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ASSESSMENT OF TSUNAMI GENERATION POTENTIAL THROUGH RAPID ANALYSIS OF SEISMIC PARAMETERS

Case study: Comparison of the Sumatra Earthquakes of 6 April and 25 October 2010

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ABSTRACT

The purpose of the research was to estimate P-wave rupture durations (T_{dur}), dominant periods (T_d) and rupture durations greater than 50 seconds (T50Ex) for two large, shallow earthquakes, which occurred off the coast of Sumatra on 6 April and 25 October 2010. Although both earthquakes had similar parameters of magnitude and focal depth, the 25 October event (Mw=7.8) generated a tsunami while the 6 April event (Mw=7.8) did not. Analysis of the above stated parameters helped understand the mechanisms of tsunami generation of these two earthquakes. Measurements from vertical component broadband P-wave quake velocity records and determination of the above stated parameters could provide a direct procedure for assessing rapidly the potential for tsunami generation. The results of the present study and the analysis of the seismic parameters helped explain why one event generated a tsunami, while the other one did not.

Keywords: *P-wave; rupture duration; dominant period; rupture duration greater than 50 seconds; direct procedure.*

1. INTRODUCTION

Seismological agencies such as the Japan Meteorology Agency (JMA), the Indonesian Tsunami Early Warning System (Ina-TEWS), the Tsunami Warning Center of West Coast/Alaska (WCATWC) and the Pacific Tsunami Warning Center (PTWC), measure and determine quickly earthquake parameters of location, depth and magnitude. Based on assigned threshold limits for earthquakes that have the potential to generate a tsunami with a height of 0.5 meters or more, JMA provides a warning for Japan in about three minutes after the origin time (OT). Similarly applying the same earthquake threshold criteria, Ina-TEWS provides early warning in about five minutes after OT. Both WCATWC and PTWC issue tsunami warnings in about five to ten minutes after OT, for shallow, North America and Pacific earthquakes, which have magnitudes greater than (Mw) ≥ 7.5. In spite of the fact that all warnings that are issued by these centers are based on earthquake parameters that meet criteria of location, depth < 70 km and magnitude > 7, not all such earthquakes generate tsunamis and some of the warnings that may be issued are improperly labeled as "false". However, none of the warnings issued in real-time can be considered as false. There is simply not sufficient seismic data in real-time to assess the tsunami potential of each event. Thus, a method that can help evaluate an event's additional, initial seismic parameters, may lead to better assessment of its potential for the generation of a destructive tsunami.

The present study was undertaken to evaluate two large, shallow earthquakes, which occurred off the coast of Sumatra on 6 April and 25 October 2010. Although both earthquakes had similar parameters of magnitude and focal depth, the 25 October event (Mw=7.8) generated a tsunami while the 6 April event (Mw=7.8) did not.

2. SEISMIC SETTING AND EARTHQUAKE PARAMETERS

Indonesia is one of the most seismically active zones on earth. Most earthquakes near the Sunda Trench are shallow, but deeper earthquakes also occur along the Benioff/Wadati zone as the Australia-Indian Plate subducts beneath the Sunda micro-plate. Figure 1 shows the historic seismic activity from 1997 to 2012 near the epicenters of the two earthquakes of 6 April and 25 October 2010. Both of these earthquakes fit well the pattern of focal depths that occur near the subsurface boundary of Australia-Indian tectonic plate and of the Sunda microplate.

As shown in Figure 1, the Centroid Moment Tensors (CMT) of both 2010 events had almost identical CMT parameters. However the 25 October earthquake generated a tsunami while the 6 April event did not. Although, moment magnitude (*M*w) is usually a good discriminant for many earthquakes as to their potential for tsunami generation, events characterized as "tsunami earthquakes, can generate larger tsunami waves than would be expected from just their moment magnitude (Kanamori, 1972; Satake, 2002; Polet & Kanamori, 2009; Lomax & Michelini, 2011).

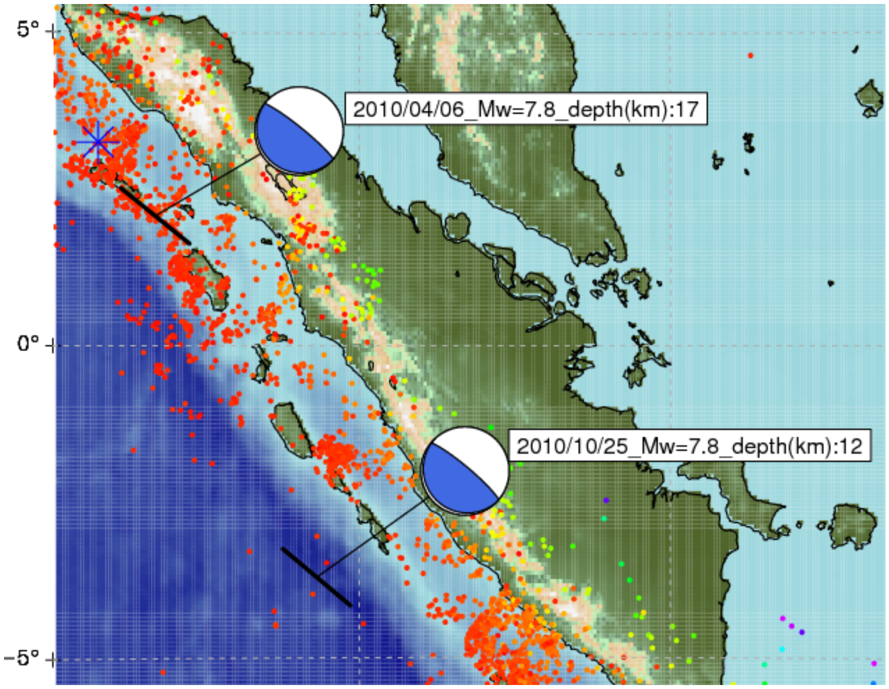

Figure 1. Centroid Moment Tensors (CMT) of the 6 April and 25 October 2010 earthquakes. Both events were shallow, had magnitudes of Mw=7.8 and reverse focal mechanism. (http://www.globalcmt.org/CMTsearch.html). <*Figure produced by using CRAN-R and GEOMAP (Madlazim, 2010; Lees, 2012>).*

The potential for tsunami generation by an shallow focus earthquake near the coast or at sea, relates to its seafloor crustal displacements, which depend on length L, width W, mean slip D, (LWD) and depth, z, of an earthquake's rupture. Correlation between LWD and M_0 can be written as:

$$M_0 = \mu LWD$$

or

$$\text{LWD} = M_0/\mu,$$

where μ is the shear modulus at the source. The seafloor displacement and thus tsunami potential should scale with:

$$LWD = M_0/\mu.$$

If μ is taken as constant for all shallow earthquakes, M_0 and the corresponding Mw should be good discriminants for tsunami potential; indeed, for a point source, the tsunami wave amplitude is expected to be directly proportional to M_0 (Okal 1988). These effects can cause an underestimate by

*M*w of an effective *LWD* value to explain the observed tsunami waves (Okal, 1988; Satake, 1994; Geist and Bilek, 2001; Lay and Bilek, 2007; Polet and Kanamori, 2009; Lomax and Michelini, 2011). To estimate Mw one cannot use a direct procedure, but may use an indirect procedure. However LWD can be estimated by using a direct procedure (Madlazim, 2011a, b, c, d).

T50Ex and T_{dur}, have good correlation to the tsunami size measures because T50Ex and T_{dur} is related directly to a component of the *LWD* source - the rupture length

L: $T_{\mathrm{dur}} \propto L/v_{\mathrm{r}}$,

where v_{r} is the rupture velocity (Lomax and Michelini, 2009; Lomax and Michelini, 2011; Madlazim, 2011b). Furthermore, v_{r} with *S*-wave velocity and shear modulus μ, increases with depth while v_{r} is found to be very low at shallow depth for tsunami earthquakes (Geist and Bilek, 2001; Polet and Kanamori, 2009; Lomax and Michelini, 2011). The dominant period T_{d}, as the peak τ_c value is obtained is applied with a 5 second sliding time window from 0 to 55 seconds after P *wave* arrival (Lomax and Michelini, 2011). The definition of T_d follows from assessment of numerous possible parameters with the goal of better discrimination of a tsunamigenic earthquake. The value of 5 seconds for the time window is sufficient to identify if T_d is greater or less than about 10 seconds.

The present study measured P-wave rupture duration (T_{dur}), dominant period (T_d) and rupture duration greater than 50 second (T50Ex) for the two large Sumatra earthquakes as recorded by the vertical components of seismographs, for the purpose of describing why the 25 October event (Mw=7.8) generated a tsunami while the 6 April event (Mw=7.8) did not.

3. DATA

The research criteria for the analysis of the two Sumatra earthquakes were: (1) what occurred after 2008 on the data available by the GEOFON-BMKG network; (2) the centroid depth was shallow (≤20 km); (3) the moment magnitudes in the Global CMT catalog of both earthquakes are almost identical at 7.8; (4) the half duration is almost the same at about 20 seconds; (5) the focal mechanism types are almost the same (reverse). The CMT parameters of the earthquakes are shown in Figure 1 and Table 1 below. In conducting the investigation, we retrieved BHZ channel waveforms of the GEOFON-BMKG network stations for these earthquakes from GEOFON-BMKG (Fig. 2). As described in Madlazim (2011b), data was used from the stations within the epicentral distance ranging from $4^{\circ} – 15^{\circ.}$ This was done in order to avoid scattering due to the upper mantle or D structures (Shearer and Earle, 2004; Hara, 2007).

Table 1. Comparison of CMT parameters of the 6 April and 25 October 2010 Sumatra earthquakes

Event	Lat	Long	Depth	St1; St2	Dp1; Dp2	Sl1; Sl2	Mw	HD (s)
2010/04/06 22:15	2.07	96.74	17.6	307; 129	7; 83	88; 90	7.8	19.5
2010/10/25 14:42	3.71	99.32	12.0	316; 130	8; 82	98; 89	7.8	19.9

(http://www.globalcmt.org/). St1: strike 1, Dp1: dip 1. Sli: slip 1, HD: Half duration

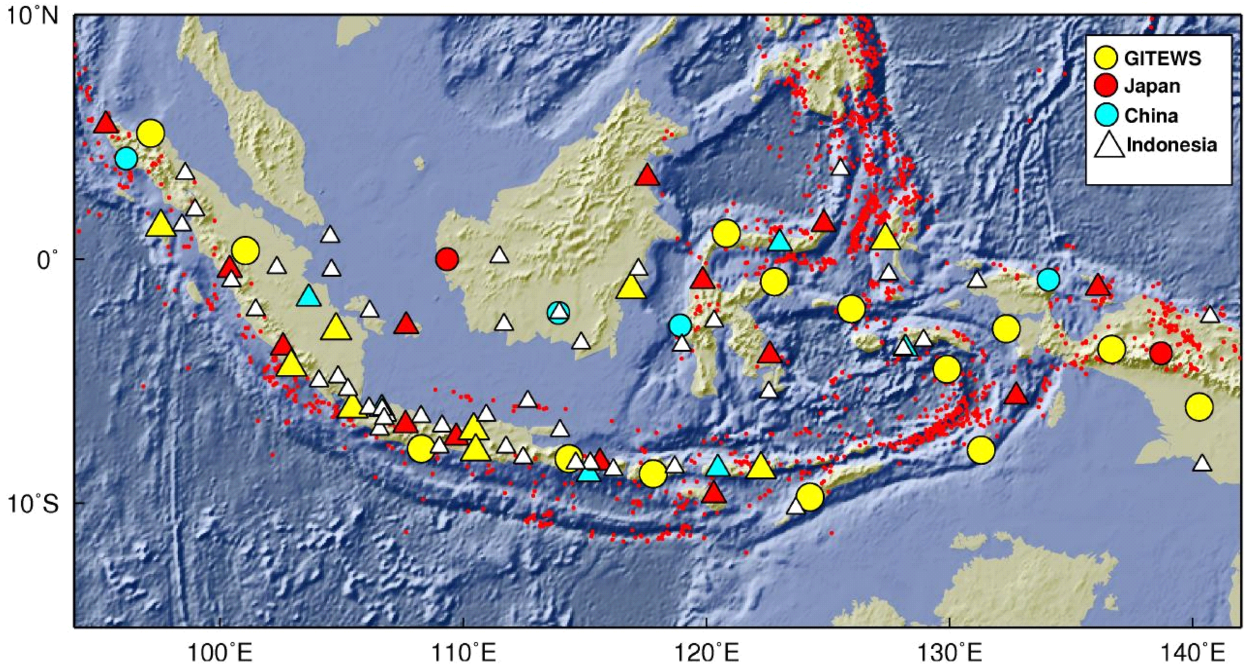

Figure 2. Stations used to estimate T_{dur}, T_d and T50Ex for the 6 April and 25 October 2010 earthquakes. (www.fdsn.org/meetings/.../fdsn_indoc_net.ppt)

4. METHOD

We determined T_{dur} for the earthquakes, through high-frequency (HF) analysis of the vertical-component, broadband seismograms as described in the literature (Lomax and Michelini, 2005; Lomax et al., 2007; Lomax and Michelini, 2009; Lomax and Michelini, 2011; Madlazim, 2011b). T_d The estimation was done by using direct procedure, namely: (1) by refining the vertical component velocity seismograms recorded by the GEOFON-BMKG networks by using a Butterworth filter at high frequency (5 - 20 Hz); (2) by picking the arrival time of the P wave automatically: (3) by integrating the vertical component velocity seismograms and comparing with the vertical component acceleration seismograms, multiplied by 2π; and (4) by the value of Td which is the culmination of the results of such integration. For estimating T50Ex we used a direct procedure by the following steps: (1) to (2) the same as those estimated Td; (3) by calculating the rms amplitude (Ar) and T50; and (4) by calculating T50Ex which is a comparison between T50/Ar. Figure 3 and 4 are flow charts which outline the direct procedure of P-wave dominant period and T50Ex, respectively.

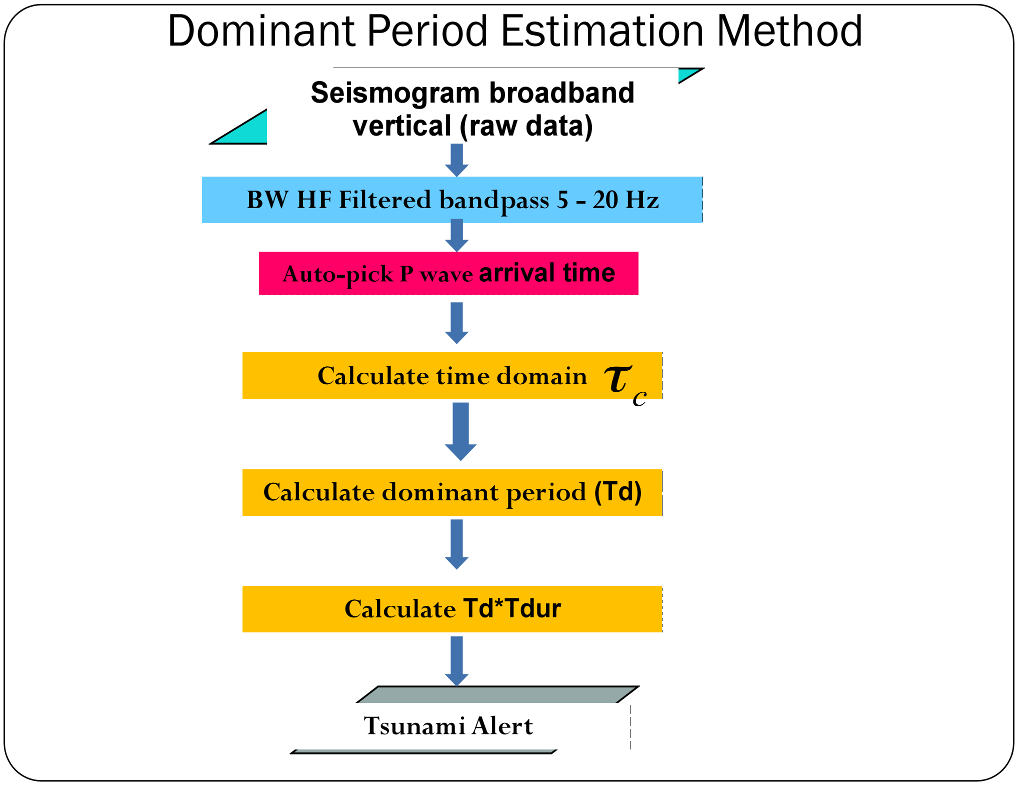

Figure 3. Direct procedure to estimate P-wave dominant periods

The importance of Tsunami generation "It", of the two Sumatra earthquakes was determined based on 0 - 4 descriptive indices "I", of tsunami effects (deaths, injuries, damage, houses destroyed), and maximum water height "h" in meters from the NOAA/WDC Historical Tsunami Database (http://www.ngdc.noaa.gov/hazard/tsu_db.shtml) in order to determine the potential of earthquake tsunami generation, where:

$$It = i_{height} + i_{deaths} + i_{injuries} + i_{damage} + i_{houses\text{-}destroyed}$$

where i_{height} = 4, 3, 2, 1, 0 for h = 10, 3, 0.5 m, h > 0 m, h = 0 m respectively (Lomax and Michelini, 2009). Based on this equation, we got values of It = 1 (no tsunami) for the 6 April 2010 earthquake and It = 13 (tsunami) for the 25 October 2010, event.

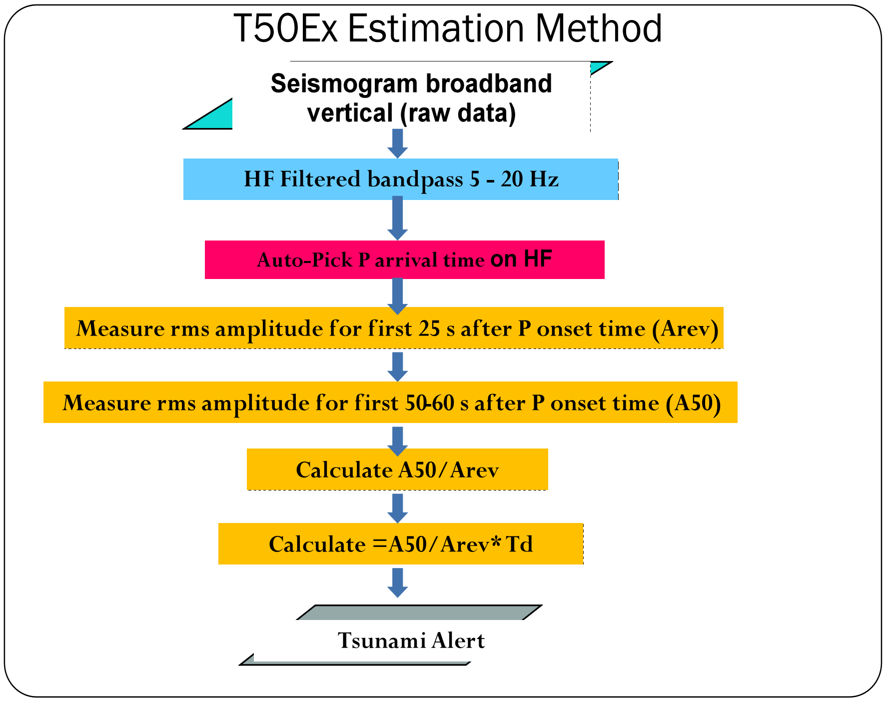

Figure 4. Direct procedure to estimate P-wave T50Ex

5. RESULTS AND DISCUSSION

The discriminant tsunami potential $T_{dur}T_d$ and T_dT50Ex correctly identified for the two tsunamigenic events with It = 13 (tsunami), Mw = 7.8 for the 25 October event and It = 1 (no tsunami), Mw = 7.8 for the 6 April event (Table 2)., more than the Mw and T_{dur} only discriminants (Lomax and Michelini, 2011; Madlazim, 2011). This result evaluated for the 6 April event in my previous study, did not use this methodology.

Table 2. Analysis result of discriminants tsunami potential by using the direct procedure

Event	**Lat**	**Lon**	**Depth (km)**	**Fault type**	**M_w**	**T_{dur}**	**T_d**	**T50Ex**	**$T_{dur}T_d$**	**T_dT50Ex**	**It**
20100406	2.07	96.74	17.6	Reverse	7.8	116	3.1	0.9	359	2.79	1
20101025	-3.71	99.32	12.0	Reverse	7.8	136	8.7	1.5	945	13.2	13

Discriminant tsunami potential $T_{dur,}$ T_d and TdT50Ex critical threshold for 6 April 2010 event, $T_{dur}T_d < 550$ s^2 and $T_dT50Ex < 10$ s^2 (no tsunami), respectively would provide important complementary information to initial location, depth and magnitude estimates for early assessment of earthquake tsunami potential. Since T_d is obtained rapidly (<60 s) after the *P* arrival, it remains to rapidly asses T_{dur} for an earthquake, in particular if $T_{dur} > 55$ s, $T_d < 10$ s and T50Ex < 1. Discriminant tsunami potential $T_{dur}T_d$ and T_dT50Ex critical threshold for the 25 October 2010 event, $T_{dur}T_d > 550$ s^2 and $T_dT50Ex > 10$ s^2 (tsunami), it remains to rapidly asses T_{dur} for an earthquake, in particular if $T_{dur} > 55$ s, $T_d > 10$ s and T50Ex > 1. By using the direct procedure (Lomax and Michelini, 2009; Madlazim, 2011b; Madlazim, 2012), we determined if T_{dur} for an earthquake is likely to exceed 55 – 60 seconds through HF analysis of vertical-component, broadband seismograms. On 5 – 20 Hz band pass filtered seismogram for local seismograms and on 1 – 5 Hz for teleseismic seismograms (Lomax and Michelini, 2011;Madlazim, 2011b). We formed the ratio of the rms amplitude from 50–60 seconds after the P with the rms amplitude for the first 25 s after the P to obtain a station for 50–55 seconds (Lomax and Michelini, 2011; Lomax and Michelini, 2012, Madlazim, 2012). Based on this study and our previous work (Madlazim, 2011b; Madlazim, 2012), with large earthquakes data sets, we estimate that measures from 11–22 stations are needed to obtain stable estimates of T_{dur}, T_d and T50Ex.

We identified the most critical parameters for discrimination of earthquake tsunami potential. The performance of the T_{dur}, T_d, T50Ex, $T_{dur}T_d$ and T_dT50Ex discriminants, though improved by the T_{dur}, T_d, T50Ex values, is dominated by the T_d, T50Ex values (Table 2), T_{dur} and T50Ex for large earthquakes is probably related primarily to rupture length, L and T_d for large earthquakes is probably related primarily to rupture width, W and slip, D. We have shown that T_{dur}, T_d, T50Ex, $T_{dur}T_d$ and T_dT50Ex may inherently account for source depth, and that $T_{dur}T_d$ and T_dT50Ex may be proportional to Amplitude of the seismogram. These results imply that rupture length, L and depth, z, alone can constrain well the tsunami potential of an earthquake. Then information on the fault width W, and slip D is of secondary importance, though perhaps provided by T_d for some event types, or implicitly through scaling relations such as $W \propto L$ and $D \propto L$. There is the suggestion that tsunami potential is more affected by T_{dur}, T_d, T50Ex, $T_{dur}T_d$ and T_dT50Ex as function LWD than the location, depth and Mw discriminants. The T_{dur}, T_d, T50Ex, $T_{dur}T_d$ and T_dT50Ex discriminants were identified better than Mw and T_{dur} for these events.

6. CONCLUSIONS

The above described analysis based on the inherent sensitivity of T_{dur} and T50Ex to rupture length, L and source depth z, indicate that the tsunami potential for these earthquake types can be well constrained by the rupture length *L* and some mean rupture depth *z*. Furthermore, the explicit information on T_d indicates that the tsunami potential for such earthquake types can be well constrained by the rupture fault width W, or the mean slip D, which are parameters of lesser importance.

The results of the analysis imply that the tsunami potential of an earthquake is not a simple function of the potency of *LWD* as it is assumed with the use of the Mw discriminant. To evaluate the tsunami potential for oceanic reverse earthquakes, further research is needed in finding direct measures and discriminants for events which are occasionally highly tsunamigenic. For the two earthquakes that were analyzed by this study, the T_{dur}, the T_d, the T50Ex, the $T_{dur\ the}$ T_d and the T_dT50Ex discriminants were identified as being better than Mw and $T_{dur.}$

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