EARTHQUAKE SOURCE PARAMETERS FOR SUBDUCTION ZONE EVENTS CAUSING TSUNAMIS IN AND AROUND THE PHILIPPINES

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ABSTRACT

We have made a set of earthquake source parameters for events which can occur in subduction zones surrounding the Philippines and cause large tsunamis and damages. The earthquake source parameters consist of location of fault (longitude, latitude, depth), fault length, fault width, strike angle, dip angle, rake angle, and slip amount, and the maximum plausible earthquake magnitude for each fault segmentation. To set these parameters, first we collated tsunami databases and reviewed the historical tsunamigenic events with other studies such as re-evaluation of historical records and magnitudes. Then, we reviewed seismicity data and Global Centroid Moment Tensor solutions. We followed the segmentation set by Bautista, and set the maximum plausible magnitude, fault width and slip amount following the scaling laws. We also utilized some geophysical studies such as slab dip models, geometry of subducting slabs, and recent studies on Global Positioning System (GPS) and plate motions.

Combining all the above-mentioned information, we identified six source regions (Manila Trench, Negros Trench, Sulu Trench, Cotabato Trench, East Luzon Trough, and the Philippine Trench) with 17 segments surrounding the Philippines. Then, we set the earthquake source parameters for these 17 segments.

These sets of earthquake source parameters can be used as input data to tsunami simulation, the results of which will be used for further tsunami hazard assessment studies that are now under implementation.

Keywords: Tsunami, Source Parameters, Subduction, Trench.

1. INTRODUCTION

Due to the present geographic and tectonic setting of the Philippines, it is prone to various natural hazards on the earth such as hydro-meteorological and geologic hazards. Earthquakes cause hazards that affect the Philippine community such as ground rupture, ground shaking, landslides, and tsunami. There are also some of the most active volcanoes of the world in the Philippines. Historical and instrumental data show evidences of their activities. Human-induced hazards and environmental hazards are also causing disasters in the Philippines.

The Philippines is located in an active seismic source zone. Both inland and offshore earthquakes are generated in the Philippine seismic source regions. Based upon the factors such as being an archipelago, seismically active nature due to active earthquake sources, along with occurrence of past tsunamis, we could say that the Philippine region is very prone to tsunami and tsunami hazards.

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2. SETTING OF EARTHQUAKE SOURCE PARAMETERS

2.1 Aim of this study

The setting of earthquake source parameters is one of the most important components of tsunami numerical modeling. This study identified some tsunami sources in subduction zones around the Philippines that might generate large tsunamis, possibly imposing damages on the Philippines. Then we produced a set of parameters of these earthquake sources as input data to tsunami simulation, the results of which will be effective for further tsunami hazard assessment studies.

2.2 Review of Tsunami Databases

Earthquake and Tsunami catalogues were collated to review the past tsunamigenic earthquakes that affected the Philippines and to identify the earthquake source regions. Three catalogues are considered: they are the NOAA-WDC Tsunami Event Database (National Geophysical Data Center-National Oceanic and Atmospheric Administration (NGDC-NOAA, http://www.ngdc.noaa.gov), Catalogue of Damaging Earthquakes in the World (Through 2008) maintained by the International Institute of Seismology and Earthquake Engineering (IISEE-Utsu, iisee.kenken.go.jp/utsu/index_eng.html), and the Philippine Tsunamis and Seiches, 1589 to 2004 (Bautista et al. in press). For source location both for NGDC and IISEE-Utsu, we considered 4° to 22° latitude and 116° to 129° longitude. For depth and magnitude, if no values are selected, the assumed minimum and maximum values are assigned. For Bautista et al. catalogue, no parameters are set as the catalogue contains only the Philippine tsunamis and seiches.

Each event was carefully evaluated to assess the validity and to identify the source regions. A paper by Berninghausen (1969) was also reviewed to validate some historical records. His paper was later discussed by Cox (1970) since Berninghausen (1969) did not use most of the existing catalogues at that time. The Catalogue of the Philippine Earthquake (South East Asia Association of Seismology and Earthquake Engineering, SEASEE, 1985) was also used to get information on the earthquake effects especially those events with conflicting locations, the accounts from this database was used to expertly judge the most possible location of events.

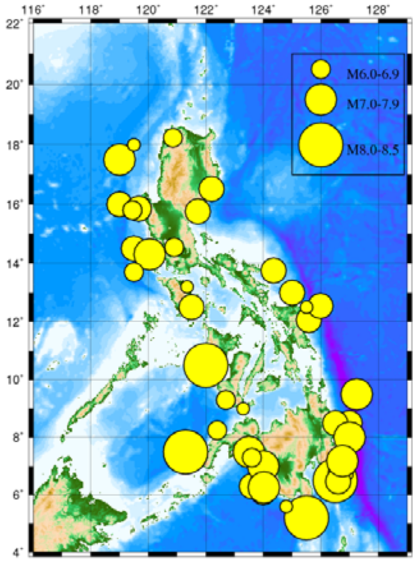

Figure 1. Map of epicenters for the final list of events considered for each earthquake source segments analysis

Works by Abe (1981) and Abe and Noguchi (1983) on magnitudes of large shallow earthquakes from 1904 to 1980 and 1897 to 1912, respectively were considered in this database analysis to set the most plausible magnitude for events in late 19th and early 20th centuries.

Many factors were considered in the database analysis; the final summary includes only the events that will be used for this study. Some of the events that were eliminated are tsunami events caused by volcanoes, those that are considered doubtful by some authors, and events with inland earthquake source. In summary, a total of 72 events were considered after eliminating some events based on the above-mentioned criteria.

As for the preliminary list of the events, it includes more than one set of earthquake parameters for many events. Thus, we have chosen the most plausible parameters for each event for further analysis. Basically, we refer to the bathymetry of the area to set the plausible location. If available, we also refer to information on intensities and damages. We also considered consistency among the reviewed catalogues. We chose the highest magnitude sometimes. Figure 1 is the map of epicenters of the events in the final list used for each earthquake source segment analysis.

2.3 Earthquake Source Characterization

2.3.1 Earthquake Source Region

Earthquake source regions were identified based on the database reviewed in the previous section, seismicity, and bathymetry. Figure 2 shows the source regions for which we set earthquake source parameters in this study. This study concentrates on the subduction zones and their interplate thrust events that can generate tsunamis and cause damages to the Philippines. We follow the segmentation given by Bautista (DOST-GIA Tsunami Risk Mitigation Project 2007). Table 1 shows the names of the trenches, their codes, and the number of segments.

Table 1. List of earthquake sources, its codes, and number of segments

Name of the Earthquake Source	Code	Number of Segments
Manila Trench	MT	4
Negros Trench	NT	2
Sulu Trench	ST	2
Cotabato Trench	CT	2
East Luzon Trough	ELT	1
Philippine Trench	PT	6
Total number of segments		17

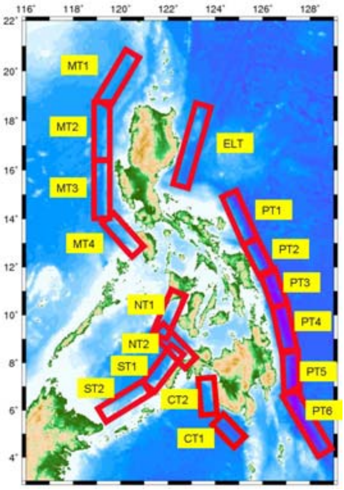

Figure 2. Earthquake source regions

2.3.2 Earthquake Source Parameterization

The following earthquake source parameters are considered in this study: location of the fault (longitude, latitude, top depth), fault length, fault width, strike angle, dip angle, rake angle, and slip amount. In addition, the maximum credible earthquake magnitude is also estimated.

Aside from the historical tsunami review, a survey of earthquake source parameters for instrumentally recorded events was done by reviewing recent earthquake databases. We downloaded seismicity data from the International Seismological Center (ISC) (http://www.isc.ac.uk). The data covers the region of 4^o to 22^o in latitude and 116^o to 129^o in longitude, period of January 1964 to April 2008, with magnitude 2.0 to 7.8, and depth range of 0 to 700 km; the total number of the events is 19,133. The SEIS-PC (Nakamura and Ishikawa 1997) was used for seismicity analysis. We also downloaded data from the Global CMT (Centroid Moment Tensor) Solution database (http://www.globalcmt.org/CMTsearch.html). The search parameters are as follows: the period January 1976 to May 2010, 0 to 10 in magnitude, depth of 0 to 100 km, and for the area, the region includes the computed area of each segment. We selected events with thrust mechanisms following Frohlich and Apperson (1992).

Location of the fault (longitude and latitude) and Depth

The location of the earthquake source is estimated based on the bathymetry, seismicity, CMT solutions, and previous studies such as segmentation by Bautista (DOST-GIA Tsunami Risk Mitigation Project 2007). The corner location of the fault is estimated based on the above-mentioned data. The source region was specified by the corner location, the length, and the width of the fault.

The depth of the earthquake source is based on historical and recent seismicity of the region. Cross-sections of seismicity are studied for each segment. In this study, we provide a table for the case when the depth of the top of the fault is 0 km. When the depth of the bottom of the fault plane exceeds a certain value (say, 60 km), it will be necessary to change the width, since significant co-seismic slips at such depths are not expected. In this study, when the depth of the bottom of the fault plane exceeds 60 km, we change the width so that the bottom depth is 60 km. Then, we recalculate the slip amount following the scaling law of Papazachos et al. (2004), which is explained below, and then the corresponding seismic moment and magnitude. This procedure is applicable when the top depth is changed.

Fault length, Fault width, and Slip amount

The fault length, fault width, and slip amount are computed using scaling laws. For historical earthquakes, magnitude is used as reference to compute the fault length, fault width, and the amount of slip. To evaluate the maximum plausible magnitude, length is calculated and then the empirical equations are used to compute the magnitude, fault width, and the amount of slip.

The empirical equations by Papazachos et al. (2004) are used in this study. The following are the equations by Papazachos et al. (2004) for dip-slip faults in subduction zones:

$$\log L = 0.55M - 2.19 \tag{1}$$

$$\log w = 0.31M - 0.63 \tag{2}$$

$$\log u = 0.64M - 2.78 \tag{3}$$

where M is magnitude, L is fault length (km), w is fault width (km), and u is the slip amount (cm). All these equations are applicable for events with a magnitude ranging from 6.7 to 9.2.

Strike, Dip, and Rake Angles

The strike is given by the strike of the trench axis.

The dip angle is estimated using seismicity and previous studies such as Jarrard (1986), Bautista (1996), and Bautista et al. (2001). The slab dip model by Lallemand et al. (2005) is used for segments in Manila Trench, Philippine Trench, and Negros Trench.

The rake angle of the slip vector in compressional tectonics is mainly dependent on the orientation of relative plate motion. Kreemer et al. (2000) showed that the compression between the Sunda and Philippine Sea plates is consumed by relatively large trench normal convergence along the Philippine and Manila trenches and strike slips motion along the Philippine fault. Rangin et al. (1999) proposed a tectonic set-up of the Philippine mobile belt, where strain between the Sunda and Philippine Sea plates is released by motions of several blocks between them. Their orientations of convergence along the Philippine and Manila trenches do not deviate for the trench normal directions for most of the segments. Therefore, we set 90^o to the values of the rake angles for most of the segments, assuming a pure thrust fault with a strike parallel to the trench or coast. For the segments MT1, MT2, and MT3, referring to the result of Rangin et al. (1999), we calculated the rake angles using the following formula (Michael 1990), $\lambda=\tan^{-1}[\tan(\theta)/\cos(\delta)]$, where λ, θ, and δ are the rake angle, the angle of the relative plate motion with respect to the strike, and the dip angle, respectively. We also refer to the distribution of rake angles of the CMT solutions if enough solutions are available.

3. RESULTS

Table 2 and 3 show the final lists of the parameters set for each segment. Seventeen segments were analysed and finally we assigned set of parameters for each. Two tables are shown below; Table 2 shows the set of parameters with reference to the fault length considering the maximum plausible magnitude, while Table 3 shows the set of parameters with reference to the magnitude of historical event that possibly occurred in the segment. Since there is no historical event for PT3, the parameters for this segment is not shown in Table 3. The modes of the rakes of the thrust events from the Global CMT catalogue are shown for NT1, ST1, CT1, ELT, and PT2. For CT2, the rake of the GCMT solution for the August 1976 event (Mw8.0) is shown. Since they do not differ much from 90^o, it is reasonable to use 90^o for further tsunami simulation using the other earthquake source parameters given in this table.

Table 2. Final list of the parameters set for each segment.

Source	Magnitude	Corner location of the fault		Length (km)	Width (km)	Strike (deg)	Dip (deg)	Rake (deg)	Slip Amount (m)
		longitude	Latitude						
MT1	8.4	119.20	17.75	277	91.00	20	41	79	3.72
MT2	8.4	119.10	16.06	254	91.16	1	36	95	3.69
MT3	8.3	119.06	13.93	238	87.88	359	40	98	3.42
MT4	8.1	120.60	12.85	190	77.40	310	25	90	2.63
NT1	8.2	121.50	9.00	206	81.01	20	32	100	2.89
NT2	8.1	122.70	7.80	174	73.66	310	32	90	2.37
ST1	8.0	121.40	7.20	167	71.97	30	45	129	2.26
ST2	8.3	119.60	6.20	230	84.00	45	45	90	3.16
CT1	7.9	124.50	4.90	135	63.84	315	25	79	1.77
CT2	8.1	123.60	5.70	190	77.40	355	35	92	2.63
ELT	8.5	124.20	18.20	317	100.00	200	37	89	4.44
PT1	8.3	125.10	15.00	230	86.20	150	33	90	3.29
PT2	8.1	126.00	13.00	190	77.40	150	34	95	2.63
PT3	7.9	126.60	11.60	143	65.95	165	45	90	1.89
PT4	8.2	127.00	10.40	206	81.01	165	36	90	2.89
PT5	8.1	127.50	8.20	190	77.40	180	35	90	2.63
PT6	8.5	127.40	6.44	325	95.00	135	39	90	4.00

Table 3. List of parameters with reference to magnitude of historical events.

Source	M	Length (km)	Width (km)	Slip Amount (m)
MT1	6.4	25.00	13.00	0.79
MT2	7.6	97.72	53.21	1.21
MT3	7.6	97.72	53.21	1.21
MT4	6.6	32.00	16.00	1.00
NT1	8.2	208.93	81.66	2.94
NT2	6.8	35.48	30.06	0.37
ST1	8.2	208.93	81.66	2.94
ST2	8.2	208.93	81.66	2.94

Source	M	Length (km)	Width (km)	Slip Amount (m)
CT1	8.0	162.18	70.79	2.19
CT2	8.0	162.18	70.79	2.19
ELT	7.2	58.88	39.99	0.67
PT1	7.3	66.83	42.95	0.78
PT2	7.1	51.88	37.24	0.58
PT4	7.6	97.72	53.21	1.21
PT5	7.5	86.10	49.55	1.05
PT6	8.3	237.14	87.70	3.40

3.1 An example of calculation of seafloor deformation

Here we show an example of seafloor deformation computed using the earthquake source parameters determined in this study (Figure 3). We followed Okada (1985) in this calculation. We use MT3 segment and the parameters provided in Table 2 for the calculation. The yellow rectangle shows the fault plane, red contours show uplift, and blue contours show subsidence.

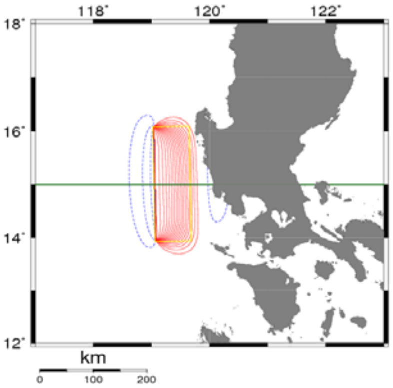

Figure 3. Seafloor deformation of MT3.

4. CONCLUSION

The Philippine archipelago is bounded by various earthquake generators that can also generate tsunamis. The setting of earthquake source parameters is one of the most important components of tsunami numerical modelling. We collated tsunami databases, both historical and instrumental data and selected events for the analysis of this study. We characterized events by considering the collated database, previous studies, documented accounts, and bathymetry data. We also collated and reviewed seismicity data and Global Centroid Moment Tensor solutions. We used scaling laws with reference to the segmentation by Bautista, and set the maximum plausible magnitude, fault width and slip amount. We also referred to some studies such as slab dip models, geometry of subducting slabs, and studies on Global Positioning System (GPS) and plate motions. We identified the tsunami sources in subduction zones around the Philippines that generated and might generate large tsunamis, possibly imposing damages on the Philippines.

Considering all these information we produced a set of earthquake source parameters of these earthquake sources as input data to tsunami simulation. The following earthquake sources were considered: the Manila Trench (MT), Negros Trench (NT), Sulu Trench (ST), Cotabato Trench (CT), East Luzon Trough (ELT), and the Philippine Trench (PT). Each earthquake source was divided into segments and each segment was given a set of parameters. The total number of segments considered is 17. The set of parameters include the magnitude, the corner location of the fault, the fault length, fault width, the strike angle, dip angle, rake angle, and the amount of slip. These parameters are important inputs for tsunami numerical modelling for the preparation of reliable tsunami hazard maps which eventually will be utilized in preparing tsunami preparedness plans of various communities in the Philippines.

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