SOURCE MODELING OF RECENT LARGE INLAND CRUSTAL EARTHQUAKES IN JAPAN AND SOURCE CHARACTERIZATION FOR STRONG MOTION PREDICTION

Kimiyuki Asano[1] **and Tomotaka Iwata**[2]

[1] *Assistant Professor, Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto, Japan*
[2] *Professor, Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto, Japan*
Email: k-asano@egmdpri01.dpri.kyoto-u.ac.jp

ABSTRACT :

Dense strong motion observation networks provided us valuable data for studying strong motion generation from large earthquakes. In recent years, several large earthquakes occurred in Japan, and a large amount of strong motion data is recorded. It is important for advancement of source modeling in scenario-based strong motion prediction to quantify detailed source characteristics of past earthquakes. We have estimated the source rupture process of these earthquakes by the kinematic waveform inversion using strong motion data. The asperity, where slip is relatively large compared to average slip over the fault, is quantified following the criteria proposed by Somerville *et al.* (1999). The stress changes during these earthquakes are cestimated from the detailed slip distributions obtained by the kinematic waveform inversion. The stress drops on and off asperities are characterized based on the stress change distributions obtained here. The stress drop on asperity is one of key parameters in source modeling, because stress drop is related to slip velocity of the source fault and associated ground motion. We compiled the stress drop on the asperities together with data set of previous studies for other inland earthquakes in Japan and others. The static stress drop on asperity depends on its depth, and we obtained an empirical relationship between static stress drop and asperity's depth. Moreover, surface breaking asperities appeared to have smaller stress drop than buried asperities.

KEYWORDS: source modeling, inland crustal earthquake, asperity, stress drop, waveform inversion

1. INTRODUCTION

The strong ground motion data from dense strong motion seismograph networks enable us to analyze the detailed source rupture process of large earthquakes, which caused earthquake disasters related to ground motions. From the results of kinematic waveform inversions, the slip distribution on the source fault of a large earthquake is known to be spatially heterogeneous. Miyake *et al.* (2003) found that the strong motion generation area, which is defined as a high slip velocity or a high stress drop area on the source fault, spatially coincides with the asperity or the large slip area of the heterogeneous slip model based on broadband strong motion simulations. Since heterogeneity in the slip and stress drop distributions controls near-source ground motions, it is important to characterize those heterogeneity in constructing a source model for reliable strong ground motion prediction.

As for spatial slip heterogeneity, Somerville *et al.* (1999) have proposed a criterion to extract asperities from the heterogeneous slip models. In their criterion, an asperity is defined as a rectangular area whose slip is 1.5 or more times larger than the average slip over the fault. According to the extraction of asperities from heterogeneous slip models, Somerville *et al.* (1999) obtained the empirical scaling relationships not only for the whole rupture area but also asperity area with respect to the seismic moment. The scaling relationships proposed by Somerville *et al.* (1999) are now widely used in strong motion prediction (e.g., Irikura and Miyake, 2006).

For spatial heterogeneity in stress drop distribution, direct estimation by calculating dynamic stress histories from spatiotemporal rupture histories are discussed in seismology (e.g., Day et al., 1998). For strong motion prediction, stress drop estimation which is calculated based on the theoretical asperity model (Das and Kostrov,

1986) is usually used to set a model (e.g., Irikura and Miyake, 2006). In order to incorporate physical information obtained from detailed source slip and stress change images into information for source modeling in practical strong motion prediction, characterization of source parameters related to asperity should be investigated.

In this paper, source models for recent large inland earthquakes are shown. These source models are estimated by using strong ground motion data. Firstly, characterization of slip distribution is studied. Then, static stress change of each earthquake is obtained, and overall characteristics of stress drop on asperities are discussed.

2. SOURCE MODELS

Here, source models of four earthquakes, which recently occurred in Japan, are studied (Figure 1 and Table 1). The source models of these events are obtained from near-source strong motion data by the kinematic waveform inversion (Hartzell and Heaton, 1983). Frequency range of strong motion data used in the waveform inversion is 0.05-1 Hz. In order to obtain the detailed slip distribution, the velocity structure models for calculating Green's functions are carefully modeled based on the optimization using Genetic Algorithms and the waveform modeling of aftershock records (e.g., Asano and Iwata, 2008a). Moreover, the sufficiently large number of strong motion stations is used to obtain a stable solution. Asperity areas of these events are identified following the procedure by Somerville *et al.* (1999).

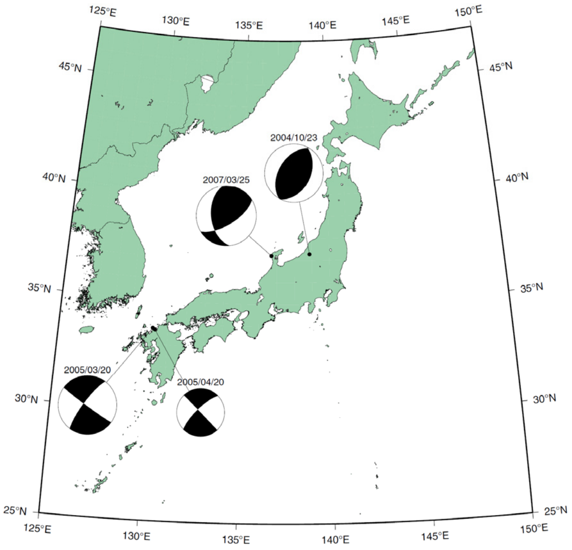

Figure 1 Epicenter and focal mechanism of earthquakes presented in this paper

Table 1 List of earthquakes studied

Earthquake	Date (JST)	M_W	Fault Type	Lat. (deg.)	Long. (deg.)	Depth (km)
(a) 2004 Chuetsu, mid Niigata prefecture	2004/10/23 1756	6.6	thrust	37.307N	138.839E	10.6
(b) 2005 West off Fukuoka prefecture	2005/3/20 1053	6.6	strike-slip	33.748N	130.165E	14.1
(c) Largest aftershock of the 2005 West off Fukuoka prefecture earthquake	2005/4/20 0611	5.6	strike-slip	33.673N	130.287E	12.9
(d) 2007 Noto Hanto	2007/3/25 0942	6.7	Oblique-slip	37.221N	136.686E	10.7

Figure 2 shows the slip models of four earthquakes studied. The 2004 Chuetsu, mid Niigata prefecture, earthquake (event (a)) is a thrust-type earthquake in an active folding mountains area, where lateral compressive strain is accumulated (Niigata-Kobe Tectonic Zone). It brought extreme ground motion to the near-source region (e.g. Mori and Somerville, 2006). This earthquake has large slip in the vicinity of the hypocenter (Asano and Iwata, 2008a). The 2005 West off Fukuoka earthquake (event (b)) is a left-lateral strike slip event in southwest Japan. The rupture mainly propagated to the southeastward. The asperity is found at southeast of the hypocenter (Asano and Iwata, 2006). Its largest aftershock (event (c)), which occurred one month after the mainshock, is also a left-lateral strike event. Source model of this event is rather simple compared to the mainshock (Asano and Iwata, 2006). The 2007 Noto Hanto earthquake (event (d)) is a thrust-type event including right-lateral strike slip component, which occurred at the western coast of the Noto peninsula. The asperity of this event is observed close to the hypocenter, and the rupture propagated upward along the dip direction. Rake angle changes from dip-slip to strike-slip during the rupture propagation (Asano and Iwata, 2007).

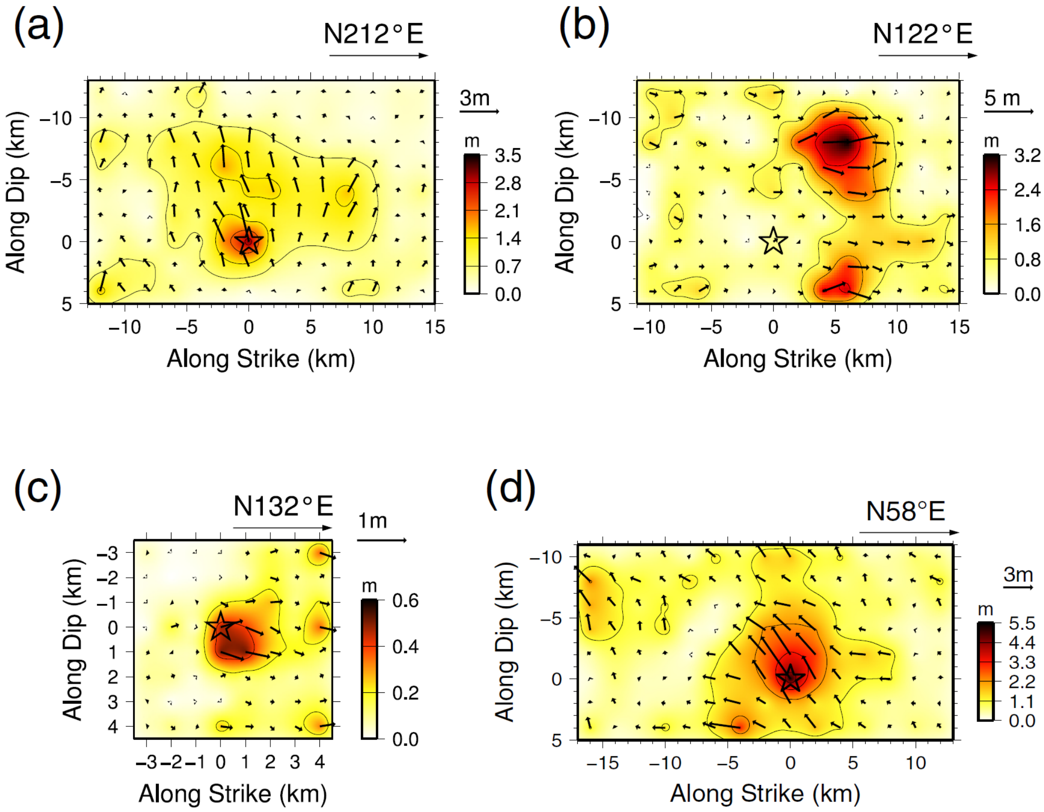

Figure 2 Slip distribution of each source model in Table 1

The relationship between combined area of asperities and seismic moment is shown in Figure 3. The combined area of asperities of these four earthquakes is compared with previous inland crustal earthquakes (Somerville et al., 1999; Miyakoshi et al., 2000) and intraslab earthquakes (Asano and Iwata, 2008b). The empirical scaling relationships for inland crustal earthquakes by Somerville et al. (1999) and for subducting plate-boundary earthquakes by Miyake et al. (2006) are also shown in Figure 3. The asperity size of these four recent earthquakes in Japan is plotted within the deviation of empirical scaling relationship. Intraslab events compiled by Asano and Iwata (2008b) have clearly smaller asperities compared to shallow crustal events with same seismic moment.

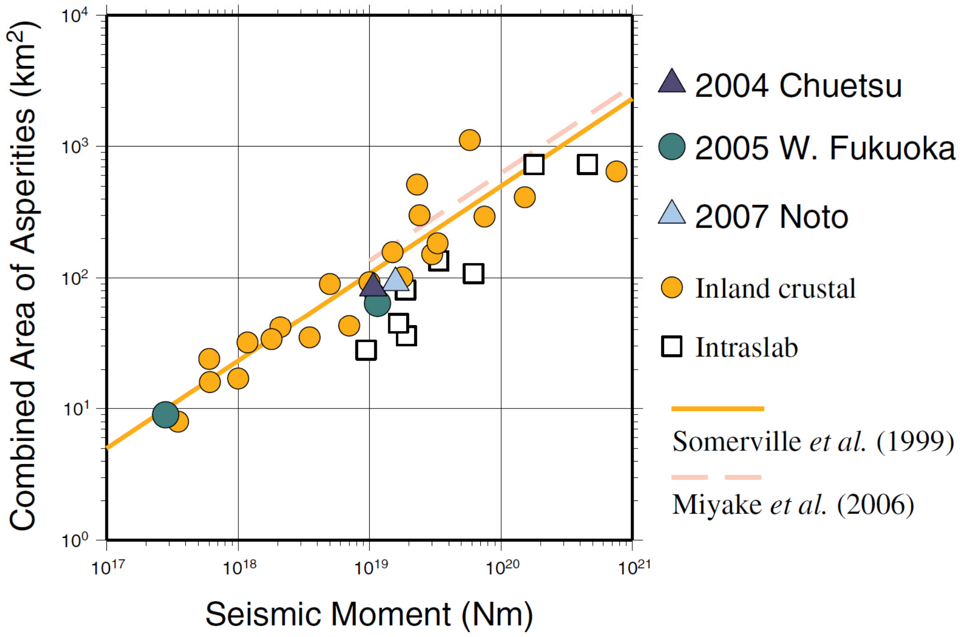

Figure 3 Relationship between combined area of asperities and seismic moment

3. STRESS DROP ON AND OFF ASPERITIES

Characterization of static stress drop distributions of inland crustal earthquakes is studied towards the advanced source modeling for strong motion prediction. Firstly, the spatial static stress change distributions of four earthquakes shown above are estimated. By including the results for five other earthquakes investigated by Iwata *et al.* (2005), the overall nature of static stress drop on asperities and its dependency on other tectonic factors (e.g., asperity depth and fault type) are discussed with respect to their potential incorporation into source modeling for strong motion prediction.

3.1. Method for Estimating Static Stress Drop On and Off Asperities

The static stress change due to an individual earthquake is estimated directly from the slip distribution. Ripperger and Mai (2004) developed a methodology to calculate static stress changes on a planar fault, based on wavenumber representation relating the static slip to the associate stress changes. The final slips at each grid point of the source model obtained by the waveform inversion are interpolated following Ripperger and Mai (2004), and its Fourier transform is taken into the wavenumber domain. The static stress change is calculated in the wavenumber domain. Finally, the spatial distribution of the static stress change is obtained by taking its inverse Fourier transform back into the space domain.

3.2 Results

Static stress drop distributions obtained in this study is shown in Figure 4. The average stress drop on and off asperity are summarized in Table 2. The average static stress drop on the asperity was estimated by averaging static stress drops of subfaults in each asperity. The average values of stress drop on asperity of these earthquakes are 7-24 MPa. The stress drop off asperities is less than 3 MPa. These values are similar to the estimation for other inland crustal earthquakes by Iwata *et al.* (2005).

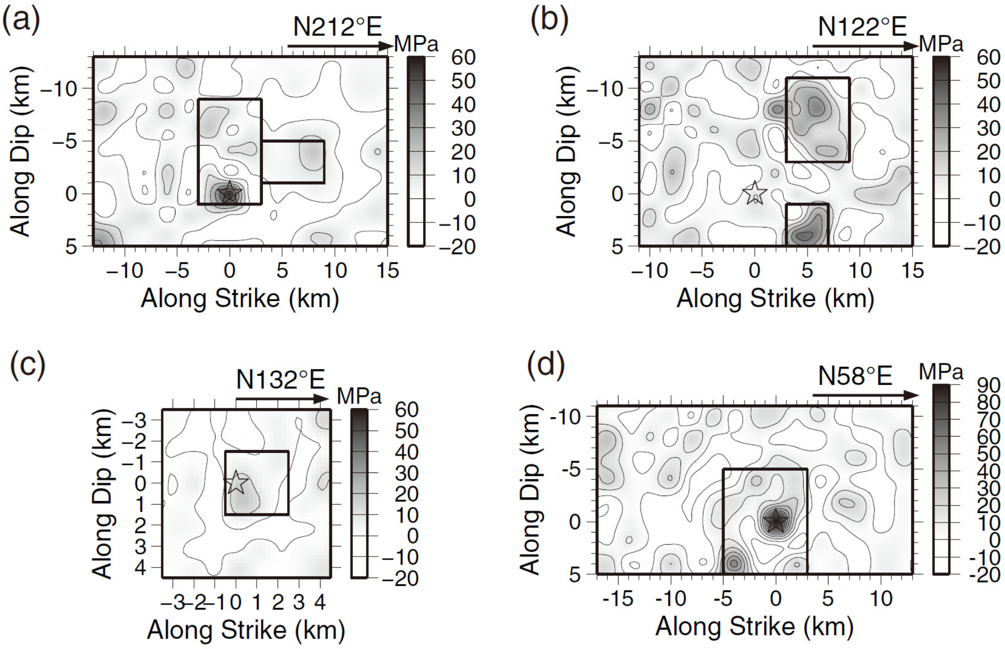

Figure 4 Static stress drop distributions obtained in this study

Table 2 Stress drop on and off asperity

Earthquake	Stress drop on asperity (MPa)		Stress drop off asperity (MPa)
(a) 2004 Chuetsu, mid Niigata prefecture	#1	7.8	1.3
	#2	7.5	
(b) 2005 West off Fukuoka prefecture	#1	15.0	2.3
	#2	24.3	
(c) Largest aftershock of the 2005 West off Fukuoka prefecture earthquake		7.2	1.1
(d) 2007 Noto Hanto		12.3	2.6

4. DISCUSSIONS

In order to see the depth dependency of stress drop on asperities, average stress drop of each asperity is plotted against its central depth in Figure 5. The result for five other inland crustal earthquakes (the 1995 Kobe, the 1997 Kagoshima, the 1999 Chi-Chi, the 1999 Kocaeli, and the 2000 Tottori) analyzed by Iwata *et al.* (2005) are plotted in the same figure. In total, 27 asperities of 9 events are shown. An empirical relationship between static stress drop on asperity ($\Delta\sigma$) and its depth (h) is estimated by the regression using this data set. The stress drop $\Delta\sigma$ is modeled as a linear function of h, $\Delta\sigma = a_0 h + a_1$, for all asperities,

$$\Delta\sigma = 0.92h + 5.3. \tag{4.1}$$

The unit of $\Delta\sigma$ and h is MPa and km, respectively. This equation is shown in Figure 5b. The standard error of the equation (1) is 6.6 MPa. The standard error of the coefficient a_0 and a_1 is 0.22 MPa/km and 2.5 MPa, respectively. Generally, the shear-strength of the lithosphere increase with depth (Scholz, 1990). Therefore, the depth dependency of static stress drop on asperity is reasonable.

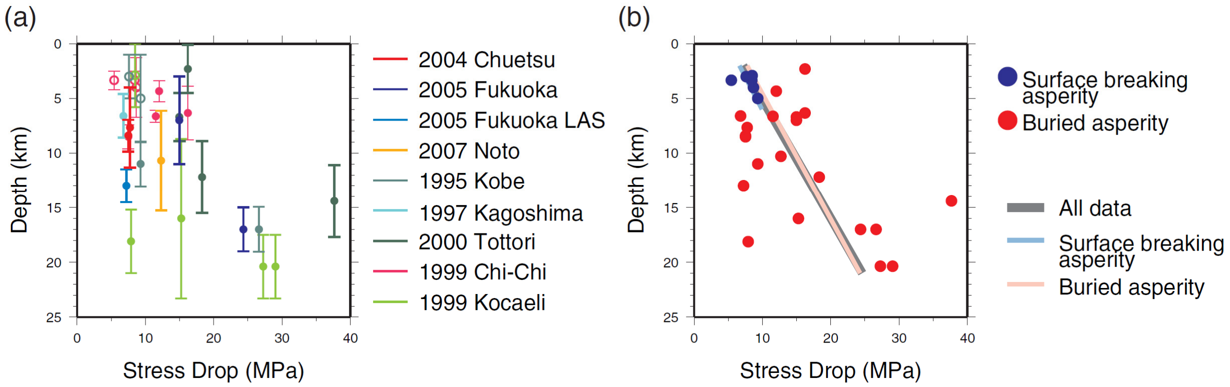

Figure 5 (a) Average static stress drop on asperities (Open and solid circles are surface breaking and buried asperities, respectively) (b) The empirical relationships between stress drop on asperity and its depth

Kagawa *et al.* (2004) pointed out the differences in ground motion characteristics and fault rupture characteristics between surface rupture and buried rupture earthquakes. They analyzed events in the database by Somerville *et al.* (1999) and several other events. They pointed out that buried rupture earthquakes generate larger ground motion in the period range around 1 s compared to the average value expected from an empirical attenuation relationship for acceleration response spectra. They discussed this phenomenon by categorizing the asperities with respect to depth. One is the shallow asperity whose depth is less than 5 km, and the other is the deep asperity whose depth is more than 5 km. Kagawa *et al.* (2004) analytically calculated the stress drop of each individual asperity by assuming an circular crack model for deep asperities and a semi-ellipsoid crack model for shallow asperities. They estimated that average stress drops of deep and shallow asperities were 24 MPa and 7 MPa, respectively.

We tried to investigate the difference between buried asperities (solid circles in Figure 5a) and surface breaking asperities (open circles in Figure 5a) in our dataset. We categorized asperities according to the existence of clear surface rupture. That is, regarding the shallow asperities defined by Kagawa *et al.* (2004), the surface breaking and buried asperities are distinguished here. The stress drop of surface breaking asperities is not larger than 10 MPa. Two other relationships are obtained to explain the difference between surface breaking and buried asperities. For surface breaking asperities,

$$\Delta\sigma = 0.82h + 5.0, \qquad (4.2)$$

and for buried asperities,

$$\Delta\sigma = 0.87h + 6.0. \qquad (4.3)$$

These relationships are also plotted in Figure 5b. The coefficients are almost equal among these three relationships. Among shallow asperities, surface breaking asperities clearly have smaller stress drop than buried asperities as shown in Figure 5. For deep or buried asperities, most of the stress drop values in Figure 5 distribute within the standard deviation (15 MPa) of Kagawa *et al.* (2004). However, the deviation of individual data is not uniform in the depth direction, and the depth dependency of the stress drop for the buried asperities could be recognized. The depth dependency of stress drop could be introduced as one of key parameters in source modeling for strong motion prediction.

5. CONCLUSIONS

The slip and static stress changes on fault of four inland crustal earthquakes recently occurring in Japan were estimated from the strong motion data. The size of asperities of these events follows the empirical scaling relationship proposed by Somerville *et al.* (1999). The average stress drops on the asperities of these earthquakes are 7-24 MPa. The mainshock of the 2005 west off Fukuoka prefecture earthquake has slightly larger stress drops than the other events analyzed in this study. The stress drop off the asperities of these earthquakes is below 3 MPa. These values are similar to the estimation of other earthquakes by Iwata *et al.* (2005). In order to characterize the heterogeneous stress drop distributions, the stress drop on the asperities was compiled as a function of its depth. The depth dependency of the static stress drop was observed. The surface breaking asperities appeared to have smaller stress drop than the buried asperities. This information could be used in advanced source modeling for strong ground motion prediction. The data set used in our study is small, and more source models should be analyzed in future studies in order to validate these empirical relationships and to investigate the effect of the fault type and tectonic environment.

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