VALIDITY OF STRONG MOTION PREDICTION RECIPE FOR INLAND-CRUST EARTHQUAKES

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ABSTRACT :

Ground motions from inland-crust earthquakes are simulated using a characterized source model with asperities in an entire rupture area. The characterized model is constructed based on the "recipe" we proposed. Validity and applicability of the "recipe" has been examined by comparing observed ground motions with synthesized ones for recent disastrous earthquakes. We show a case of the 2007 Chuetsu-oki (Mw 6.6) as one of examples. This earthquake occurred very close to the Kasiwazaki-Kariwa Nuclear Power Plant. Ground motions from this earthquake are well simulated based on the characterized source model. We find the "recipe" is useful for predicting design ground motions for earthquake safety designs as long as the source fault is specified through investigation of active folds and faults and the fault parameters are given considering regional characteristics.

KEYWORDS: Strong motion prediction, recipe, characterized source model, outer fault parameters, inner fault parameters, the 2007 Niigata-ken Chuetsu-oki earthquake

1. INTRODUCTION

Ground motions from earthquakes are deterministically estimated, based on fault modeling. A recipe of making fault models for the prediction of strong ground motion are proposed combining the active fault information with scaling relations of fault parameters from the waveform inversion of source processes using strong motion data. We outline the methodology of making the characterized source model for strong motion prediction, which is called the "recipe". Then, we examine validity and applicability of the "recipe" for recent disastrous earthquakes. We show results of estimating strong ground motions for the 2007 Chuetsu-oki (Mw 6.6) that happened very close to the Kasiwazaki-Kariwa Nuclear Power Plant as one of examples. It is very important to make clear whether ground motions are predictable based on detailed surveys of active faults for earthquake safety design of nuclear power plants.

2. OUTLINE OF STRONG MOTION PREDICTION

2.1. Scaling Relationships of Fault Parameters

One of the most important ideas for strong motion prediction is that fault parameters are given from the scaling relationships. The conventional scaling relations of fault parameters such as rupture area and average slip on fault with seismic moment are mostly determined geologically from surface offsets and geophysically from forward source modeling using teleseismic data and geodetic data (e.g. Kanamori and Anderson 1975). Those fault parameters are only available for simulating very long period motions, but not for near-source strong motions dominating short period motions of less than 1 sec of engineering interest.

We found new scaling relations of areas and slips of asperities with respect to total seismic moments from the results of the waveform inversion using strong motion data (Somerville et al, 1999). Therefore, there are two kinds of the scaling relationships for the fault parameters. One is the conventional scaling relations such as rupture area versus seismic moment and fault slip versus seismic moment. The other is the new ones such as asperity area versus seismic moment and asperity slip versus seismic moment. Based on the two kinds of scaling relationships mentioned above, the source model for predicting strong ground motions is characterized by the outer, inner, and extra fault parameters.

The scaling for the outer fault parameters, i.e. relationship between seismic moment and rupture area, for inland crustal-earthquakes are summarized as shown in Fig. 1 (Irikura et al., 2004). For earthquakes with relatively small seismic moment less than 10^{19} Nm, the total fault area S seems to follow the self-similar scaling relation with constant static stress drop in proportion to the two-thirds power of seismic moment Mo. For large earthquakes more than 10^{19} Nm, the scaling tends to depart from self-similar model (Irikura and Miyake 2001) corresponding to the saturation of fault width due to the seismogenic zone size. Further, one more stage should be added for extremely large earthquakes more than 10^{21} Nm from the idea of Scholtz (2002) as changing from L-model into W-model. The scaling relationships in this study as shown by broken lines in Fig. 1 are drawn assuming the fault width saturates with about 20 km long.

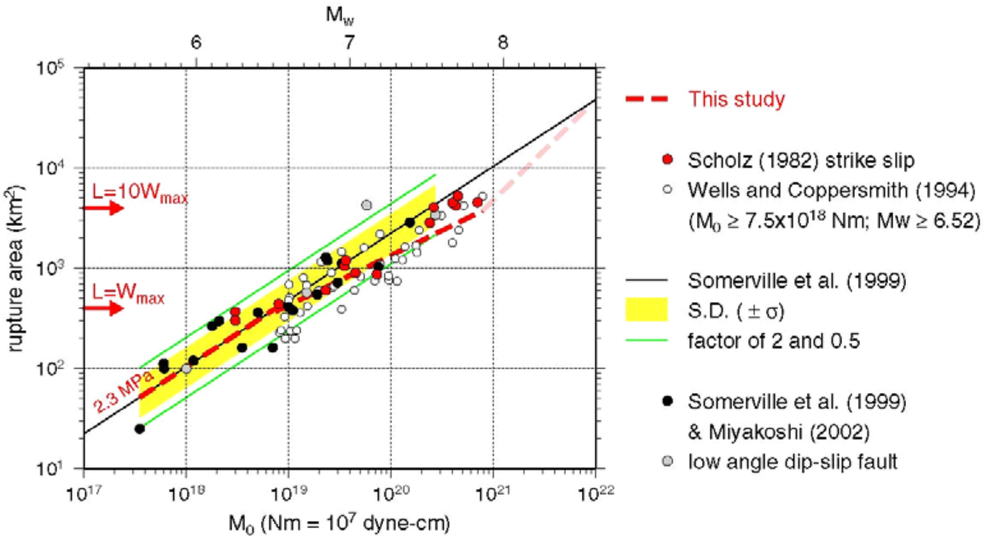

Figure 1 Empirical relationships between seismic moment and rupture area for inland crustal-earthquakes (Irikura and Miyake, 2001).

The inner fault parameters are introduced in this study as the area and stress drop of asperities that define slip heterogeneity inside the source fault, having much more influence on strong ground motions than the outer fault parameters. The relationships between rupture area S as the outer fault parameter and combined area of asperities S_a as the inner fault parameter are shown in Fig. 2 (Irikura et al., 2004). The ratio S_a/S seems to be almost constant regardless of the rupture area, about 0.22 for the inland earthquake. Then, stress drop on the asperities $\Delta\sigma_a$ is derived as a product of the average stress drop over the fault $\Delta\bar{\sigma}_c$ and the ratio of asperity area S_a to total rupture area S (e.g., Madariaga 1979).

$$\Delta\sigma_a = \Delta\bar{\sigma}_c \cdot S/S_a \quad (1)$$

Another empirical-relationship between seismic moment Mo and flat level of acceleration source spectrum A_o related to the inner source parameters is shown in Fig. 3, initially found by Dan et al. (2001).

$$A_0 = 2.46 \cdot 10^{17} \cdot (M_0 \cdot 10^7)^{1/3} \quad (2)$$

where the unit of M_0 is $N \cdot m$. The acceleration level A_0^a generated from the asperities is theoretically proportional to the square root of the product of the asperity area S_a and asperity stress drop $\Delta\sigma_a$ by Madariaga (1977).

$$A_0^a = 4\sqrt{\pi}\beta v_r \Delta\sigma_a \sqrt{S_a} \quad (3)$$

where β and v_r are S wave velocity of the media and rupture velocity. A_0^a in (3) is approximately replaced by the acceleration level A_0 in (2) because short-period motions are mostly generated from the asperities.

Then, S_a is estimated as follows:

$$S_a = \left(\frac{7\pi^2}{4} \beta v_r \right)^2 \cdot \frac{(M_0)^2}{S \cdot (A_0)^2} \tag{4}$$

In this case, the stress drop of the asperities $\Delta\sigma_a$ is also given as a product of $\Delta\bar{\sigma}_c$ and S/S_a using (1).

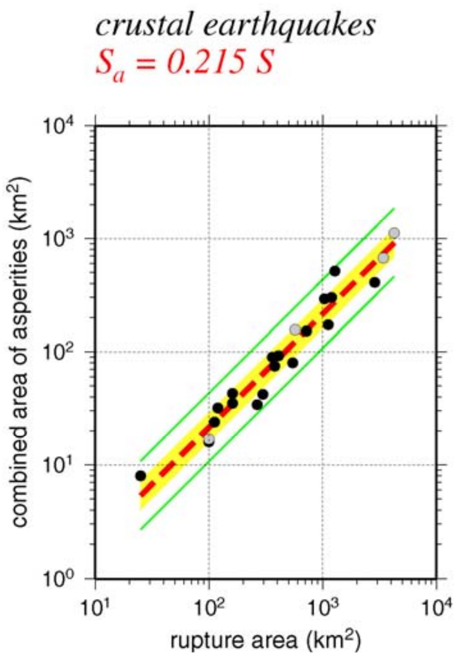

Figure 2 Empirical relationships between combined area of asperities and total rupture area (thick broken line) for inland crustal earthquakes (Irikura and Miyake, 2001). Shadow ranges (standard deviation). Thin solid lines show a factor of 2 and 1/2 for the average. Database obtained by the waveform inversions for the inland crustal earthquakes is Somerville et al. (1999) and Miyakoshi (2002)

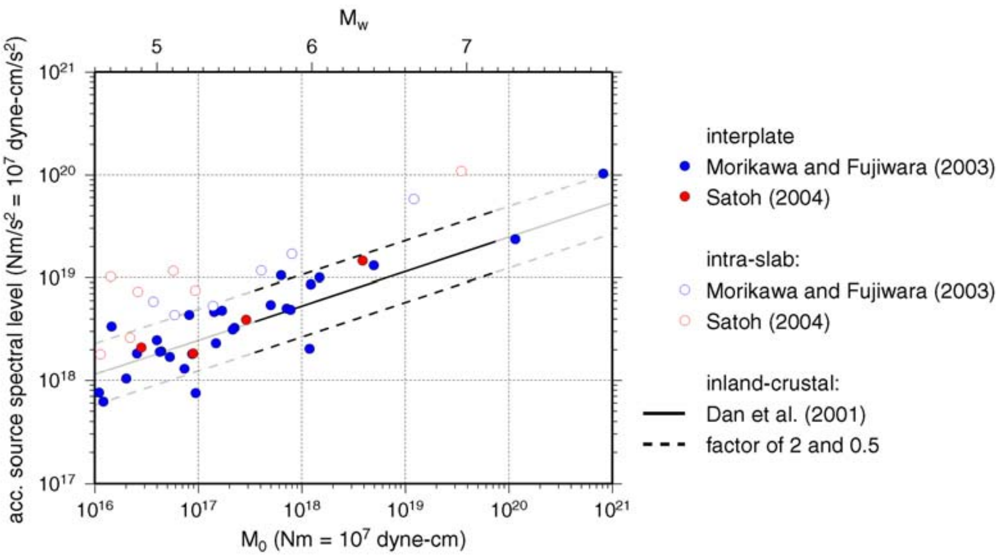

Figure 3 Empirical relationship between seismic moment and acceleration source spectral level for inland crustal earthquakes.

2.2. Recipe for Source Modeling

Strong motions for large earthquakes are simulated, based on the characterized source model defined by three kinds of parameters, outer, inner, and extra fault parameters. We developed a "recipe" for predicting strong ground motions (Irikura and Miyake 2001) to define those fault parameters of source modeling for future large earthquakes.

The source model is constructed by the following procedure. First, the outer fault parameters are given as follows. Step 1: Fault Length (L) is given from geo-morphological and geological survey of active faults, Fault Width (W) is estimated from of thickness of seismogenic zone and dip angle of the faults, and then Total Rupture Area ($S = LW$) is evaluated. Step 2: Total Seismic Moment (M_0) is given from the empirical scaling relation, M_0 versus S. Step 3: Average Stress Drop ($\Delta\bar{\sigma}_c$) on the source fault is estimated from the theoretical equation for circular crack model by Eshelby (1957) at the first stage of Fig. 1 (Mo < 10^{19} Nm), from the equation derived by Fujii and Matsu'ura (2000) at the second stage and the Knopoff's equation (1958) for strike slip fault with infinite length and the Starr's equation (1928) for dip slip fault with infinite length at the third stage, respectively.

Next, the inner fault parameters are given to characterize stress heterogeneity inside the fault area. Step 4: Combined Area of Asperities (S_a) is estimated from the acceleration source spectral level based on the empirical relation such as (2) or observed records. Step 5: Stress Drop on Asperities ($\Delta\sigma_a$) is derived as a product of $\Delta\bar{\sigma}_c$ as the outer fault parameter and S_a/S from Step 4. Step 6: Number of Asperities (N) is related to the segmentation of the active faults, e.g. two per a segment. Step 7: Average Slip on Asperities (D_a) is given as $2.0 \cdot D$ based on the empirical relationship by Somerville et al. (1999). Step 8: Effective Stress on Asperity (σ_a) is considered to be identical to stress drop on asperity $\Delta\sigma_\alpha$. Effective stress of background slip areas (σ_β) is given to coincide with the average stress drop ($\Delta\bar{\sigma}_c$) over the entire rupture area. Step 9: Parameterization of Slip-Velocity Time Functions is given to be the Kostrov-like slip-velocity time functions as a function of peak slip-velocity and rise time based on the results of dynamic simulation by Day (1982). The peak slip-velocity is given as a function of effective stress, rupture velocity and f_{max}.

Finally, the extra fault parameters are the rupture starting point and rupture velocity to characterize the rupture propagating pattern in the fault plane. For inland crustal earthquakes, rupture nucleation and termination are related to geomorphology of active faults (e.g., Nakata et al. 1998).

Strong motions for large earthquakes are simulated using the characterized source models defined by the "recipe". Detailed examination for strong motion prediction has been made, comparing simulated ground motions with observed ones for recent disastrous earthquakes (e.g. Irikura et al., 2004).

3. Ground Motions for the 2007 Niigata-ken Chuetsu-oki Earthquake (Mw=6.6)

This earthquake occurred on July 16, 2007, northwest off Kashiwazaki in Niigata Prefecture, Japan, causing severe damage such as ten people dead, about 1300 injured, about 1000 collapsed houses and major lifelines suspended for more than a day in the near-source region. In particular, strong ground motions from the earthquake struck the Kashiwazaki-Kariwa nuclear power plant (hereafter KKNPP), triggering a fire at an electric transformer and other problems such as leakage of water containing radioactive materials into air and the sea, although the radioactivity levels of the releases were as low as those of the radiation of the natural environment in a year.

The source mechanism of this earthquake has been identified to be a reverse fault with the SW-NE strike and SE dip from the aftershock distribution re-determined using the OBS seismometers (ERI, Univ. of Tokyo 2008) as shown in Fig. 4. Results of the rupture processes inverted by using strong motion data also show the source fault with the SW-NE strike and SE dip that gives slip distribution to match well observed data (e.g. Horikawa, 2007). PGA's at the KKNPP are considerably larger than the empirical attenuation-distance relationships in

Japan obtained by Si and Midorikawa (1999) as shown in Fig. 5. The surface motions there had the PGA of more than 1200 gals and even underground motions on one of the base-mats of the reactors locating five stories below the ground had the PGS of 680 gals.

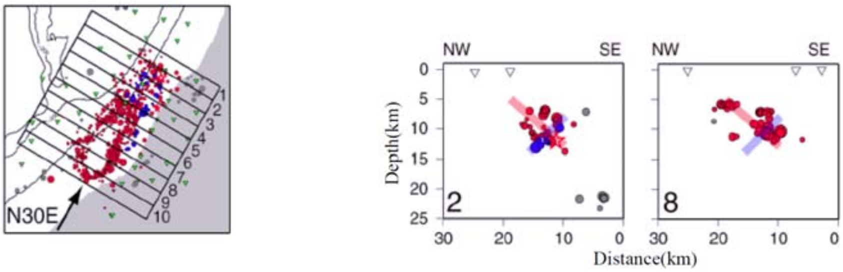

Figure 4 Aftershock distributions in the horizontal plane (left) and cross section perpendicular to the strike (right) using the OBS seismometers (ERI, Univ. of Tokyo,2008).

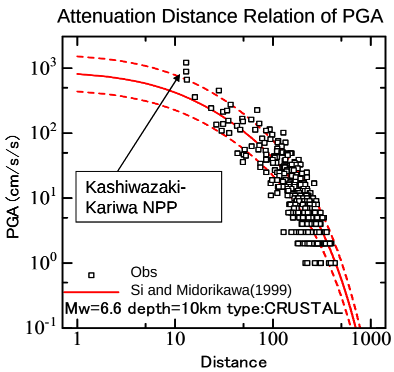

Figure 5 Relationship of observed peak horizontal ground accelerations versus shortest distances to source fault. Red solid and dotted curves show the empirical PGA attenuation distance relationship for surface data by Si and Midorikawa (1999) and its standard deviation

The strong motion records obtained at stations close to the mainshock had two or three distinctive pulses. In particular, the records on the base-mats of the Nuclear Reactors of the KKNPP site show three significant pulses. We estimated the locations of asperities using time differences between those pulses at several near-source stations. We found that three asperities are located southwest and south-southwest of the hypocenter in Fig. 6. In this study, we called those asperities to be ASP1, ASP2 and ASP3. We chose appropriate records of aftershocks used as the empirical Green's function, taking into account locations and fault mechanisms of the aftershocks. As a result, we adopted the record of Aftershock 1 on July 16 at 21:08 for ASP 1 and ASP2, and Aftershock 2 on August 4 at 0:16 for ASP3.

We obtained the best-fit model by the forward modeling to minimize the residuals between the observed and synthesized motions. The combined areas of those three asperities were about 30 km^2. The stress drop is about 24 MPa for ASP1 and ASP2 and about 20 for ASP3. The synthesized motions at KKZ1R2, KKZ5R2, NIG005 and NIG018 are compared with the observed ones in Fig. 7. The synthesized waveforms agree with the observed ones fairly well. In particular, three pulses appearing in the observed records at KKZ1R2 and KKZ5R2 located at B5F in underground of Unit 1 and Unit 5, respectively, are well reproduced in the synthesized velocity and displacement.

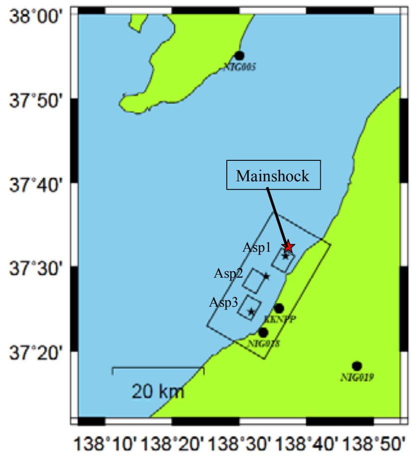

Figure 6 Map showing source model (rectangular) consisting of three asperities (Asp1, Asp2 and Asp3) in this study and the locations of K-net stations and KKNPP (circle) and the epicenter of the mainshock (red star).

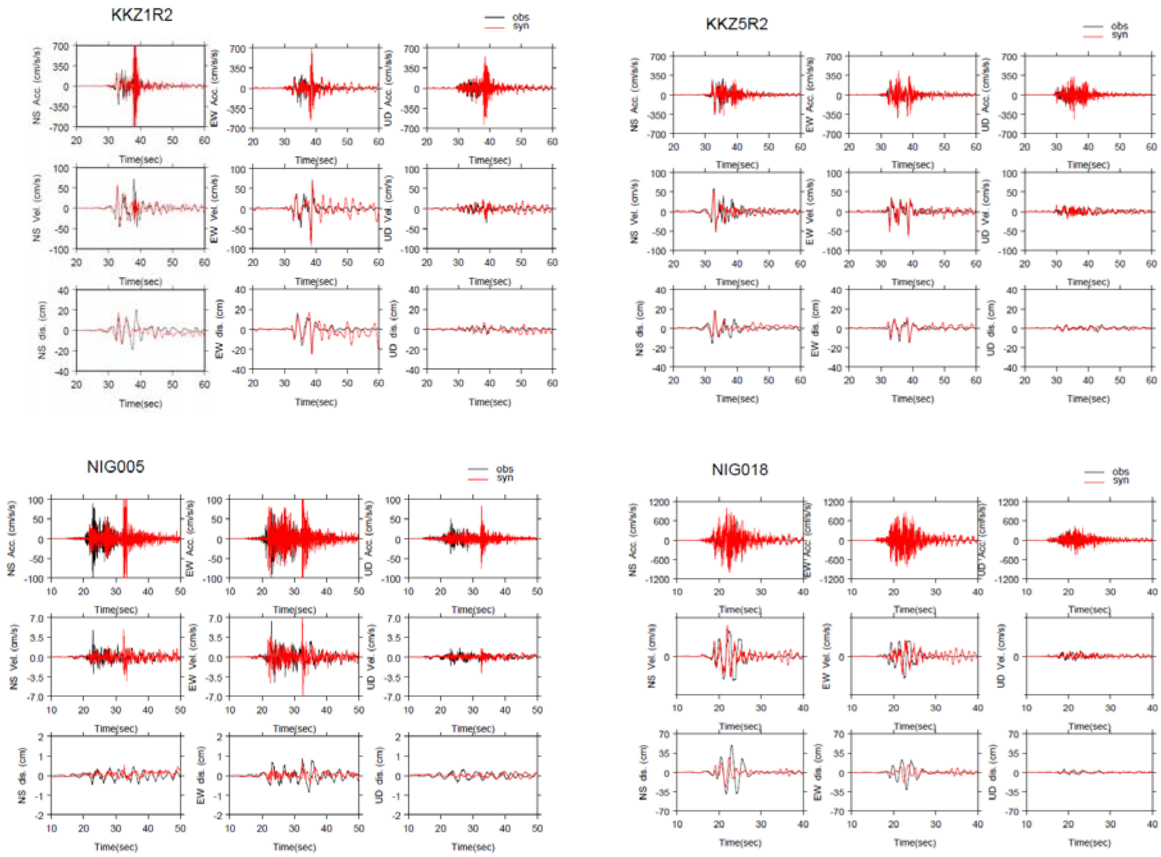

Figure 7 Comparison between the observed records (black) and synthesized motions (red). Acceleration (top), velocity (middle) and displacement (bottom) are shown at KKZ1R2 , KKZ5R2, NIG005 and NIG018.

4. Application of the "Recipe" for the 2007 Niigata-ken Chubu Earthquake (Mw=6.6)

Here we apply the "recipe" to the estimation of strong ground motions from the 2007 Niigata-ken Chubu earthquake. Fault length L and width W as the outer fault parameters are given at 26 km and 22 km, respectively, based on the investigation of the active fault (Sugiyama, 2008) and the hypocenter distribution (Earthquake Research Institute, 2008) in and around the source region of this earthquake. Seismic moment is given from the scaling of the outer fault parameters. The areas and stress drop of the asperities as the inner fault parameters are given using the empirical relation, acceleration level versus seismic moment by Dan et al. (2001), following the "recipe" by the Earthquake Research Committee in Japan (2007).

Then, the characterized source model with two asperities with large and small areas inside the rupture area is made. The area of the large asperity has twice as large as that of the small one. The locations of those two asperities are located as shown in Fig. 8. We call this model to be Model 1. Synthesized motions are calculated using the empirical Green's function method (Irikura, 1986). Synthesized velocity waveforms at KSHSG4 (-250 m deep at Service Hole of the Kashiwazaki-Kariwa Power Plant) and NIG019 (surface) for Model 1 are shown by green lines in the middle of Fig. 9. The synthesized motions are clearly underestimated compared with the observed ones.

We make a revised source model called Model 2 with 1.5 times stress drop of the asperities, keeping the asperity areas constant. Another modification is that the starting point of Asp2 is located at the center of the asperity, learning from the best-fit model of the earthquake.

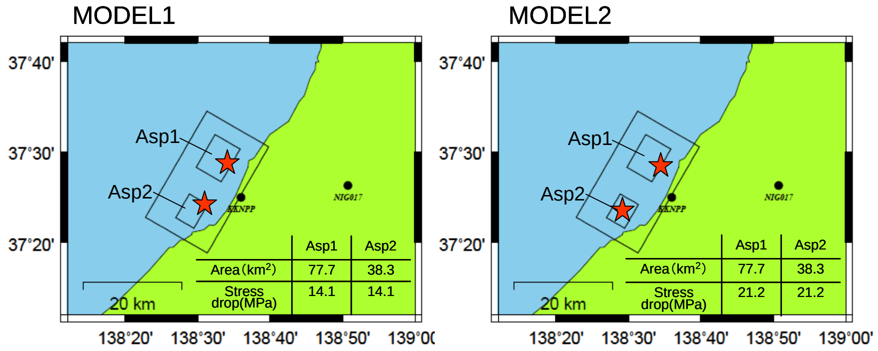

Figure 8 Map showing the analyzed two models and location of stations used for analysis. The MODEL1 was set by Recipe for predicting strong ground motion. The MODEL2 is different from the stress drop and the rupture of the MODEL1. The star in the map are shown the rupture start point each asperities.

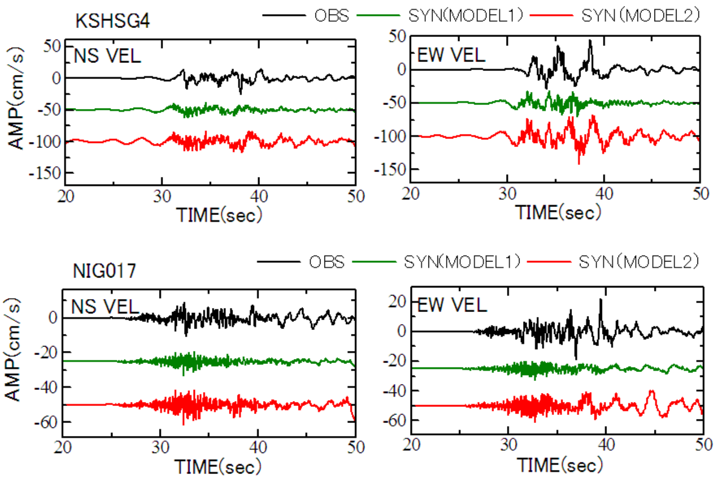

Figure 9 Comparison between the synthesized motions by MODEL1(green) and MODEL 2(red) and observed motions(black) at KSHSG4 and NIG017.

We find that the synthesized motions for Model 2 have almost the same level as the observed ones as shown by red lines in the bottom of Fig. 9. This means that the "recipe" should be modified, considering regional characteristics of the fault parameters such as stress drop and rupture starting point of each asperity to make more reliable evaluation of ground motions.

5. Conclusion

We have developed a "recipe" for predicting strong ground motions based on two kinds of scaling relationships for outer fault parameters such as fault area and seismic moment and inner fault parameters such as areas and stress drop of asperities. Ground motions from earthquakes are evaluated using the characterized source model based on the "recipe". Verification and applicability of the characterized source model and the "recipe" have been examined by comparing observed ground motions with synthesized ones for recent disastrous earthquakes. We show a case of the 2007 Chuetsu-oki (Mw 6.6) as one of examples. Ground motions from the 2007 Chuetsu-oki earthquake are well simulated using the characterized source model as long as the source fault is correctly specified through investigation of active folds and faults. However, the ground motions synthesized using the fault parameters based on the original "recipe" are clearly underestimated. Stress drop and rupture starting point of each asperity have to be modified considering regional characteristics of the fault parameters. The stress drop of the asperities is assumed to be 1.5 times as high as that from the "recipe" and the rupture starting point is not the edge of the asperity but located at the center to get almost the same level of synthesized ground motions as observed records. Further improvements of the "recipe" are required considering regional characteristics of the outer, inner, and extra fault parameters to make more reliable evaluation of ground motions for earthquake safety designs.

Acknowledgements:
We appreciate National Research Institute for Earth Science and Disaster Prevention (NIED) for providing the K-NET, KiK-net and F-net data. We also thank to Tokyo Electric Power Company (TEPCO) for providing strong ground motion data at the Kashiwazaki-Kariwa Nuclear Power Plant.

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