Scaling relations of seismic moment and rupture area for outer-rise earthquakes

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Abstract

A new piece-wise scaling relation for rupture area (S) and seismic moment (M_0) was obtained for outer-rise earthquakes using data compiled from previous seismological studies. The compiled source parameters were examined carefully to ensure that rupture area dimensions represent the “actual” rupture area. Twenty sets of S and M_0 pairs for ten earthquakes from independent studies were used for regression analysis. To estimate rupture areas of outer-rise earthquakes whose fault down dip tips, respectively, do and do not reach the oceanic lithosphere base, regression parameter b in $S = (M_0/a)^{1/b}$ is 2 with the corresponding regression parameter $\log_{10} a_2$ being $1.402(\pm 0.250)$, and b is 1.5 with the corresponding regression parameter $\log_{10} a_1$ being $6.401(\pm 0.187)$. The piece-wise scaling relation developed here can fit outer-rise earthquake data from Mw 7.2 to Mw 8.4 and can be used to estimate rupture areas of earthquakes greater than Mw 8.4.

Keywords

outer-rise earthquakes, piece-wise scaling relations, earthquake source model, seismic moment

Introduction

Outer-rise normal fault earthquakes are rare phenomena compared to subduction thrust earthquakes. Nonetheless, some of them have generated destructive tsunamis in the past, such as the 1933 Sanriku-oki earthquake (e.g. Kanamori 1971; Aida 1977), 1977 Sumbawa earthquake (e.g. Lynnes and Lay 1988; Gusman et al 2009), and 2009 Samoa earthquake (e.g. Beavan et al 2010; Lay et al 2010). Because outer-rise earthquakes tend to occur after a giant megathrust earthquake (e.g. Christensen and Ruff 1988), large outer-rise earthquakes similar to the 1933 Sanriku-oki earthquake have been a concern after the 2011 Tohoku-oki earthquake (e.g. Lay et al 2011). To conduct tsunami hazard assessment for outer-rise earthquakes, the scaling relationship plays a vital role in establishing a link between fault geometry and earthquake magnitude (e.g. Álvarez Gómez et al 2012; Goda et al 2016). In the development of scaling relations in previous studies, outer-rise earthquakes were included in datasets for regression analysis. For example, the 2007 Kuril Islands and 2009 Samoa earthquakes were included in a tsunamigenic subset in Goda et al (2016) and the 1933 Sanriku-oki, 1977 Sumbawa, and 2007

Kuril Islands earthquakes were included in a normal fault subset in Blaser et al (2010). As these studies were not focused on outer-rise earthquakes, their fault parameters may not be necessarily predicted by scaling relationships developed in those studies. However, Álvarez Gómez et al (2012) has developed a scaling relation using only fault parameters of outer-rise earthquakes obtained from published literature. Due to the rare occurrence of outer-rise earthquakes, there are few relevant detailed studies and only twelve datasets were collected by Álvarez Gómez et al (2012).

Recently, finite fault slip models have become available for large earthquakes in the SRCMOD database (Mai and Thingbaijam 2014) and USGS earthquake catalog (Hayes 2017). They can be used to extract or estimate the fault parameters including fault length, fault width, average slip, and seismic moment. These parameters can be utilized in the development of new scaling relationships for outer-rise earthquakes.

In this study, we compile the source parameters from both previous seismological studies and finite fault slip models provided by SRCMOD and the USGS earthquake catalog. Then, we redefine the width and length of the finite fault slip models and perform regression analysis using this dataset. To estimate the rupture area of outer-rise earthquakes over a wide range of magnitudes, we create a piece-wise scaling relationship with a fixed slope. Moreover, we compare our new scaling relation for outer-rise earthquake with other scaling relations from previous studies.

Fault parameters for regression analysis

In this study, twenty sets of the fault parameters, rupture areas (S), and seismic moment (M_0) pairs, are compiled from previous studies (See Table 1). Half of the datasets (ten pairs) for five outer-rise earthquakes were directly provided by previously published literature. In those studies, the dimensions of the rupture area of the earthquakes have been estimated in different ways. Some were estimated from the aftershock area (e.g. Kanamori 1971; Abe 1972) and others were estimated based on the inverted teleseismic data and/or tsunami observations (e.g. Aida 1977; Ben-Menahem 1977; Lynnes and Lay 1988; Fujii and Satake 2008).

In addition to the source parameters directly provided by published literature, ten finite fault slip models from seven outer-rise earthquakes are included in the regression analysis. Some of these finite fault slip models are available in online databases in SRCMOD (Mai and Thingbaijam 2014) and the USGS earthquake catalog (Hayes 2017), and the others are included in the published literature (e.g. Lay et al 2009; Harada et al 2013). For the 2007 Kuril earthquake, there are four models available, and those for

Table 1. Fault parameters obtained from previous studies and finite fault slip models

Location	Date	L	W	S	M ₀	Mw	Reference
	yyyy-mm-dd	km	km	km ²	N·m		
Sanriku-oki	1933-03-02	185	100	18500	4.3×10^{21}	8.4	Kanamori (1971)
		185	50	9250	4.3×10^{21}	8.4	Ben-Menahem (1977)
		370	100	37000	1.9×10^{22}	8.8	Aida (1977)
Rat Island	1965-03-30	50	80	4000	3.4×10^{20}	7.6	Abe (1972)
South of Sumbawa	1977-08-19	200	70	14000	2.7×10^{21}	8.2	Gusman et al (2009)
		200	70	14000	3.0×10^{21}	8.2	Lynnes and Lay (1988)
		150	70	10500	2.9×10^{21}	8.2	Kato and Tsuji (1995)
Mariana Islands	1990-04-05	40	25	1000	1.4×10^{20}	7.4	Satake et al (1992)
Region		61	24	1473 ^a	1.5×10^{20}	7.4	Hayes (NEIC, Mariana 2014) ^b
Loyalty Islands	1995-05-16	87	48	4215 ^a	3.9×10^{20}	7.7	Hayes (NEIC, Loyalty 2014) ^b
Kuril	2007-01-13	130	30	3900	1.0×10^{21}	8.0	Tanioka et al (2008)
		120	40	4800	5.6×10^{20}	7.8	Fujii and Satake (2008)
		183	34	6168 ^a	1.6×10^{21}	8.0	Ji (UCSB, Kuril 2007) ^b
		173	27	4713 ^a	1.6×10^{21}	8.0	Sladen (Caltech, Kuril 2007) ^b
		175	53	9317 ^a	2.4×10^{21}	8.2	Lay et al (2009) ^c
		227	38	8714 ^a	2.6×10^{21}	8.2	Hayes (NEIC, Kuril 2014) ^b
Samoa	2009-09-29	123	35	4362 ^a	1.1×10^{21}	8.0	Hayes (NEIC, Samoa 2009) ^b
Bonin Islands	2010-12-21	49	33	1606 ^a	1.4×10^{20}	7.4	Hayes (NEIC, Bonin 2010) ^b
Vanuatu Region	2010-12-25	54	27	1466 ^a	1.1×10^{20}	7.3	Hayes (NEIC, Vanuatu 2014) ^b
Sanriku-oki	2012-12-07	77	9.6	738 ^a	8.7×10^{19}	7.2	Harada et al (2013) ^c

^a:Rupture area estimated based on the definition of autocorrelation width Bracewell (1986)

^b:Finite fault slip model from the USGS catalog Hayes (2017) or SRCMOD Mai and Thingbaijam (2014)

^c:Finite fault slip model in published literature provided by corresponding author of the publication

the other six earthquakes, which listed in Table 1, there is one model for each earthquake. The fault dimensions used in the finite fault slip models were chosen to cover the entire fault rupture; thus, the “actual” dimensions of the rupture area are smaller than the area defined by the slip models.

To estimate the “actual” fault length and width using a finite fault slip model, we adopt the approach of Mai and Beroza (2000), which is based on the definition of the autocorrelation width (Bracewell 1986), defined as $f * f = \int f(u)f(u-x)dx$, normalized by the zero-lag value of the autocorrelation function:

$$W^{ACF} = \frac{\int_{-\infty}^{\infty} (f * f)dx}{f * f|_{x=0}} \quad (1)$$

The slip functions (f) along strike and down-dip are obtained by the summation of the slip value of subfaults along the down-dip and strike directions, respectively. The effective length (L_{eff}) and effective width (W_{eff}) are calculated from the slip function using the definition of autocorrelation to estimate the “actual” dimensions of the rupture area. Figure 1 shows an example of the estimated L_{eff} and W_{eff} of the 2010 Mw 7.4 earthquake in the Bonin Islands region. Although the fault area dimension is smaller than that of the analysis area of the finite fault slip model, the seismic moment for regression remains unchanged.

Scaling relations for outer-rise earthquakes

We conducted a regression analysis for the rupture areas (S) and seismic moments (M_0) listed in Table 1. The equation of the scaling relation adopted in this study is:

$$S = \left(\frac{M_0}{a} \right)^{\frac{1}{b}} \quad (2)$$

where M_0 is the seismic moment ($N \cdot m$) and S is the rupture area (m^2). Equation 2 is transformed in logarithmic form using $\log_{10} M_0$ and $\log_{10} S$ for the actual regression analysis. The result is as follows:

$$\log_{10} S = 0.661(\pm 0.044) \times \log_{10} M_0 - 4.162(\pm 0.927). \quad (3)$$

The numbers in parentheses are standard deviations ($SD, \pm \sigma$). The regression parameter, b , was estimated to be $1/0.661$, which is close to 1.5, suggesting that the rupture area was proportional to two-thirds the power of seismic moment. This result suggests that the fault widths of most earthquakes in our datasets are not saturated and the equation 3 can be used to calculate the rupture area for the outer-rise earthquakes whose fault width is not saturated.

To obtain a scaling relationship for large outer-rise earthquakes whose fault width is saturated, the data

listed in Table 1 have been divided by a moment magnitude (Mw^s), which is assumed to be the minimum moment magnitude of an earthquake whose fault width is saturated. As expected, the piece-wise linear function obtained here closely approximates a straight line. Because only the fault of the 1933 Sanriku-oki earthquake may have reached the bottom of the oceanic lithosphere (e.g. Kanamori 1971; Aida 1977), the regression parameter, b , for earthquakes whose fault widths are saturated cannot be constrained by the source parameters compiled here. Therefore, we set the regression parameters, $b_1 = 1.5$ and $b_2 = 2$, as a priori (e.g. Somerville et al 1999; Irikura and Miyake 2001) and the logarithmic form of the piece-wise scaling relation is shown as follows:

$$\log_{10} S = \begin{cases} \frac{2}{3}(\log_{10} M_0 - \log_{10} a_1) & (Mw < Mw^s) \\ \frac{1}{2}(\log_{10} M_0 - \log_{10} a_2) & (Mw \geq Mw^s) \end{cases} \quad (4)$$

where a_1 and a_2 are the regression parameters.

Based on the data listed in Table 1, we estimated both a_1 and Mw^s simultaneously using a grid-search method. We calculated the root mean squared error (RMSE) of the rupture area (S) for each set of parameters. As shown in Figure 2, the resolving power regarding Mw^s is low when the moment magnitude is larger than 8.2. If we consider a threshold of $RMSE < 0.125$, any moment magnitude equal to or larger than 8.2 can be a candidate for Mw^s . If the fault width of the 1933 Sanriku-oki earthquake is already saturated as suggested by Kanamori (1971) and Aida (1977), Mw^s would be approximately between 8.2 and 8.3. For Mw^s of 8.2 and 8.3, the corresponding regression parameters, $\log_{10} a_1$, are 6.401 with a SD of 0.187 and 6.408 with a SD of 0.183, respectively. For the outer-rise region near the Japan Trench, when the fault width is saturated, the fault width is 100 km (thickness of lithosphere is ~ 70 km) based on Kanamori (1971). Assuming that the aspect ratio is $L/W = 1$, when the fault width is saturated, the rupture area is 10^4 km^2 . By substituting the fault rupture area into equation 4, both regression parameters $\log_{10} a_1$ corresponding to Mw^s 8.2 and 8.3 provide moment magnitudes of 8.2. Therefore, we select 8.2 for Mw^s .

a_2 can be calculated using the following equation:

$$\log_{10} a_2 = \frac{4}{3} \log_{10} a_1 - \left(\frac{Mw^s}{2} + \frac{9.1}{3} \right). \quad (5)$$

By substituting a_1 and Mw^s into equation 5, we obtain $1.402(\pm 0.250)$ for $\log_{10} a_2$.

Discussion

We compare the scaling relationship of the outer-rise earthquakes obtained in this study with those of previous studies in Figure 3. The broken black line is the scaling relation obtained by Álvarez Gómez et al (2012), which is a straight line with a slope of 1.92. The scaling relation of Álvarez Gómez et al (2012) fits the data of larger earthquakes but fails to predict earthquakes between Mw 7.0 and Mw 7.5. This suggests that relatively small outer-rise earthquakes whose fault down dip tips do not reach the bottom of the lithosphere need to be considered separately.

In the study of Goda et al (2016), the outer-rise earthquakes (e.g. the 1933 Sanriku-oki and 2007 Kuril Island earthquakes) have been considered as tsunamigenic earthquakes. However, the rupture area of the earthquakes predicted by the scaling relation of Goda et al (2016) (black dotted line in Figure 3) are significantly larger than the data listed in Table 1. Outer-rise earthquakes occur in oceanic lithosphere, although some can generate large tsunamis, they should be separated from those tsunamigenic earthquakes on the subduction interface due to the difference in the physical properties of lithosphere such as the rigidity of rocks.

The dotted-dashed line in Figure 3 indicates the scaling relation for normal fault earthquakes obtained by Blaser et al (2010), which includes the source parameters of outer-rise earthquakes in the normal fault earthquakes dataset. Many of the normal earthquakes compiled in Blaser et al (2010) were continental earthquakes. Compared to the datasets compiled in this study, the scaling relation obtained by Blaser et al (2010) predicts a larger fault rupture area. This type of discrepancy may result from a difference between the rigidity of the upper crust of continental lithosphere and the upper mantle of oceanic lithosphere. For most continental earthquakes, the fault rupture is confined in the upper crust (e.g. Shimazaki 2013; Watts and Burov 2003). However, faults of outer-rise earthquakes can extend into the upper mantle. The rigidity of the upper mantle is considerably greater than that of the continental crust (Mooney et al 1998). Therefore, lower rigidity is a reason for the larger fault-rupture area predicted by the scaling relation for normal earthquakes obtained by Blaser et al (2010). This suggests that the scaling relation for normal fault earthquakes in the continental region is not suitable for evaluating the rupture area of normal fault earthquakes in the outer-rise region.

In the previous studies discussed above, straight scaling relations were obtained directly from the rupture area and seismic moment datasets. To obtain a scaling relation directly from large outer-rise earthquake datasets, it is better to have more datasets than we have compiled here. Unfortunately, due to the rarity

of large outer-rise earthquakes, the data quantity is unlikely to increase substantially in the near future.

The sparse data problem can be partially overcome by adopting a physically based method using the circular crack model (Kanamori and Anderson 1975) and fault width saturated model demonstrated in this study, which sets regression parameter b a priori.

M_w^s in this study is determined from the upper limit of the down dip tip depth of an outer-rise earthquake fault, which is equal to the thickness of the oceanic lithosphere in the outer-rise region near the Japan Trench (70 km) as suggested by Kanamori (1971). However, Obana et al (2012) suggested that the tensional stress regime extended to a 40 km depth after the 2011 Tohoku earthquake. A scaling relation assuming 40 km for the upper limit of the down dip tip depth can be easily obtained using M_w^s corresponding to a rupture area of 70 km $\times$ 70 km.

Conclusions

We compiled the data on rupture area and seismic moment from previous studies and finite fault slip models to create a new scaling relation for outer-rise earthquakes. The rupture areas of the finite fault slip models were estimated based on the definition of the autocorrelation width (Bracewell 1986). Because the fault width, except for the 1933 Sanriku-oki earthquake, are perhaps not saturated, the entire dataset can be fit by a scaling relation with a slope of 2/3 (i.e. the rupture area is proportional to two-thirds the power of seismic moment). To create a scaling relation for both small and large outer-rise earthquakes, we fit the rupture area and seismic moment by constraining the scaling relation with two different slopes, which provides better estimation for the outer-rise earthquakes larger than the 1933 Sanriku-oki earthquake (M_w 8.4).

List of abbreviations

- RMSE: Root Mean Squared Error
- SD: Standard Deviations
- USGS: United States Geological Survey
- NEIC: National Earthquake Information Center

Declarations

Availability of data and materials

One of the discretized finite fault model data for 2007 Kuril earthquake and 2012 Sanriku-oki earthquake were provided by Prof. Thorne Lay and Prof. Tomoya Harada. Other discretized data of finite fault slip models were downloaded from the website of USGS (<https://www.usgs.gov/natural-hazards/earthquake-hazards>) and SRCMOD (<http://equake-rc.info/srcmod/>).

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

X.Z. T.K. ,K.H., Y.D. and H.F conceived of the presented idea. X.Z. collected the data with support from T.K. ,K.H. and Y.D. X.Z. performed the calculations and wrote the manuscript with input from all authors. All authors provided critical feedback and helped shape the research, analysis and manuscript.

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Preparing illustrations and figures

- (1) **Figure 1:** Slip distribution of an outer-rise earthquake and effective dimension of the finite fault slip model; Slip distribution of the 2010 outer-rise earthquake in the Bonin Islands region from Hayes (NEIC, Bonin 2010). The black heavy lines in the bottom and right panels, respectively, show the autocorrelation length and width. The black fine lines in the bottom and right panels are the slip function. The location of the black heavy lines is determined to cover the area with large slip. The epicenter of the earthquake is zero along strike and dip
- (2) **Figure 2:** Distribution of the root mean square error for the rupture area; Distribution of the root mean square error for the rupture area. (i.e. $RMSE = \sqrt{\frac{1}{n} \sum_{i=0}^n (\log_{10} S - \log_{10} S_c)}$, where S is the

rupture area from Table 1 and S_c is the rupture area calculated from the scaling relation)

(3) **Figure 3:** Comparison of the scaling relations and data; Comparison of the scaling relations and data, the red solid line is the scaling relation obtained by this study and red dashed lines represent the standard deviation on a log-log scale, black dotted line is obtained by Goda et al (2016), black dotted-dashed line is obtained by Blaser et al (2010), and black dashed line is obtained by Álvarez Gómez et al (2012). Red circles are the source parameters directly taken from previous literature and red triangles are the source parameters estimated from finite fault slip models.

Figure 1

Figure 2

Figure 3

Figures

Figure 1

2

Figure 1

Slip distribution of an outer-rise earthquake and effective dimension of the finite fault slip model; Slip distribution of the 2010 outer-rise earthquake in the Bonin Islands region from Hayes (NEIC, Bonin 2010). The black heavy lines in the bottom and right panels, respectively, show the autocorrelation length and width. The black thin lines in the bottom and right panels are the slip function. The location of the black heavy lines is determined to cover the area with large slip. The epicenter of the earthquake is zero along strike and dip

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