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RECIPE FOR PREDICTING STRONG GROUND MOTIONS: THE STATE OF THE ART AND FUTURE PROSPECTS

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ABSTRACT

We propose a recipe for the prediction of strong ground motion based on the most recent findings of seismology and earthquake engineering. The fault parameters of seismic sources for simulating ground motions are characterized from the waveform inversion results using strong motion data. Then, the source model of a future large earthquake is defined by three kinds of parameters, which we call: outer, inner, and extra fault parameters. The outer fault parameters define the entire source area and seismic moment of the earthquake. The inner fault parameters are parameters characterizing fault heterogeneity inside the fault area. The extra fault parameters are related to the propagation pattern of the rupture. Ground-motion time histories in broadband periods are estimated using a hybrid scheme, long period motions in a numerical calculation for the 3D velocity structure and short period motions in stochastic simulation technique for the source model given by the recipe. The validity and applicability of the procedures for characterizing the earthquake sources for strong ground prediction are examined in comparison with the observed records and broadband simulated motions for the 1995 Kobe, and 2000 Tottori as inland crustal earthquakes and the 2003 Tokachi-oki as subduction-zone earthquakes. Examples of the seismic hazard maps for future large earthquakes with high probability of occurrence potential are shown following the idea of the recipe proposed here.

Introduction

The 1995 Kobe earthquake with M_w 6.9 hit densely populated region including Kobe and its satellite cities and caused heavily damage such as collapse of buildings and bridges, fires, and fatality over 6,400. This earthquake occurred on well-mapped active faults. Therefore, earthquake scientists knew beforehand there might be a bare possibility of earthquake occurrence, although nobody predicted when it would happen. Several damaged earthquakes such as the 1999 Kocaeli (Turkey) earthquake and the 1999 Chi-Chi earthquake also occurred on well-mapped active faults.

Then, from these earthquakes we have learned that earthquake damage resulted from

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destructive ground motions which were generated by rupture propagation effects inside the source as well as geological conditions. It shows that strong ground motion prediction is one of key factors for mitigating disasters for future earthquakes.

So far, most of strong motion predictions in earthquake hazard analysis have been made using empirical methods based on attenuation-distance curve for PGA (peak ground acceleration) and PGV (peak ground velocity) as a function of magnitude, fault distance, ground condition. Unfortunately, they have not reflected recent results of rapidly progressing research in seismology, such as source processes in earthquake faults and wave propagation characteristics in irregular sedimentary layers. For example, heavily damage during the Kobe earthquake was mainly caused by directivity pulses related to fault rupture process and basin-edge effects due to geological configurations.

Accumulated data of strong ground motions have been providing us very important knowledge about rupture processes of earthquakes, propagation-path, and site-amplification effects on ground motion, the relation between ground motion and damage, and so on. We made a framework of strong motion prediction. The strong motion from the scenario earthquake is evaluated from source modeling and Green's function estimation based on geological and geomorphological surveys of active faults, analyses of strong motion recordings, geophysical profiling of underground structures, and so on. The results will lead to improvement of the building code and bridge earthquake-resistant design.

We have developed a recipe to popularize the prediction of ground motions for engineering purpose based on seismological results (e.g., Irikura and Miyake, 2001; Irikura *et al.*, 2004). We summarize the procedure that is currently used to characterize earthquake rupture models for the prediction of ground motions, based on geological investigations of capable earthquake faults and seismological studies of source models. The source model with slip heterogeneity consisting of asperities and a background area are constructed based on a statistical analysis of the source inversion results of crustal earthquakes ranging from about 6 to 7 in moment magnitude (Mw). Then, for strong motion estimation we adopt an asperity model satisfying scaling relations for the heterogeneity of slip on the fault surface in a deterministic manner. Further, we applied the same idea to the prediction of the subduction-zone earthquakes. The validity and applicability of strong ground prediction are examined in comparison with the observed records and actual damage from recent large earthquakes such as the 1995 Hyogo-ken Nanbu (Kobe) earthquake and the 2000 Tottori earthquake as inland crustal earthquakes, and the 2003 Tokachi-oki earthquake as subduction-zone earthquakes.

The seismic hazard maps for future large earthquakes with high probability of occurrence potential are made following the idea of the recipe proposed here by two governmental organizations, the Head Quarter of Earthquake Research Center and Central Disaster Prevention Council in Japan.

We here introduce two examples of the seismic hazard maps mentioned above, one is for hypothetical median tectonic line (east segments) earthquakes as an inland crustal earthquake and the other is for the Tokachi-oki earthquake as a subduction-zone earthquake, which is made to examine the validity of the methodology.

How to Set Asperities?

Estimation of the asperity location form future earthquakes is challenging issue as well as the source characterization. As some proofs of the characteristic source models, Kikuchi and

Yamanaka (2001) proposed the repetition of asperities for subduction-zone earthquakes, comparing the source inversion results for both present and past large earthquakes by retrieving the historical waveforms. Location of the asperities seems to be overlapped for the event pairs of the 1952 and the 2003 Tokachi-oki earthquakes by Yamanaka and Kikuchi (2003), and for the 1968 Tokachi-oki and the 1994 Sanriku-oki earthquakes by Nagai *et al*. (2001). For inland crustal earthquakes, location of the asperities can be constraint by integrating the information of the geological, geomorphological, seismological, geodetic surveys.

For Inland Crustal Earthquakes:

- Coincidence of the surface offsets measured along the active faults and locations of asperities on fault segments (e.g., Wald and Heaton (1994) for the 1992 Landers earthquake).
- Seismicity; Less active inside the asperities and relatively more active surrounding the asperities before the earthquake. Measuring *b*-values, *a*-values, and local recurrence time as indication where asperities may be located (e.g., Wyss *et al*., 2000).
- Reflected (scattered) waves: less reflection (scattering) coefficients inside asperities and relatively high outside asperities. Locked segments with weaker scattering and low microseismicity, and segment boundaries with stronger scattering and stationary microseismicity. The locked segments are ruptured as asperities for future earthquakes (e.g., Nishigami, 2000).

For Subduction-Zone Earthquakes:

- Repetitious characteristics of asperities (e.g., Kikuchi and Yamanaka, 2001; Nagai *et al*., 2001; Yamanaka and Kikkuchi, 2003) and asperity map (Yamanaka and Kikuchi, 2004).
- Back-slip obtained by the GPS analyses indicating coupling-rate of the plate boundary.

Recipe for Predicting Strong Ground Motion

We outline a recipe for predicting strong ground motions from future earthquakes, which is proposed by Irikura and Miyake (2001) and Irikura *et al*. (2004). The recipe is made by the source characterization based on the multiple-asperity source model, and the hybrid method for simulating ground motions in a broadband period range. We adopted the characterized source model which consists of asperities and background area. The source model is characterized by three kinds of parameters, which we call: outer, inner, and extra fault parameters. The outer fault parameters define the entire source area for possible earthquake. The inner fault parameters are parameters characterizing fault heterogeneity inside the fault area. The extra fault parameters are related to the propagation pattern of the rupture. Hybrid method (e.g., Kamae *et al*., 1998; Irikura and Kamae, 1999) is used for calculating broadband ground motions.

Outer Fault Parameters - Estimation of Seismic Moment for Possible Earthquake –

Step 1. Total Rupture Area ($S = LW$)

Total fault length L of the possible earthquake is defined as a sum of the lengths of the fault segments that simultaneously activated. Fault width W is proportional to the total fault length before reaching thickness of the seismogenic zone W_{max}.

W (km) = L (km) for $L < W_{max}$ (1)

W (km) = $W_{max} / \sin\delta$ (km) for $L >= W_{max}$ (2)

where, δ indicates dip angle.

Step 2. Total Seismic Moment (M_0)

Total seismic moment is estimated from the 3-stage scaling relationships between seismic moment and rupture area, which are empirical relationships for equations of (3) and (4), and theoretical relationship for equation (5) (Fig. 1(a)). Dynamic rupture simulation supports the 3-stage scaling relationships (Dalguer *et al.*, 2004).

S (km^2) = 2.23 x 10^{-15} x $M_0^{2/3}$ (3)

for $M_0 < 7.5 \times 10^{25}$ dyne-cm after Somerville et al.(1999)

S (km^2) = 4.59 x 10^{-11} x $M_0^{1/2}$ (4)

for $M_0 >= 7.5 \times 10^{25}$ dyne-cm after Irikura and Miyake (2001)

S (km^2) = 5.30 x 10^{-25} x M_0 (5)

for $M_0 >= 7.5 \times 10^{27}$ dyne-cm considering Scholz (2002)

Step 3. Average Static Stress-Drop ($\Delta\sigma_c$)

Average static stress-drop for the rupture area is estimated by assuming circular-crack model by Eshelby (1957) or considering tectonic loading stress (e.g., Fujii and Matsu'ura, 2000) naturally explaining the 3-stage scaling relationships between seismic moment and rupture area.

Inner Fault Parameters – Slip Heterogeneity or Roughness of Faulting –

Step 4. Combined Area of Asperities (S_a)

From the empirical relationship between S_a and S (Somerville *et al*. 1999, Irikura and Miyake, 2001), combined area of asperities is specified to be about 22% of total rupture area for inland-crustal earthquake.

Step 5. Stress Drop on Asperities ($\Delta\sigma_a$)

$\Delta\sigma_a$ is derived as a product of $\Delta\sigma_c$ and S_a /S from *Step 4*, based on the multiple-asperity source model (e.g., Das and Kostrov, 1986; Madariaga, 1979).

Step 6. Number of Asperities (N)

Number of asperities concerns the segmentation of the target active fault system. Locations of the asperities are assumed from surface offsets measured along fault.

Step 7. Average Slip on Asperities (D_a)

D_a is assumed based on *Step 6* and empirical relationships from dynamic simulations of the slip distribution for the multiple-asperity source model. For examples, we use D_a /D = 2.3 for N = 1, D_a /D =2.0 for N = 2, D_a /D = 1.8 for N =3, where N is number of asperities (e.g., Dalguer *et al.*, 2004).

Step 8. Effective Stress on Asperities (σ_a) *and Background Slip Area* (σ_b)

We treat stress drop on asperities ($\Delta\sigma_a$) as effective stress on asperities (σ_a) for strong motion simulation. The effective stress on asperities is also constrained to satisfy the empirical relationship between seismic moment and acceleration source-spectral level shown in Fig. 2. The effective stress on background slip area is just given to match the total moment.

Step 9. Slip-Velocity Time Functions

We assume the Kostrov-like slip-velocity time functions based on the results of dynamic simulation by Day (1982). Peak slip-velocity is given as a function of effective stress, f_{max}, and rupture velocity. Rise time for asperity and background area is assumed as a function of width of asperity and rupture area respectively, and rupture velocity.

Extra Fault Parameters – Propagation Pattern of Rupture –

Extra fault parameters are rupture starting point, pattern of the rupture propagation, and rupture velocity. For inland crustal earthquakes, rupture nucleation and termination are related to geomorphology of active faults (e.g., Nakata *et al*., 1998; Kame and Yamashita, 2003). For subduction-zone earthquakes, the pattern of the rupture propagation are referred to the past earthquakes (e.g., from shallow to deep for the Japan trench, or vice versa for the Nankai trough).

Hybrid Method – Towards Broadband Ground Motion Simulation –

Broadband ground motions are effectively calculated with a hybrid method (e.g., Kamae *et al*., 1998; Irikura and Kamae, 1999), numerically simulated long-period motions with e.g. 3D finite difference method and semi-empirically simulated short-period motions with e.g. stochastic Green's function method. The matching filters for combining those two motions have to be carefully tuned depending on shapes of slip velocity functions. Recent days, the filters are usually selected for 1 sec and 5 sec for the inland-crustal and subduction-zone earthquakes, respectively. Strong ground motions are simulated in a broadband period range from 0.1 to 10 seconds.

(a) (b)

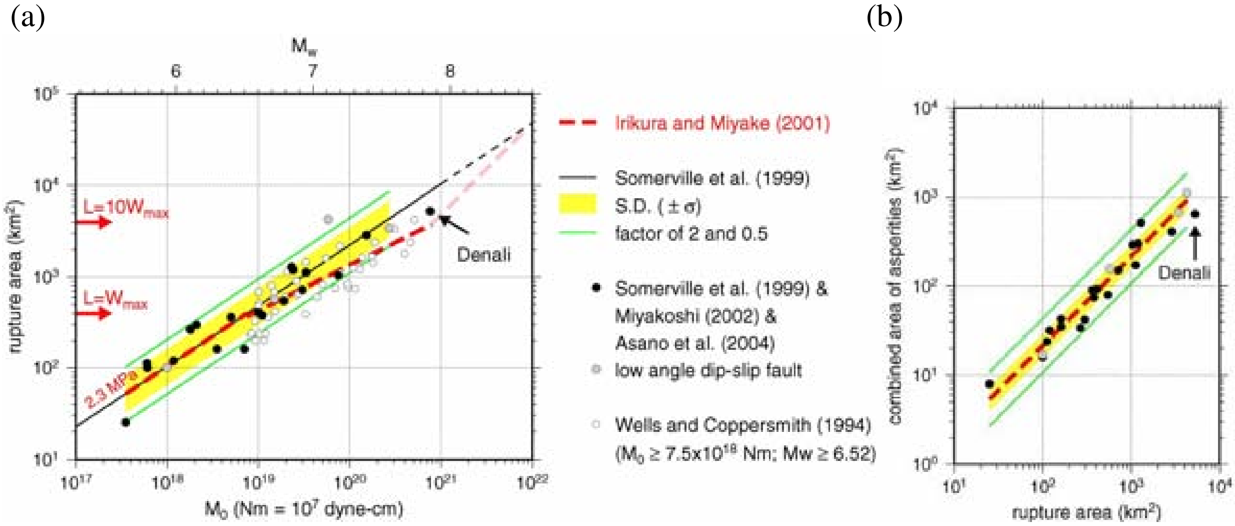

Figure 1. (a) Empirical relationships between seismic moment and rupture area for inland crustal earthquakes. Red broken lines are 3-stage scaling relationships proposed by our studies (after Irikura and Miyake, 2001; Irikura et al., 2004). (b) Empirical relationships between combined area of asperities and total rupture area for inland crustal earthquakes (after Irikura and Miyake, 2001).

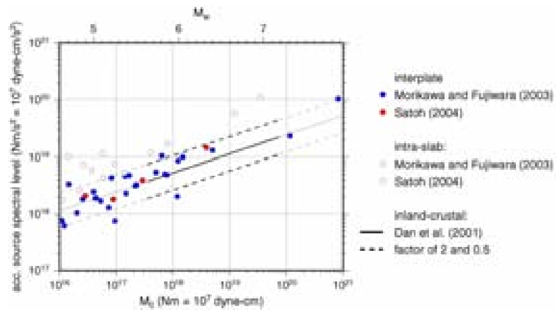

Fig. 2. Empirical relationship between seismic moment and acceleration source-spectral level.

Application to the Inland Crustal and Subduction-Zone Earthquakes

In Japan, the seismic hazard maps for future large earthquakes with high probability of occurrence potential are made following the idea of the recipe proposed here by two governmental organizations, the Earthquake Research Committee of the Head Quarter of Earthquake Research Center, and the Central Disaster Prevention Council of the Cabinet Office. Both organizations adopt characterized source model. The Earthquake Research Committee calculates ground motion by the hybrid method for inland crustal earthquakes and the stochastic Green's function method for subduction-zone earthquakes. The Central Disaster Prevention Council mainly calculates ground motions using the stochastic Green's function method. The reason why the stochastic Green's function method is used for the subduction-zone earthquakes owes lack of information of underground structures in wide areas from source to objective region.

We have confirmed that the ground motions calculated based on the characterized source models gave a good fit to those observed during the 1995 Kobe earthquake (e.g., Kamae and Irikura, 1998; Irikura *et al*., 2004), 1997 Kagoshima earthquake (e.g, Miyakoshi *et al*., 2000; Miyake *et al*., 2003), and the 2000 Tottori earthquake (e.g, Ikeda *et al*., 2000) as inland crustal earthquakes in the broadband period range.

Here we introduce one of examples of the seismic hazard maps for hypothetical median tectonic line (east segments) earthquakes by the Earthquake Research Committee (2005). Figure 3 shows the characterized source model for the median tectonic line. The both cases have two asperities with same location, and rupture propagates from west to east for case 1, and from east to west for case 2. The simulated PGV shown in Figure 4 is validated by the comparison of the empirical attenuation relationship for PGV by Si and Midorikawa (1999) (Figure 5). Even the both cases show similar attenuation curves, the simulated ground velocities at near-source station are quite different (Figure 6) due to the rupture directivity effect. This indicates significance of the ground motion simulation assuming the scenario earthquake.

Next example is ground motion validation for the 2003 Tokachi-oki earthquake by Earthquake Research Committee (2004). Figure 8 shows the characterized source model for 2003 the Tokachi-oki earthquake. The ground motions are simulated by the hybrid method. Matching filter for the hybrid method is adopted as 5 sec. The comparison of observed and simulated PGV shown in Figure 9 supports the applicability of the recipe for the subduction-zone earthquake. The spatial pattern between the observed and synthetic PGV shows good agreement (Figure 11).

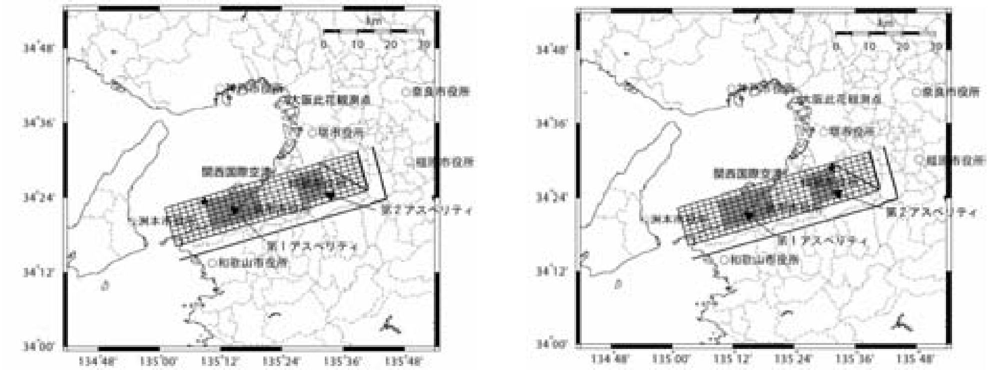

Figure 4. Characterized source model for scenario earthquake on the median tectonic line. Left and right panels show case 1 and 2, respectively (after Earthquake Research Committee, 2005).

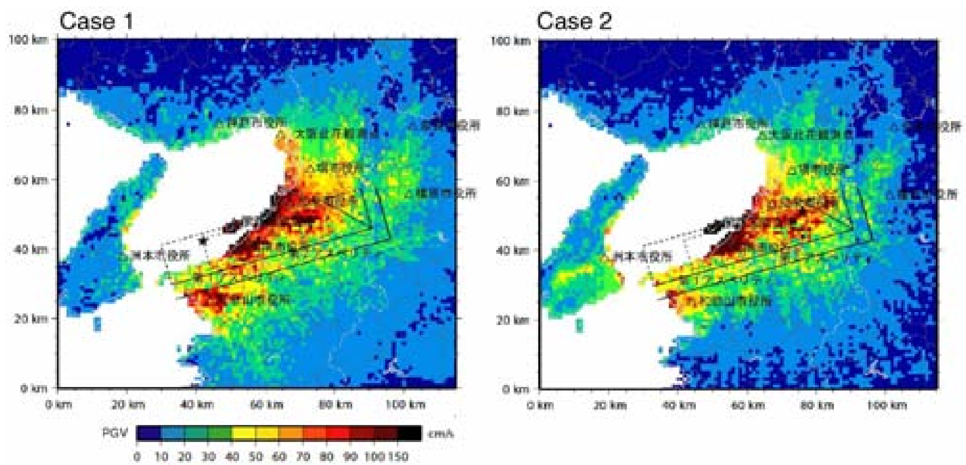

Figure 5. Simulated PGV for the case 1 and 2 (after Earthquake Research Committee, 2005).

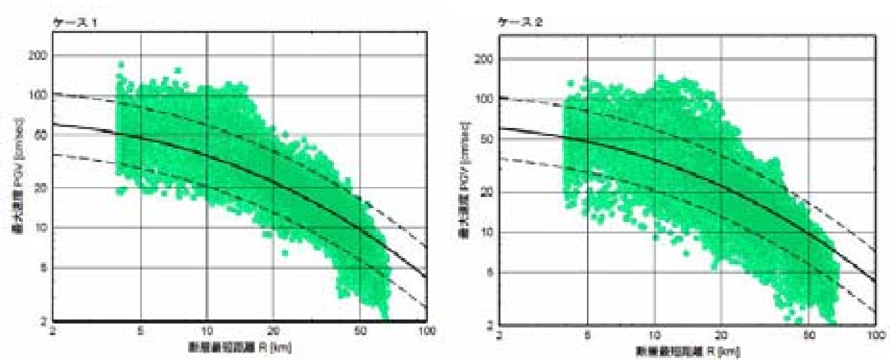

Figure 6. Comparison of the simulated PGV to the empirical attenuation relationship by Si and Midorikawa (1999). Left panel is for case 1 and right one for case 2 (after Earthquake Research Committee, 2005).

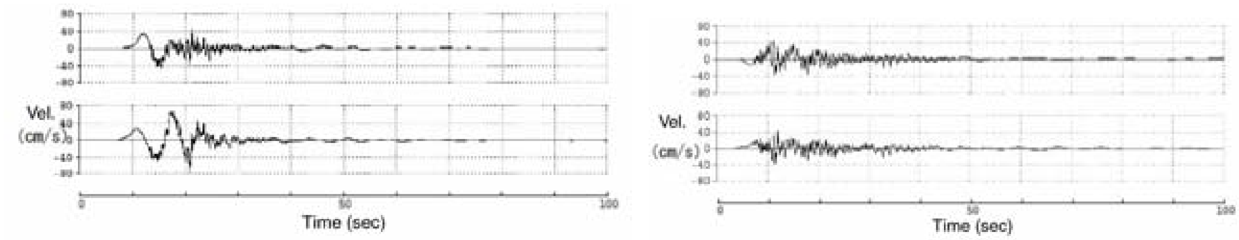

Figure 7. Simulated ground velocities at Izumi city hall for case 1 (left) and case 2 (right) (after Earthquake Research Committee, 2005).

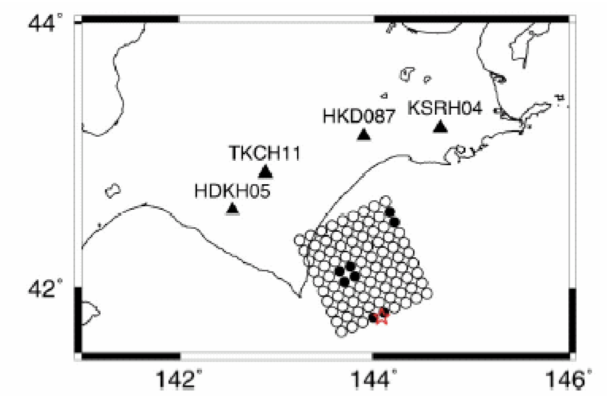

Figure 8. Characterized source model for the 2003 Tokachi-oki Earthquake (after Earthquake Research Committee, 2004).

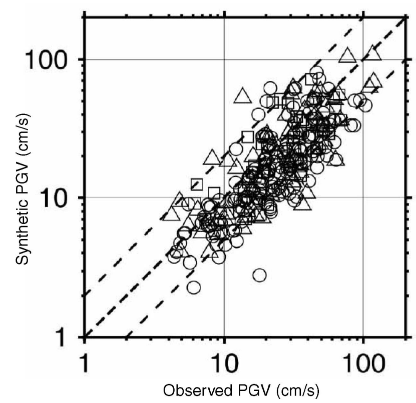

Figure 9. Observed and simulated PGV. (after Earthquake Research Committee, 2004).

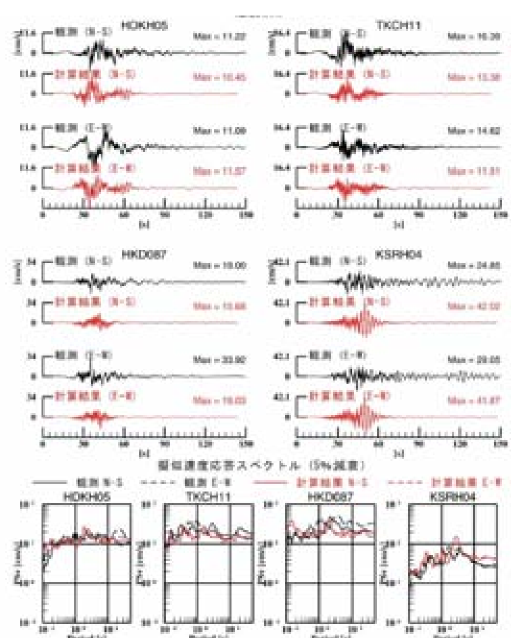

Figure 10. Ground motion time histories of observation (black) and synthetics (red). The lower panels display pseudo-velocity response spectra with 5% damping (after Earthquake Research Committee, 2004).

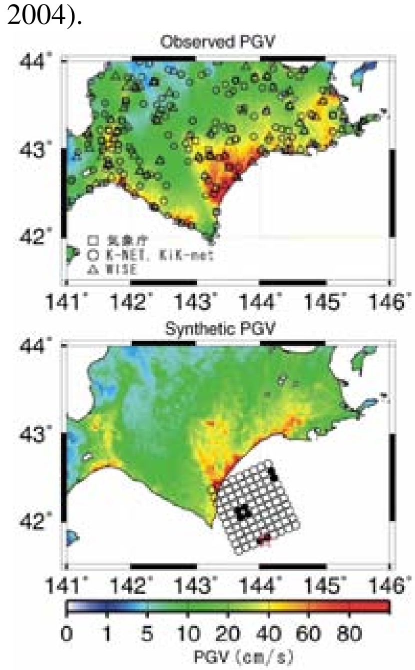

Figure 11. Spatial pattern of observed (upper) and synthetic (lower) PGVs. (after Earthquake Research Committee, 2004).

Conclusions

A recipe for estimating strong ground motions from specific earthquakes is proposed based on source characteristics from the waveform inversion using strong motion data. The characterized source model for predicting strong ground motions for future large earthquakes is constructed by two kinds of scaling relationships: one is M_0 versus entire source area for the outer fault parameters and the other is M_0 versus asperity areas. The most important parameters featuring strong ground motions are sizes of asperities and effective stress on each asperity, which characterizes the amplitudes and periods of directivity pulses causing earthquake damage.

The recipe proposed here is applied for the deterministic seismic hazard maps in Japan for specified seismic source faults with high probability of occurrence potential. The applicability of our idea for hypothetical median tectonic line earthquakes as an example of the inland crustal earthquake is validated by the comparison of the empirical attenuation relationship for PGV by Si and Midorikawa (1999). The validity of our methodology is examined for the 2003 Tokachi-oki earthquake as a example of subduction-zone earthquake, showing a good agreement in spatial pattern of PGV as well as waveform between the observed and synthetics, because this earthquake provided us wonderful records obtained in dense strong-motion network.

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