisis we face urgent risk of other great earthquake all over the country. Importance of the ground motion prediction is increasing.

This paper aims at stating a series of ground motion prediction works the authors have been conducted, in which a source modeling procedure has been proposed and applied for ground motion prediction that takes into account a complex feature of the source process [Sekiguchi and Yoshimi, 2006; Yoshimi and Sekiguchi, 2006a; Sekiguchi et al., 2008; Sekiguchi and Yoshimi, 2011; Sekiguchi et al., 2011].

MULTI-SCALE HETEROGENEIOUS SOURCE MODEL

Modeling of earthquake scenario begins with a kinematic source model (we refer it as an initial source model), which can be either an asperity-background source model [Sekiguchi et al, 2008] or a source model inverted from waveforms [Sekiguchi and Yoshimi, 2011]. Once the initial source model is provided, possible source processes of the great earthquakes are modeled to have multi-scale heterogeneity in both distributions of the slip and the rupture velocity considering characteristic properties of a source area and adequate variation in source parameters.

Multi-scale slip distribution

Multi-scale heterogeneity is added to the slip distribution with following iterative operations. At first, uniform size patches are randomly distributed on the fault plane. Then the slip amount of the fault area inside every patch is increased or decreased by a certain amount keeping the total seismic moment unchanged. The radius of the set of patches starts from a half of that of the smallest asperity, and then it decreases with factor of 1.5 as the procedure is iterated. Slip fluctuation amplitude begins with a half of the average slip on the fault, and then it decreases by factor of 1.5 as iteration. Among the iterative operations the total area of the patches is kept constant, to be as large as the sum of the asperity areas. Finally, the amplitude of the slip spectrum is adjusted to decay $k^{-1.75}$ so as the source model to follow an empirical characteristic obtained by stochastic characterization of earthquake slip complexity from many published source models [Mai and Beroza, 2002].

Multi-scale rupture velocity distribution

Multi-scale heterogeneity is also introduced to the rupture velocity using the same set of patches used to give fluctuation to the slip distribution. At first, the velocity vector of the rupture propagation at every point on the fault is picked from the initial source model and stored. Then the rupture speed is fluctuated with the similar iterative manner as the slip is fluctuated while the rupture speed is increased if the slip is increased, and vice versa. Amplitude of the speed fluctuation is constant, independent of the patch size. Finally, the rupture triggering time at every point on the fault plane is determined referring the initial velocity vector and fluctuated rupture speed distributions. Amplitude of fluctuations of rupture velocity is set following Miyakoshi and Petukhin (2005).

In computation, slip velocity time functions are calculated following Nakamura and Miyatake (2000) for each point on the fault considering the spatially variable slip, stress drop and rise time.

GROUND MOTION SIMULATION OF GREAT EARTHQUAKES ALONG NANKAI TROUGH

One application of the multi-scale heterogeneous source modeling is the great earthquakes along the Nankai trough, namely Nankai and Tonankai earthquakes, whose probability of occurrence are respectively about 60 percent and 70 percent in the next 30 years [Headquarters of Earthquake Research Promotion, 2012]. Site of our special concern has been Osaka basin, west Japan, where over ten millions of people live and numerous factories have been accumulated. These earthquakes will bring about strong ground motion especially at longer period to the basin.

Source models for the Nankai and Tonankai earthquakes

For the anticipated Nankai and Tonankai earthquake, a set of source models proposed by the Central Disaster Management Council (CDMC) [CDMC, 2002] had been chosen as initial source models (Fig.

1a). Since their source spectra lack high frequency component (>0.1 Hz) compared to omega-square spectra (Fig. 1b), we modified them by adding multi-scale heterogeneity into slip and rupture velocity so as the resultant ground motions show omega-squared spectral decay [Sekiguchi and Yoshimi 2006].

A number of multi-scale heterogeneous source models had been generated with various sets of random patches. Also, macroscopically varied source models had been made with varying macroscopic source parameters (e.g. the average stress drop, average rupture velocity, hypocenter location). The former is aimed at investigating the influences of small-scale fluctuation of slip and rupture velocity, while the latter is aimed at grasping total variation of the ground motion of the earthquakes.

Subsurface structure model

Subsurface structures are modeled as follows. The computation domain is set to be large enough for wave propagation simulation. It extends from deep upper mantle to the ground surface and includes source areas and Osaka basin. Hence, the subsurface structure should be composed of the subducting plate, crust, deep sedimentary basins and accretionary wedges. However, we excluded the accretionary wedge and sediment layers other than the Osaka basin, because those soft layers were found slightly to affect the computed ground motion in the Osaka basin for the Nankai earthquake [Yoshimi and Sekiguchi, 2006]. Thereby subsurface structure model is comprised of two parts: Osaka sedimentary basin and the crust structure. For the velocity structure of the Osaka basin, a 3D velocity model (GSJ model) was employed. The GSJ model had been constructed based on geological/geophysical dataset over the area [Horikawa et al., 2003] expressing realistic basement shapes and gradually changing material properties (Fig. 2). The other part, a 3D crust structure, is roughly modeled incorporating large structures, the Conrad and the Moho discontinuities and shape of the Philippine Sea slab (PHS) [Furumura, 2002] allocating appropriate velocity and density to each member. The shape of the PHS slab is used as the shape of the fault surface. Source nodes are distributed on the upper boundary of the PHS slab resulting in a complex curved surface as a fault surface (Fig. 1a, For detail, see Sekiguchi et al., [2008]).

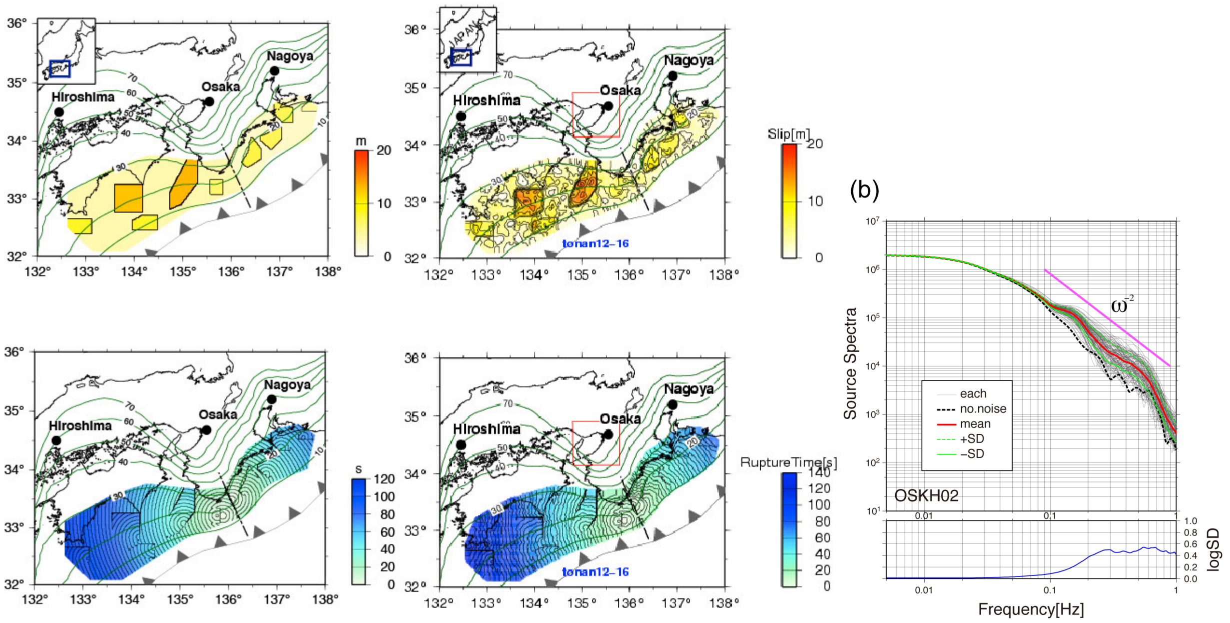


Figure 1. (a) Source models of hypothetical Nankai and Tonankai earthquake (left: initial model, right: modified model, up: fault slip, bottom: rupture time, green contour: depth to the PHS slab). **(b)** Source spectra at Osaka basin for 100 source models (broken line: for initial model, red: for mean of modified model) and their standard deviation (blue line in the bottom panel) [Modified from fig.1 of Yoshimi and Sekiguchi (2010)]

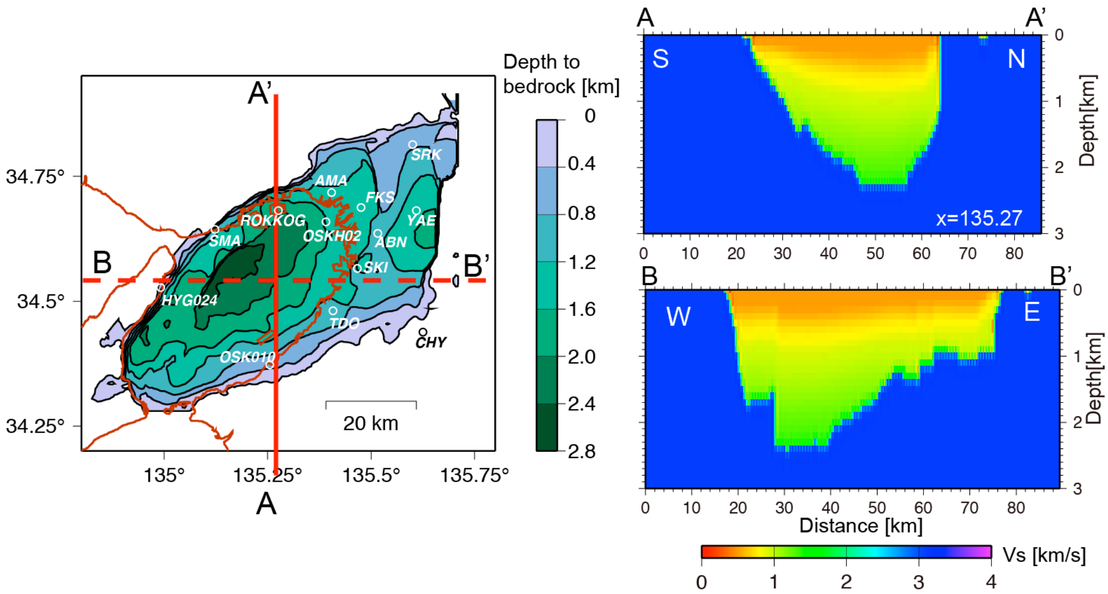


Figure 2. 3D Osaka basin model. Left: depth to the basement, right: depth profiles of S-wave velocity (Vs) along S-N (A-A') and W-E (B-B') lines. [Modified from fig.2 of Yoshimi and Sekiguchi (2010)]

Computed ground motions in the Osaka basin

Ground motions are computed with a 3D FDM [Pitarka et al. 1999] incorporating the 3D velocity structure and the complex source process. Computed ground motions in the basins, in general, are dominated by direct pulses and prolonged surface waves with dominant period varying with the velocity structure beneath (Fig. 3a). Multi-scale heterogeneous source model produces stronger ground motion than the initial source model (Fig. 3b), as is expected from comparison of the source spectra (Fig. 1b). Velocity amplitude in the basin stations ranges around 50 to 100 cm/s.

Ground motions are also computed with parameter variation both of the microscopic parameters (fluctuation within heterogeneous source models) and the macroscopic source parameters (average stress drop, rupture velocity and the hypocenter location etc.) to obtain possible variation of the ground motion level.

Effect of small-scale fluctuation on ground motion variation

Varying microscopic parameters, ground motions from 100 source models have been computed. Fig. 4a and 4b respectively displays mean values and the coefficient of variation of the peak ground velocity (PGV) and the velocity response spectra (h=0.05) at period T [s] (Sv(T)) for the Osaka basin (red rectangle in Fig. 1a). In general, the deeper the basin, the larger is the PGV. The largest PGV is observed around the deepest portion of the basin and the PGV attenuates towards basin edges especially toward the east. As for Sv(T), spatial pattern differs among natural periods. For the period 3.5 sec and 5.5 sec, peaks are aligned along lines parallel or perpendicular to the basin edges to form mesh-like spatial patterns while at period 7.5 sec relatively smooth pattern is seen, which indicates wave interference and period dependent surface wave excitation control the patterns. Variations of the PGV and Sv's are also controlled by the nature of the wave propagation in the basin structure. as they are dependent of the basin shape. These suggest that even in the statistic analysis of the ground motion, we have to pay attention to the multi-dimensional effects of wave excitation.

Effect of macroscopic source parameters on ground motion variation

Varying macroscopic parameters (see Fig.5), ground motions have been also computed. Figure 6 displays variation of the PGV and Sv(6.0) at eleven selected stations on the Osaka basin (Fig2). Compared with the variation due to microscopic parameter, variation of the macroscopic parameter considered here changes drastically the ground motion. Among the cases shown in Figure. 5, the case of 50 percent larger average stress drop on asperity produces largest ground motions in the Osaka basin. The PGV and velocity response spectra at basin sites become twice as those of the base case. On the contrary, the case of deeper hypocenter gives quite small ground motion to the basin. It is because the rupture propagation from the deeper hypocenter does not produce forward directivity effect.

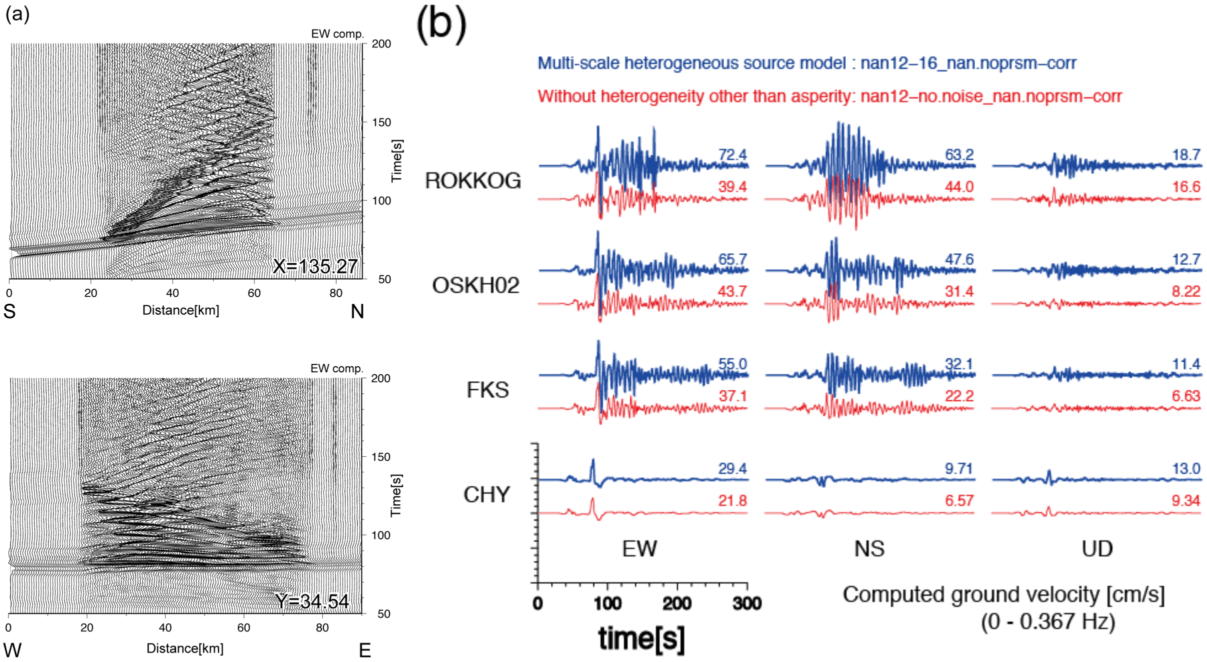


Figure 3. (a) Example of surface velocity waveforms for hypothetical Nankai earthquake (EW component) along the S-N (upper) and W-E (bottom) lines (Fig.2). **(b)** Comparison of velocity waveform in/around the Osaka basin with and without multi-scale heterogeneity in source model.

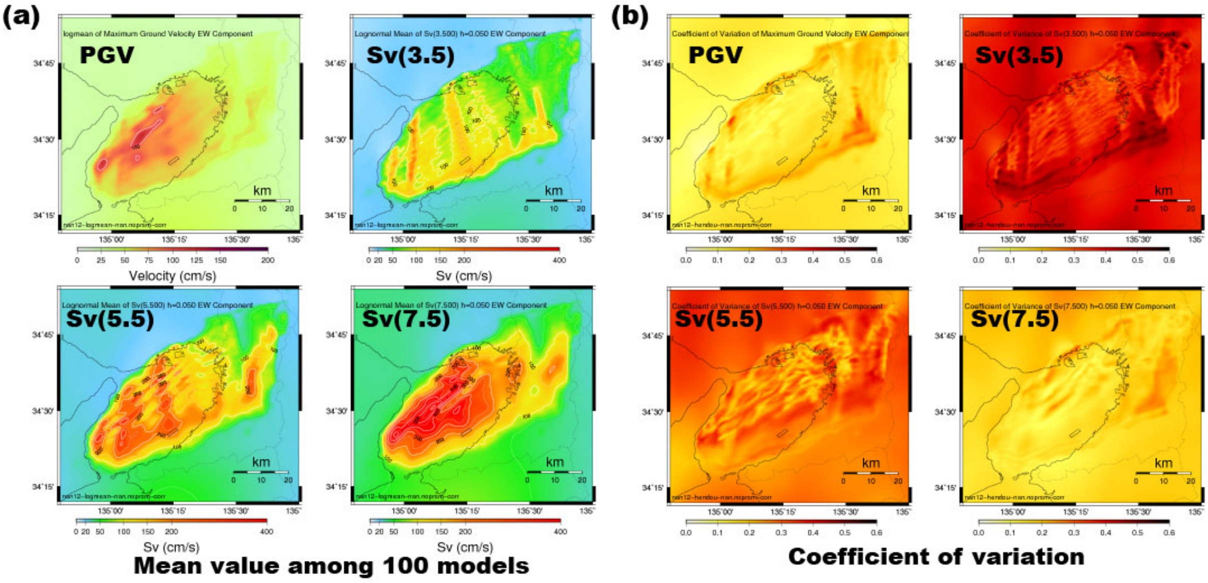


Figure 4. (a) Mean value (among 100 simulations) distribution of PGV, Sv(3.5), Sv(5.5) and Sv(7.5) for EW component. **(b)** Distributions of the coefficient of variation of PGV, Sv(3.5), Sv(5.5) and Sv(7.5).

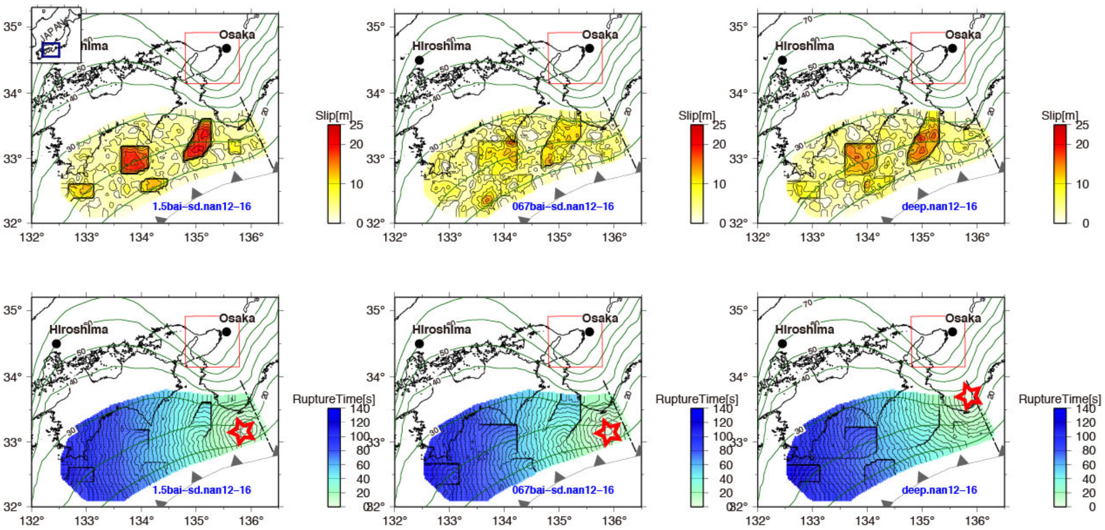


Figure 5. Variation of source models for anticipated Nankai earthquake with varied macroscopic parameters: +50 % stress drop (left), -30 % stress drop (middle), and deeper hypocenter (right).

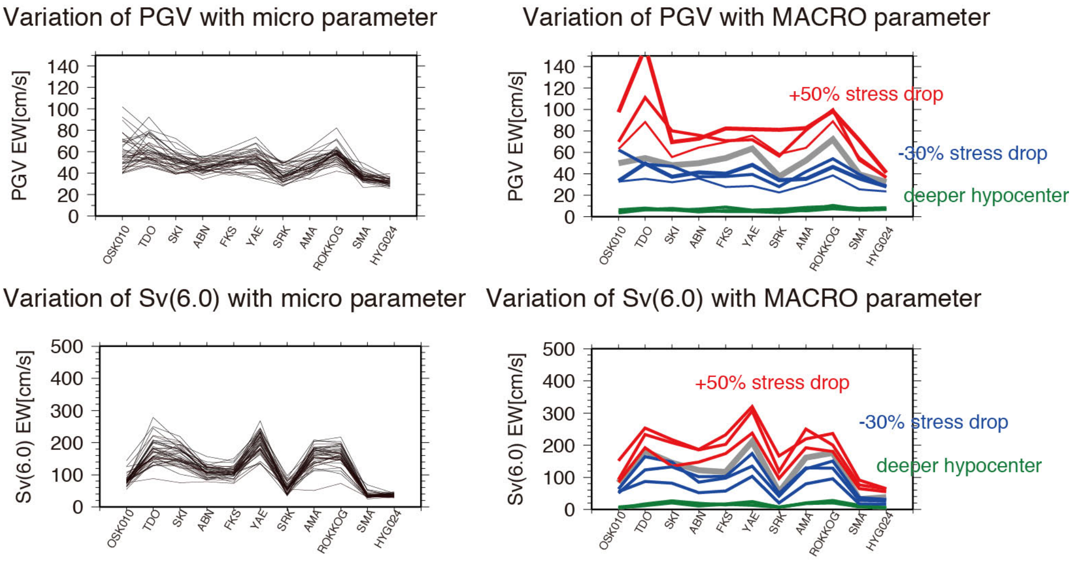


Figure 6. Variation of PGV an Sv(6.0) with micro parameter (left) and with MACRO parameters (right) at selected sites in the Osaka basin. Red lines: case of larger stress drop, blue lines: smaller stress drop, green lines: case of deeper hypocenter, gray lines: base heterogeneous model.

GROUND MOTION PREDICTION OF GREAT EARTHQUAKES NEAR KANTO REGION

Great interplate earthquake in Kanto region is another application of the multi-scale source modeling. As two oceanic plates are subducting beneath the Kanto Basin, there are two possible zones for great interplate earthquakes close to the Kanto region. One is the boundary between the northward subducting Philippine Sea (PHS) slab and the crust, namely northeastern dipping source plane from the Sagami trough beneath the Kanto region. The other is the boundary between the westward subducting Pacific (PAC) slab and the crust or PHS slab, westward dipping source plane from the Japan trench toward the Kanto region.

The former zone extends beneath the Kanto region at a depth ~30km making the interplate earthquake here potentially destructive. This zone is the source area of the historically well-known devastating interplate earthquakes, 1923 Taisho Kanto earthquake and 1703 Genroku Kanto earthquake. Another great interplate earthquake is likely to occur in the reasonably near future because the recurrence period is about 200 years simply derived from the interval between the latest two events.

The latter zone spreads along the eastern margin of the Kanto region. Northern portion of this zone, where the Pacific Plate subducts beneath the crust, has ruptured during the 2011 Tohoku earthquake and its aftershocks. Contrary, the southern portion, where the PAC slab subducts beneath the PHS slab, Off Boso Peninsula region, did not ruptured at the events. Although earthquakes of this region observed since Meiji era (1868) do not excess magnitude 7.5, a tsunami generating M8-class earthquake is suggested to have ruptured in 1677 (Enpo era) from historical record [Usami, 2003]. Considering this region is next to the source area of the huge M9 events and shear stress is accumulated by 10 cm/yr subduction of the PAC slab since the 1677 event, interplate earthquakes are highly expected.

Ground motion and its variance due to the anticipated Kanto and Off Boso earthquakes has been investigated with various earthquake scenarios with adequate variation of source parameters. On constructing the source models, we assume that repeating great earthquakes share some inherent characteristics that closely related to its tectonic setting, namely the asperity distribution, with certain variation in source parameters substantial for nonlinear process. Therefore, for the Kanto earthquake, asperity distribution of the 1923 event is assumed as inherent characteristics and the other source parameters (e.g., stress drop, rupture velocity, etc.) are variable. For the case of Off Boso Peninsula earthquakes, no information about asperity being available, asperity distribution of the 1923 Kanto earthquake is adopted.

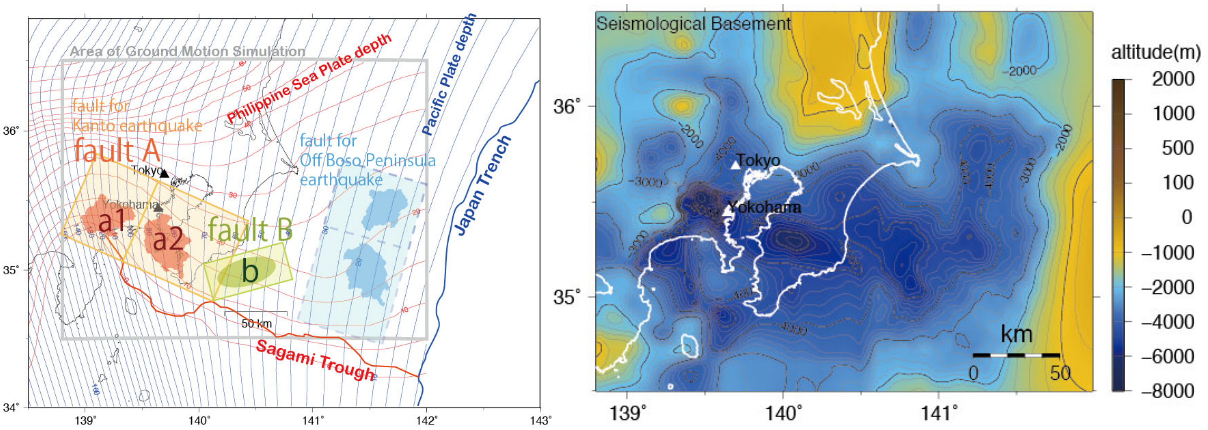


Figure 6. (a) Subducting plates beneath Kanto region and source faults for anticipated great interplate earthquakes: Kanto earthquake and Off Boso earthquake. Contours represent depth to the PHS and PAC slabs. (b) Altitude distribution of seismic basement of the 3D velocity model used in computation modified from CDMC model with gravity anomalies.

Source models for the Kanto earthquakes

A bunch of source scenarios have been constructed fixing the area of the asperities based on the source model of the 1923 Kanto earthquake [Sato et al., 2005], considering possible combination of the asperity activation and variation of the source parameters within a certain ranges supported by stochastic analysis of source properties [for detail see Sekiguchi et al. 2011a].

Source area assumed for the Kanto earthquakes comprises of two parts: fault A and B (Fig.6a). The fault A is the source area of the 1923 Kanto earthquake [Sato et al., 2005]. The fault B is part of the source area of the 1703 Kanto earthquake needed for explaining terrace uplift [Shishikura et al, 2004]. While the source area of the 1703 event is sum of the fault A, B and far off the Boso Peninsula [e.g. Matsuda et al. 1974], the third part is omitted because it gives small contribution to the strong ground motion in the Kanto region.

Two inherent asperities are assumed on the fault A (asperities a1 and a2), which is common feature among inversion source models of the 1923 earthquake [Wald and Sommerville, 1995; Kobayashi and Koketsu, 2005; Sato et al., 2005]. For the fault B, since no inversion model is available other than average slip estimated from terrace uplift [Shishikura, 2004], characteristic of the asperity a2 is adopted to an asperity on the fault B (asperity b) with modification of the total slip and slip direction.

The variable source parameters are the average stress drop (average over the fault), the average rupture velocity, the hypocenter location, and multi-scale heterogeneities. Variation range of the average stress drop is set following the empirical relation between magnitude and the rupture area [Murotani et al., 2008]. Variation range of the average rupture velocity is set referring the average and standard deviation (SD) value for intraplate earthquakes [Yamada et al., 2007, Miyakoshi and Petukhin (2005)]. As for the hypocenter position, there is no reliable data to locate hypocenters of the future Kanto earthquakes other than the hypocenter of the 1923 Kanto earthquake. Another hypocenter is assumed at southeast of the asperity a2 so to cause the largest forward directivity effects to the Kanto region.

Source models for the Off Boso earthquakes

For the Off Boso region, source models are constructed supposing the repetition of the 1677 earthquake of M8. As no information about exact rupture area or asperity distribution is available, the inverted source model of the 1923 Kanto, M8, earthquake is used as the initial model; consequently, source models with two asperities are assumed while the geometry and slip direction are modified as to be appropriate for the source region. As for the location of the source area, at least the source should be north to the triple junction of the PHS slab, PAC slab and North American plate. Then, as the source length is comparable to the north-south distance of the unruptured zone, there only remains uncertainty of the depth of the source area. Here, three source locations are assumed: shallow, middle and deep part of the upper boundary of the PAC slab. The hypocenter location is set so as the forward directivity effects on the land to become the largest [Sekiguchi et al., 2011b].

Subsurface structure model for Kanto area and computation method

A 3D velocity structure model is constructed combining a 3D Kanto basin velocity model [CDMC, 2004], PHS slab geometry [Ishida, 1992; Sato et al., 2005; Toda et al., 2008; Uchida et al., 2009], PAC slab geometry [Ishida, 1992; Noguchi, 1998], and Moho discontinuity [Ryoki, 1999]. The sedimentary structure is extrapolated from the CDMC model to the east using gravity anomaly data (Fig. 6b).

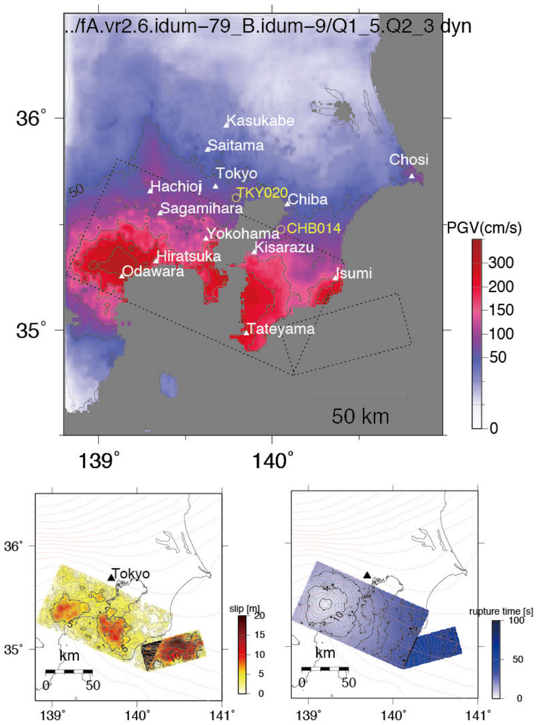
The ground motions are computed with a four-step hybrid technique. We first calculate low-frequency ground motions at the engineering basement with a 3D finite difference method [Pitarka, 1999]. We then calculate higher-frequency ground motions at the engineering basement using a stochastic Green’s function method modified after Onishi and Horike (2000), and combine the lower- and higher-frequency motions using a matched filter. We finally calculate ground motions at the surface by computing the response of the alluvium-diluvium layers with the equivalent linear method [DYNEQ: Yoshida and Suetomi, 1996] to the combined motions at the engineering basement.

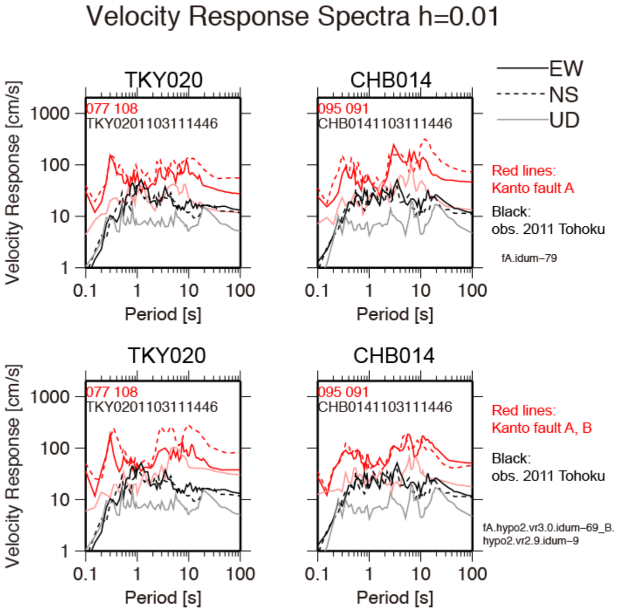
Computed ground motions on the Kanto basin and their variation

Kanto earthquakes

Among all the combination of the asperities, we found the 1923 Kanto earthquake, namely combination of asperities a1 and a2, generates close to the largest ground motion, while the strongest is given by the largest rupture area (al, a2 and b) and east hypocenter (Fig. 7a). For these strong scenarios, intense ground motions with PGV exceeding 50 cm/s are obtained in the area above the fault plane. Above the southern, or shallow, portion of the fault plane, PGV on the surface reaches 200-250 cm/s.

Figure 8 shows comparison of the velocity response spectra at CHB014 and TKY020 between the simulated Kanto earthquake (combination of al+a2 and a1+a2+b) and observed ground motions during the 2011 Tohoku M9 earthquake. Predicted ground motions are much stronger than the observation of the Tohoku earthquake for wide period range.





(Left) **Figure 7.** PGV distribution (top) for the hypothetical Kanto earthquake similar to the 1703 event with its multi-scale heterogeneous source model (bottom).

(Right): **Figure 8.** Velocity response spectra of the computed ground motions (red lines) compared with the records of the 2011 Tohoku M9 earthquake (black lines).

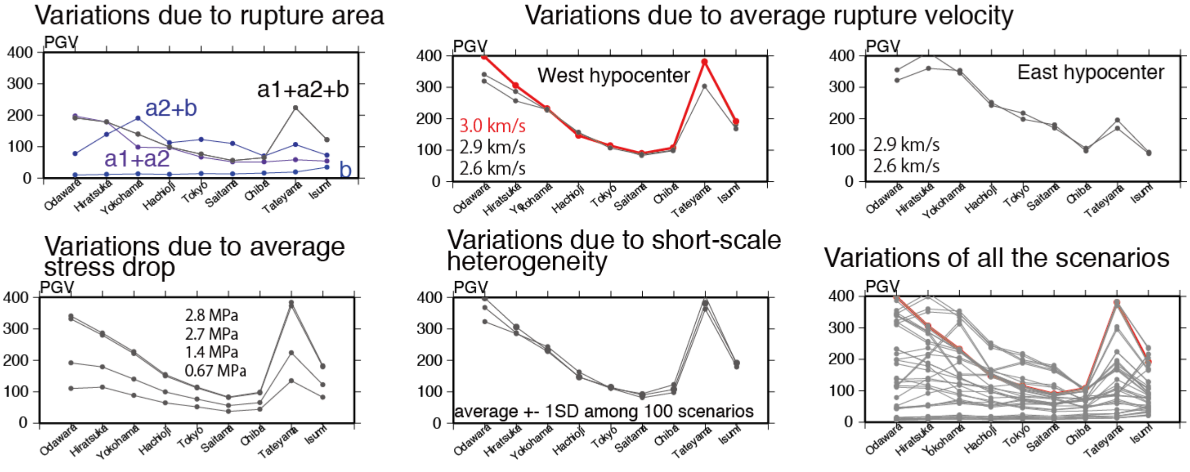


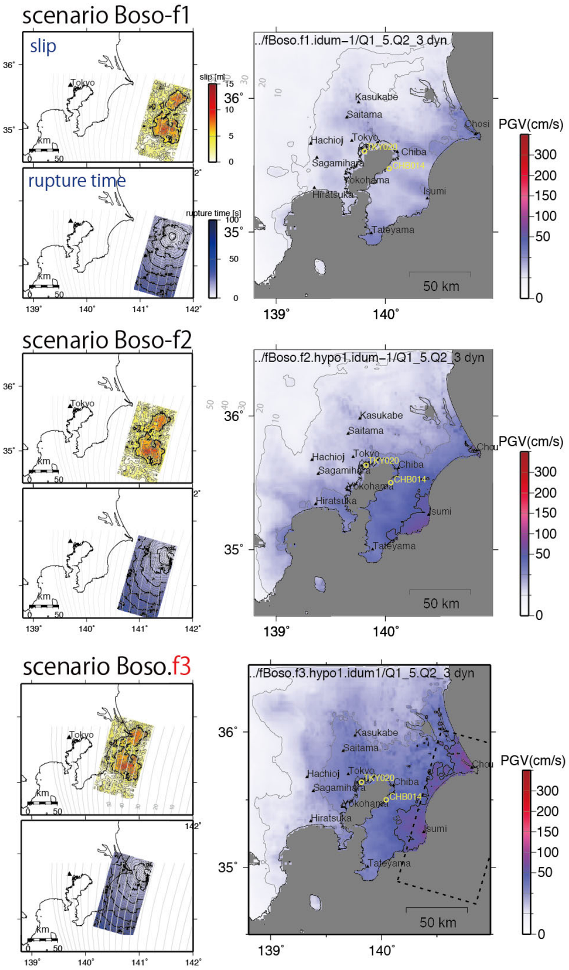
Figure 9. Variation of the PGV at selected site in the Kanto basin due to variation of source parameters.

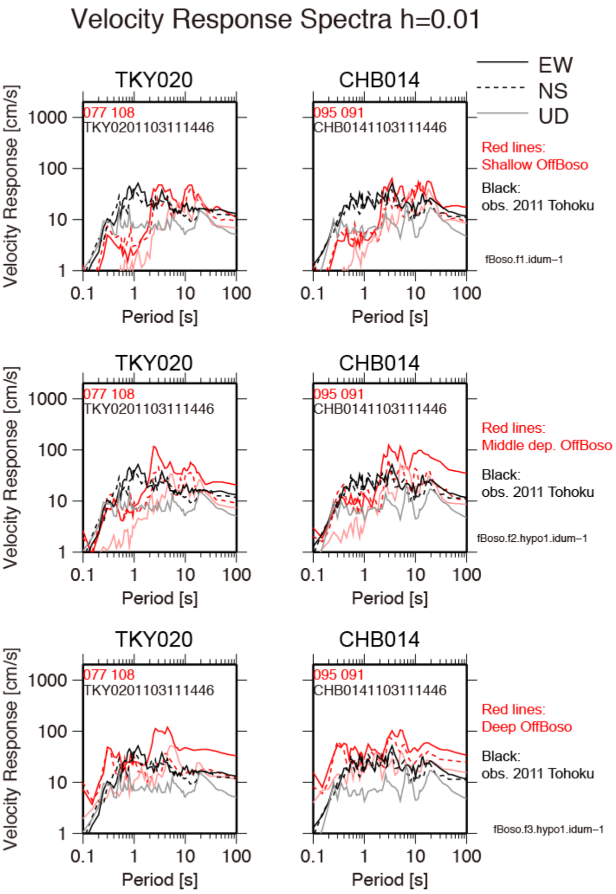
Figure 9 displays variation of the PGV at multiple sites in the Kanto region (Fig.7) due to all the combination of the source models considered in this study. The source parameter whose variation gives largest variation of ground motion is the average stress drop. The average + 1SD of stress drop is twice of the average and makes PGV almost twice larger. The PGV variation due to rupture area depends mainly on the activation of the fault A, while influence of the activation of the fault B is limited to southeastern Boso Peninsula. The relocation of the hypocenter causes large difference in PGV distributions in some areas like to the northwest of the fault. On the other hand, the variation of the average rupture velocity causes small differences in the ground motions. This indicates that the forward directivity effects are not significant in wide area for low-angle thrust faults, and that in the area just over the source fault, high frequency radiation from just below is dominant.

Off Boso Peninsula earthquakes

The scenario deepest and closest to the land, Boso-f3, generates largest PGV among three Off Boso earthquake scenarios (Figure 10). PGV is tens of cm/s over the Boso Peninsula reaching 50 cm/s in the southeast of the peninsula. Ground motion is not severe but can be strong especially on the Boso Peninsula.

Figure 11 shows comparison of the velocity response spectra at CHB014 and TKY020 between the simulated Off Boso earthquakes and observed ground motions during the 2011 Tohoku M9 earthquake. Though they are much smaller than those predicted for the Kanto earthquake, simulated ground motions for the Off Boso earthquakes are as strong as the ground motion of the Tohoku earthquake in the Kanto region at longer period range over several seconds. Note that these results are to be validated in terms of wave propagation because the shallow subsurface structure of the Off Boso region is just a extrapolation from a proposed subsurface model (Figure 6b), still, much precaution should be taken against, especially, long period ground motion of these earthquakes.





(Left): **Figure 10.** PGV distributions for three hypothetical Off Boso earthquakes and their multi-scale heterogeneous source models.
(Right): **Figure 11.** Velocity response spectra of the computed ground motions (red lines) compared with the records of the 2011 Tohoku M9 earthquake (black lines).

CONCLUSIONS

Ground motions have been simulated in sedimentary basins for anticipated great interplate earthquakes along the plate boundaries surrounding Japan. Possible multi-scale heterogeneous rupture scenarios have been modeled combining characteristic properties of the source area and adequate variation in source parameters. Ground motions for anticipated Nankai and Tonankai earthquakes to the Osaka basin, and those for Kanto earthquakes and Off Boso Peninsula earthquakes to the Kanto basin have been simulated and their variations been investigated to ascertain importance of considering source process complexity and consequent variation in ground motion prediction. Thus, future works should emphasize on validation of source process modeling for great interplate earthquakes, for which the 2011 Tohoku M9 earthquake and its large aftershocks might provide precious information.

ACKNOWLEDGMENTS

We thank Dr. Reiji Kobayashi for providing us with the inversion results. We thank the Central Disaster Management Council for providing us with the subsurface structure models of the Kanto Basin. We are also grateful to Dr. Nozomu Yoshida, Dr. Masanori Horike, and Dr. Arben Pitarka for providing us with computation codes. Observed ground motion records by K-NET NIED are used. Some figures were drawn using Genetic Mapping Tool v.4 (Wessel and Smith, 1998).

REFERENCES

Central Disaster Management Council (2002). Conference document, *16th conference of the Special Board of Inquiry on Tonankai and Nankai earthquake*, http://www.bousai.go.jp/jishin/chubou/nankai/16/, (J).

Central Disaster Management Council (2004). Material for Twelfth Committee, Special Committee for Earthquake beneath the Tokyo Metropolitan Area, 2-1 (in Japanese).

Furumura, T. (2002). “Numerical simulation of seismic wave propagation and strong ground motions in 3D heterogeneous media.” *Fall meeting of the Seismological Society of Japan*, A70 (in Japanese).

Headquarters for Earthquake Research Promotion (2012). “Long-term evaluation of subduction earthquakes.” *http://sparc1038.jishin.go.jp/main/choukihyoka/kaikou.htm* (in Japanese).

Horikawa, H., Mizuno, K., Ishiyama, T., Satake, K., Sekiguchi, H., Kase, Y., Sugiyama,Y., Yokota, H., Suehiro, M., Yokokura, T., Iwabuchi, Y., Kitada, N. and Pitarka, A. (2003). “A three-dimensional subsurface structure model beneath the Osaka sedimentary basin, southwest Japan, with fault-related structural discontinuities.” *Annual Report on Active Fault and Paleoearthquake Researches, Geological Survey of Japan* **3**, 225-259. (J)

Ishida M. (1992). “Geometry and Relative Motion of the Philippine Sea plate and Pacific Plate beneath the Kanto-Tokai District, Japan”, Journal of Geophysical Research, Vol. 97, pp. 489-513.

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

Mai, P.M. and Beroza, G.C. (2002). “A spatial random field model to characterize complexity in earthquake slip.” *Journal of Geophysical Research* **107**, doi:10.1029/2001JB000588.

Miyakoshi, K. and Petukhin, A.(2005). “Delineation of rupture velocity of heterogeneous source model extracted from source inversion results of inland earthquakes”, Abstract of Japan Geoscience Union Meeting 2005, S046P-002.

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

Nakamura, H. and Miyatake, T. (2000) “An approximate expression of slip velocity time functions for simulation of near-field strong ground motion”, Zisin (J. Seismol. Soc. Jpn.), Vol. 53, pp. 1-9 (in Japanese with English abstract).

Noguchi, S. (1998) “Seismicity, focal mechanisms and location of volcanic front associated with the subducting Philippine Sea and Pacific Plates beneath the Kanto district, Japan”, Bull. Earthq. Res. Inst. Univ. Tokyo, Vol. 73, pp. 73-103 (in Japanese with English abstract).

Onishi Y, and Horike, M. (2000) “Application of the Method for Generating 3-component Strong Ground Motions using the Stochastic Green’s Function to the 1995 Hyogo-ken Nanbu Earthquake”, J Struct Eng 46B, pp.389–398 (in Japanese with English abstract)

Pitarka, A. (1999). “3D elastic finite-difference modeling of seismic motion using staggered grids with nonuniform spacing.” *Bulletin of the Seismological Society of America* **89**, 54-68.

Ryoki K. (1999) “Three-dimensional depth structure of the crust and uppermost mantle beneath southwestern Japan and its regional gravity anomalies", Zishin (J Seism Soc Japan), Vol. 52, pp. 51-63 (in Japanese with English abstract).

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, Vol. 309, pp. 462-464.

Sekiguchi, H. and Yoshimi, M. (2006). "Multi-scale heterogeneous source model for wide-band ground motion prediction from giant earthquakes along subduction zones." *Chikyu Monthly extra edition* (in Japanese).

Sekiguchi, H. and Yoshimi, M. (2011). "Broadband ground motion reconstruction for the Kanto Basin during the 1923 Kanto earthquake." *Pure and Applied Geophysics*, vol.169, pp.609-630, DOI 10.1007/s00024-010-0142-9.

Sekiguchi, H., Yoshimi, M. and Horikawa, H. (2011a). "Broadband ground motion simulation for great interplate earthquakes with multi-scale heterogeneous source modeling." *The 4th International IASPEI/IAEE Symposium on the Effect of Surface Geology on Seismic Motion*,Paper 3.8

Sekiguchi, H., Yoshimi, M. and Horikawa, H. (2011b). "Ground Motion Prediction for Great Interplate Earthquakes in Kanto Basin Considering Variation of Source Parameters", *AGU Fall meeting*, S43C-2257.

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." *Journal of Seismology*, doi 10.1007/s10950-007-9077-8.

Toda, S., Stein, R.S., Kirby, S.H. and Bozkurt, S.B. (2008) "A Slab Fragment Wedged under Tokyo and Its Tectonic and Seismic Implications", Nature Geoscience, Vol. 1, pp. 771-776, doi:10.1038/ngeo318.

Usami, T. (2003) "Materials for Comprehensive List of Destructive Earthquakes in Japan, [416]-2001", University of Tokyo Press, 605pp.

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. Seism. Soc. Am., Vol. 85, pp. 159-177.

Yamada, M., Senna, S., Fujiwara, H. (2007) "Statistical Analysis of Predicted Ground Motions on the Basis of a Recipe for Strong-motion Prediction ~For Variety of Source Paramenters~", Journal of Japan Association for Earthquake Engineering, Vol.7, No.1,pp.43-60 (in Japanese with English abstract).

Yoshimi, M. and Sekiguchi, H. (2006a). "Strong ground motion prediction with multi-scale heterogeneous source models for huge subduction-zone earthquakes along the Nankai trough, Japan." *Proceedings of 1st European Conference of Earthquake Engineering and Seismology*, ID1044.

Yoshimi, M. and Sekiguchi, H (2006b). "Long-period ground motion prediction for Osaka sedimentary basin: ground motion reconstruction for mid-size earthquake considering accretionary wedge." *Proceedings of the 61st Japan Society of Civil Engineers Annual Meeting*, 561-562 (in Japanese).

Yoshimi, M. and Sekiguchi, H. (2010). "Variability fluctuation of predicted ground motion in 3D basin controlled by multi-dimensional amplification." *Proceedings of 14th European Conference of Earthquake Engineering*, ID1354.

Wessel, P. and Smith, W.H.F. (1998) "New, improved version of the generic mapping tools released", EOS Trans. AGU, Vol. 79, pp.579.