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TOWARD INDONESIAN TSUNAMI EARLY WARNING SYSTEM BY USING RAPID RUPTURE DURATIONS CALCULATION

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ABSTRACT

Indonesia has an Indonesian Tsunami Early Warning System (Ina-TEWS) since 2008. The Ina-TEWS has used automatic processing on hypocenter; Mwp, Mw (mB) and Mj. If earthquake occurred in Ocean, depth < 70 km and magnitude > 7, then Ina-TEWS announce early warning that the earthquake can generate tsunami. However, the announcement of the Ina-TEWS is still not accuracy. Purpose of this study is to estimate earthquake rupture duration of large Indonesia earthquakes that occurred in Indian Ocean, Java, Timor Sea, Banda Sea, Arafura Sea and Pacific Ocean using a direct procedure and software developed Lomax and Michelini for rapid assessment of earthquake tsunami potential by deriving two simple measures from vertical component broadband P-wave velocity record. The first is the high-frequency apparent rupture duration, Tdur which may be related to can be related to the critical parameters rupture length (L), depth (z), and shear modulus (μ). The second is a confirmation of the earlier finding by Lomax and Michelini, namely that the rupture duration has a stronger influence to generate tsunami than Mw and Depth. We analyzed at least 510 vertical seismogram recorded by GEOFON-IA and IRIS-DMC networks. Our analysis shows that the seismic potency, LWD, which is more obviously related to capability to generate a tsunami than former. The larger Tdur the larger is the seismic potency LWD because Tdur is proportional to L/vr (with vr – rupture velocity). We also suggest that tsunami potential is not directly related to the faulting type of source and for events that have rupture duration greater than 50 s, the earthquakes generated tsunami. With available real-time seismogram data, rapid calculation, rupture duration discriminant can be completed within 3 to 8 min after the P-onset.

Key words: Rupture duration; Tsunami early warning; Body wave; Earthquake dynamics.

1. INTRODUCTION

Indonesia is surrounded by the Indo-Australian and Philippine Sea tectonic plates, which subduct beneath the Eurasian plate, with five big islands and several peninsulas. Indonesia has experienced thousands of earthquakes and hundreds of tsunamis over the past four hundred years [1]. Sumatra and Java are two of the most vulnerable islands to tsunami impact since they are located directly in front of the Indo-Australian plate [2,3,4]. Papua, Sulawesi, Sumbawa, Flores and Sumba are other islands that also have been experiencing several earthquake and tsunamis, although not as frequently as Sumatra and Java. Fig. 1 shows the epicenters of earthquakes that have occurred in the region.

The Indonesian islands along the Great Sunda Arc are particularly susceptible to earthquake and tsunami hazards. According to the Harvard Centroid-Moment-Tensor Catalog (http://www.globalcmt.org), more than 30 earthquakes with magnitude 7 or greater occurred during the last 30 years along the Sunda subduction zone [5]. The largest event with a magnitude Mw=9.3 was the Sumatra-Andaman earthquake of 26 December 2004 which had a rupture of over 1100 km [6,7,8] and generated a catastrophic, ocean-wide tsunami. Also during the last decades, devastating earthquakes and tsunamis occurred near the islands of Sumba and Sumbawa at the southeastern part of the Sunda subduction zone. The largest were the Mw = 8.3 Sumba earthquake of 1977, the East Java Earthquake (Mw = 7.8) of 1994 and the Mw = 7.7 Pangandaran earthquake in 2006 [5]. Most recent was the Mw = 7.4 Metawai earthquake and tsunami of 25 October 2010.

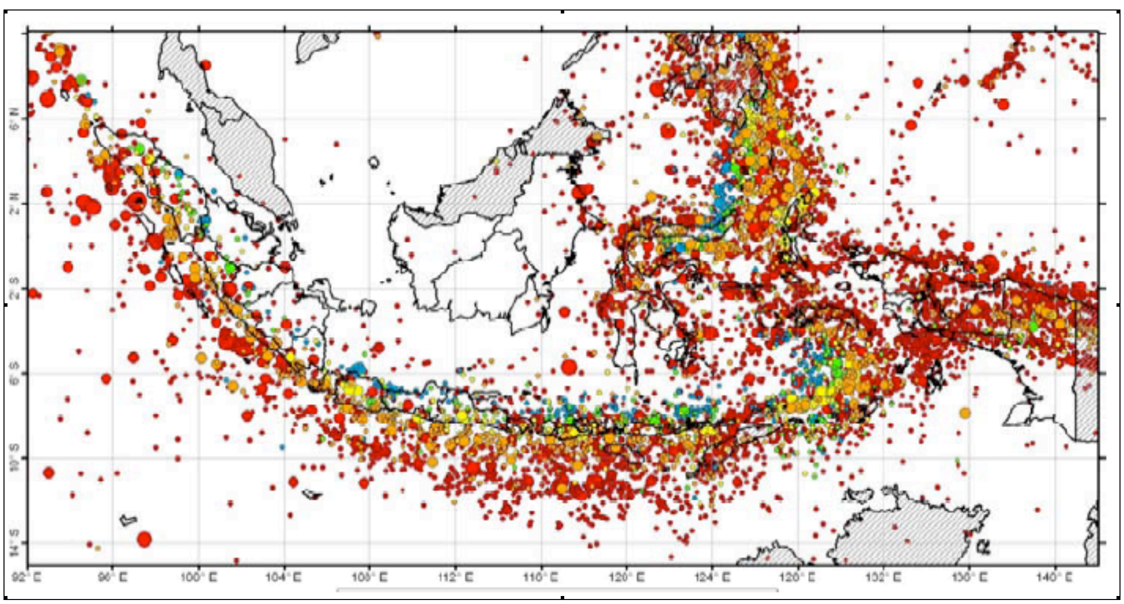


Fig. 1. Epicenters Indonesia earthquake occurred in range 1900 -2009 for magnitude > 5 [9].

The development of Ina-TEWS is being carried out by the Indonesian Government with support of donor countries (Germany, China, Japan, USA, and France) and international organizations (UNESCO, UNDP, UNOCHA, ISDR etc.). Preliminary operation begun in mid-2005 and Ina-TEWS was finally launched in November 2008. Indonesia was characterized as the riskiest country because of its proximity to tsunami generation regions of the Indian tectonic plate. Thus, the country developed a national system, namely, "The Indonesian Tsunami Early Warning System" (Ina-TEWS). Operational components of Ina-TEWS include monitoring, processing, and telecommunication systems. The monitoring system includes land monitoring of seismic observations (160 broadband seismometers, 500 accelerometers) and GPS observation (40 units), sea surface monitoring with Buoys (22) and 80 tide gauges. BMKG (the Meteorological and Geophysics Agency), is the organization responsible for operating the National Operational Centre, which collects and processes all seismic data, determines earthquake locations, analyzes whether an earthquake is potentially tsunamigenic, issues earthquake information and tsunami warnings and integrates other observation data for confirmation or subsequent cancellation of the warning [8].

Ina-TEWS integrates all monitoring information coming from seismic, GPS, buoy and tide gauges, as well as the modeling system - taken from the tsunami database and geospatial data. The system provides recommendations to the officer-on-duty when the level of warning warrantees it and the time that such warning should be issued. Currently, the decision on whether an event is tsunamigenic is based on earthquake parameters such as magnitude, location and depth. Sometimes, the decision requires support from various detailed information sources, tsunami modeling and related data in the DSS system. DSS consists of information retrieval system. Additionally received data and information become a decision bonus, which is shared in the dissemination network. Overview of all the information on data and maps give assistance to the operator in selecting the kind of information that should be disseminated for a certain area [10]. The decision can be wrong if the earthquake parameters are not accurate.

Failures in warning for tsunamis have occurred in Indonesia because earthquake parameters - such as magnitude, location and depth estimates of the Ina-TEWS - were not accurate. For example, BMKG announced that the Mentawai earthquake of October 25, 2010 presented no tsunami threat and cancelled the warning about one hour after the earthquake's origin time when, in fact, a tsunami had been generated. This Mentawai tsunami left 270 people with significant injuries and 142 with minor injuries. Also, there was considerable damage on the Mentawai Islands, where 6 out of 27 coastal villages that were destroyed and 517 homes were either ruined or carried away by the tsunami.

The present study provides an analysis of seismic data of large Indonesian earthquakes as recorded by the vertical components of seismographs, for the purpose of providing a more accurate, rapid and direct procedure in assessing tsunami potential by estimating a quake's rupture duration (Tdur). Additionally, the study analyzes the relation of rupture duration versus the centroid moment tensor magnitude (Mw) and the earthquakes' focal depth.

2. DATA AND METHOD

Analysis was performed on at least 510 seismograms of fifty-one events which had epicenters in the Indian Ocean, Java, Timor Sea, Banda Sea, Arafura Sea and the Pacific Ocean, which satisfied the following criteria: (1) had faulting geometry with thrust, strike-slip or normal (2) had moment magnitude (Mw) between 6.7 and 9.0, and (3) had availability of at least ten high-quality teleseismic digital P-wave recordings with good azimuthal coverage and high signal to noise ratio for each event. Rupture duration was obtained for each event by using data of 10 vertical broadband teleseismic [11,12,13], P-wave data (2° – 30°). We used a direct procedure [11,12,13] to estimate quake rupture duration. The procedure was used to assess tsunami potential by estimating rupture duration (Tdur) with a measure of delay time of 90% rms amplitude T0.9, delay time of 80% rms amplitude T0.8, delay time of 50% rms amplitude T0.5 and delay time of 20% rms amplitude T0.2. These parameters are simple to measure on observed P-wave seismograms and can be correlated to critical parameters of rupture length (L), width (W), slip (D) and focal depth - also needed for assessing tsunami potential. This direct, period-duration procedure gives improved identification of recent earthquakes which produced large or destructive tsunamis, relative to the use of Moment Magnitude (Mw)[14].

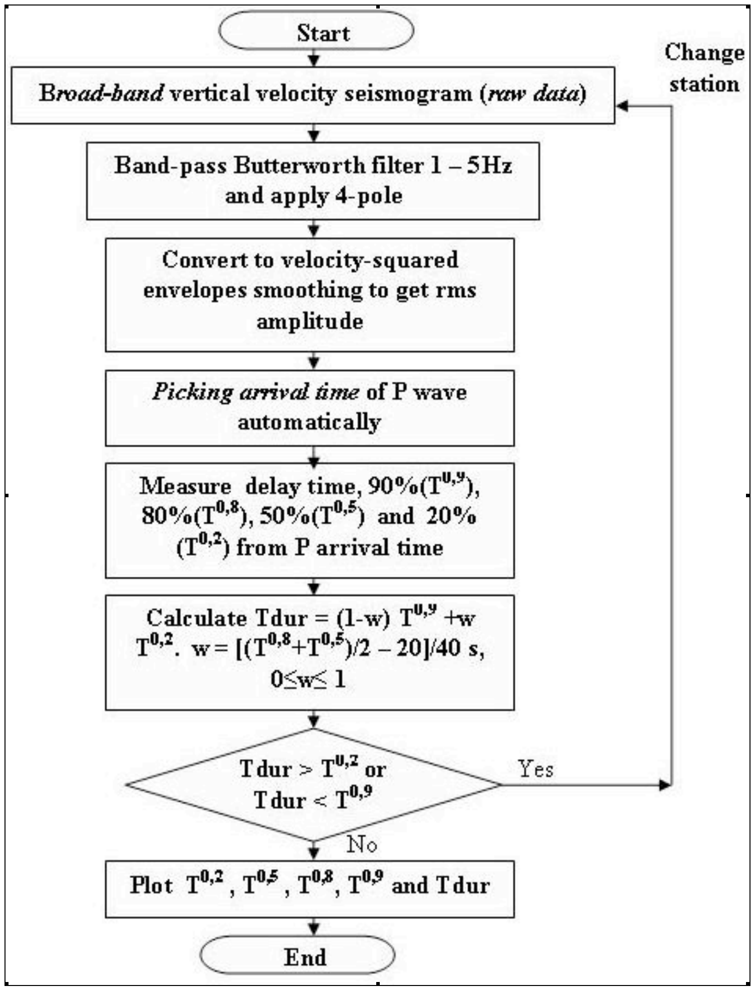
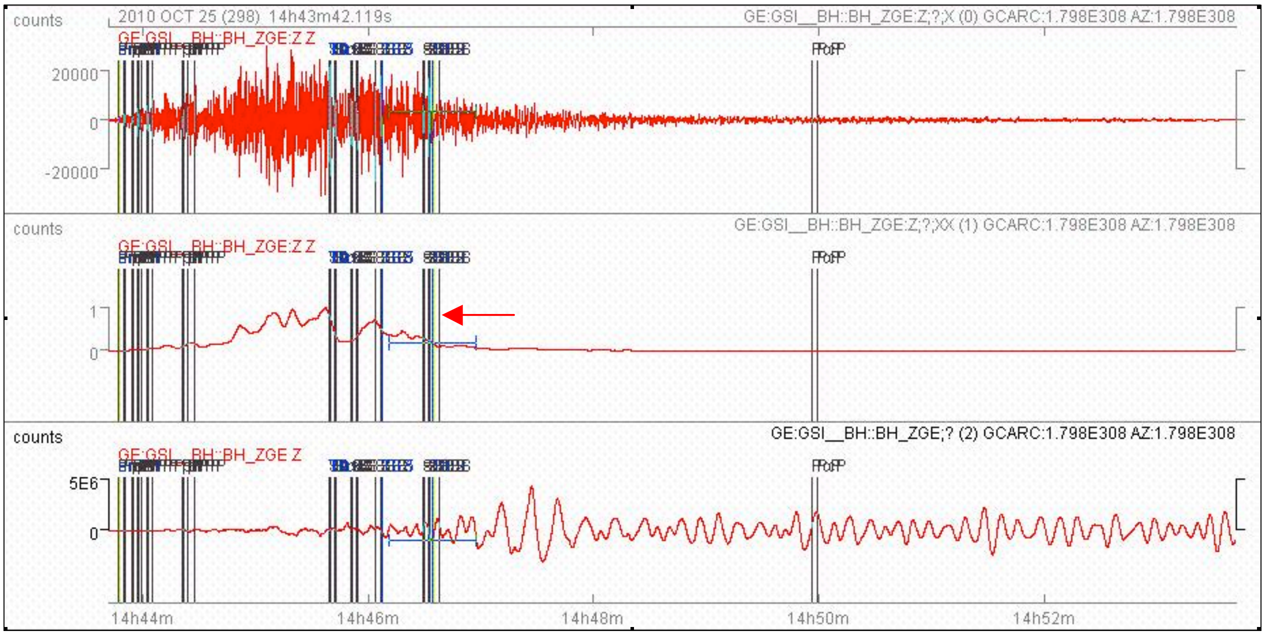


Fig. 2. Direct procedure to calculate rupture duration

For each event the vertical seismograms recorded by stations of the GEOFON-IA and IRIS-DMC networks were used, at different distances and azimuths and then calculated the average rupture duration to get a better estimate. As discriminants for tsunami potential, we first consider the rupture duration, “Tdur “ calculated from the envelope decay of squared, high-frequency, HF; 1–5 Hz bandpass [14,15] of P-wave seismograms at teleseismic distance [11,12,13]. Fig. 2 is a flow chart which outlines the procedure. An example of the analysis of rupture duration processing is illustrated by Fig. 3.



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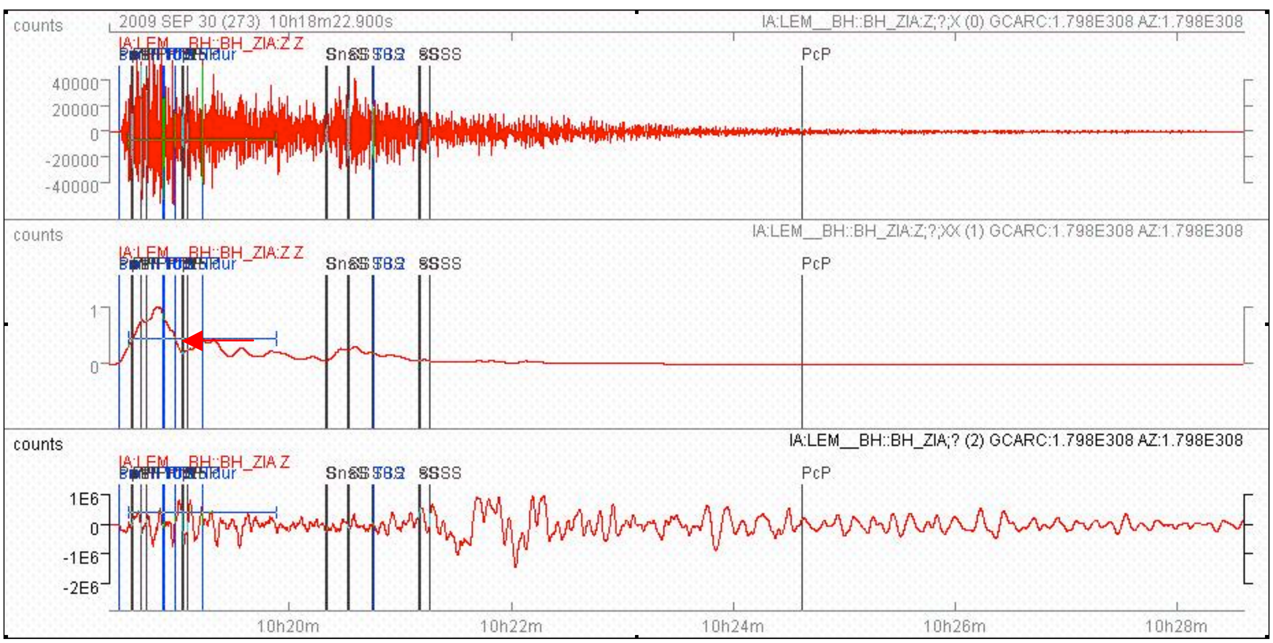

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Fig. 3. Single-station, period-duration processing examples for (Top) 2010 October 25, *M*w 7.8, T_{dur} = 119 s, Mentawai, Indonesia tsunami earthquake, station GE.GSI at 5.366°, and (Bottom) period-duration processing examples for September 30, 2009, Padang non-tsunami earthquake (Mw 7.6, Tdur = 25s, station IA.LEM at 9.433°, Butterworth-filtered HF seismogram (trace 0), smoothed, velocity squared envelope (trace 1) showing raw, broadband velocity seismogram (trace 2). Automatic P pick; T0,9, T0,8, 5T0,5 and T0,2 are delay time from P arrival time; "Tdur" is rupture duration (red arrow).

3. RESULTS AND DISCUSSION

In order to analyze the relationship between rupture duration, centroid moment tensor magnitude (Mw) and focal depth, rupture durations were estimated by using data provided by the Global CMT catalogue (http://www.globalcmt.org) on moment magnitudes and focal depths. Based on the analysis, it became clear that rupture duration increases when the centroid moment tensor magnitude also increases (Fig. 4a). Thus, the results of the present study were in good agreement with those of Bilek and Lay (1999). Figures 4a and 4b illustrate that for earthquakes that have moment magnitude (Mw) greater than 7 and focal depth less than 70 km, no tsunami is generated if the rupture duration is less than 50 seconds. Table 1 provides estimates of rupture duration for large earthquakes occurring in the Indonesian region. Also, table 1 illustrates that tsunami potentials do not only depend on earthquake magnitude and focal depth. All of the earthquakes occurring in the ocean with magnitudes Mw > 7 and depths <70 km (Ina-TEWS' criteria), did not generate tsunamis. As shown by Table 1, centroid moment tensor magnitude (Mw) is found to be a good discriminant for many, past, tsunamigenic earthquakes, but not for all. It was determined that rupture durations have effects which are greater than those of other discriminants (Mw, focal depth and type of faulting). Most of the earthquakes that generated tsunamis have rupture duration greater than 50 seconds. These results are also in agreement with those obtained by other studies (Okal, 1988)[16]; Geist and Yoshioka 1996)[17] and Lomax and Michelini, 2011). There is a higher probability of tsunami generation when the earthquake rupture duration (Tdur) is longer and the rupture length is greater. Also, the rupture duration gives more information on tsunami impact, Mo/μ, depth and size than Mw and other currently used discriminants. Figure 4a and 4b illustrate more information of the effect of rupture duration on tsunami generation. The longer the rupture duration, the shallower is the source of the earthquake. For rupture durations greater than 50 seconds, focal depth less than 50 km, and moment magnitudes Mw>7, the rupture length is longer, because "Tdur" is proportional to L and greater Mo/μ, which is also proportional to L. So, with rupture duration information more can be known of the four parameters.

The local earthquake of January 1, 1996 represents an anomaly, since the rupture duration was 33 seconds (Table 1 on shadow raw), yet it generated a local tsunami [4,18]. This anomalous phenomenon explains the issuance of false warnings from greater events with short duration but which have a high-frequency P signal. The 1996 event may have been one of those associated with fast ruptures, higher than normal stress drop, shorter length (L), but larger D.

Table 1. Assessment of tsunami potential in Indonesia using rupture duration estimation

Global CMT Catalog							**Author**	**NGDC /TL/BMKG**		
Origin Time	**Lat. (°)**	**Long. (°)**	**Depth (km)**	**M_w**	**Fault type**	**Region**	***Tdur* (s)**	**H_{max} (m)**	**NR**	**TP**
19910704_1143150	-8.02	124.73	17	6.7	Tr	Flores	**19**			**nT**
19921212_0529499	-8.34	122.49	20	7.7	Tr	Flores	**78**	**26.20**	**26**	**T**
19921220_2053006	-6.60	130.52	70	7.2	OT	Banda sea	**39**			**nT**
19940215_1707517	-5.15	104.27	16	6.8	SS	S_Sumatra	**21**			**nT**
19940602_1817340	-11.03	113.04	15	7.7	Tr	Banyuwangi	**130**	**13.90**	**24**	**T**
19941008_2144135	-1.19	127.87	15	6.8	SS	Halmahera	**13**			**nT**
19950127_2016521	-4.43	134.45	22	6.8	N	Papua	**36**	**NA**	**1**	**nT**
19950213_1504304	-1.31	127.57	15	6.7	SS	Halmahera	**11**			**nT**
19950319_2353218	-4.18	135.10	19	6.8	SS	Papua	**21**			**nT**
19950514_1133286	-8.60	125.26	16	6.9	N	Flores	**53**	**4.00**	**1**	**T**
19951108_0714260	2.00	94.77	29	6.9	Tr	N_Sumatra	**21**			**nT**
19960101_0805100	0.74	119.93	15	7.9	Tr	Sulawesi	**33**	**3.43**	**16**	**T**
19960217_0559305	-0.89	136.95	33	8.2	Tr	Papua	**114**	**7.68**	**162**	**T**
19981109_0538486	-6.94	128.95	25	7.0	Tr	Banda sea	**37**			**nT**
19981129_1410451	-2.03	125.00	16	7.7	SS	Ceram sea	**55**	**2.70**	**1**	**T**
20000504_0421334	-1.29	123.59	19	7.5	SS	Sulawesi	**96**	**5.00**	**1**	**T**
20000604_1628465	-4.73	101.94	43	7.9	Tr	Bengkulu	**43**			**nT**
20001025_0932321	-7.28	105.43	46	6.8	Tr	Sunda Strait	**17**			**nT**
20010116_1325143	-4.38	101.42	20	6.8	Tr	S_Sumatra	**23**			**nT**
20010213_1928451	-5.40	102.36	21	7.3	Tr	S_Sumatra	**28**			**nT**
20021010_1050419	-1.79	134.30	15	7.5	SS	Papua	**134**	**3.00**	**1**	**T**
20021102_0126259	2.65	95.99	23	7.2	Tr	N_Sumatra	**33**			**nT**
20030526_1923385	2.61	128.88	34	6.9	Tr	Halmahera	**15**			**nT**
20040128_2215340	-3.11	127.30	17	6.6	OS	Seram sea	**13**			**nT**
20040205_2105128	-3.62	135.53	13	7.0	OS	Papua	**36**			**nT**
20040207_0242437	-4.03	134.78	12	7.3	SS	Papua	**68**	**NA**	**NA**	**T**
20040725_1435254	-2.68	104.38	600	7.3	N	S_Sumatra	**8**			**nT**
20041111_2126580	-7.87	125.12	17	7.5	Tr	Alor sea	**76**	**2.00**	**NA**	**T**
20041226_0101900	3.09	94.26	29	9.0	Tr	Aceh	**460**	**50.90**	**999**	**T**
20050302_1042169	-6.54	129.99	196	7.1	OS	Banda sea	**9**			**nT**
20050328_1610315	1.67	97.07	26	8.6	Tr	Nias	**112**	**3.00**	**17**	**T**
20050410_1029178	-1.68	99.54	12	6.7	Tr	Nias	**37**	**0.40**	**1**	**nT**
20050514_0505246	0.42	98.24	39	6.7	Tr	Nias	**21**			**nT**
20050519_015525	1.88	96.74	12	6.8	Tr	Nias	**13**			**nT**
20050705_015263	1.56	96.93	16	6.6	Tr	Nias	**29**			**nT**
20060127_165948	-5.61	128.20	397	7.6	N	Banda sea	**8**			**nT**
20060314_0657375	-3.35	127.31	13	6.7	N	Seram sea	**117**			**T**
20060516_1528312	0.01	96.98	14	6.8	N	Nias	**12**			**nT**
20060717_0819287	-9.25	107.41	34	7.6	Tr	Tasikmalaya	**170**	**10.00**	**196**	**T**
20070912_2349037	-2.46	100.13	43	7.9	Tr	S_ Sumatra	**168**	**NA**	**NA**	**T**
20070912_1111156	-3.78	100.99	17	8.5	Tr	S_Sumatra	**174**	**5.00**	**47**	**T**
20070913_0335369	-2.31	99.39	22	7.0	Tr	S_Sumatra	**25**			**nT**
20080220_0808454	2.69	95.98	15	7.3	Tr	Simelue	**45**			**nT**
20080225_0836424	-2.66	99.95	14	7.2	Tr	S_Sumatra	**37**	**0.12**	**1**	**nT**
20090103_1944090	-0.38	132.83	15	7.7	Tr	Papua	**30**	**NA**	**NA**	**nT**
20090526_1923385	2.61	128.88	34	6.9	Tr	Halmahera	**36**			**nT**
20090816_0738286	-1.56	99.45	12	6.7	Tr	S_Sumatra	**34**	**0.18**	**1**	**nT**
20090902_0755075	-8.12	107.33	53	7.0	Tr	Tasikmalaya	**13**			**nT**
20090930_1016092	-0.79	99.67	78	7.6	Tr	Padang	**27**	**0.27**	**1**	**nT**
20100406_2215191	2.07	96.74	18	7.8	Tr	N_Sumatra	**116**	**0.44**	**6**	**T**
20101025_1442222	-3.71	99.32	12	7.8	Tr	Mentawai	**136**	**7.00**	**22**	**T**

T:Tsunami; nT:non-Tsunami; $T_{du}r$: *rupture* duration; Tr: *thrust*; SS:*strike-slip*; N:Normal : OT: oblique] *thrust*; OS: *oblique strike slip faulting*; H_{max}: maximumwaterheight; NR: *number of runups;* NGDC: *National Geophysical Data Centre* (http://www.ngdc.noaa.gov/hazard/); TL, *Tsunami Laboratory (*http://tsun.sscc.ru/nh/tsunami.php); NA:*not available data;* TP:T*sunami potensial*. Definition: tsunami occurred if (1) $H_{max} \geq 0,5$ m and NR more then one times.

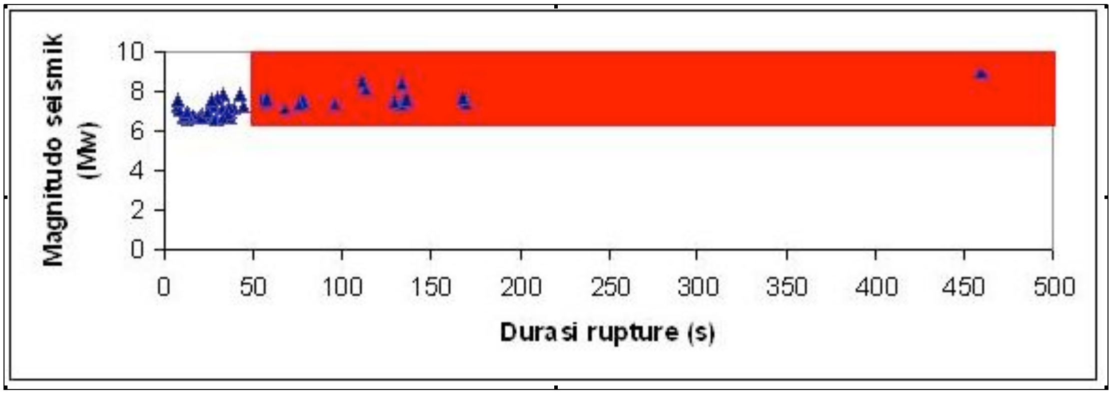

Fig. 4 (a) The relation between magnitude (Mw) and rupture duration, red zone is tsunami potential.

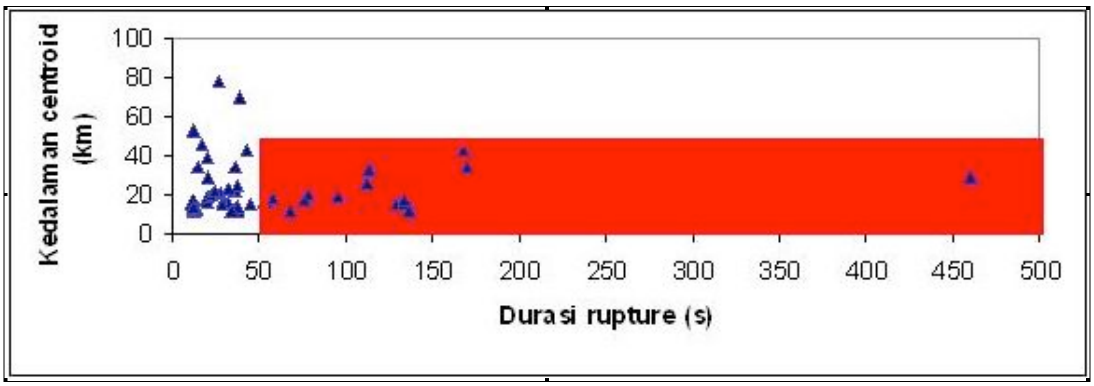

Fig. 4 (b) The relation between source depth and rupture duration, red zone is tsunami potential

Out of 51 earthquakes shown in Table 1 with Mw between 6.7 and 9.0, sixteen (or 31%) had rupture duration, Tdur > 50 s, and all sixteen (100%) produced a tsunami. By contrast, from 35 earthquakes with Tdur < 50 s only one (or 2.8%) produced a tsunami and 25% of the earthquakes had strike-slip faulting, while 75% earthquakes of the total of 51 have reverse faulting and generated tsunamis. This determination indicates that earthquake rupture duration has a stronger influence in generating tsunami than Mw and focal depth. Many earthquakes have Mw greater and shallower than others, but such earthquakes did not generate tsunamis. For example, the June 4, 2000 earthquake had magnitude (Mw = 7.9) greater than that of the February 7, 2004 (Mw=7.3) (Table 1). However, the average rupture duration of the June 4, 2000 earthquake was 43 seconds which was shorter than that of the February 7, 2004, which was 68 seconds. Apparently, the shear modulus of the source of the June 4, 2000 earthquake was greater than that of the February 7, 2004. Therefore, the ratio of seismic moment (Mo) to shear modulus, μ (Mo/μ = LWD) for the June 4, 2000 earthquake is smaller than the ratio of Mo to μ (Mo/μ) of the February 7, 2004 event. Consequently, the length of rupture caused by June 4, 2000 earthquake was shorter than the rupture length of the February 7, 2004 earthquake. The smaller ratio of Mo to μ, the shorter is the rupture length and the shorter is the rupture duration as well [19]. These results are good agreement with the results of Bilek and Lay (1999) [21] which showed strong trends of decreasing normalized source duration with increasing depth below the sea floor and that the estimated shear modulus of the seismogenic zone increases over depth ranging from 5–50 km.

Of the events that had rupture duration greater than 50 seconds, four events involved strike-slip faulting (Table 1, with darker shadow) and nine involved thrust faulting. All such events generated tsunamis. Based on the analysis, it is suggested that the tsunami potential is not directly related to the faulting mechanism of an earthquake. These results are a good agreement with Lomax and Michelini (2011). Many of the earthquakes have thrust, normal, or strike-slip faulting with rupture duration less than 50 seconds and these events did not generate tsunamis.

Most of the earthquakes indicated a trend of decreasing rupture duration with increasing depth below the seafloor (Fig. 4b). This finding is also in good agreement with the results of Bilek and Lay (1999). All of the events that have rupture duration greater than 50 seconds, had shallow depths (≤ 50 km) and generated tsunamis. However, as previously stated, not all shallow earthquakes generated tsunamis if the rupture duration was less than 50 seconds.

The performance of Ina-TEWS needs to be evaluated against a set of parameters preset by the international community. These parameters are considered crucial in evaluating tsunamigenic earthquakes and in disseminating correctly tsunami advisories to civil defense administrators and the general public – and thus minimize false warnings and unnecessary panic. One of the most critical aspects of a tsunami warning system is to be able to estimate earthquake parameters with reasonable accuracy in the shortest possible time. Earthquake location and magnitude are the two critical parameters to be estimated, so that the right scenario for evaluation can be chosen [21].

As primary discriminants in evaluating tsunami potentials, the Ina-TEWS uses the centroid-moment tensor magnitude Mw, representing the seismic potency LWD, which is estimated through an indirect, inversion procedure. The estimated Mw and the implied LWD value vary with the depth of faulting, assumed earth model and other factors and is only available within a period of 30 minutes or more after an earthquake. The use of more direct procedures for hazard assessment, when available, could avoid these problems and help in a more effective early warning (Lomax and Michelini, 2011).

4. CONCLUSIONS

Examination of the rupture duration of large earthquakes occurring in the ocean in the Indonesian region, illustrates the need for rapid and accurate information about the potential of tsunami generation. Analysis of rupture durations for fifty-one events using the direct procedure, determined that of the 51 earthquakes in Table 1 with moment magnitude Mw between 6.7 and 9.0, sixteen (or 31%) had rupture duration, Tdur > 50 seconds and all sixteen generated tsunamis. Of the thirty five of the earthquakes which had rupture duration Tdur < 50 seconds, only one (2,8%) generated a tsunami. Only 75% of the fifty-one earthquakes were associated with reverse faulting generated tsunamis. This means that earthquake rupture duration can be used as a discriminant for more accurate and rapid tsunami warning. Earthquakes that have a strike-slip fault type can also generate a tsunami, when the average rupture duration is greater than 50 seconds. The present analysis and results suggest that tsunami potential is not directly related to the faulting mechanism of an earthquake. With available real-time seismographic data, a rapid calculation of the direct, rupture duration discriminant can be completed within 3-8 min after the P wave arrival and thus help in issuing more effective and reliable early tsunami warning. It is recommended that rupture duration should be included as a primary discriminant for Ina-TEWS operations.

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