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Seismic Source Characterization for Future Earthquakes

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1. Introduction

Although the great advance in science and technology, currently there is no available methodology to predict an earthquake. One of the most important task in seismology is the develop of methodologies that allow predict and simulate strong ground motions. High accelerations are produced by earthquakes of large magnitude in urban areas located in relative close proximity to seismic sources. Strong ground motions allows to generate models that are necessary to understand the seismic source and to generate response spectra, both useful information in structural engineering.

One of the methodologies to simulate strong ground motion produced for big earthquakes is the empirical Green's function method (EGFM). This method developed by Irikura (1986), requires a small magnitude earthquake with hypocenter near to the main earthquake. An important characteristic of the EGFM is that information of structure and site effects are included in the simulations, since records of the element event used as seeds already include them. This means that instrumentation and detailed studies to know the cortical structure and site effect are not necessary. Another important characteristic of the EGFM is that allow model in the frequency interval of 1-10 Hz, in this range many buildings, bridges and civil constructions have their dominant vibration periods.

EGFM is a methodology applied in Mexico to simulated different big earthquakes. Applying this methodology, Garduño (2006) generate a source model for July 15, 2006 earthquake in the state of Guerrero Mexico, Aguirre Gonzalez (phone inquire) generate a source model for April 25, 1989 San Marcos Mexico earthquake, and Ramirez-Gaytán *et al.* (2010) applying this methodology generate a source model for January 22, 2003 Tecoman earthquake.

In these three different studies the relationships proposed by Somerville *et al.* (2002) for subduction earthquakes was applied. Somerville *et al.* (2002) relationships related the seismic moment with inner and outer source parameters. The comparison between the inner and outer parameters generated in these 3 different simulations, show poor adjust with Somerville *et al.* (2002) relations. The fit in some cases are minor to 27% respect to proposed by Somerville *et al.* (2002). The results obtained in the studies mentioned above might

suggest that not all of the relationships proposed by Somerville *et al.* (2002) are applicable to the subduction zone in Mexico.

Under this premise, an immediate doubt arises: Somerville *et al.* (2002) relationships are appropriate to be applied in the simulation of strong ground motion for Mexico subduction zone?

In the first part of this document we show an interesting application of the application of EGFM in Mexico conducted by Ramirez-Gaytan *et al.* (2010). In this study we take the strong ground motions generated in the model with best fit. Although of good fit the principal values of inner and outer parameters of source are shorter comparing with Somerville *et al.* (2002) relations. As consequence of these results, in the second part of this document we show the results of the investigation conducted to estimate a new relationships between seismic moment versus inner and outer seismic source parameters, but with the particularity that in this case we use only data from Mexican subduction earthquakes.

2. Tecomán earthquake: Physical implications of seismic source modeling, applying the empirical green's function method

In the study of Ramirez-Gaytan *et al.* (2010) a source model for Tecomán Mexico earthquake (21 January 2003, 20:06) was generated. The presence of soft soils and the location of 8 of the

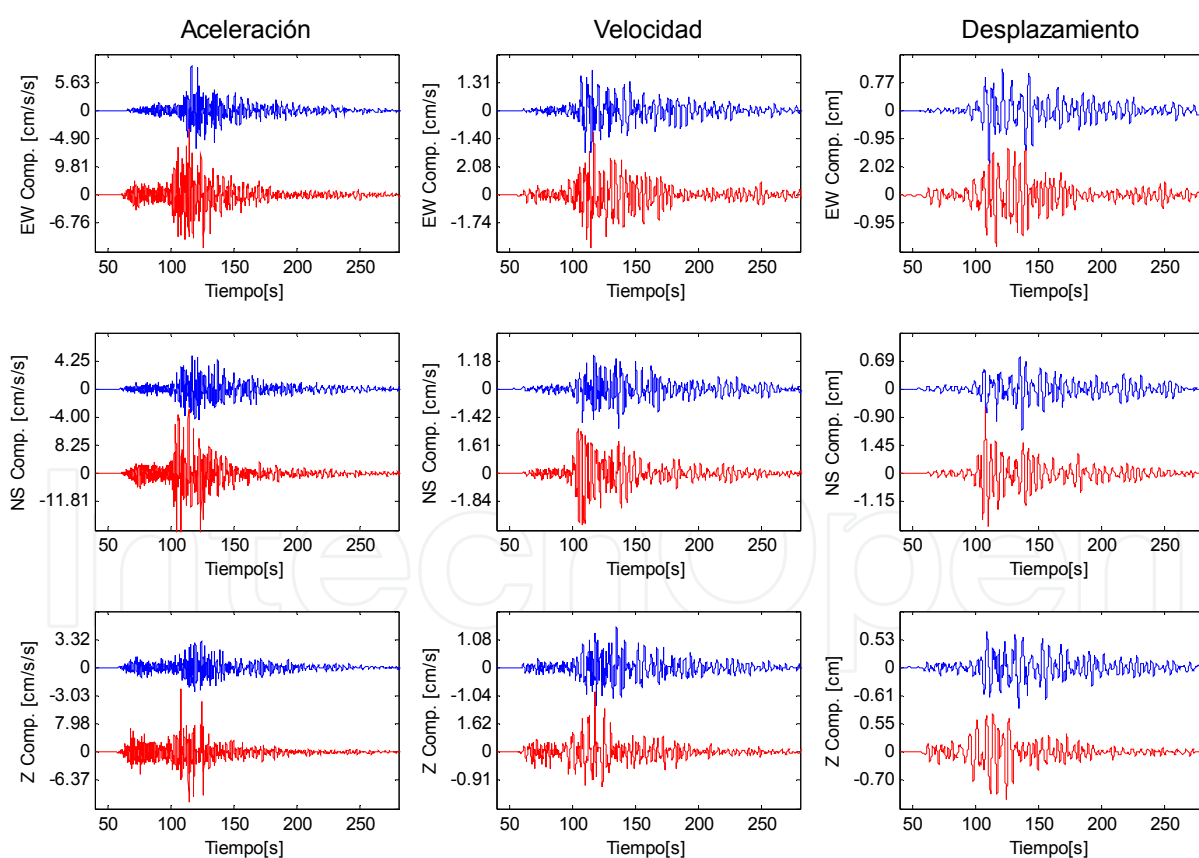


Fig. 1. Comparison between synthetics and observed records. Shown in Blue, synthetics records simulated using empirical Green's function method. Shown in red, observed records. Columns from left to right: acceleration, velocity, and displacement. Rows from top to bottom: EW, NS, and Z components.

10 major cities of Colima state where the earthquake spread are important factors to model the seismic source. To generate the model applied to the empirical Green's function method (EGFM) the Tecomán earthquake ($M_w = 7.5$) was used as target event and, the November 19, 2006 ($M_w = 5.5$) earthquake was used as element event.

In this investigation data from 4 broad band and 1 acceleration sensor of regional stations were used. These five stations provided good azimuthal coverage of Tecomán earthquake. The process of modeling the target event was done in 4 stages, each one involving one, two three and four SMGA for each stage respectively. The observed waveforms were adjusted gradually by the synthetics waveforms and the residual values progressively decreased in each stage from 1 to 3 SMGA's. The model with 4 SMGA showed an increased value in residual and poor adjustment. Thus the best fitting was obtained by modeling the target event with 3 SMGA. This model presents the best fit in terms of the lowest residual. In addition to the above, the model keeps a close resemblance with the dislocation model found by Yagi *et al.* (2004).

At the recording site of MANZ, the authors made a spectral analysis to compare weak and strong ground motions in order to identify if some energy is biased concentrated at certain frequencies in the interval of 1-10 Hz. The synthetics waveforms and Fourier spectrums shown in figures 1 and 2 show a good fitting with the observed ones in the five stations. The latter roughly corresponds to the dislocation model found by Yagi *et al.* (2004).

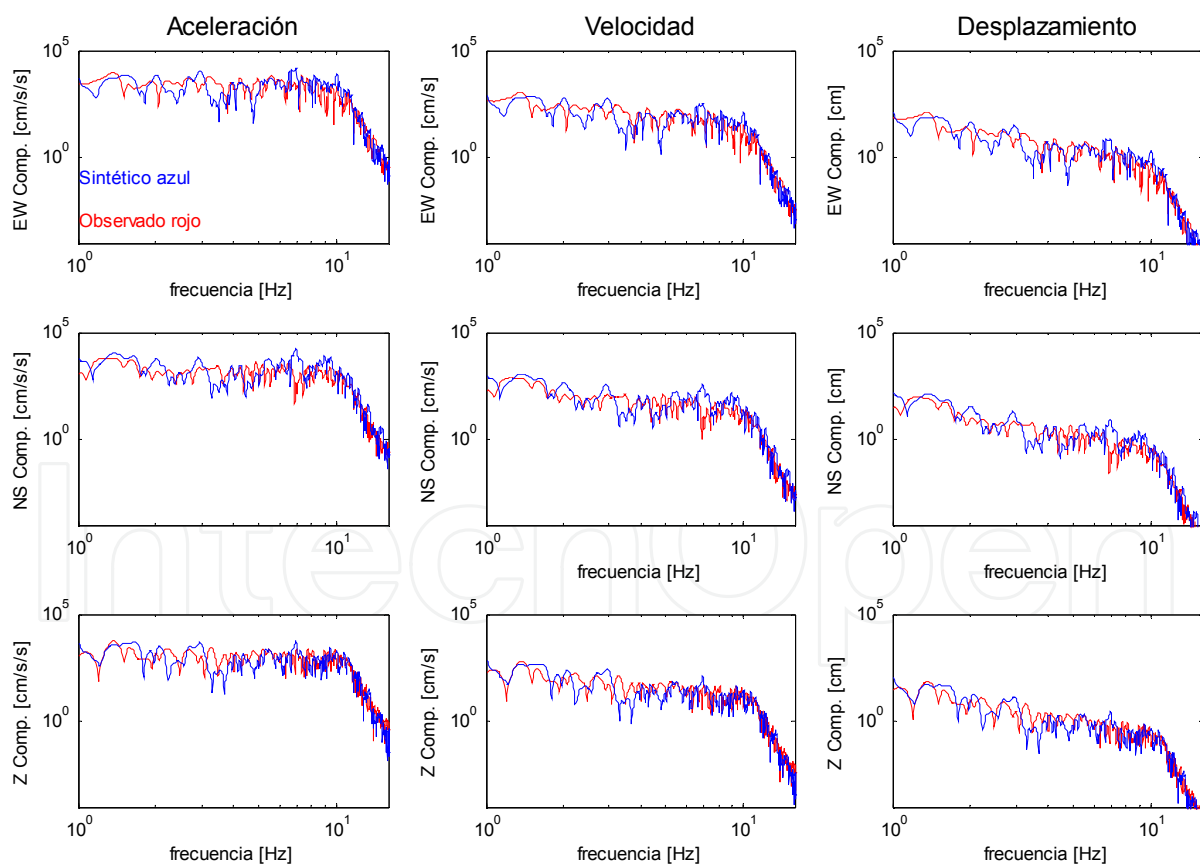


Fig. 2. Comparison between synthetics and observed Fourier spectra. Blue color, synthetics Fourier spectra simulated using EGFM. Red color, observed fourier spectra. Columns from left to right: acceleration, velocity, and displacement. Rows from top to bottom: EW, NS, and Z components.

As part of our investigation we quantified individual and average characteristics of SMGA, rupture area, dislocation time and rise time. These values are related against the seismic moment of these events ($M_0 = 1.6 \times 10^{20}$ Nm); the results obtained were compared with relationships proposed by Somerville *et al.* (2002) for subduction earthquakes (table 1). These relationships involved the seismic moment (M_0), the fault area, dislocation time, and the rise time. In addition to the above the seismic moment and the following characteristics of SMGA: total area of the SMGA were considered in the comparison, area of bigger SMGA, radius of bigger SMGA, and distance from hypocenter to nearest SMGA.

	A: This study	B. Somerville <i>et al.</i> (2002)	C. Ratio (=A/B)
Rupture area	5.95E+03	8.01E+03	7.43E-01
Dislocation time	3.00E+01	4.80E+00	6.25E+00
Rise time	4.00E-01	2.38E+00	1.68E-01
Total area of SMGA	7.40E+01	2.00E+03	3.70E-02
Area of largest SMGA	3.55E+01	1.30E+03	2.73E-02
Radio of largest SMGA	3.36E+00	2.20E+01	1.53E-01
Hypocentral distance of nearest SMGA	1.37E+01	2.10E+01	6.53E-01

Table 1. Comparison (column C) between the relationship proposed by Somerville *et al.* (2002) for subduction earthquakes (column B) and the results of this study (column A).

The results of these comparisons show that the relationships between M_0 and rupture area, M_0 and hypocentral distance to the nearest asperity, adjust moderately well, which is not the case for the rest of the relationships described above. As commented before, studies conducted by others investigators to simulate Mexican earthquakes show the same poor adjust with Somerville *et al.* (2002) relations. The next doubt arises: Somerville *et al.* (2002) relations are appropriate to be applied in the simulation of strong ground motion for Mexico subduction zone?. To answer the last question we conducted a study to estimate new relationships using only data from Mexican subduction earthquakes.

3. Source scaling relationship of Mexican subduction earthquakes for the prediction of strong ground motions

In this study authors use fault slip models from Mexican subduction zone to investigate the source scaling relationships, and made a global compilation of source parameters to examine their relationships with Seismic Moment.

In the past, for several years many studies have been carried out to investigate source scaling of earthquakes whose objective is to understand the self similarity. This is an important topic in the develop of source scaling relationships. These relationships provide a way to understand the rupture mechanism, also provide deterministic parameters in the prediction of strong ground motions. The heterogeneities in the slip and stress drop distributions controls the generation of source ground motion, proving then that are important to characterize the heterogeneities of past earthquakes in constructing a source model for reliable prediction of strong ground motions.

A quantitative criteria for the rupture area estimation and asperity area from large subduction earthquakes was proposed by Somerville *et al.* (2002). In their criteria, the

asperity is defined as a rectangular area whose slip is 1.5 or more times larger than the average slip over the fault. In their study, Somerville *et al.* (2002) compiled the slip models of ten large subduction earthquakes, and obtained empirical scaling relationships between inner and outer source parameters as well as seismic moment. In other hand, Miyake *et al.* (2003) used broadband strong ground motion simulations. In that study they 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, coincides spatially with the location of asperity or the large slip area of the heterogeneous kinematic slip models.

In our study, we construct the scaling relationship of the source parameters, and compiled slips models of 9 large earthquakes in Mexican subduction zone from kinematic slip models developed by several investigators. Our objective was to make a comparison between this new relationships that use only data from Mexican subduction earthquakes versus Somerville *et al.* (2002) who uses data from large subduction earthquakes world wide. The earthquakes and source parameters analyzed in our study are listed in table 2 and are shown in figure 3.

No	Eartquake	Date (dd/mm/yy)	Depth* (km)	Mw*	Mo * (dina-cm)	Area * (km ²)	Strike; Dip; Rake * (°)	Reference
1	Michoacán	19/09/1985	17.00	8.01	1.10 E + 28	25020	300; 14; 72	Mendoza and Hartzell (1989)
2	Manzanillo	09/10/1995	15.00	7.96	1.15 E + 28	17000	309; 14; 92	Mendoza and Hartzell (1999)
3	Michoacán	11/01/1997	40.00	7.10	6.06 E + 26	1312.5	292; 18; -106	Santoyo <i>et al.</i> (2005)
4	Petatlán	14/03/1979	15.00	7.39	1.72 E + 27	14400	293; 14; 90	Mendoza and Hartzell (1997)
5	Playa Azul	25/10/1981	15.00	7.25	7.00 E + 26	2700	300; 14; 90	Mendoza <i>et al.</i> (1993)
6	San Marcos	25/04/1989	15.00	6.90	2.39 E + 26	2520	276; 10; 66	Zuñiga <i>et al.</i> (1993)
7	Tecomán	22/01/2003	20.00	7.50	2.05 E + 27	5950	300; 22; 93	Yagi <i>et al.</i> (2004)
8	Zihuatanejo	21/09/1985	20.00	7.42	2.49 E + 27	3500	300; 14; 100	Mendoza <i>et al.</i> (1993)
9	Oaxaca	30/09/1999	40.00	7.47	1.72 E + 27	3712.5	295; 50; -82	Castro R and Euclides Ruiz (2005)

Table 2. Source parameters of nine large subduction earthquakes used in this study.

A rectangular geometry of the fault was utilized for the finite fault. The rupture area and asperity area were extracted following the procedure proposed by Somerville *et al.* (1999). The definition of asperity used in this study follows the one proposed by Somerville *et al.* (1999). An asperity is defined to enclose fault elements whose slip is at least 1.5 times larger than the average slip over the fault and is subdivided if any row or column has an average slip less than 1.5 times the average slip. The asperity is then trimmed until all of the edges have an average slip equal or larger than 1.25 times the slip averaged over the entire rupture area. The discretization of the fault into fault element, place limits on the size of the smallest asperity. In view of this discretization that requires an asperity to have a minimum of two elements if the slip of each is 2 or more times the average slip; a minimum of 4 elements if the slip of each is 1.5 or more times the average slip, or the slip of one is 2 or more or the slip of two others is 1.5 or more times the average slip.

The 9 earthquakes have a total of 20 asperities, with earthquakes composed from 1 to 5 asperities. Total number of asperities of the 9 the earthquakes was 20 with an average of 2.22 asperities. For irregular shape asperities, the procedure of Somerville *et al.* (1999) can

generate contrasting solutions depending upon whether we start with row-wise or column-wise operations. In this case we mainly make subjective selection of the best solution based on our knowledge of the earthquake. This subjective selection generally works well and produces a reasonable value for the combined area of asperities.

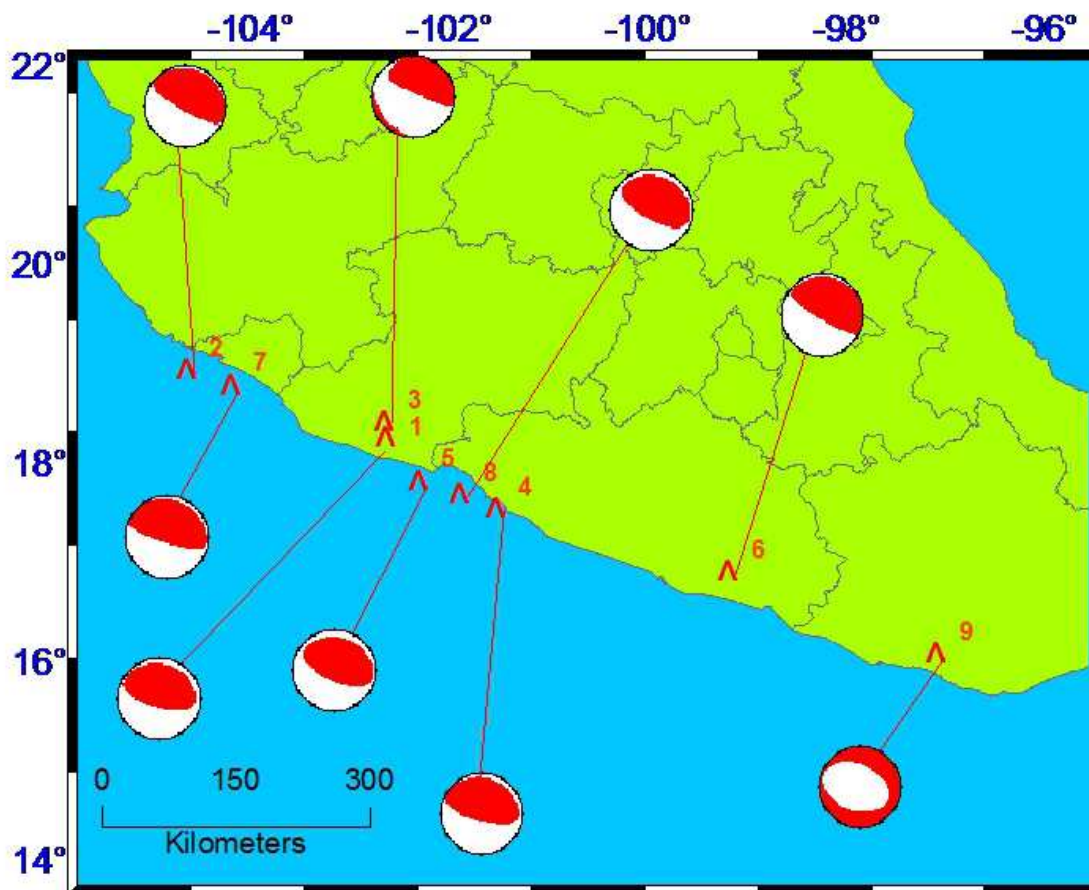


Fig. 3. Distribution of earthquakes used in this study and corresponding focal mechanism.

We carried out regression analyses of the obtained fault parameters for the large subduction Mexican earthquakes listed in table 2 with moment magnitudes range from M_w 6.9 to 8.1. We compared fault parameters with those for large subduction world - wide earthquakes of M_w 7.1 to 8.1 summarized by Somerville *et al.* (2002).

Table 3 show the relationship between seismic moment and each seismic source parameter obtained in this study. These scaling relationships are important for establishing general rules for developing source models for simulating strong ground motions. For each parameter it is first shown the unconstrained equation, followed by the constrained equation to be self similar. The self similar model is convenient to use, and in many instances its use can be justified because provides a reasonable good description of nature Somerville *et al.* (1999).

In this study of large subduction Mexican earthquakes, we find that the scaling of fault parameters with seismic moment fit reasonably well by a self similar model. For the case of the relation of average slip versus seismic moment the unconstrained relation suggest a nonself-similar scaling, for this case the physical interpretation suggest the absence of scale factor in the average slip of Mexican subduction earthquakes.

Rupture area vs. seismic moment.	$A=3.69 \times 10^{-15}M_o^{2/3}$
Average slip vs. seismic moment.	$D=6.60 \times 10^{-8}M_o^{1/3}$
Combined area of asperities vs. seismic moment.	$A_2=6.56 \times 10^{-16}M_o^{2/3}$
Area of largest asperity vs. seismic moment.	$A_l=4.96 \times 10^{-16}M_o^{2/3}$
Average number of asperities	2.2
Area of fault cover by asperities	0.194
Average slip contrast	2.42
Hipocentral distance to center of closets asperities vs. seismic moment.	$R_A=8.84 \times 10^{-9}M_o^{1/3}$
Hipocentral distance to center of largest asperities vs. seismic moment.	$R_a=1.19 \times 10^{-8}M_o^{1/3}$
Slip duration vs. seismic moment.	$A_l=2.11 \times 10^{-9}M_o^{1/3}$

Table 3. Scaling relations of slip models is assuming self similarity.

3.1 Average slip versus seismic moment

The relationship between average slip D and seismic moment determined without constraining the slope is:

$$D = 6.35 \times 10^{-2}M_o^{0.1138}$$

Constraining the slope to be 1/3, the relation is:

$$D = 6.60 \times 10^{-8}M_o^{1/3}$$

As show in figure 4 comparisons of constrained equations indicates that the estimated average slip of large Mexican subduction earthquakes is larger than constrained equation provided by Somerville *et al.* (2002).

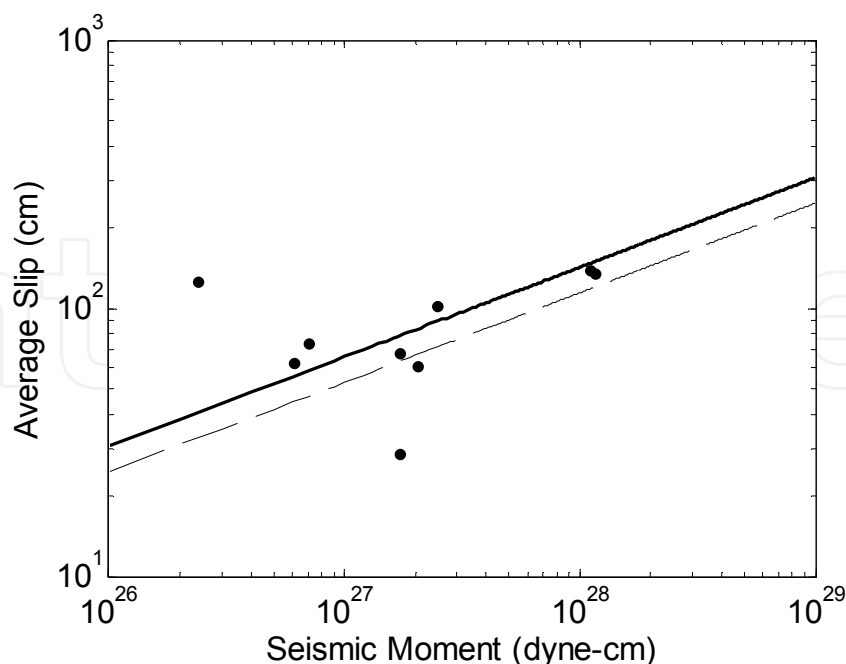


Fig. 4. Relationship between average slip and seismic moment. Dots represent individual events, solid line is the result of this study and dashed line represents the results obtained by Somerville *et al.* (1999).

3.2 Rupture area versus seismic moment

The relationship between rupture area A and seismic moment determined without constraining the slope is:

$$A = 8.96 \times 10^{-15} M_0^{0.6525}$$

Constraining the slope to be $2/3$, the relation is:

$$A = 3.69 \times 10^{-15} M_0^{2/3}$$

As show in figure 5, comparison of constrained equation indicates that the estimated rupture area of large Mexican subduction earthquakes is shorter than constrained equation provided by Somerville *et al.* (2002).

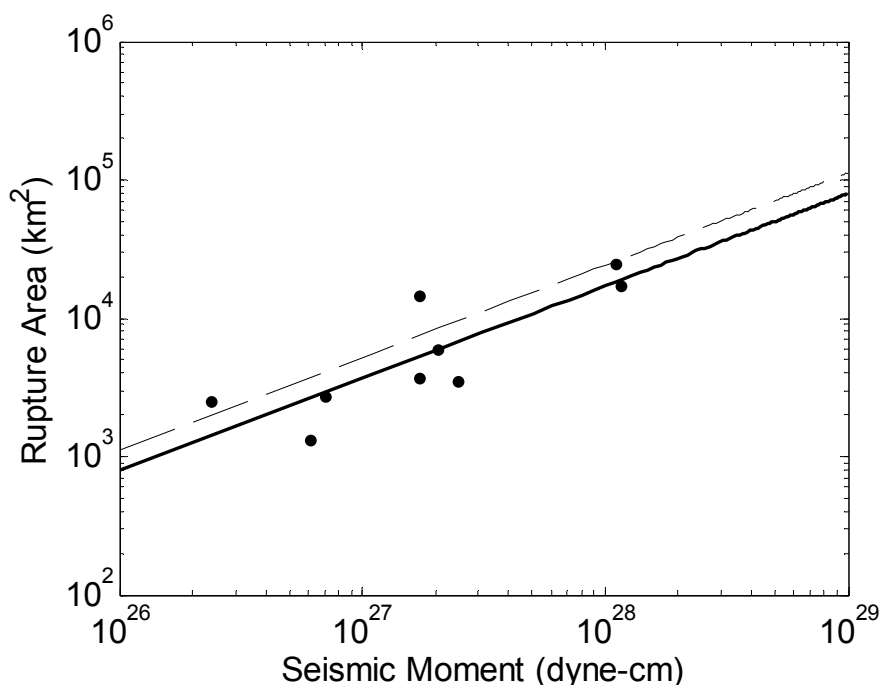


Fig. 5. Relationship between rupture area and seismic moment. Dots represent individual events, solid line is the result of this study and dashed line represents the results obtained by Somerville *et al.* (1999).

3.3 Combined area of asperities versus seismic moment

The relationship combined area of asperities A_2 and seismic moment determined without constraining the slope is:

$$A_2 = 6.21 \times 10^{-18} M_0^{0.7409}$$

Constraining the slope to be $2/3$, the relation is:

$$A_2 = 6.56 \times 10^{-16} M_0^{2/3}$$

As show in figure 6, comparison of constrained equation indicates that the estimated combined area of asperities of large Mexican subduction earthquakes is shorter than constrained equation provided by Somerville *et al.* (2002).

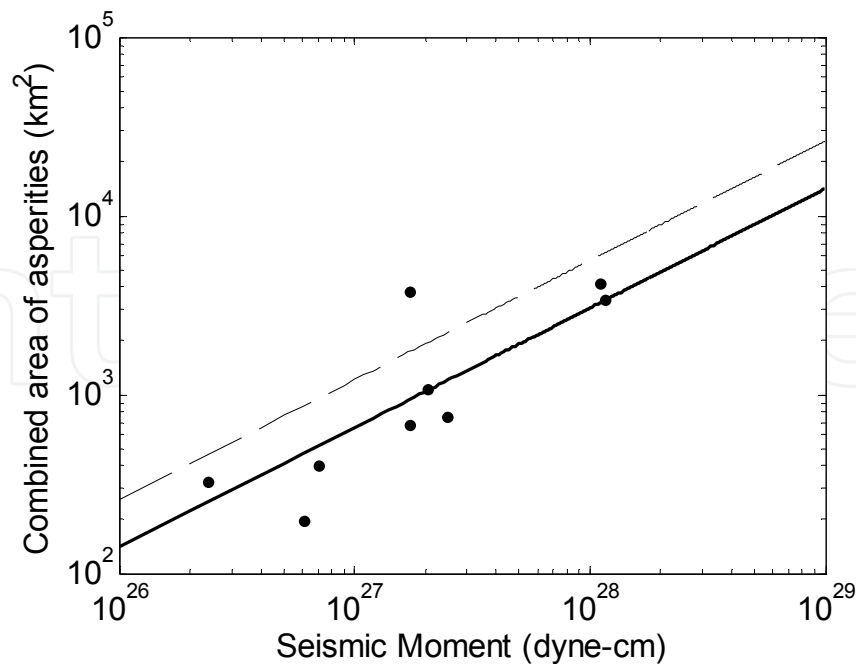


Fig. 6. Relationship between combined area of asperities and seismic moment. Dots represent individual events, solid line is the result of this study and dashed line represents the results obtained by Somerville *et al.* (1999).

3.4 Area of largest asperity versus seismic moment

The relationship between the area of largest asperity A_l and seismic moment determined without constraining the slope is:

$$A_l = 2.11 \times 10^{-15} M_0^{0.6436}$$

Constraining the slope to be $2/3$, the relation is:

$$A_l = 4.96 \times 10^{-16} M_0^{2/3}$$

As show in figure 7, comparison of constrained equation indicates that the estimated area of largest asperity of large Mexican subduction earthquakes is shorter than constrained equation provided by Somerville *et al.* (2002).

3.5 Hipocentral distance to center of closets asperity versus seismic moment

The relationship between the hipocentral distance to the closes asperity R_A and seismic moment determined without constraining the slope is:

$$R_A = 2.61 \times 10^{-6} M_0^{0.2427}$$

Constraining the slope to be $1/3$, the relation is:

$$R_A = 8.84 \times 10^{-9} M_0^{1/3}$$

As show in figure 8, comparison of constrained equation indicates that the estimated hipocentral distance to closest asperity of large Mexican subduction earthquakes is shorter than constrained equation provided by Somerville *et al.* (2002).

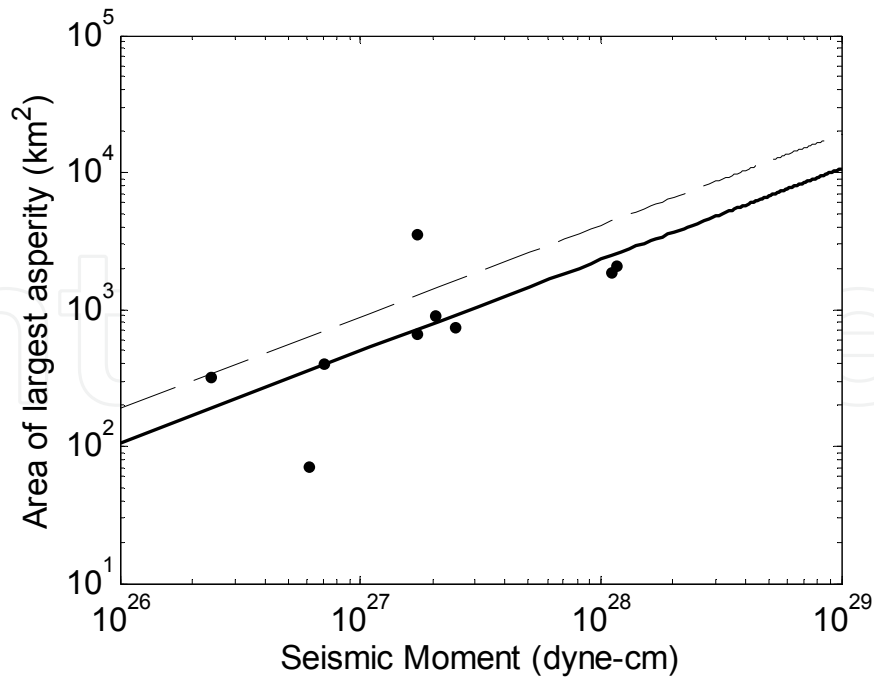


Fig. 7. Relationship between area of largest asperity and seismic moment. Dots represent individual events, solid line is the result of this study and dashed line represents the results obtained by Somerville *et al.* (1999).

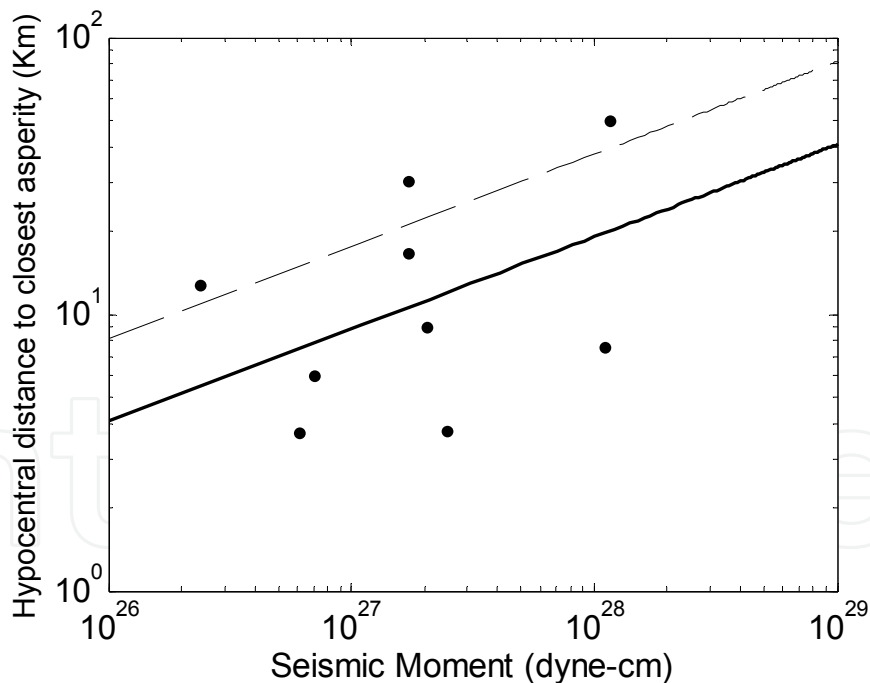


Fig. 8. Relationship between distance from de hypocenter to the center of the closest asperity and seismic moment. Dots represent individual events, solid line is the result of this study and dotted line represents the results obtained by Somerville *et al.* (1999).

The comparison between the parameters estimated both relations compared here, shows that the relationships proposed in this study provides lower estimation than relations proposed by Somerville *et al.* (2002), particularly in the cases of the total rupture area and

the combined area of asperities. Curiously only in the case of average slip the relationship proposed in this study provides larger estimation than the relationship proposed by Somerville *et al.* (2002). The relationship between seismic moment versus total rupture area and seismic moment versus average slip for large Mexican subduction earthquakes might explain the result obtained by Ramirez-Gaytán *et al.* (2010), Garduño (2006) and Aguirre Gonzalez in the simulation of April 25, 1989 San Marcos Mexico earthquake. If seismic moment is the result of the product of area, average slip, and rock shear modulus, then a decrease in the area of seismic source and combined area of asperities implies a necessary increase of average slip in order to keep a similar seismic moment. However in this case (the relationship of average slip versus seismic moment) the unconstrained relationship show a no self-similar scaling, this suggest the absence of common or constant scale factor in the average slip of Mexican subduction earthquakes.

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Earthquake Research and Analysis - New Frontiers in Seismology

Edited by Dr Sebastiano D'Amico

ISBN 978-953-307-840-3

Hard cover, 380 pages

Publisher InTech

Published online 27, January, 2012

Published in print edition January, 2012

The study of earthquakes combines science, technology and expertise in infrastructure and engineering in an effort to minimize human and material losses when their occurrence is inevitable. This book is devoted to various aspects of earthquake research and analysis, from theoretical advances to practical applications. Different sections are dedicated to ground motion studies and seismic site characterization, with regard to mitigation of the risk from earthquake and ensuring the safety of the buildings under earthquake loading. The ultimate goal of the book is to encourage discussions and future research to improve hazard assessments, dissemination of earthquake engineering data and, ultimately, the seismic provisions of building codes.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Jorge Aguirre Gonzales, Alejandro Ramirez-Gaytán, Carlos I. Huerta-López and Cecilia Rosado-Trillo (2012). Seismic Source Characterization for Future Earthquakes, *Earthquake Research and Analysis - New Frontiers in Seismology*, Dr Sebastiano D'Amico (Ed.), ISBN: 978-953-307-840-3, InTech, Available from: <http://www.intechopen.com/books/earthquake-research-and-analysis-new-frontiers-in-seismology/-seismic-source-characterization-for-future-earthquakes>

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