MAGNITUDE DETERMINATION USING ACCELERATION RECORDS FROM THE INDONESIAN STRONG MOTION NETWORK

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ABSTRACT

We developed an empirical magnitude formula for Indonesia using absolute value acceleration integral computed from accelerograms. We used 68 records from the Indonesia strong motion network operated by the Meteorological Climatological and Geophysical Agency (BMKG) for 13 earthquakes that occurred in the Indonesia region between November, 2008 and March, 2010 with focal depths less than 150 km and $Mw \geq 5.9$. We followed Wu and Teng (2004) with slight modification to include a term for focal depth to construct a formula for the new magnitude *MewBMKG*. We used the least square method under constraints to estimate the coefficients for absolute value acceleration integral, hypocentral distances, and focal depths.

We compared the estimates of *MewBMKG* to the moment magnitudes from the Global CMT catalog. We found a good agreement between them. The RMS of their differences is 0.27 in the magnitude unit. No saturation is observed up to magnitude 7.7. *MewBMKG* will be able to be obtained within 3 minutes after earthquakes occurs using data from stations in the epicentral distance less than 300 km. This meets the requirement of the Indonesia Tsunami Early Warning System (InaTEWS). We also determined a magnitude, M_{BMG}, (Iman 2007), for which the maximum displacements obtained from accelerograms are used. Differences between M_{BMG} and the moment magnitudes from the Global CMT catalog are smaller than those between *MewBMKG* and the moment magnitudes from the Global CMT catalog. We discussed possible problems in calculation of these magnitude scales for their implementation into the InaTEWS.

Keywords: Magnitude, Accelerogram, Tsunami warning, InaTEWS.

1. INTRODUCTION

The Indonesia Tsunami Early Warning System (InaTEWS) was designed first in 2005 after the great tsunami of Aceh on December 26, 2004. From the lesson learned as well as from observations of historical tsunamis in Indonesia, the first tsunami wave will arrive within 20 minutes after an earthquake occurs. The InaTEWS is currently issuing a tsunami warning within 5 minutes based on earthquake parameters such as magnitudes which should be obtained within 3 minutes after earthquakes occur. However, magnitude determination sometimes underestimated very large events such as the 2004 Aceh. Therefore, it is imperative for the InaTEWS to determine accurate magnitudes as quickly as possible. The purpose of this study is to determine magnitudes of strong earthquakes using acceleration records. For this aim, we determine an empirical magnitude formula base on the absolute value acceleration integral. The result using this method is then compared with those from the BMG magnitude, M_{BMG} (Iman 2007) and moment magnitude, *Mw*, from the Global CMT catalog.

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2. DATA

We chose 13 earthquakes ($M_w \geq 5.9$) whose focal depths are shallower than 150 km that occurred in Indonesia region between November, 2008 and March, 2010 (Table 1). We used the earthquake parameters (origin time, latitude, longitude, and depth) from USGS and their *Mw* from the Global CMT catalog. The accelerogram waveform data from the accelerograph network of the BMKG in their ASCII format are used. All data were converted to SAC (Seismic Analysis Code) format.

Table 1. List of 13 events used in this study.

No	Event	Origin time (yyyy/mm/dd, hh:mm:ss)	Epicenter (degree)	Depth (km)	*Mw* (GCMT)	*Mew* *BMKG*	M_{BMG}
1	Ternate	2008/11/09, 00:00:00.70	1.88N, 127.36E	96	6.6	6.25	6.54
2	Manokwari	2009/01/03, 19:43:50.65	0.41S, 132.88E	17	7.7	7.46	7.54
3	Manokwari	2009/01/03, 22:33:40.29	0.69S, 133.30E	23	7.4	7.11	7.21
4	Siberut	2009/08/16, 07:38:21.70	1.48S, 99.49E	20	6.7	6.97	6.86
5	Tasikmalaya	2009/09/02, 07:55:01.05	7.78S, 107.30E	46	7.0	7.11	7.24
6	Padang	2009/09/30, 10:16:09.25	0.72S, 99.87E	81	7.6	7.71	7.49
7	Jambi	2009/10/01, 01:52:27.33	2.52S, 101.50E	9	6.6	6.59	7.07
8	Saumlaki	2009/10/24, 14:40:43.72	6.13S, 130.38E	130	6.9	6.77	7.12
9	Sinabang	2009/12/09, 21:29:02.58	2.77N, 95.91E	19	5.9	5.99	5.81
10	Siberut	2009/12/23, 01:11:58.20	1.43S, 99.39E	19	5.9	6.19	6.24
11	Tual	2009/12/26, 08:57:27.48	5.53S, 131.21E	83	6.1	6.44	6.28
12	Saumlaki	2010/02/15, 21:51:48.56	7.19S, 128.78E	130	6.2	5.84	6.29
13	Pagai	2010/03/05, 16:07:01.26	3.37S, 101.04E	26	6.7	6.28	6.40

3. THEORY AND METHODOLOGY

3.1. Empirical Magnitude Formula using Absolute Value Acceleration Integral, √Es

To compute the total effective shaking embodied in waveforms of near-field acceleration recordings, Wu and Teng (2004) defined an absolute value acceleration integral, $\sqrt{Es}$, as:

$$\sqrt{Es} = \int_{Tp}^{Te} \sqrt{V^2 + N^2 + E^2}\, dt \,, \qquad (1)$$

where V, N, and E are vertical, north–south, and east–west components of acceleration signals (in gal) respectively, T_p is the P-wave arrival time, and T_e is the end-of-event time of the strong-shaking duration. T_e is defined as the time when the acceleration amplitude drops below 20% of the maximum amplitude and remains below it for 5 seconds. An example of the acceleration records of north-south component, absolute amplitude of three-component data, and absolute value acceleration integral are shown in the top, middle, and bottom traces of Figure 1, respectively.

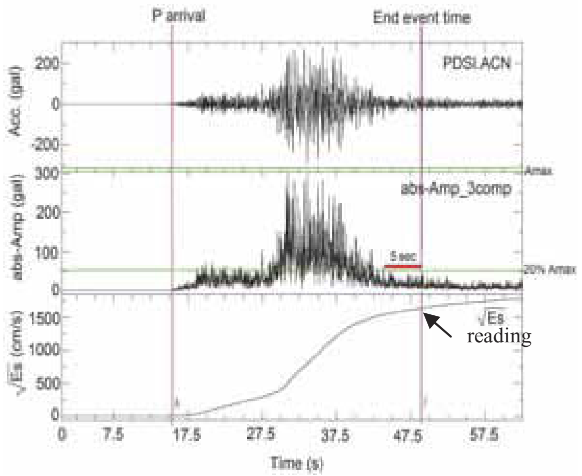

Figure 1. An example of waveform data and processed time series for the September 30, 2009 Padang earthquake (*Mw* 7.5) at PDSI station.

The following is the formula used in this study:

$$M = A + B \cdot \log\left(\sqrt{Es}\right) + C \cdot \log(R) + D \cdot R + E \cdot H \,, \qquad (2)$$

where $\sqrt{Es}$ is absolute value acceleration integral (cm/s), R is hypocentral distance (km), H is focal depth (km). The coefficients A, B, C, D, and E are the model parameters. There are two differences between this formula and that of Wu and Teng (2004). First, we included a term of focal depth. Second, we did not include a term of site corrections considering a limited number of data. We set initial values to each model parameter based on physical considerations and tendencies of data. Then, we performed inversion under constraints (e.g., Tarantola and Valette 1982) to determine the model parameters so that the magnitudes from absolute value acceleration integral were consistent with moment magnitude from the Global CMT catalog.

3.2. Determination of BMG Magnitude, M_{BMG}

To compare the result of magnitudes obtained by absolute value acceleration integral, we obtained BMG magnitude, M_{BMG} introduced by Iman (2007). This M_{BMG} formula also uses accelerogram data. We used the same data as we did in magnitude determination using absolute value acceleration integral. The formula of M_{BMG} is as follows:

$$M_{BMG} = \log_{10} A_D + 2.15\log_{10} R - 1.88, \tag{3}$$

where A_D is the maximum displacement amplitude (μm) and R is hypocentral distance (km). The displacement is obtained by twice integration after a third-order Butterworth low cut filter with the corner frequency of 0.1 Hz is applied. We manually picked the maximum displacement amplitude within a reasonable time window corresponding to source time from three component records.

4. RESULTS

4.1. Magnitude Determination using $\sqrt{Es}$

We used 68 acceleration records from 13 earthquake events shown in Table 1. After converting waveforms and calculating the absolute value acceleration integral, we determined the coefficients A, B, C, D, and E using the least square method under constraints. The estimated coefficients are 0.557, 1.310, 1.389, 0.001, and -0.005, respectively. Thus, the empirical moment magnitude is given by:

$$MewBMKG = 0.557 + 1.310\log\left(\sqrt{Es}\right) + 1.389\log(R) + 0.001R - 0.005H \tag{4}$$

Here, we use *MewBMKG* to reflect that this magnitude is derived empirically through absolute value acceleration integral computed using acceleration records from the Indonesia strong motion network operated by BMKG.

Figure 2 shows the comparison between the *Mw* from the Global CMT catalog and the *MewBMKG* magnitudes for 13 events used. The *MwBMKG* are calculated from their average for each event. There is a good agreement between them. The RMS of their differences is 0.27. *MewBMKG* does not saturate up to magnitude 7.7. We plot the difference between *MewBMKG* and *Mw* from the Global CMT catalog for all of 68 data as a function of hypocentral distance (Figure 3a) and focal depth (Figure 3b), respectively. The differences scatter around zero, which suggest that there is no significant systematic bias with respect to magnitude, hypocentral distance and focal depth.

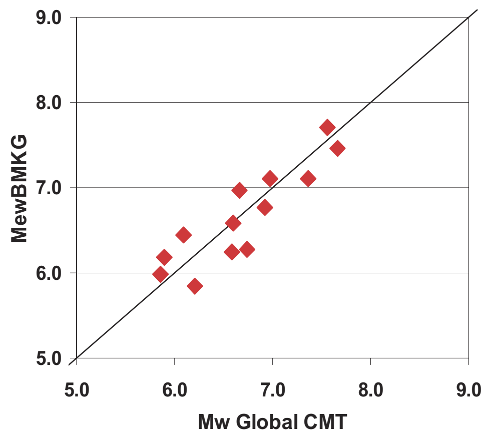

Figure 2. Comparison between *Mw* GCMT and *MewBMKG*.

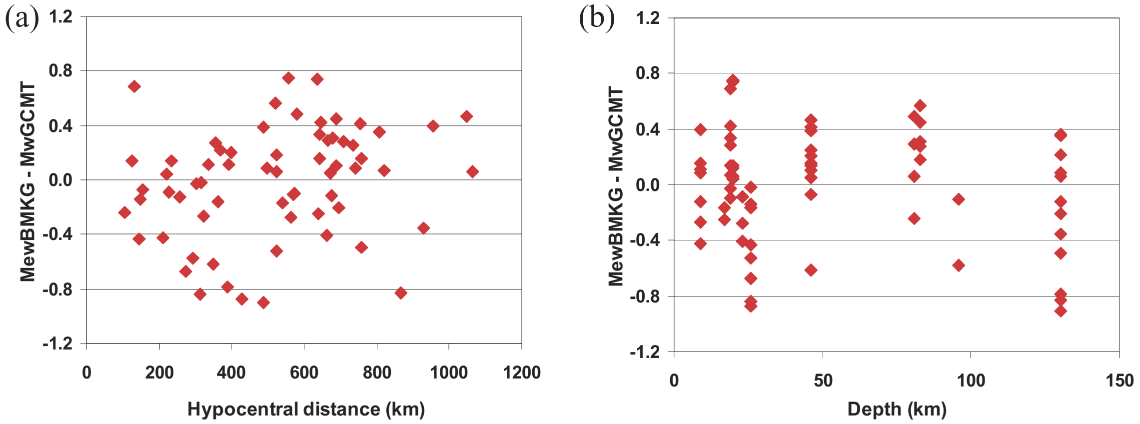

Figure 3. Difference between the MewBMKG and Mw GCMT for all of 68 data used. (a) As a function of the hypocentral distance. (b) As a function of the focal depth.

Figure 4 shows the comparisons of attenuation curves of Wu and Teng (2004) and this study for the Siberut earthquake *(Mw* 6.7*,* depth 20 km) and the Saumlaki earthquake *(Mw* 6.9*,* depth 130 km). The attenuation relations of Wu and Teng (2004) and that of this study are similar to each other for shallow events (Figures 4a). For deeper events (Figures 4b), there is a significant difference between them. The attenuation relation of this study explains the observed $\sqrt{Es}$ better. This is mainly due to including the term for focal depth in this study.

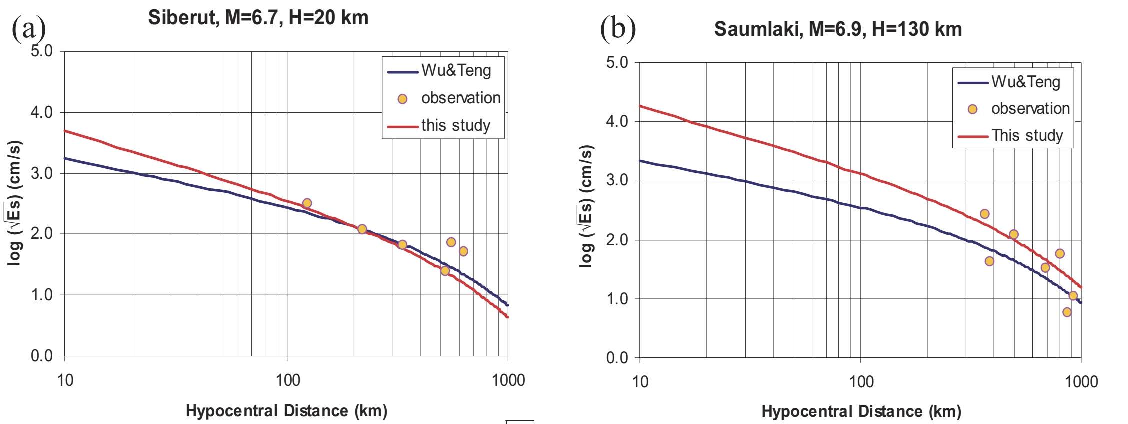

Figure 4. Attenuation curves of √Es obtained by this study and Wu and Teng (2004).

4.2. Magnitude Determination of BMG Magnitude, M_{BMG}

The comparison between the *Mw* from the Global CMT catalog and BMG magnitude, M_{BMG}, for 13 events used is shown in Figure 5. M_{BMG} are calculated from their average for each event. There is a good agreement between them. The RMS of their differences is 0.23. M_{BMG} does not saturate up to magnitude 7.7.

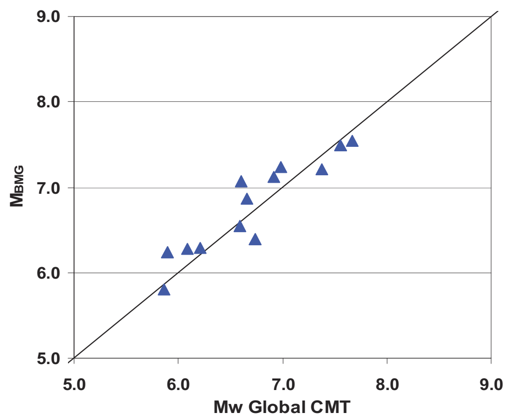

Figure 5. Comparison between *Mw* GCMT and M_{BMG}.

5. DISCUSSION

As mentioned in sections 4.1 and 4.2, the RMS of the differences between these magnitudes (*MewBMKG* and M_{BMG}) and *Mw* from the Global CMT catalog are 0.27 and 0.23, respectively. Therefore, for the current dataset the estimates of M_{BMG} agree better with *Mw* from the Global CMT catalog. However, we would like to point out some possible problems in calculation of M_{BMG}.

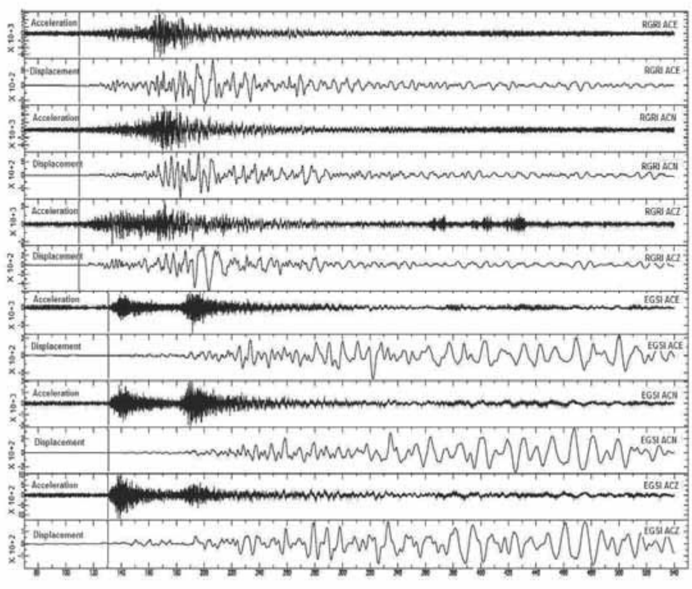

Figure 6. Examples of the original accelerograms and displacement calculated by twice integration.

Figure 6 shows acceleration records (stations RGRI and EGSI) for the Siberut earthquake (*Mw* 6.7, depth 20 km). The corresponding twice integrated displacement records are also shown for each acceleration record. Before integration, a high pass filter with a corner frequency of 0.1 Hz is applied. It will be desirable to study optimal filter in this procedure. We observe that the displacement records sometimes have large amplitudes of long period waves (for example station EGSI). These long period waves may cause overestimation of magnitude. Also, it will make it difficult to measure the maximum displacements automatically within a reasonable time window corresponding to source times.

Figure 7 shows the distribution of the end-of-event times of √Es and the times of maximum displacements. The times of maximum displacement are shorter than the end-of-event times. However, it will be difficult to pick the maximum displacement where there are long period waves. The times of maximum displacements picked automatically are longer than the end-of-event times in some stations in which there are long period waves. Application of the procedure of this study to set an end-of-event time will be helpful to make calculation of M_{BMG} more stable. When we apply this technique, the time required to determine both magnitude scale are the same. The end-of-event times are less than 3 minutes after earthquake occurrences at epicentral distances less than 300 km. Therefore, *MewBMKG* will be able to obtain within 3 minutes using stations distributed at epicentral distances less than 300 km. This meets the requirement of the InaTEWS in which the location and magnitude of earthquakes should be determined within 3 minutes and the warning should be issued within 5 minutes after earthquakes occur.

High-gain broadband seismograms recorded at near-field distance may saturate for large earthquakes. Accelerogram data could be utilized as the backup for such a case. Now, the BMKG have launched a project to install 500 accelerographs spreading around Indonesia region. Therefore, with this dense accelerograph network, we can determine a reliable *MewBMKG* rapidly for large earthquake from the near-field records and will be useful for improvement of InaTEWS.

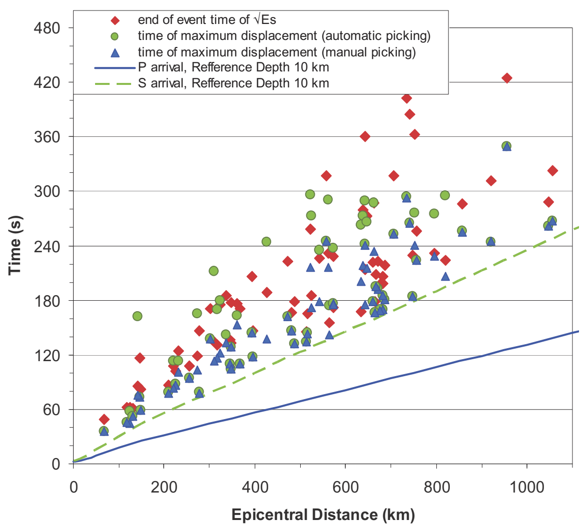

Figure 7. Distribution of the end-of-event times of √Es and the times of maximum displacement.

6. CONCLUSIONS

We developed an empirical formula to calculate a new magnitude *MewBMKG* for Indonesia using absolute value acceleration integral, $\sqrt{Es}$, computed using acceleration records from the Indonesian strong motion network operated by the Meteorological Climatological and Geophysical Agency (BMKG). We modified the formula given by Wu and Teng (2004) by including a term for focal depth. Then, we determined the coefficients in the formula so that *MewBMKG* is consistent with the moment magnitudes from the Global Centroid Moment Tensors solutions. The RMS of the differences between *MewBMKG* and *Mw* from the Global CMT catalog is 0.27 in the magnitude unit for the current data set used in this study consisting of the 68 records from 13 earthquakes. The shallow and intermediate depth events are included in the data set. There is no significant systematic bias with respect to moment magnitude, hypocentral distance (up to 1,200 km), and focal depth (up to 130 km). Our results suggest that this magnitude scale does not saturate for large earthquakes up to magnitude 7.7. The observed absolute value acceleration integral and those computed for this magnitude agree well with each other. *MewBMKG* will be able to be obtained within 3 minutes after earthquakes occurs using data from stations in the epicentral distance less than 300 km, which meets the demand of InaTEWS.

We also calculated the BMG magnitude, M_{BMG}, introduced by Iman (2007), and compare their estimates to *Mw* from the Global CMT catalog. The RMS of their differences is 0.23. Therefore, M_{BMG} agrees better with *Mw* from the Global CMT catalog. However, there might be possible problems for this magnitude due to long period waves. Therefore, we suppose that *MewBMKG* will be useful for rapid and reliable quantification of earthquake sizes, and improvement of InaTEWS.

RECOMMENDATION

The purpose of this study is to determine magnitudes using acceleration records without the magnitude saturation problem for large earthquakes. The BMKG should determine earthquake locations and magnitudes within 3 minutes after earthquakes occur. *MewBMKG* will be able to be obtained within 3 minutes using data from stations in the epicentral distances less than 300 km. This method can utilize accelerogram data as the backup of seismogram data when a large earthquake occurs. The *MewBMKG* formula could be improved using accumulation of data from large events and/or from near-field records after the planned 500 accelerograph stations are installed. Also, the reliability of *MewBMKG* formula should be tested using data from stations in the epicentral distances less than 300 km. Intensive studies will be necessary to shorten the time required to obtain the magnitude by the method of this study and to treat the possible problem of tsunami earthquakes.

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REFERENCES

Earthquake Search; USGS, http://earthquake.usgs.gov/earthquakes/eqarchives/epic/

Global CMT Catalog Search, http://www.globalcmt.org/CMTsearch.html

Iman, S., 2007, Individual studies by participant at IISEE/BRI, Japan, 1, 1-28

Tarantola, A. and Valette B., 1982, J. Geophys. Res., 50, 159-170

Wu, Y. M. and Teng, T. L., 2004, Tectonophysics, 390, 205-216