Citation: Widiarso, A., A. Katsumata (2022), Rapid magnitude estimation using local earthquake waveform data and the application to earthquakes in Indonesia including the 2010 Mentawai tsunami earthquake, Synopsis of IISEE-GRIPS Master's Thesis.

RAPID MAGNITUDE ESTIMATION USING LOCAL EARTHQUAKE WAVEFORM DATA AND THE APPLICATION TO EARTHQUAKES IN INDONESIA INCLUDING THE 2010 MENTAWAI TSUNAMI EARTHQUAKE

Aziz Widiarso[1]
MEE21717

Supervisor: Akio KATSUMATA[2]

ABSTRACT

This study aims to estimate earthquake magnitude quickly using vertical component data from Broadband seismographs for improvement of tsunami warnings. We formulate using displacement and integrated displacement data with a cut-off of more than 100 seconds. Empirical relationships were obtained for displacement and integrated displacement with moment magnitude. Data selection of seismic records was done before estimating the relationships of amplitudes by observing the amount of data to unselect records with gaps and the maximum amplitude to eliminate spike data. We compared the magnitudes of the formulas for displacement (M_D) and integrated displacement (M_{ID}). We found that M_{ID} yielded better estimates than M_D. M_{ID} also produced appropriate estimates for earthquakes with strike-slip focal mechanisms. On the other hand, for deep earthquakes, M_D yielded a better estimate. In the case of the 2010 Mentawai tsunami earthquake, M_{ID} produced an underestimated whereas the estimate was obtained no more than 3 minutes after the earthquake origin time.

Keywords: Magnitude estimation, M_{ID}, M_D, tsunami earthquake.

1. INTRODUCTION

Magnitude is one of the principal parameters of an earthquake; it represents the released energy and potential impact on the area near the earthquake's epicenter. In contrast to the earthquake's intensity with a different value for a particular area, an earthquake has one value of magnitude. By using earthquake magnitude information, a government can determine the appropriate response regarding the evacuation of affected areas and warnings for potential disasters such as tsunamis. There are two methods to estimate the magnitude of an earthquake: empirical method and theoretical method. The empirical method uses evidence-based on gathered experience or observation data without any or a small amount of theoretical evidence. On the other hand, the theoretical method works with logical assumptions and theory based on research.

Badan Meteorologi Klimatologi Geofisika (BMKG) uses Seiscomp3 for processing the earthquake waveform. Seiscomp3 is a seismological software for data acquisition, processing, distribution, and interactive analysis developed by GEOFON, Germany. Seiscomp3 offers various types of magnitude estimation inside the program. Including empirical methods such as M_{Lv}, m_b, m_B, and M_{JMA}

[1] Agency for Meteorology, Climatology, and Geophysics, Indonesia.
[2] Professor, Toyama Univ.

and theoretical methods M_{WP} and M_W by the waveform inversion methods. BMKG uses summary magnitude (M_{SUM}) in the first information release and updates the magnitude using M_W afterwards. M_{SUM} is a weighted average of the individual magnitudes over by Seiscomp3. M_{SUM} gives attempts to be the best possible compromise between all magnitudes. Since M_{SUM} depends on the calculation of other magnitudes, the accuracy and speed of the calculation are related to other magnitudes. For the local station, M_{SUM} considers M_{Lv} and M_{JMA}. However, local magnitude (M_{Lv}) is saturated for earthquakes bigger than 6.5 (Sitaram & Borah, 2007), and M_{JMA} indicated saturation during the 2011 Great East Japan earthquake (Hirose et al., 2011). It became necessary to formulate a new magnitude estimation that can estimate the proper magnitude in 5 minutes to give better earthquake information and tsunami warning.

2. DATA

We used data from vertical component broadband seismographs because it is more sensitive to long-period waves, which can overcome the problem of magnitude saturation (Aki, 1967). Broadband seismograph records long-period seismic waves well, but instrument correction is still necessary to normalize the more extended period waves. We used 135 earthquakes of more than magnitude 6 in 10 years period from 2012 to 2021. We eliminated 14 deep earthquakes (>400 km) from our calculation. The distribution of earthquakes can be seen in Fig. 1, where the open circle represents the earthquake, and the triangle symbolizes the broadband seismograph.

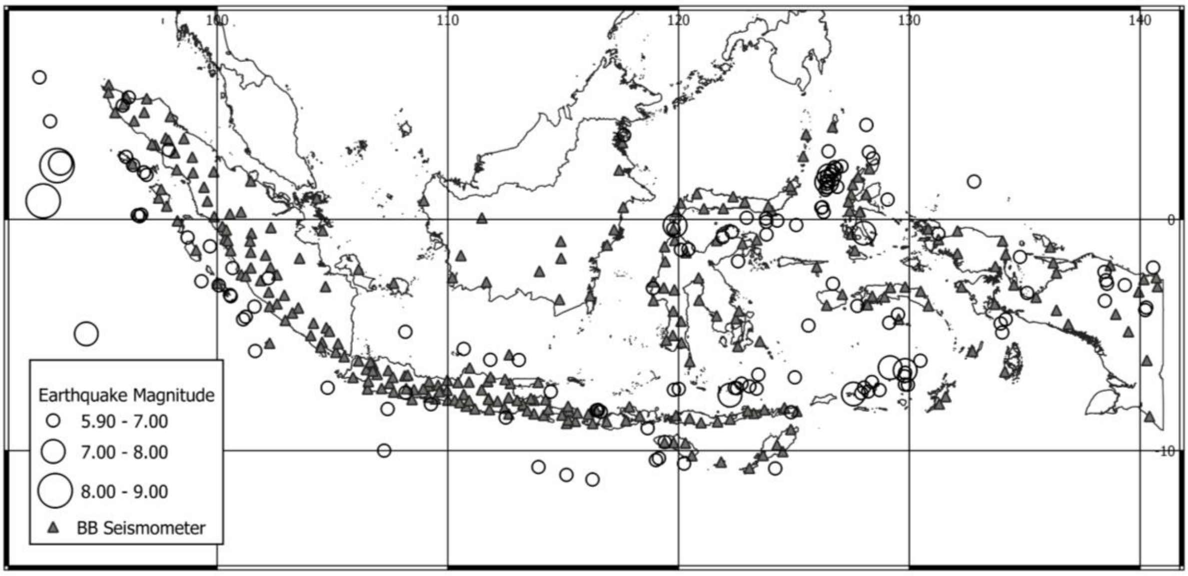

Figure 1. Distribution of the 2012-2021 earthquakes and broadband seismometers.

3. METHODOLOGY

We formulated the empirical earthquake magnitude formula by observing the relation between magnitude to the maximum amplitude of long period wave and hypocentral distance of the stations. Several steps of data processing are required for the process of calculating the formula.

3.1 Data preparation

Instrumental response correction was conducted in the time domain to normalize the damped long period waves during the recording process. In time domain process is necessary for rapid real-time processing. We used the recursive filter for instrument response correction proposed by Katsumata et al. (2021).

The recursive filter was obtained by calculating the z-transform of the inverse response in the Laplace transform expression. The recursive formula utilized the two lower poles of station to calculate the constants used in the formula. We transform the velocity data into displacement and integrated displacement by applying the numerical integrations. Then, low-cut Bessel filters with cut-off 100 seconds were applied to suppress the baseline shifting due to multiple integration prosses. The cut-off of 100 seconds was chosen refers to Katsumata et al. (2013).

3.2 Maximum amplitude data selection

Most magnitude estimation formulas require a specific time window to determine the maximum amplitude to be selected. The time window serves to specify what part or phase of the seismic wave will be used in the calculation. For example, M_{WP} uses the P wave phase of an earthquake wave. A wide time window will produce a magnitude with a small error but require more time in the calculation. On the other hand, a narrow time window results in a fast calculation with a high error value (Leyton et al., 2018). We calculated magnitude formula using any earthquake wave phase adopted from Katsumata et al. (2013). When any phase can be used for calculations, a specific time window for finding the maximum amplitude is not required. This makes the calculation process simple and robust.

3.3 Data selection

Our earthquake seismic wave database contains bad quality data such as gaps, spikes, and high noise data. We want to eliminate the bad quality data from the formulation. The gaps data were selected by observing the number of data recorded in one stream, and spikes data were removed observing the deviation with the logarithmic regression for each earthquake event. We calculated logarithmic regression of maximum amplitude to hypocentral distance for each earthquake, then calculated the standard deviation of maximum amplitude to model. We got 0.59 as standard deviation from our dataset. The data limit is determined to be twice the standard deviation, and stations that exceed this limit are assumed to be the bad quality data.

3.4 Formulation

The empirical method uses evidence based on observational data that has been collected. We looked for the correlation between the maximum amplitude and station distance by determining the values of the constants *a*, *b*, and *c* in Eq. 1.

$$M = a \log_{10} A + b \log_{10} R + c \,, \tag{1}$$

where A and R are the maximum amplitude and hypocentral distance, respectively. Determination of constants *a*, *b*, and *c* is done by minimizing the difference between M in Eq. 1 and M_W from Global CMT. Constant *a* was determined first, then *b* and *c* were calculated using the weighted least square method. When the values of constants *a*, *b*, and *c* are determined simultaneously, the great earthquake will diverge further from M_W (Katsumata et al., 2013). The weight factor was used because of the least frequent occurrence of large earthquakes.

4. RESULT AND DISCUSSION

The *a, b,* and *c* constants derived from the weighted least square method are shown in Table 1. M_D has a higher *a* constant rather than M_{ID}. This relationship has been seen in previous research for velocity and displacement data (Katsumata, 2001; Katsumata et al., 2013, 2021). The magnitude quality was then assessed by comparing the M_{ID} and M_D to the M_W from Global CMT.

M_D has differences ranging from -0.38 to 0.35 with a standard deviation of 0.1453, while M_{ID} differences range from -0.4 to 0.32 with a standard deviation of 0.1269. M_{ID} gives a better magnitude estimation than M_D by the smaller standard deviation. Figure 2 shows the distribution of magnitude differences of M_D and M_{ID} to $M_{W.}$ M_D has more dispersed data than $M_{ID,}$ which is denser around the zero line. Large earthquakes are estimated well with a difference of ±0.1 magnitude compared to small earthquakes with ±0.3 magnitude, even though small earthquakes have a more significant number of occurrences in this data set.

Table 1. Constants for M_D and M_{ID}.

	a	***b***	***c***
M_D	0.898	1.308	5.835
M_{ID}	0.789	1.167	5.359

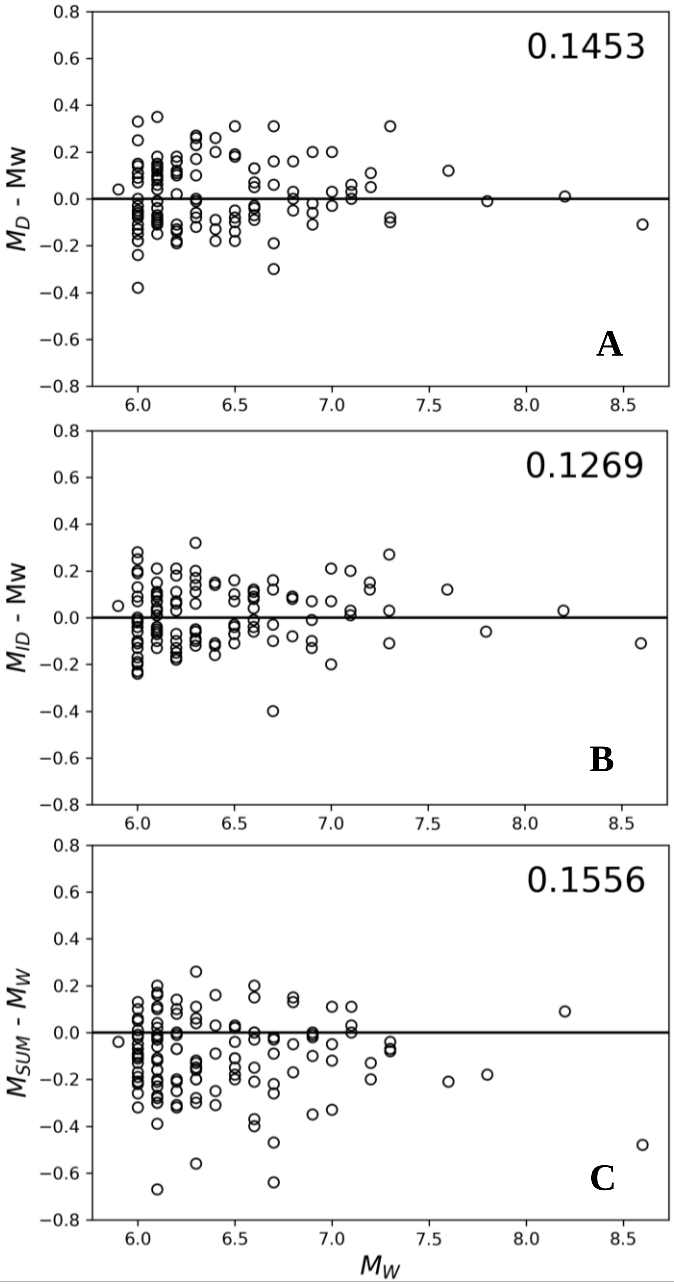

Figure 2. Difference of moment magnitude (M_W) to magnitude from displacement (A), integrated displacement (B), and summary magnitude (C).

For comparison with the current system at BMKG, the difference between M_{SUM} and M_W is shown in Fig. 2. M_{SUM} has differences ranging from -0.67 to 0.26 with a standard deviation of 0.1556. M_{SUM} tends to give underestimated magnitude since most magnitudes are below the zero line. Small earthquakes are reasonably well estimated, but large earthquakes are remarkably underestimated. This shortcoming is terrible for a tsunami warning considering that large earthquakes have the potential to generate a tsunami.

Indonesia has a high potential for strike-slip earthquakes. Intraplate faults are found in most areas, such as the Great Sumatran and Palu-Koro faults. In the data set, all earthquakes with a magnitude more than 7.5 were strike-slip. The strike-slip earthquake is shown as a red circle in Fig. 3. The magnitude estimation gives appropriate results even for strike-slip, even though the data used for the calculation was the vertical component seismogram that is sensitive to a typical dip-slip earthquake.

As we mentioned, the 14 deep earthquakes were eliminated from the calculation. The inhomogeneous anelastic attenuation (Q_S) properties at the crust, shallow and deeper parts of the upper mantle, could impact the recorded amplitude by seismograph at the surface (Katsumata, 2001). The properties difference differ from amplitude scaling for shallow and deep earthquakes. In addition, as deep earthquakes do not have enough energy to move the surface, there is no potential for a tsunami. We compared the magnitude estimation of M_D, M_{ID}, and M_{SUM} for 14 earthquakes deeper than 400 km. In contrast to the results for shallow

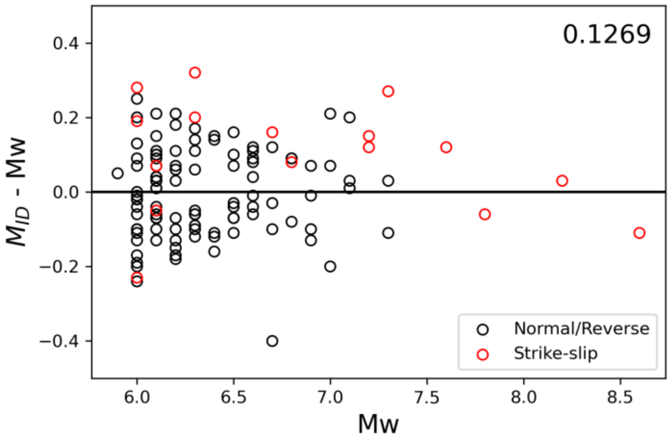

Figure 3. Magnitude estimation for strike-slip earthquake.

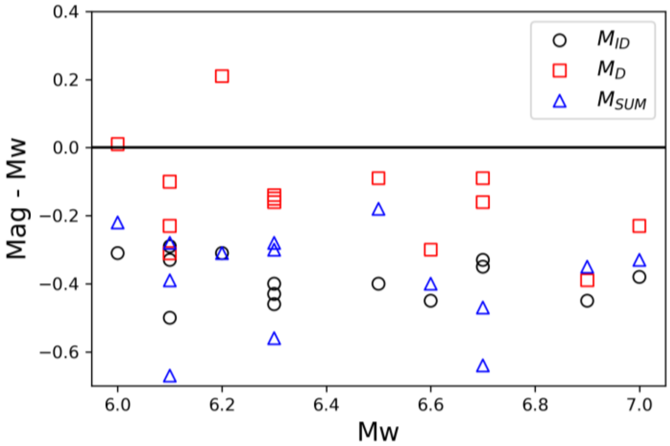

Figure 4. Magnitude estimation for deep earthquakes.

earthquakes, M_D gives a better estimation than M_{ID} for deep earthquakes, while M_{SUM} has the most underestimated value (Fig. 4).

For the estimation of time required in the calculation, we calculated the M_{ID} for the 2010 Mentawai tsunami earthquake over time using 22 nearest seismographs and then compared it to M_{SUM}. Figure 5 shows M_{ID}, M_{SUM}, M_{BA}, and M_W as the solid black line, solid grey line, blue dash line, and red dash line, respectively. M_{BA} is magnitude formula proposed by Katsumata, et. al. (2021) for tsunami earthquakes. The M_{BA} formula can estimate the magnitude and source duration of an earthquake by comparing the observation data and synthetic data with various source duration. The M_{BA} precisely estimated the 2010 Mentawai earthquake by 7.84. The M_{SUM} fluctuated in the first 2 minutes and reached the final magnitude of 7.1 after 2.5 minutes. On the other hand, M_{ID} raised stably and reached 7.4 after 3 minutes. The difference in characteristics is due to the direct link between M_{ID} and the earthquake waveform, whereas M_{SUM} is calculated from the average of other magnitudes. Three minutes is a good time for tsunami warning dissemination considering the tsunami golden time at the Sunda Strait segment varies from 5 to 40 minutes (Ponangsera et al., 2021). However, the estimation was underestimated by 0.4 from the moment magnitude as expected.

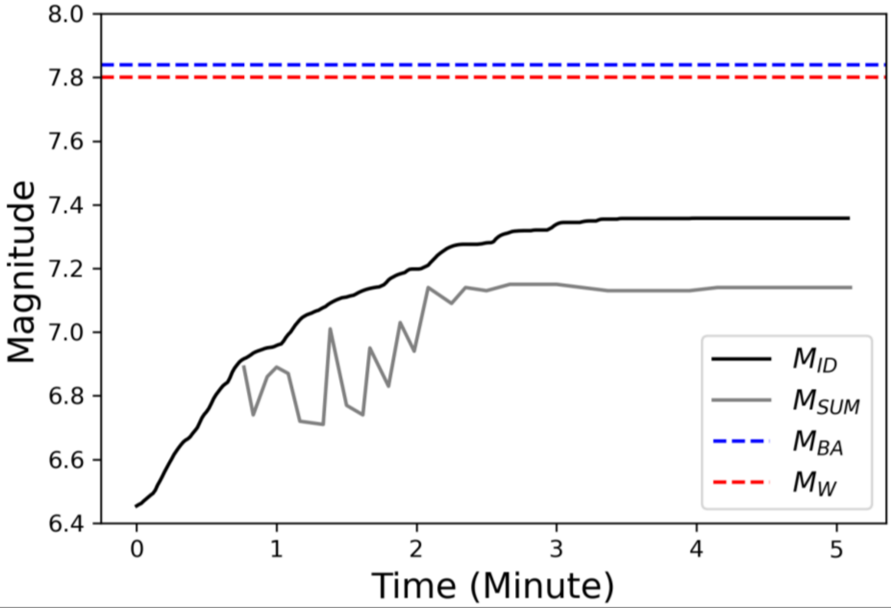

Figure 3. The 2010 Mentawai tsunami earthquake magnitude estimation.

5. CONCLUSION

We calculated an empirical formula for rapid earthquake magnitude estimation using Broadband seismograph data. The formula was formulated by observing the relationship between the maximum logarithmic amplitude of earthquake waveform with a cut-off of more than 100 seconds and the logarithmic hypocentral distance of each station with the moment magnitude (M_W) of the Global CMT. Two formulas were proposed in this research, ie., magnitude displacement (M_D) and magnitude integrated displacement (M_{ID}).

M_{ID} produced a better magnitude estimate than M_D with smaller standard deviation values, 0.1269 and 0.1453, respectively. The M_{SUM} formula used by BMKG for information on the first earthquake and tsunami tended to underestimate the magnitude of a large earthquake. M_{ID} provided a reasonable estimate of earthquakes with a strike-slip mechanism even though it only used vertical component data in its calculations. M_D and M_{ID} gave an underestimated magnitude for deep earthquakes, but overall, M_D was better for deep earthquakes.

Tsunami earthquakes tend to give underestimated magnitude estimates. We calculated M_{ID} and M_{BA} for the 2010 Mentawai tsunami earthquake. As expected, M_{ID} produced an underestimated magnitude of 7.4 with a difference of 0.4 from $M_{W,}$ while M_{BA} yielded a better estimate of 7.84. The M_{ID} estimation speed was quite good, producing a final magnitude 3 minutes after the earthquake's origin time.

ACKNOWLEDGMENT

I would like to express my deepest appreciation to my supervisor Dr. Akio Katsumata-sensei and my advisor Dr. Bunichiro Shibazaki-sensei for the knowledge and guidance that enabled me to finish my research. Second, I want to thank BMKG for providing the data, all my courses mate, and my fiance for supporting me through all these courses.

REFERENCES

Aki, K. (1967). Scaling law of seismic spectrum. Journal of Geophysical Research, 72(4), 1217–1231. https://doi.org/10.1029/JZ072i004p01217

Hirose, F., Miyaoka, K., Hayashimoto, N., Yamazaki, T., & Nakamura, M. (2011). Earth, Planets and Space, 63(7), 513–518. https://doi.org/10.5047/eps.2011.05.019

Katsumata, A. (2001). Magnitude determination of deep-focus earthquakes in and around Japan with regional velocity-amplitude data. Earth, Planets and Space, 53(5), 333–346. https://doi.org/10.1186/BF03352390

Katsumata, A., Tanaka, M., & Nishimiya, T. (2021). Rapid estimation of tsunami earthquake magnitudes at local distance. Earth, Planets and Space, 73(1), 72. https://doi.org/10.1186/s40623-021-01391-7

Katsumata, A., Ueno, H., Aoki, S., Yoshida, Y., & Barrientos, S. (2013). Rapid magnitude determination from peak amplitudes at local stations. Earth, Planets and Space, 65(8), 843–853. https://doi.org/10.5047/eps.2013.03.006

Leyton, F., Ruiz, S., Baez, J. C., Meneses, G., & Madariaga, R. (2018). How Fast Can We Reliably Estimate the Magnitude of Subduction Earthquakes? Geophysical Research Letters, 45(18), 9633–9641. https://doi.org/10.1029/2018GL078991

Ponangsera, I. S., Kurniadi, A., Ayu Puspitosari, D., & Hartono, D. (2021). Determination of tsunami run-up and golden time in the megathrust subduction zone of the sunda strait segment. E3S Web of Conferences, 331, 07007. https://doi.org/10.1051/e3sconf/202133107007

Sitaram, M. V. D., & Borah, P. K. (2007). Signal duration and local Richter magnitudes in northeast India: An empirical approach. Journal of the Geological Society of India, 70(2), 323–338.