# PROCEDURE OF EVALUATING FAULT PARAMETERS OF SUBDUCTION PLATE-BOUNDARY EARTHQUAKES WITH SURFACE FAULT BREAKINGS FOR STRONG MOTION PREDICTION

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**Abstract**. For prediction of ground motions from subduction plate-boundary earthquakes, the Recipe by the Headquarters for Earthquake Research Promotion (*e*.*g*., 2016, [1]) is used to determine fault parameters in Japan. The underlying physics in the current Recipe are based on the circular crack equation by Eshelby (1957, [2]). This circular crack equation is applicable to smaller sized earthquakes of *MW*8 or less with no surface fault breakings. However, for larger events, where the rupture reaches surface and the stresses are released at the surface, the boundary conditions are different from those of a circular crack. Therefore, in this study, we adopted an alternative equation for the stress drop for larger events obtained by the dynamic fault rupturing simulations, and proposed a new procedure of evaluating fault parameters for subduction plate-boundary earthquakes with surface fault breakings. The proposed fault model consists of asperities, background, and large-slip and very large-slip areas near the surface. We validated our procedure on the example of the 2011 Tohoku, Japan, earthquake (*MW*9.0) in terms of predicting strong ground motions.

**Key Words**: Fault model, Subduction plate-boundary earthquake, Surface fault breaking, Strong motion prediction

### Introduction

Based on the severe accident at Fukushima Daiich NPPs caused by the large tsunami in the 2011 Tohoku, Japan, earthquake (*MW*9.1), Nuclear Regulation Authority (2013, [3]) published ‘Examination guideline for design-basis tsunami and design policy’ and showed three examples of source areas of large tsunamis as in Figure 1. Among them, the largest area is located along the Nankai Trough and South-West Islands Trench, about 2000 km long, and its moment magnitude is 9.6.

Shimazaki (2012, [4]) described his understanding that recent subduction plate-boundary earthquakes of *MW*8 in Japan correspond to crustal earthquakes with no surface breaking and that the 2011 Tohoku, Japan, earthquake of *MW*9 corresponds to crustal earthquakes with a surface breaking which is recognized by trench investigation. He interpretated that the recent subduction plate-boundary earthquakes of *MW*8 are inferior to *MW*9 earthquakes and that the *MW*9 earthquakes are the most basic subduction plate-boundary earthquakes.

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| *FIG. 1. Tsunami source areas caused by subduction plate-boundary earthquakes around Japan (modified from Nuclear Regulation Authority, 2013, [3])* |

Moreover, Tajima *et al*. (2013, [5]) pointed out that subduction plate-boundary earthquakes transfer, as their magnitudes become greater, from the first stage in which the fault length, width, and slip grow proportionally to each other (self-similar) to the second stage in which the fault width saturates because of the thickness of the seismogenic layer and the fault length and slip grow proportionally to each other.

Hereafter in this paper, according to Scholz (2002, [6]), we call subducting plate-boundary earthquakes with no surface fault breakings small earthquakes and those with surface fault breakings large earthquakes.

The headquarters for Earthquake Research Promotion, Japan (*e*.*g*., 2016, [1]) published a procedure of evaluating fault parameters, so called Recipe, for predicting ground motions from subduction plate-boundary earthquakes based on the averaged stress drop equation of the circular crack model (Eshelby, 1957, [2]):

 (1)

Here, ** is the averaged stress drop, *M*0 is the seismic moment, and *S* is the fault area.

This official procedure was adopts an asperity model (Das and Kostrov, 1986, [7]) as a source model, and it validated by reproducing strong ground motions recorded in the 1978 Miyagi-Oki earthquake (*MW*7.6) and the 2003 Tokachi-Oki earthquake (*MW*8.1).

However, these earthquakes belong to the first-stage earthquakes. The averaged stress drop equation (1) of the circular crack model can be applied to the earthquakes in the first stage, but it can not be applied to the earthquakes in the second stage of *MW*9 class because the stress is released on the ground surface or sea bottom.

On the other hand, Dorjpalam *et al*. (2015, [8]) carried out a number of dynamic fault rupturing simulation of long thrust faults with surface fault breakings and obtained an approximate description of the averaged dynamic stress drop equation.

Hence, we categorized subduction plate-boundary earthquakes into small and large earthquakes, and applied the averaged dynamic stress drop equation for long rectangular faults obtained by Dorjpalam *et al*. (2015, [8]) to large earthquakes to calculate their averaged dynamic stress drops and obtain scaling laws of fault parameters.

Next, we proposed a new procedure of evaluating fault parameters for subduction plate-boundary earthquakes with surface fault breakings. Here, we adopted an asperity model and added some large-slip and very-large-slip areas (Sugino *et al*., 2014, [9]) to it to generate both strong ground motions and large tsunamis.

Finally, we evaluated fault parameters for the 2011 Tohoku earthquake and reproduced strong ground motions to show the validation of our proposed procedure for subduction plate-boundary earthquakes with surface fault breakings.

1. **Scaling Law of Fault Parameters of Subduction Plate-Boundary Earthquakes with Surface Fault Breakings**

**2.1.Dataset of fault parameters of subduction plate-boundary earthquakes**

We collected fault lengths *L*, widths *W*, seismic moments *M*0, and short-period levels *A* to examine an empirical relationship between the seismic moment and fault area and that between the seismic moment and short-period level. Here, the short-period level is the flat level of the acceleration source spectra in the short-period range.

Table 1 lists the collected fault parameters of 56 subduction plate-boundary earthquakes ([10] to [18]).

Figure 2 shows a relationship between the fault width and length. Watanabe *et al*. (2002, [19]) described that the fault width is proportional to the fault length when the fault length is about 300 km or shorter and that the fault width is constant and about 150 km when the fault length is longer. Hence, in Figure 2, we classified the earthquakes into small ones with the fault length shorter than about 300 km, plotted by the solid circles, and large ones with the fault length longer then about 300 km, plotted by the open circles. Here, we classified the 2005 Nias earthquake (*MW*8.6) and the 1957 Andreanof Is. earthquake (*MW*8.6) with their fault lengths of 295 km into large earthquakes.

#### 2.2.Scaling law between seismic moment and fault area

Dorjpalam *et al*. (2015, [8]) obtained an approximate description of the averaged dynamic stress drop equation as follows:

 (2)

Here, **# is the averaged dynamic stress drop.

We evaluated the averaged dynamic stress drop **# of the large earthquakes in Table 1 by equation (2) from the seismic moment *M*0, fault length *L*, and fault width *W*. The averaged dynamic stress drop **# evaluated for each earthquake are listed in Table 1. The geometric mean of the averaged dynamic stress drop was calculated to be 1.0 MPa.

We also evaluated the averaged stress drop ** of the small earthquakes by equation (1), and the results are listed in Table 1.

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| TABLE 1: Fault parameters of subduction plate-boundary earthquakes    \* indicates large earthquakes.  †1 **is the averaged stress drop calculated by equation (1) for small earthquakes. **is the averaged dynamic stress drop **# calculated by equation (2) for large earthquakes.  †2 *asp*is the averaged stress drop on the asperity calculated by equation (8) for small earthquakes. *asp*is the averaged dynamic stress drop **#*asp* on the asperity calculated by equation (7) for large earthquakes. |

We obtained an empirical scaling law between the fault area and the seismic moment of large earthquakes from equation (2) when adopting **#=1.0 MPa as follows:

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| *FIG. 2. Relationship between fault width and length of subduction plate-boundary earthquakes*  *FIG. 3. Relationship between fault area and seismic moment of subduction plate-boundary earthquakes* |

 (3)

The red line in Figure 3 shows the obtained relationship between the fault area and the seismic moment. The data in Table 1 are also plotted in this figure. The broken line in the figure is the empirical relationship of equation (4) proposed by Utsu (2001, [20]), which is adopted in the Recipe by the Headquarters for Earthquake Research Promotion (*e.g*., 2016, [1]).

 (4)

This empirical relationship leads to the averaged stress drop ** of 3.0 MPa by equation (1).

The red line by equation (3) is almost the same as the broken line by equation (4) at the moment magnitudes of 8.5 and 9.0. However, the red line becomes larger than the broken line at the moment magnitudes of about 9.5. This is because *S* in equation (3) is proportional to *M*0 for large *M*0, while *S* in equation (4) is proportional to *M*02/3.

#### 2.3.Scaling law between seismic moment and short-period level

The short-period level is calculated from the area of the asperity *Sasp* and the dynamic stress drop on the asperity **#*asp* as follows (Dan *et al*., 2001, [21]; Dan *et al*., 2011, [22]):

 (5)

Here, the static stress drop *asp* on the asperity is assumed to be the same as the dynamic stress drop **#*asp*, and ** is the *S* wave velocity of the seismogenic layer.

On the other hand, the averaged dynamic stress drop **# is defined by

 (6)

In order to calculate the dynamic stress drop on the asperity **#*asp* for each earthquake listed in Table 1, we deleted **# and *Sasp* from equations (2), (5), and (6), and obtained

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| *FIG. 5. Relationship between averaged slip and fault length of subduction plate-boundary earthquakes*  *FIG. 4. Relationship between short-period level and seismic moment of subduction plate-boundary earthquakes* |

 (7)

The short-period level *A* is obtained for only one large earthquake, *i*.*e*. the 2011 Tohoku earthquake, and we evaluated the dynamic stress drop on the asperity **#*asp* by equation (7) to derive **#*asp*=19.9 MPa. Here, we adopted **=4 km/s (Yoshida *et al*., 2011, [23]).

As for the small earthquakes, the stress drop on the asperity *asp* can be calculated by

 (8)

Here, we deleted ** and *Sasp* from equation (1), *A*=4**(*Sasp*/**)1/2*asp*2, and **=(*Sasp*/*S*)*asp*.

We evaluated the stress drop on the asperity *asp* of the small earthquakes by equation (8), and the results are listed in Table 1.

We obtained an empirical scaling law between the short-period level and the seismic moment of large earthquakes from equation (7) when adopting **#*asp*=19.9 MPa as follows:

 (9)

The red line in Figure 4 shows the obtained relationship between the short-period level and the seismic moment. The data in Table 1 are also plotted in this figure. The broken line in the figure is the empirical relationship of equation (10) proposed by Dan *et al*. (2001, [21]), which is adopted in the Recipe by the Headquarters for Earthquake Research Promotion (*e.g*., 2016, [1]).

 (10)

This empirical relationship leads to the stress drop on the asperity *asp* of 8.3 MPa by equation (8).

The red line by equation (9) is almost the same as the broken line by equation (10) at the moment magnitudes of 8.5 and 9.0. However, the red line becomes slightly larger than the broken line at the moment magnitudes over 9.5. This is because *A* in equation (9) is proportional to *M*01/2 for large *M*0, while *A* in equation (10) is proportional to *M*01/3.

We need to accumulate more short-period levels for large earthquakes, because we have only one short-period level for large earthquakes.

#### 2.4.Confirmation of relationship between fault length and averaged slip

We confirmed the relationship between the averaged slip and the fault length expected from the scaling law between the fault area and the seismic moment of equation (2). By using the definition of the seismic moment *M*0=*DS*, we derived the averaged slip by

 (11)

Here, we assumed the fault width *W* to be 200 km and the shear rigidity ** to be 4.8×1010 N/m2 (Dorjpalam *et al*., [8]).

The red line in Figure 5 shows the relationship between the averaged slip *D* and the seismic moment by equation (11). The broken line in the figure shows the relationship by equation (4) of Utsu (2001, [20]). Here, we adopted the empirical relationship between the fault width *W* and the fault length *L* of *L*=2*W* for both small and large earthquakes.

The average slip of small earthquakes grows proportionally to the fault length, while it is constant of about 10 m for the fault length longer than about 1000 km.

### Procedure for Evaluating Fault Parameters of Large Subduction Plate-Boundary Earthquakes

Based on the averaged dynamic stress drop **# over the entire fault of 1 MPa and the dynamic stress drop **#*asp* on the asperity of 19.9 MPa, we proposed a new procedure of evaluating fault parameters for predicting strong ground motions from subduction plate-boundary earthquakes with surface fault breakings, as shown in Figure 6.

Here, we classified earthquakes with the areas of 30,000 km2 or over into large earthquakes, because we had classified the 2005 Nias earthquake with the area of 30,975 km2 into large earthquakes. This areal criterion may vary because the boundary between large earthquakes and small earthquakes depends on whether the rupture reaches the sea bottom or not. In the figure, we introduced large-slip areas and added very-large-slip areas for earthquakes of *MW*8.9 or which had been proposed by Sugino *et al*. (2014, [9]) to simulate tsunamis, shown in Figure 7.

### Validation of the Proposed Procedure by the 2011 Tohoku Earthquake

#### 4.1.Fault parameters evaluated by the proposed procedure

We evaluated fault parameters for the 2011 Tohoku earthquakes by the proposed procedure in Figure 6. Here, we assumed the fault length to be 500 km and the fault width to be 200 km as shown in Table 1. We took the *S*-wave velocity of 4.0 km/s from Yoshida *et al*. (2011, [23]), and assumed the density of 3.0 g/cm3 by the relationship between the *S*-wave velocity and the density (Ludwig *et al*., 1970, [24]).

Figure 9 shows the fault model for the 2011 Tohoku earthquake. Here, we assigned the asperities on the deep part of the fault and the large-slip and very-large-slip areas on the shallow part according to the results by Lay *et al*. (2012, [25]). We set the boundary depth between the deep and shallow parts to be 22.7 km as Dan *et al*. (2013, [11]) did. They separated the deep part of the fault, generating strong motions and Tsunamis, and the shallow part, generating Tsunamis, based on the slip distribution inverted by Yoshida *et al*. (2011, [23]).

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| *FIG. 6. Procedure of evaluating fault parameters for predicting strong ground motions from subduction plate-boundary earthquakes with surface fault breakings* |

We decided the size and location of each asperity and its rupture initiation location and timing from the results identified by Kawabe and Kamae (2013, [12]). We decided the locations and shapes of the large-slip and very-large-slip areas from the results identified by Sugino *et al*. (2014, [9]). We assigned **#*asp*=19.9 MPa to all asperities, and this value is almost the same as those of 10.5 to 23.1 MPa, idendified by Kawabe and Kamae (2013, [12]). We assigned 10.8 m to the large-slip area and 23.1 m to the very-large-slip area, and these values are a little smaller than 14.6 m and 31.2 m, respectively, modelled by Sugino *et al*. (2014, [9]).

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| *FIG.7. Slip distribution for predicting tsunami (modified from Sugino et al. (2014), [9])* |

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| *FIG.8. Example of a fault model for the 2011 Tohoku earthquake* |

#### 4.2.Simulation of the strong ground motions

We simulated ground motions at MYGH12, FKSH17, and IBRH14 by the empirical Green’s function method (Dan *et al*., 1989, [26]). We used the bore-hole records from Event 1 to Event 4 in Kawabe and Kamae (2013, [12]) as empirical Green’s functions. We processed the records by a band-pass filter of 0.1 to 10 Hz. The fault parameters (seismic moment, area, stress drop) were also taken from Kawabe and Kamae (2013, [12]).

Figure 9 shows the fault model, the locations of the recording stations, and the epicentres of Event 1 to Event 4. Here, we adopted the strike of N195E and the dip of 15 degrees. The rupture propagation velocity was set to be 0.72 times 4.0 km of *S*-wave velocity (Yoshida *et al*., 2011, [23]) according to the statistical results by Geller (1976, [27]).

Figure 10 compares the synthesized time histories and pseudo velocity response spectra (5% damping) with the observed ones during the 2011 Tohoku earthquake (*MW* 9.0). The observed time histories and response spectra are found to be reproduced by the empirical Green’s function method. Especially synthesized time histories and response spectra at IBRH14 agree well with the observed ones.

**Conclusions**

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| *FIG.9. Location of ground motion simulation stations for the 2011 Tohoku earthquake and element earthquakes as empirical Green’s functions (*▼*:observation stations,* ◆*:element earthquakes)* |

First, we classified subduction plate-boundary earthquakes into small earthquakes and large earthquakes. Then we calculated the averaged dynamic stress drop over the entire fault and the dynamic stress drop on the asperities for large earthquakes, and obtained empirical scaling law between the fault area and the seismic moment and that between the short-period level and the seismic moment.

Next, we proposed a procedure of evaluating fault parameters for ground motion prediction of large earthquakes with surface fault breakings based on the averaged dynamic stress drop over the entire fault and the dynamic stress drop on the asperities. We also considered large-slip and very-large slip areas on shallow part of the fault to simulate large tsunamis.

Finally, we evaluated the fault parameters of the 2011 Tohoku earthquake (*MW*9.0) and simulated the observed strong ground motions to validate our proposed procedure.

#### Acknowledgments

Some parts of this study are the results of the research project by National Research Institute for Earth Science and Disaster Resilience, Japan, in the fiscal year of 2017.

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| *(a) Time histories at MYGH12*    *(b) Time histories at FKSH17*  *FIG.10. Comparison of the synthesized time histories and their pseudo velocity response spectra (5% damping) with the observed ones during the 2011 Tohoku earthquake (MW 9.0)* |

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| *(c) Time histories at IBRH14*    *(d) Pseudo velocity response spectra (5% damping)*  *FIG.10. Comparison of the synthesized time histories and their pseudo velocity response spectra (5% damping) with the observed ones during the 2011 Tohoku earthquake (MW 9.0)* |

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