STUDY OF RAPID BROADBAND MOMENT MAGNITUDE DETERMINATION FOR TSUNAMI EARLY WARNING SYSTEM IN MALAYSIA

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ABSTRACT

We studied several methods to determine the moment magnitude, focusing on broadband P wave moment magnitude for the purpose of tsunami early warning system in Malaysia. We determined M_{wp}^k based on the method by Kanjo et al. (2006). We also determined M_{wp} based on the original method of Tsuboi et al. (1999) for comparison. Next we determined M_{wpd}' using the duration-amplitude procedure that was simplified from the original method by Lomax and Michelini (2008). Finally, we performed the moment tensor inversion using the program coded by Yagi to obtain M_w. We applied all these methods on 20 shallow earthquakes' data inside the region of 30°N – 15°S and 85°E – 150°E which occurred from 2005 to 2008 and $M_w^{CMT} \geq 6.0$ plus one supplemental data of the December 26, 2004 Sumatra-Andaman earthquake. Then we compared our results with the moment magnitude from the Global CMT catalog (M_w^{CMT}).

From the analysis, we found that for larger events ($M_w > 8.0$), M_{wp}^k showed good estimation while M_{wp} results showed underestimation. On the other hand, for smaller events, M_{wp}^k showed overestimation while M_{wp} results showed good estimation. However, in general, both M_{wp}^k and M_{wp} estimates correlate well with M_w^{CMT}. M_{wpd}' estimates produced very good results with large events. For M_w determination using moment tensor inversion method, the results were in good agreement with M_w^{CMT} although we found underestimations for tsunami earthquakes and great earthquakes such as the July 17, 2006 and December 26, 2004 events. All in all, this study has provided the base ground of improving the tsunami early warning system in Malaysia.

Keywords: Tsunami, M_{wp}, M_{wpd}, Broadband P wave Moment Magnitude

1. INTRODUCTION

Malaysia is not an earthquake-prone country. However, due do its location which is near seismically active plate boundaries, the country is susceptible to seismic risks and has been affected by tremors from large earthquakes which occurred at these plate boundaries. The mega-thrust earthquake of December 26, 2004 generated a very large tsunami that inundated 13 countries in the Indian Ocean region including Malaysia. Since that time, the Malaysian National Tsunami Early Warning System (MNTEWS) has been implemented to provide tsunami early warning to the country. The MNTEWS is currently using the Antelope system as its main seismic processing system. The system uses the body wave magnitude scale, m_b, for magnitude calculation. We know that m_b has saturation effect at around 6.2 and above (Stein and Wysession, 2003). Therefore, it is not suitable for estimating the size of large earthquakes. On the other hand, the moment magnitude scale gives a more accurate estimate for magnitude of large earthquakes. From the viewpoint of tsunami early warning system, the detection of a tsunamigenic earthquake and estimating its size at the earliest stage is indispensable. Therefore, this

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study is being carried out to facilitate the process of upgrading the tsunami early warning system in Malaysia by analyzing broadband seismic data using several techniques of P wave moment magnitude determination.

2. DATA ACQUISITION

We had chosen 20 earthquakes ($M_w \geq 6.0$) with hypocenter depths shallower than 100 km which occurred from the year 2005 – 2008 inside the region of 30°N – 15°S and 85°E – 150°E and retrieved the waveform data from the Data Management Center of the Incorporated Research Institution for Seismology (IRIS-DMC) via internet. We also supplemented the data with December 26, 2004 Sumatra-Andaman Earthquake. We retrieved only BHZ channel data from stations with the maximum distance of 85 degrees from the event's epicenter.

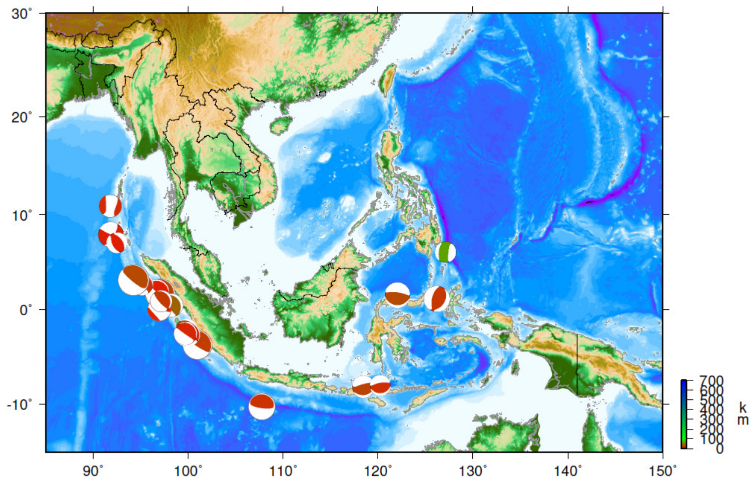

Figure 1. Location of analyzed events. The focal mechanism plot downloaded from Global CMT catalog search (http://www.globalcmt.org/CMTsearch.html)

3. THEORY AND METHODOLOGY

3.1 Determination of broadband P wave moment magnitude, M_{wp}^k

Following Tsuboi et al. (1995, 1999), we determined the moment magnitude using the vertical component of broadband P wave seismograms (M_{wp}). The scalar seismic moment, M_0, for each station is obtained from the peak of maximum amplitude value of the integrated displacement of P wave train, using the following equation (Tsuboi et al., 1995):

$$M_0 = \max\left(\left|\int u_s(x_r, t)dt\right|\right) 4\pi\rho\alpha^3 r \quad (1)$$

where u_s (x_r, t) is the vertical component of far-field P wave displacement at station x_r, ρ and α are the mean density and P wave velocity along the propagation path, respectively, and r is the epicentral distance. The moment magnitude, M_w, is then obtained from

$$M_w = (\log_{10} M_0 - 9.1)/1.5 \quad (2)$$

(Kanamori, 1977) without a correction for radiation pattern. In equation (3), 0.2 is added to the above equation to compensate for radiation pattern as explained by Tsuboi et al., (1995) and obtained the M_{wp}.

$$M_{wp} = M_w + 0.2 \quad (3)$$

Kanjo et al. (2006) further modified the method by using a distance-dependent apparent P wave velocity ($\alpha = 0.16\Delta + 7.9$ km/sec) derived from a fit to the apparent P wave velocity from the IASP91 earth model instead of a constant apparent P wave velocity ($\alpha = 7.9$ km/sec) as used by Tsuboi et al. (1995, 1999). In this study, we used both of these values to compare the results from each other on our data. We denoted our results as $M_{wp}{}^{k}$ to refer to the application of Kanjo et al. (2006)'s method. We analyzed the portion of 130 seconds of the seismogram beginning from 10 seconds before the initial P wave arrival time. Then we calculated the seismic moment and M_{wp} based on equations (1), (2), and (3). The moment magnitude estimate for each event was then obtained by averaging the moment magnitudes for all stations of each event.

3.2 Determination of P wave moment magnitude using duration-amplitude procedure, $M_{wpd}{}'$

The duration-amplitude procedure by Lomax and Michelini (2008) determines apparent source durations, T_0, from high-frequency broadband P wave seismograms, and estimate moments through integration of displacement records over the interval t_p to $t_p + T_0$, where t_p is the P-arrival time. In this study, we simplified this method to determine the apparent source duration, T_d, and calculate the duration-amplitude magnitude, $M_{wpd}{}'$.

First, we obtained the vertical component of broadband seismograms from each station and converted it to high-frequency records using 1 – 2 Hz band-pass filtering. After performing the envelope and smoothing function, we measured the set of time delays after the P arrival time in which the envelope function lastly dropped below 25 percent (T^{25}) of its peak value (Hara, 2007a,b). Then, we calculated the apparent source duration, T_d, with

$$T_d = T^{25} - T_P \tag{4}$$

where T_P is the P wave arrival time. In order to prevent the inclusion of S wave phase in the data set, $T_d < T_S - T_P$. We then obtained the average T_d for all stations to get the T_d estimates for the event.

Next we calculated the seismic moment using the following equation,

$$M_0^d = kC_M \max\left[\int_{t_P}^{t_P+T_0} u^+(t)dt, \int_{t_P}^{t_P+T_0} \left|u^-(t)\right| dt\right] \tag{5}$$

where k is a constant included to compensate for any unknown errors and biases in the terms of C_M and in the correction of u(t) for attenuation and geometrical spreading. C_M is a constant that depends on the density and P wave speed at the source and station, and also corrections for radiation pattern and free-surface amplifications. For simplicity reason, we assumed that C_M and the corrections were physically exact, thus k = 1, and the term C_M is defined by $C_M = 4\pi\rho\alpha^3 r$, where $\alpha = 0.16\Delta + 7.9$ km/sec. The moment magnitude can then be calculated based on equation (2) as follows,

$$M_{wpd}{}' = \left(\log_{10} M_0^d - 9.1\right)/1.5 \tag{6}$$

We evaluated the seismic moment for each station using vertical component seismograms with the following procedure: (1) Cut each seismogram from 10 sec before the P-arrival to the P-arrival time plus the source duration, T_d, or 10 sec before the S arrival, whichever is earlier, to obtain P wave seismograms. (2) Integrate the P wave velocity seismogram to obtain the displacement seismogram. (3) Integrate the displacement seismogram separately over $u^+(t)$ and $|u^-(t)|$ and choose the maximum of these two integrals to calculate the moment estimate. (4) Apply equation (5) and (6) to the seismogram to calculate the M_0 and $M_{wpd}{}'$ estimate.

3.3 Determination of moment magnitude, M_w, using moment tensor inversion method

The general expression of a vertical component of observed seismic waveform at station j is as in equation (7).

$$u_j(t) = \sum_{q=1}^{5} \int d\tau \iiint_V G_{jq}(t-\tau, x, y, z) M_q(\tau, x, y, z) dV + e_0 \quad (7)$$

where V is the source space, G_{jq} is the complete Green's function, M_q is elementary moment density tensor and e_0 is observation error. Equation (7) can also be written in vector form as the following:

$$\mathbf{d}_j = \mathbf{G}(T(t), x_c, y_c, z_c)_j \mathbf{m} + \mathbf{e}_j \quad (8)$$

where **d** is the N-dimensional data, **G** is a N x 5 coefficient matrix, **m** is a five-dimensional model parameter vector and **e** is the error vector. By using the least-square method, equation (8) can be solved, provided that the observation waveform (**d**) and convolution Green's function with source time function (**G**) are known. This method requires the assumption of the location of hypocenter and the information of the duration and shape of the source time function. The grid search method is then used to determine these parameters.

In this study, we used prem-modify-model velocity structure to find the moment tensor solution. We calculated the Green's function and body wave inversion using the program coded by Yagi. In his program, we will try to find the best fit between the observed waveform and theoretical waveform and determine the best depth and source duration time with minimum variance.

4. RESULTS

4.1 Determination of broadband P wave moment magnitude, M_{wp}^k

We applied this method using two values of apparent P wave velocity, which are $\alpha = 0.16\Delta + 7.9$ km/sec as proposed by Kanjo et al. (2006) and $\alpha = 7.9$ km/sec as in the original method by Tsuboi et al. (1995, 1999) to determine M_{wp}^k and M_{wp}, respectively. In general, the M_{wp}^k obtained correlates well with M_w^{CMT} although most of the events with $M_w^{CMT} < 8.0$ are overestimated in this study. The results of the M_{wp} obtained are in better agreement with M_w^{CMT} for the events that are overestimated by M_{wp}^k. However, M_{wp} underestimated the M_w^{CMT} for larger events. The comparison between the results with M_w^{CMT} is shown in Figure 2. In general, the M_{wp}^k and M_{wp} obtained are in good agreement with M_w^{CMT} and consistent with the overall result as obtained by Kanjo et al. (2006). Figure 3 shows the average M_{wp}^k and M_{wp} deficits for each event plotted as a function of $M_w^{CMT.}$. The trend shown in Figure 3 is consistent with the results of Whitmore et al. (2002) in which there is a decreasing deficit with increasing $M_w^{CMT.}$. From this result, we can see that by using $\alpha = 0.16\Delta + 7.9$ km/sec, we can determine the magnitude for larger earthquakes with better estimate.

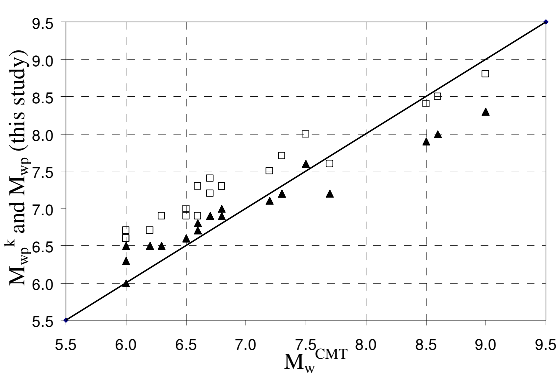

Figure 2. Comparison of M_{wp}^k and M_{wp} (this study) with M_w^{CMT}. (M_{wp}^k: open square, M_{wp}: solid triangle)

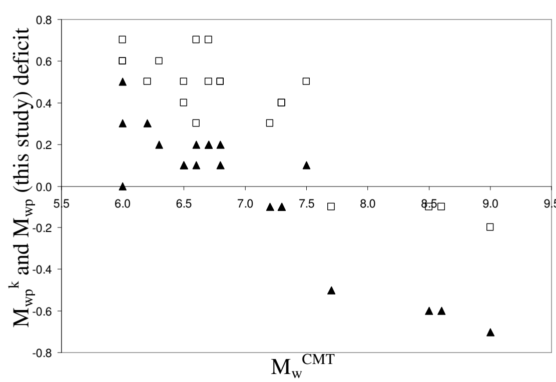

Figure 3. Magnitude deficit (Magnitude average (this study) - M_w^{CMT}) plotted as a function of $M_w^{CMT.}$. (M_{wp}^k: open square, M_{wp}: solid triangle)

4.2 Determination of P wave moment magnitude using duration-amplitude procedure, M_{wpd}'

For this method, we use a simplified approach to determine the apparent source duration, T_d, and then use the measured duration to obtain M_{wpd}'. From Figure 4, we can see that the M_{wpd}' obtained for large events ($M_w^{CMT} > 8.5$) fits perfectly with M_w^{CMT} but gradually becomes overestimated as the M_w^{CMT} decreases. The trend of this result is quite similar to the result of the previous method. However, this method gives better estimate with larger earthquakes compared with the previous method. This means that by considering the apparent source duration carefully, we can determine the size of large earthquakes with better estimate.

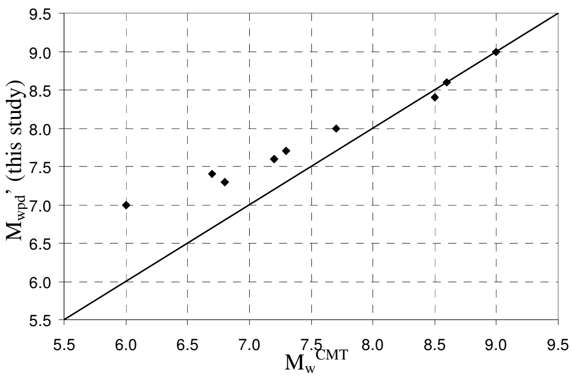

Figure 4. Comparison of M_{wpd}' (this study) with M_w^{CMT}.

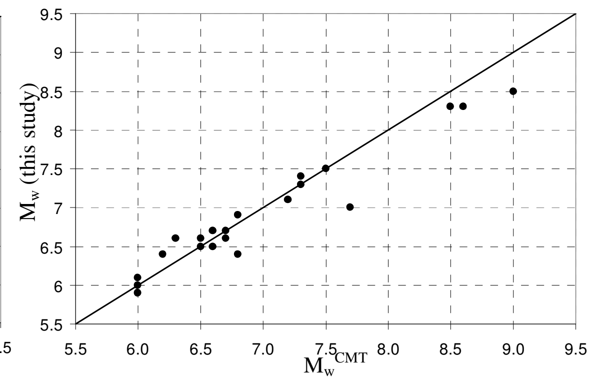

Figure 5. Comparison of M_w (this study) with M_w^{CMT}.

4.3 Determination of moment magnitude, M_w, using moment tensor inversion method

The results of M_w determination and the example output of the moment tensor inversion program are shown in Figures 5 and 6, respectively. We can see that the M_w obtained from this study correlates very well with M_w^{CMT}. Magnitude difference between them is in the range of -0.4 to 0.3. However, we can also see that the differences between July 17, 2006 tsunami earthquake and December 26, 2004 mega-thrust earthquake are relatively larger than the others (-0.5 and -0.7, respectively).

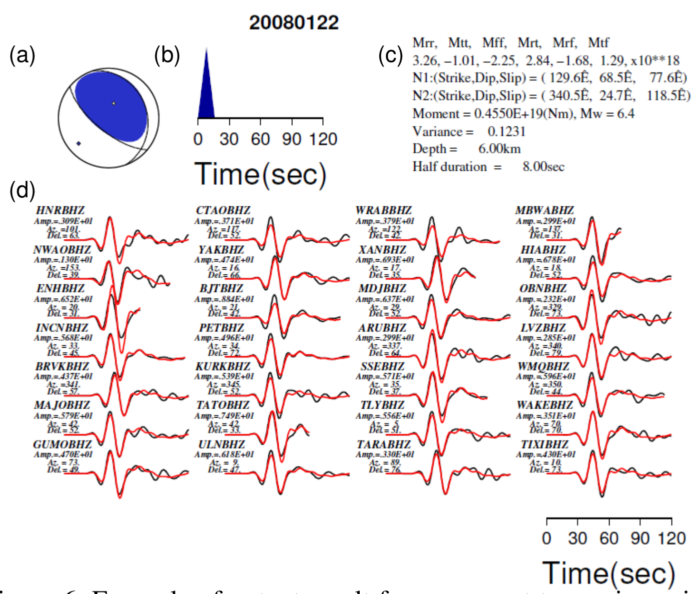

Figure 6. Example of output result from moment tensor inversion program by Yagi. The upper part shows (a) the focal mechanism, (b) the source time function and (c) the source parameters. The lower part (d) shows the waveform fitting. Red and black lines indicate theoretical and observational waveforms, respectively.

5. CONCLUSIONS

From our analysis, we found that M_{wp}^k is overestimated for smaller events ($M_w < 8.0$), while M_{wp} is underestimated for larger events ($M_w > 8.0$). However, in general, both M_{wp}^k and M_{wp} estimates correlate well with M_w^{CMT}. On the other hand, M_{wpd}' estimate produced very good results with large events due to the usage of duration-amplitude procedure. For determination using moment tensor inversion method, the obtained moment magnitudes were in good agreement with M_w^{CMT}. However, we could not acquire a good estimate for tsunami earthquakes and great earthquakes such as the July 17, 2006 and December 26, 2004 events. This is because the moment tensor inversion program determines M_w using body wave signals while M_w^{CMT} is determined by using long period surface waves. The analysis using short period body waves cannot determine the size of very large earthquakes.

6. ACTION PLAN

In order to use the broadband P wave moment magnitude scale into the current seismic processing system in Malaysian Meteorological Department (MMD), we need to integrate the calculation program into the system. However, this needs further discussion between MMD and the system developer, Boulder Real Time Technologies, Inc. (BRTT). Nevertheless, this study has provided the base ground of improving the tsunami early warning system in this country. It is important because from the aspect of tsunami hazard assessment, a rapid and accurate determination of an earthquake size, together with the other source parameters, is essential to classify whether the earthquake is tsunamigenic or not. In consequence, a tsunami early warning or other appropriate information can be disseminated. Therefore, on the basis of this study, I plan to work together with the department and the system developer to construct a way of implementing the broadband P wave moment magnitude determination method in our tsunami early warning system. Other than that, I also plan to further studying other recent methods for magnitude determination in the future for further understanding the earthquake source process.

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