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SOURCE MODELING AND STRONG GROUND MOTION SIMULATION FOR THE 1999 CHI-CHI, TAIWAN EARTHQUAKE

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SUMMARY

In order to protect lives and properties from large earthquake, various measures should be taken, including repair and retrofitting of structures, revising seismic design methods, and formulating earthquake disaster prevention manuals. If the strong ground motion resulting from an earthquake is predictable, then these measures can be optimized from the financial aspect as well. In this sense, accurate prediction of ground motion is considered to contribute to substantial reduction in the damage due to an earthquake.
An appropriate source model is a prerequisite for accurate prediction of ground motion. Heterogeneity should be incorporated in the source model to consider the complexity and heterogeneity of large-scale earthquakes. It is also necessary for the model to be capable of reproducing broadband strong ground motions assuming a wide variety of structures.
This paper reports on the characterization of the Chi-Chi, Taiwan Earthquake (Mw7.6) with the aim of establishing a technique of source modeling incorporating the heterogeneity of sources. The complicated source of the Chi-Chi Earthquake was modeled by four rectangular asperities, with the relationship between the total area of the asperities and the seismic moment being expressed by existing empirical equations.

INTRODUCTION

The Chi-Chi Earthquake (Mw7.6) hit Central Taiwan on 17:47 GMT on September 20, 1999, causing fatalities and damage to a large number of structures. A month earlier, another large earthquake struck Turkey (Kocaeli Earthquake, Mw7.4), causing severer damage. Major earthquakes causing serious damage continue to occur one after another at various parts of the world, calling for an effective method of preventing or mitigating earthquake-induced damage.

Seismic motions are most intense near the source area, with damage concentrated in the area in most cases. If the broadband strong ground motions can be appropriately predicted for an extensive area

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including near source regions, then effective countermeasures can be formulated and applied, substantially contributing to earthquake disaster prevention and damage mitigation.

The key subject for achieving accurate strong ground motion prediction is source modeling. Near source strong ground motion should be appropriately modeled, as it is particularly affected by the heterogeneous slip distribution over the fault plane and the propagation properties of fault rupture.

Kamae and Irikura [1] proposed a method of source modeling in which the parameters, such as asperity size, seismic moment, and stress drop, are quantified by forward modeling using the empirical Green's function method while assuming the asperities at segments with large slips in the fault plane based on the results of waveform inversion (Asperity-model). They applied this model to the 1995 Hyogoken-Nambu Earthquake, exhibiting that the Asperity-model determined from waveform inversion using long-period ground motion records is effective in predicting broadband strong ground motions including the short period bands.

On the other hand, Somerville et al. [2] attempted to statistically sample the heterogeneity of slips on the fault plane. They sampled asperities from the waveform inversion results of inland crustal earthquakes, showing that the areas of rupture zones and asperities are scaled by seismic moment (Mo). Miyakoshi et al. [3] later conducted investigation by a similar method, concluding that the rule of scaling holds for Mo values greater than those used for statistical analysis by Somerville et al.

In this study, the authors formulated an optimum source model for broadband strong ground motion evaluation of the 1999 Chi-Chi Earthquake in Taiwan to verify the effectiveness of the Asperity-model for a large-scale earthquake and characterize the source properties. Strong ground motion records of the main-shock and after-shocks were obtained at a number of sites including those very close to the source area, based on which complicated slip distribution data have been reported through waveform inversion analysis. Accordingly, all requirements are met for applying forward modeling by the empirical Green's function method to this earthquake.

CHI-CHI EARTHQUAKE

The cause of the Chi-Chi Earthquake of a low angle thrust type is attributed to the activity of the Chelumgpu fault stretching from north to south in central Taiwan. Surface break emerged along the Chelumgpu fault, with the vertical gap exceeding 10 m at certain points. Table 1 gives the source parameters. Figure 1 shows the source location and epicenter.

In Taiwan, the Central Weather Bureau (CWB) prepared a strong ground motion observation network (TSMIP) under which earthquake has been monitored at approximately 700 sites [4]. During the 1999 Chi-Chi Earthquake, strong ground motion records of the main-shock were obtained at about 400 sites among them [5]. The maximum acceleration and maximum velocity were between 300 and 1000 cm/s/s and between 40 and 300 cm/s, respectively, in the source region. Figure 1 shows the distribution of near source seismic stations where the main-shock record was obtained. The seismic stations are densely distributed on the side of the footwall (west) but fewer on the hanging wall side (east), due to being in the central mountains.

Based on these records, the estimation of the source rupture process is being carried out. Sekiguchi and Iwata [6] presented a complicated source process by waveform inversion using samples from 31 sites within 70 km of the epicenter, excluding those of complicated site characteristics and those influenced by the ground surface fault displacement, while setting the target at the 2 to 20 sec velocity waveform. They assumed the source area to be 79 by 39 km from the after-shock distribution. Figure 2 shows the source rupture process. The assumed total slip distribution is extremely heterogeneous. Large slips concentrate on the north side of the fault plane, some exceeding 10 m. The slips on the south side are much smaller. The rupture is assumed to have propagated primarily from the source to the north, while extending deeper toward the east.

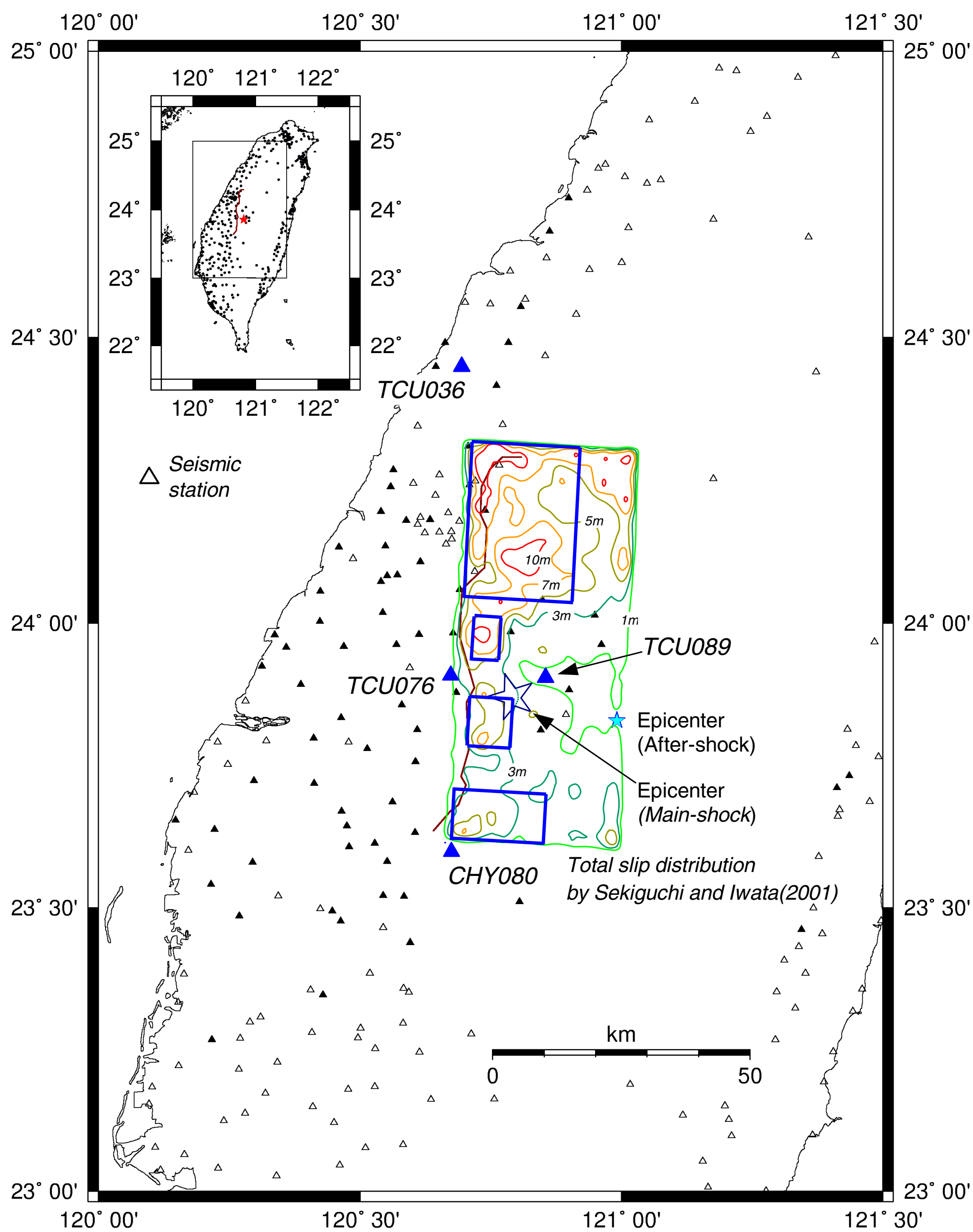


Figure 1. Map of seismic station locations that were able to observe main-shock motion (Δ) and after-shock motion (▲). Also shown are the surface break, total slip distribution (Sekiguchi and Iwata) and proposed 4 rectangular asperities.

Table 1. Source Parameter of the Chi-Chi earthquake, Taiwan

Epicenter		23.86N , 120.81E
Strike, Dip, Slip	deg.	3, 29 , 0
Depth	km	7.0
Seismic moment	Nm	1.7×10^{20}
Source area	km^2	3,042(78×39)
Source rupture velocity	km/s	2.8

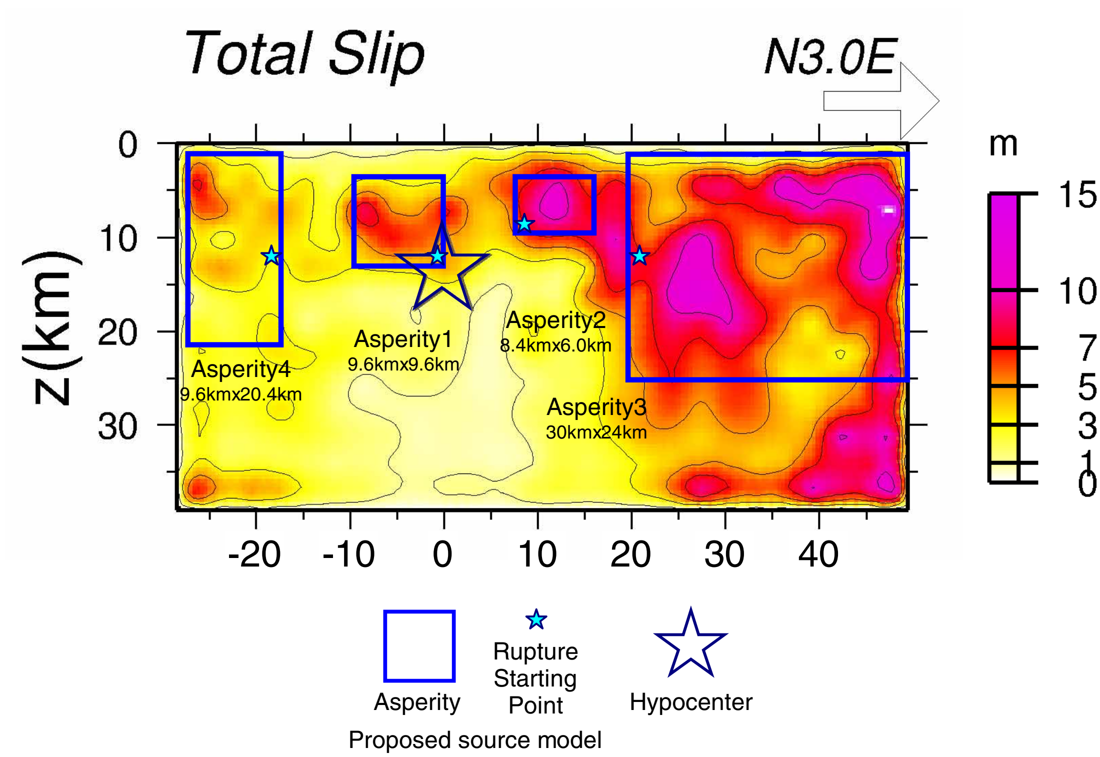


Figure 2. Source model consisting of four asperities estimated from forward modeling using the empirical Green's function method. Proposed source model is superimposed on the total slip distribution by Sekiguchi and Iwata (2001). We assumed that ground motions are generated only from the asperity (rectangular area) in the fault plane.

METHOD

The authors formulate a source model with the aim of reproducing the broadband strong ground motion waveforms by forward modeling using the empirical Green's function method similarly to the techniques employed by Kamae and Irikura [1]. The method of Irikura [7],[8] is used for the synthetics of waveforms on the fault plane. The source heterogeneity is expressed by arranging multiple rectangular homogenous asperities on the fault plane. In light of past findings, the initial locations of asperities are determined by assuming that strong ground motions with period bands ranging from short to long are generated from segments with large slips on the fault plane. Sekiguchi and Iwata's ultimate slip distribution is referred to in this paper.

The records of an earthquake event that occurred at 18:32 GMT on September 20 with a ML of 5.07 are used for empirical Green's functions. The main-shock motions of this event were observed at 65 sites including near-source stations. The source displacement spectra are determined from the waveforms observed at near-source observation sites, from which the corner frequencies (*fc*) are read to determine the stress drop and area by Brune's equations. The seismic moment is set from the flat level on the long period side, assuming the source displacement spectra to be model ω^{-2}. Table 2 gives the after-shock parameters employed for the empirical Green's function method.

In the forward modeling, attention is paid to characteristic waveforms found in the observed waveforms, such as pulses due to the forward directivity effect, and the locations and size of the asperities are adjusted to reproduce the period and amplitude of characteristic waveform.

In Sekiguchi and Iwata's waveform inversion, the fault surface is assumed to be a smoothly inclined curved surface based on after-shock distribution. However, a flat surface with a strike of 3° and dip of 29° is assumed in the present study. Multi-hypocenter rupture is assumed for the rupture mode of the fault. Specifically, rupture is assumed to begin from the multi-hypocenter and propagate radially. When the rupture fronts reach the asperities, the asperities are assumed to rupture radially. The rupture propagation velocity and shear wave velocity are assumed to be 2.8 km/s and 3.5 km/s, respectively. During the waveform synthetics, the *fmax* values of the main-shock and after-shocks are corrected according to the method by Kamae et al.[9]

Table 2. Source Parameter for after-shock

Date (GMT)		1999/09/20 18:32
Magnitude (ML)		5.07
Epicenter		23.829N , 120.9912E
Depth	km	16.83
Source area	km^2	1.44

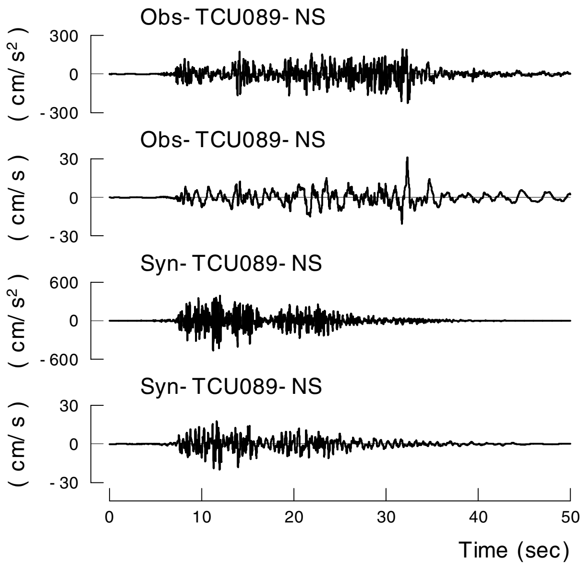
SOURCE MODEL AND SYNTHETICS

Figure 3 shows the acceleration and velocity time history waveforms during the main-shock at TCU089, a near-source observation site. The absence of pulse waveforms suggests that this site is located behind the propagation of fault rupture (on the backward side). Also, the three segments with relatively large amplitudes in the acceleration waveforms suggest that these waveforms arrived from three points surrounding TCU089 with certain time lags. Accordingly, it is inferred that no asperity exists in the east of the source, as far as the near source area is concerned, and that three or more asperities exist near TCU089.

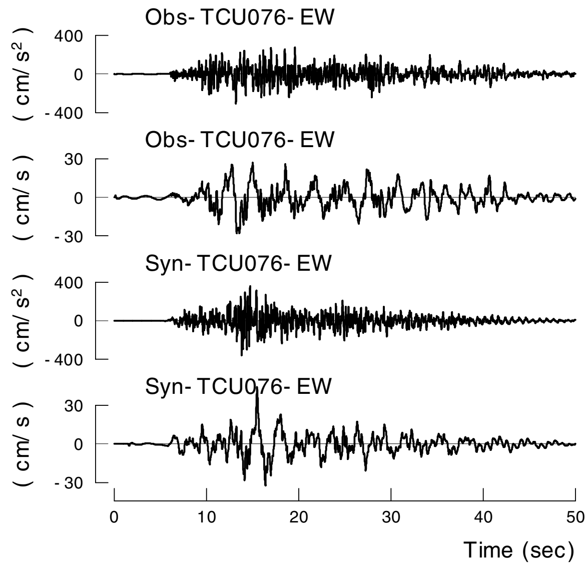
Figure 1 and Figure 2 shows the assumed Asperity-model having four asperities. This was made by adding an asperity at the region with a large slip in the north-west of the source to the source model assumed by Kamae and Irikura [10] by a hybrid simulation method combining stochastic Green's function method [11] and the 1-D discrete wave-number method. The addition of the fourth asperity improved the synthesized waveforms at sites between near source asperity 1 and asperity 4.

Figure 3 compares the synthesized and observed waveforms at four seismic stations, TCU089, TCU076, CHY080, and TCU036, located in the center, west, south, and north, respectively, of the fault plane. For TCU089, the three segments of waveforms with large amplitudes are reproduced. The second wave group is generated from asperity 2. For TCU076, pulse waveforms in the initial portion of the velocity time history waveform are reproduced. The amplitudes are also reasonably reproduced. The observed waveforms at CHY080 are characterized by the short durations and large amplitudes, which can be attributed to the directivity effect of fault rupture. Similar characteristics are represented in the synthesized waveforms by placing asperity 3 in the south of the fault. TCU036 is a site where the contributions from asperity 4 are anticipated. The durations and envelope shapes of the synthesized waveforms reproduce the observed waveforms.

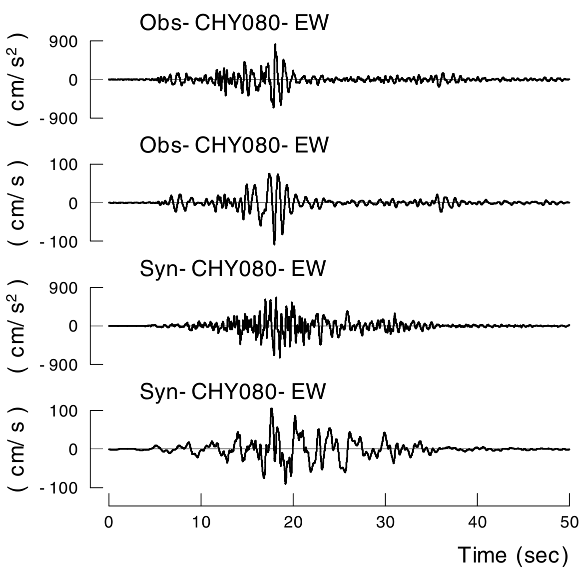
The observed waveforms are thus well-reproduced by the source model estimated in this study. The asperity model formulated in this study is therefore considered effective as a model incorporating the source heterogeneity. On the other hand, differences between the observed and synthesized waveforms are found in the amplitude and envelope shapes at certain sites, requiring detailed investigation in regard to the accuracy of small seismic waveforms used for the synthetics of waveforms, as well as modeling of localized heterogeneity.



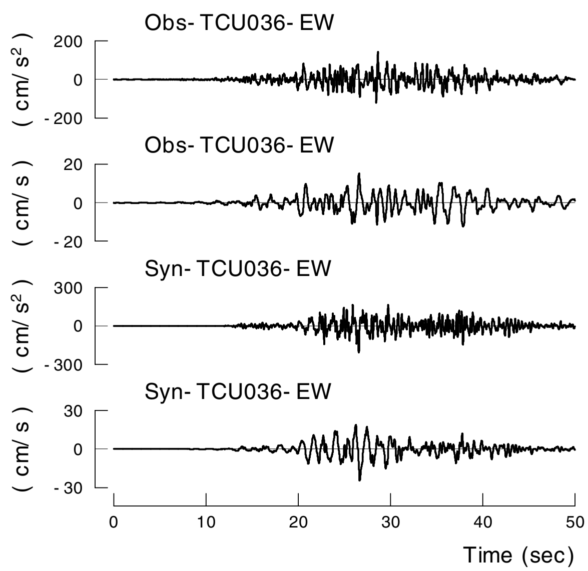
(a) TCU089



(b) TCU076



(c) CHY080



(d) TCU036

Figure 3. Comparison between the observed and synthetics motion at TCU089, TCU076, CHY080 and TCU036.

SOURCE CHARACTERIZATION

Modeling of heterogeneous sources is a key subject for strong ground motion prediction of future earthquakes. The characterized source model [12] is attracting attention as one of the modeling methods. This is a technique whereby the source parameters are characterized based on source models of past earthquakes. In this paper, the relationship between the characteristics of the asperities of the Chi-Chi Earthquake obtained by the present research and the empirical characteristics is described.

Figure 4 shows the relationship between the seismic moment and the asperity area of inland crustal earthquakes determined by the same method as the method used by Somerville et al. The results obtained by forward modeling using the empirical Green's function method are also shown in the figure, including the results of the Chi-Chi Earthquake. The results of the present research are found to nearly fulfill the empirical equation, though the areas are slightly larger than the empirical equation.

Figure 5 shows the relationship between the rupture area and the total area of asperities [13]. The total area of asperities determined in this study is 1,058 km^2. Since the area of the rupture zone is 3,042 km^2, the ratio of the asperity area to the total area is 0.35, which is slightly larger than the empirically characterized value of 0.215. This may be because the size of asperity 3, which is located in the south of the fault plane, is not precisely adjusted due to the small number of observation sites further south and because the north side of the fault plane, which showed complicated rupture process, is represented by a single asperity.

CONCLUSIONS

The authors attempted source modeling of the Chi-Chi Earthquake by forward modeling using the empirical Green's function method. The heterogeneous source was expressed by arranging rectangular homogeneous asperities on the fault plane. As a result, a heterogeneous source model having four asperities was formulated. The relationship between the seismic moment and the area of asperities satisfied the existing empirical equations. It was therefore found that a heterogeneous source model can be formulated for future major earthquakes by empirical characterization obtained from statistical treatment of past earthquakes.

On the other hand, the formulated source model posed several problems to be solved, such as the expression of the complicated rupture process in the north of the fault plane by a single asperity and the insufficient adjustment of the asperity size in the south of the fault plane. The authors intend to continue tackling these problems.

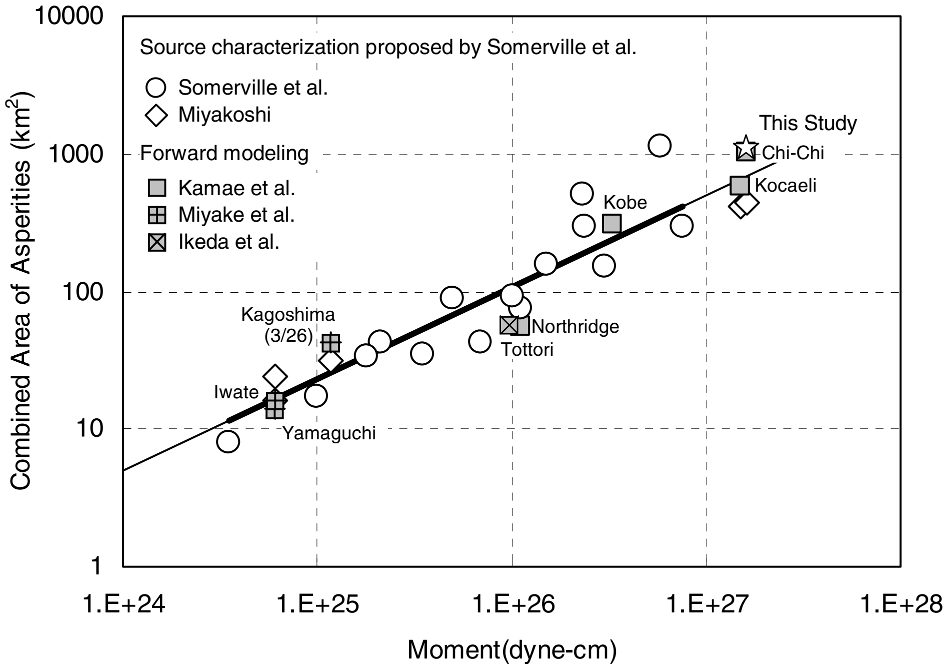


Figure 4. Relationship between combined area of asperities and seismic moment based on slip distributions estimated bay waveform inversion and forward modeling. The thick continuous line shows the empirical relationship proposed by Somerville et al.

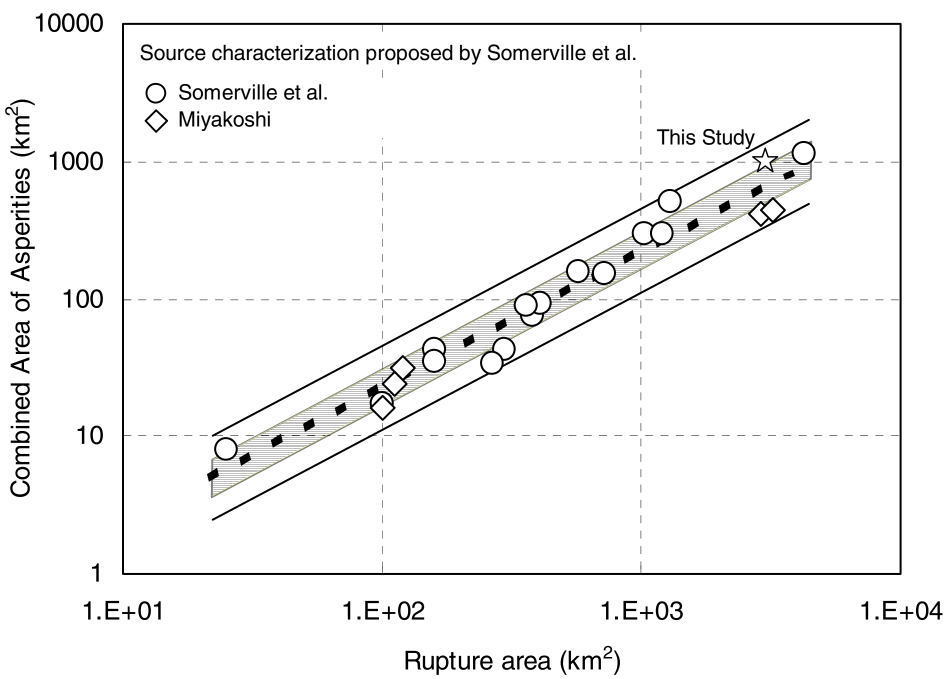


Figure 5. Relationship between combined area of asperities and Rupture area. The thick broken line shows the empirical relationship proposed by Irikura and Miyake [13]. Shadow zone shows a rage of standard deviation. The thin lines show a factor of 2 and 1/2 for the average.

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