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DEVELOPMENT OF AN EXTENDED HARA MODEL FOR MW DETERMINATION OF MODERATE-MAGNITUDE EARTHQUAKES

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ABSTRACT

This study discusses the evaluation of Hara's model to estimate seismic moment magnitude (M_W) by using teleseismic waveform data, and then presents the development of an extended Hara model. Both models use the maximum amplitude of displacement and epicenter distance, as well as the duration of high-frequency energy radiation, of the vertical component of earthquake P-wave records. Nineteen moderate-magnitude ($5.0 \leq M_W \leq 7.0$), shallow (depths ≤ 70 km), Sumatra subduction megathrust earthquake data sets recorded by the KAPI seismograph station (Kappang, South Sulawesi) in 2010 and 2011 were used in this study. The analysis is performed to obtain the maximum amplitude of displacement, epicenter distance, and the duration of high-frequency energy radiation on the first arriving P-wave. The main results show that Hara's model (2007) overestimates M_W to be less than 7.0 compared with that obtained from the Global Centroid Moment Tensor (CMT) catalog. The extended Hara model was developed with the use of the same basic equation, and the resulting coefficients are $\alpha = 0.538792$, $\beta = 0.783840$, $\gamma = 0.242616$, and $\delta = 4.929095$. The mean and standard deviation of the difference between the extended Hara model and the Global CMT catalog are 0.01 and 0.14, respectively.

Keywords: Earthquake; Hara's model; Moment magnitude (Mw); Sumatra subduction megathrust

1. INTRODUCTION

Indonesia is frequently hit by earthquakes of varying magnitudes. After the devastating December 26, 2004 Aceh Sumatra earthquake, Indonesia has been assisted by other countries, such as Germany, the US, China, Japan, and France, to acquire state-of-the art seismograph and accelerograph technologies for use in different earthquake monitoring systems throughout Indonesia. One of the objectives of these systems is to provide an accurate estimate of earthquake magnitude. Seismic moment magnitude (M_W) is one of the most common magnitude measures in the earthquake community.

Rapid magnitude calculations can be conducted through several methods, such as mB (Bormann and Saul, 2008 and 2009), W phase moment tensor inversion (Kanamori & Rivera, 2008), Mwpd (Lomax & Michelini, 2009), and Mwp (Tsuboi et al., 1995). Seismologists around the world state that rapid magnitude calculations of earthquakes are a challenging task.

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Hara suggested that M_W can be estimated from the waveform analysis results of long- distance broadband seismograph vertical component records. This analysis is performed to obtain the maximum amplitude of displacement, epicenter distance, and the duration of high-frequency energy radiation on the first arriving P-wave. The original database used by Hara comprised high-magnitude earthquakes, so evaluating whether Hara's model is applicable to earthquakes of moderate magnitude is interesting. The next question that needs to be addressed if the evaluation results are unsatisfactory is how Hara's model can be modified. This study addresses both questions by using teleseismic data from earthquakes in the Sumatra megathrust subduction zone recorded by a long-distance seismograph station in Sulawesi.

2. METHODOLOGY

Hara (2007) developed an algorithm to calculate M_W by using teleseismic waveform data, particularly the vertical component of earthquake records. In the process, the maximum amplitude of displacement and the epicenter distance, as well as the duration of high-frequency energy radiation, are examined. The process in analyzing teleseismic waveform data is summarized in Figure 1.

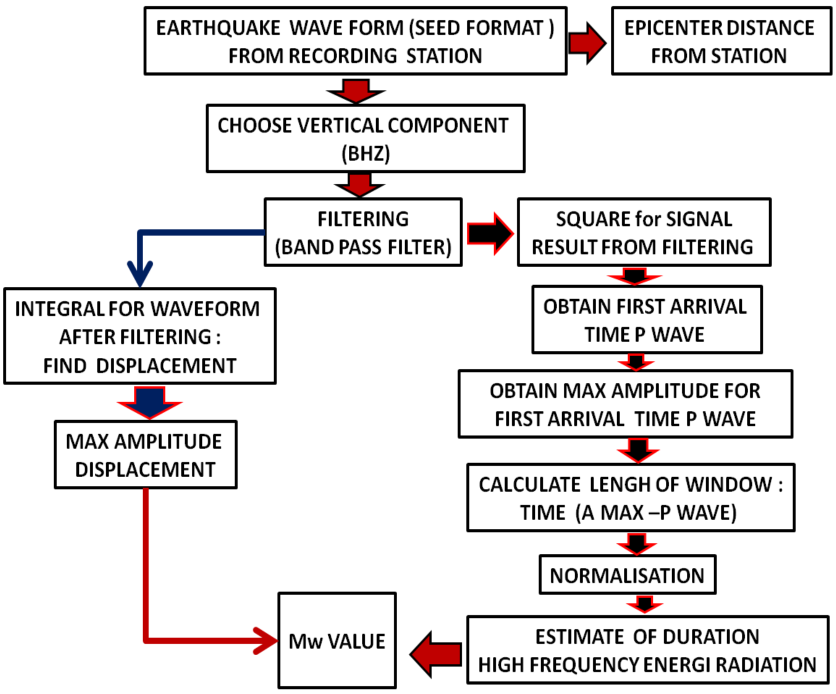


Figure 1 Stages in waveform analysis in Hara's model

Hara's model is formulated as follows:

$$M_W = \alpha \log A + \beta \log \Delta + \gamma \log t + \delta \tag{1}$$

where M_W is the moment magnitude, A is the maximum amplitude of displacement (m), Δ is the epicenter distance (km), t is the estimated time duration of high-frequency energy radiation (s), and α, β , γ , δ are the free coefficients.

Hara used 69 shallow earthquakes from 1995 to 2006 with a magnitude ≥ 7.2 and depth ≤ 50 km to develop his model, which he found had good agreement with the Harvard CMT measurement. By using the least squares method, he estimated the following: $\alpha = 0.79 \pm 0.03$, $\beta = 0.83 \pm 0.05$, $\gamma = 0.69 \pm 0.03$, and $\delta = 6.47 \pm 0.17$. A comparison of Hara's results and those of the Harvard CMT catalog show that these two models are generally consistent with each other. As an example, the December 26, 2004 Aceh earthquake and the March 28, 2005 Nias earthquake achieved similar results (M_W = 9.0 and M_W = 8.6, respectively). However, other earthquakes attained different results. As an example, the November 3 2002 Denali earthquake had M_W = 7.1, whereas the December 26, 2004 Aceh earthquake had M_W = 7.8

3. CURRENT DATA SET

In this study, 19 earthquakes that occurred in 2010 and 2011 in the Sumatra subduction interface megathrust zone were investigated. The selected earthquakes met the following three criteria: $5.0 \leq M_W \leq 7.0$, shallow depth (≤ 70 km), and a thrust-type focal mechanism. The data on the earthquakes were taken from the Indonesia Agency for Meteorology, Climatology, and Geophysics (BMKG).

Hara's model requires teleseismic records, so we used the KAPI seismograph station as the reference station when obtaining far-field earthquake data. The main consideration in selecting the station located in Kappang, South Sulawesi was its greater than 10° location from the epicenters of the considered earthquakes. The other factors for selecting this station were KAPI's installation on a rock outcrop and its relatively remote location. Note that the KAPI station is one of the stations representing the joint cooperation between Indonesia and the Comprehensive Nuclear-Test-Ban Treaty Organization.

Table 1 summarizes the information about the 19 earthquake data sets used. Figure 2 shows the locations of the earthquakes and the KAPI station. The waveform data sets were retrieved from the database maintained by BMKG.

Table 1 Data from the Sumatra subduction interface megathrust in 2010 and 2011

No.	Time (y/m/d)	Origin Time (UTC)	Long (deg)	Lat (deg)	Depth (km)	M_W	Amplitude (m)	Distance (deg)	Duration (s)
1	2010/04/11	05:59	101.64	−5.66	17	5.2	1.03E-05	18.1	102.2
2	2010/08/02	23:13	104.48	−7.07	46	5.1	1.22E-05	15.4	90.6
3	2010/08/21	05:42	96.45	2.01	24	5.9	1.06E-04	24.3	81.1
4	2010/09/30	09:54	94.06	4.84	45	5.2	9.78E-06	27.0	88.4
5	2010/10/25	19:37	99.97	−3.37	23	6.3	3.53E-04	19.9	87.0
6	2010/10/25	23:00	100.12	−3.55	14	5.9	1.39E-04	19.7	71.5
7	2010/10/26	23:45	99.66	−2.60	19	5.4	2.83E-05	20.2	89.1
8	2010/11/09	11:16	99.17	−1.92	28	5.4	1.75E-05	20.8	87.4
9	2010/12/21	14:07	95.59	2.44	23	5.8	1.24E-04	25.3	86.2
10	2011/01/01	15:19	101.22	−4.73	21	5.8	9.29E-05	18.5	110.5
11	2011/01/15	11:23	96.13	2.26	17	5.8	9.20E-05	24.7	62.6
12	2011/01/15	16:26	96.22	2.30	12	5.5	7.12E-06	24.6	54.1
13	2011/01/17	19:20	102.45	−5.37	35	6.0	1.50E-04	17.3	77.0
14	2011/01/18	11:33	96.17	2.38	15	5.9	1.01E-04	24.7	98.2
15	2011/01/22	07:38	95.32	2.74	15	5.7	1.12E-05	25.6	125.1
16	2011/01/26	15:42	96.52	1.87	23	6.0	9.63E-05	24.2	91.3
17	2011/04/06	14:01	96.82	1.40	24	5.9	8.17E-05	23.8	96.9
18	2011/05/28	17:07	103.31	−5.98	26	5.7	6.72E-05	16.5	90.7
19	2011/08/22	20:12	103.93	−-6.68	31	6.1	1.44E-04	15.9	118.0

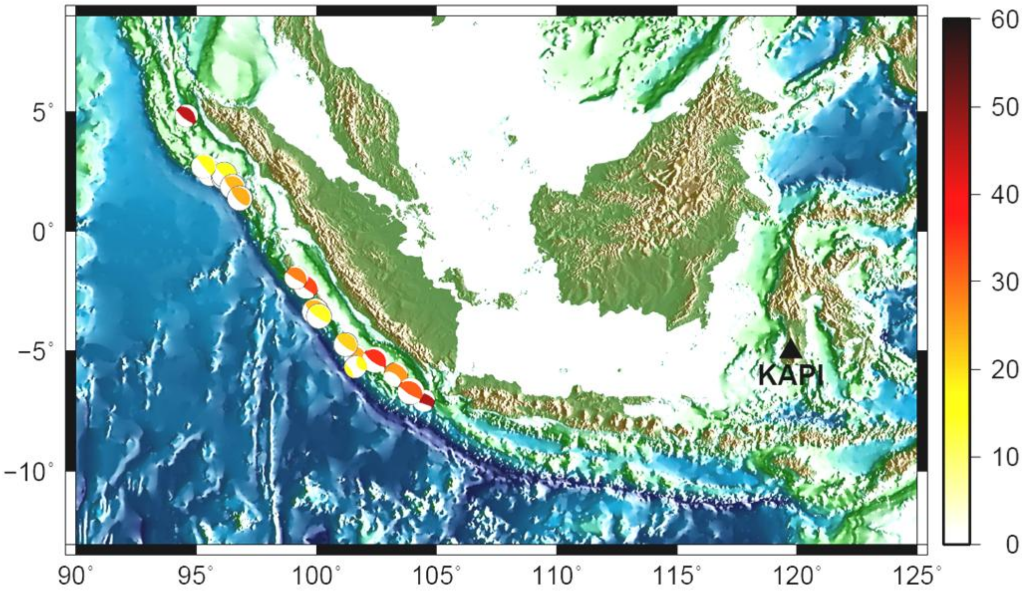
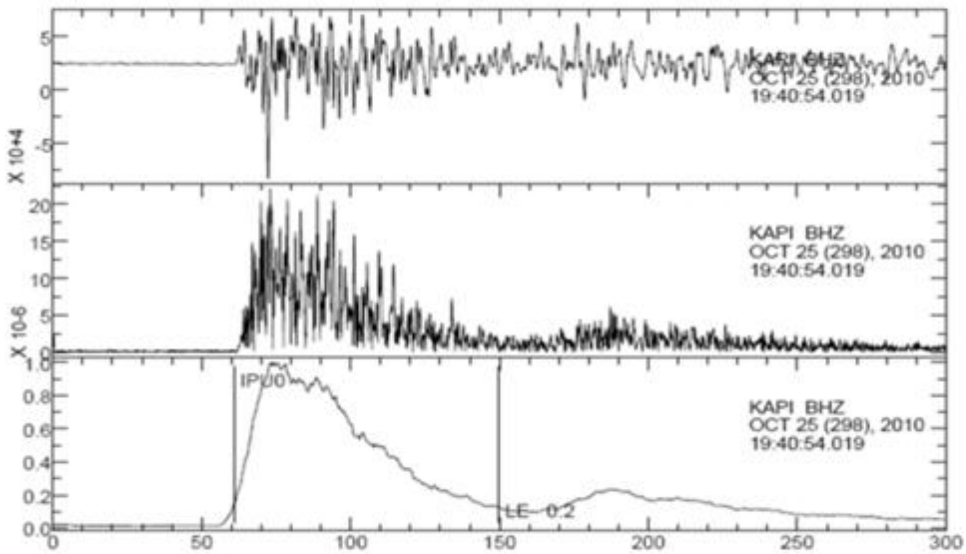


Figure 2 Data from the Sumatra subduction interface megathrust and KAPI station

For each data set, we analyzed the maximum amplitude of displacement, epicentral distance, and the duration of high-frequency energy radiation. Figure 3 shows some examples of waveform analysis. Figure 3(a) depicts the waveform analysis for the earthquake that occurred on October 25, 2010, with origin time 19:40:54 and M_W = 6.3. The parameters obtained from the analysis are amplitude of displacement (A) = 3.53×10^{-4} m, epicentral distance (Δ) = 19.85°, and duration (t) = 86.979 s. Figure 3(b) shows the waveform analysis for the earthquake that occurred on October 26, 2010, with origin time 23:49:09 and M_W = 5.4. The parameters obtained from the analysis are A = 2.83×10^{-5} m, Δ = 20.23°, and t = 89.098 s. Table 2 shows the parameters of A, Δ, and t from the 19 earthquakes.



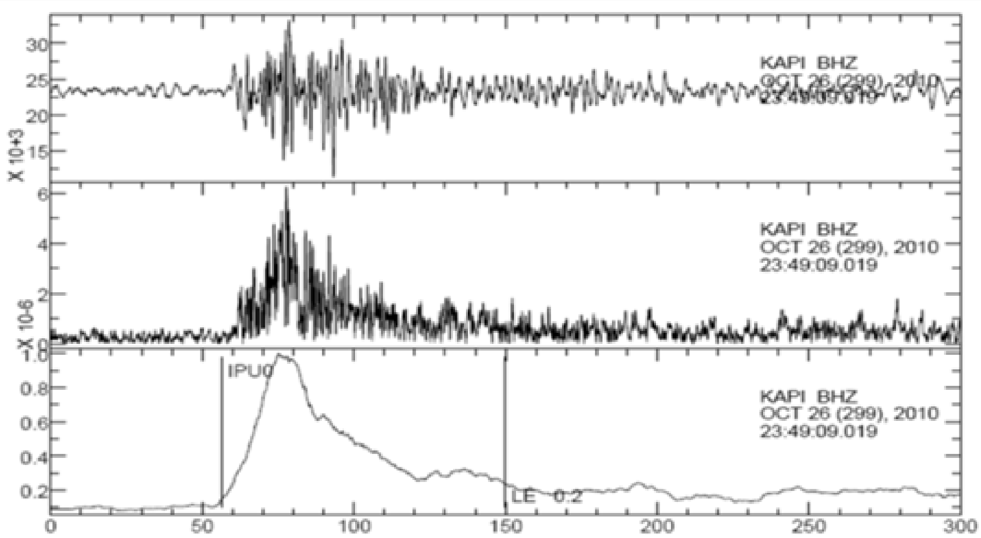


Figure 3 Waveform analysis from the vertical component (BHZ) by Hara's model; a) M_W = 6.3 earthquake that occurred on October 25, 2010; b) M_W = 5.4 earthquake that occurred on October 26, 2010

4. EVALUATION OF HARA'S MODEL

The evaluation of Hara's model was performed with the use of the 19 earthquake data sets. Basing on the parameters of A, Δ, and t, we calculated M_W with Hara's model. For comparison, we used the corresponding data from the Global CMT catalog (see Table 1). Figure 4 shows the comparison between Hara's model and the Global CMT catalog.

We can clearly observe that all M_W values from Hara's model are greater than the corresponding M_W values from the Global CMT catalog. The following equation was used to examine further this overestimation:

$$\Delta M_W = M_{W\text{-}Hara} - M_{W\text{-}Global\ CMT} \quad (2)$$

where $M_{W\text{-}Hara}$ is the M_W by Hara's model, $M_{W\text{-}Global\ CMT}$ is the M_W from the Global CMT catalog.

The overestimation ranges from 0.95 to 1.78, with a mean and standard deviation of 1.50 and 0.18, respectively. Therefore, the original Hara's model is not applicable to the calculation of the moment magnitude of moderate earthquakes and that a modification to Hara's model is needed for moderate earthquakes whose M_W ranges from 5.0 to 7.0.

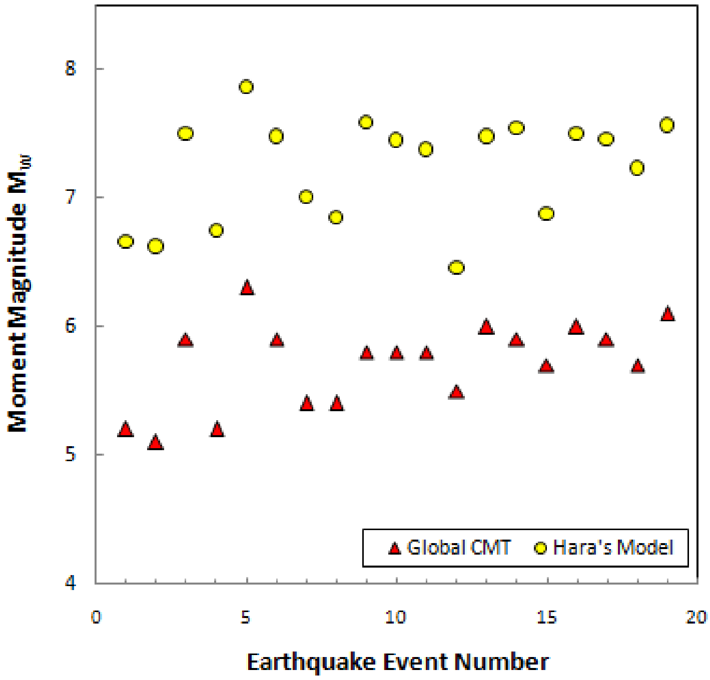


Figure 4 Comparison of M_W: Hara's model and the Global CMT catalog

5. MODIFICATION OF HARA'S MODEL

The 19 earthquake data sets, along with the M_W values from the Global CMT catalog, were subsequently used to develop a modification of Hara's model for moderate-magnitude earthquakes. The basic equation is Equation (1), and by using the least square method, we estimated the new values for the coefficients α, β, γ, and δ. The resulting extended Hara model is as follows:

$$M_W = 0.538792 \log(A) + 0.783840 \log(\Delta) + 0.242616 \log(t) + 4.929095 \tag{3}$$

The goodness of Equation (3) is evaluated with the use of an equation similar to Equation (2). The difference between the extended Hara model and the Global CMT catalog ranges from −0.23 to 0.23, with a mean and standard deviation of 0.01 and 0.14, respectively. The values of Mw for both methods have a very small difference such that the change in Mw value is insignificant. This result means that the developed model performs well. The mean and standard deviation are very small. The implication of this result for the near future is that we can rapidly calculate Mw after the occurrence of an earthquake in a certain area. However, we cannot predict Mw. We already validated the use of the Global CMT catalog because it is a reference in calculating the Mw value with the use of the moment tensor.

Figure 5 shows the comparison between the extended Hara model and the Global CMT catalog.

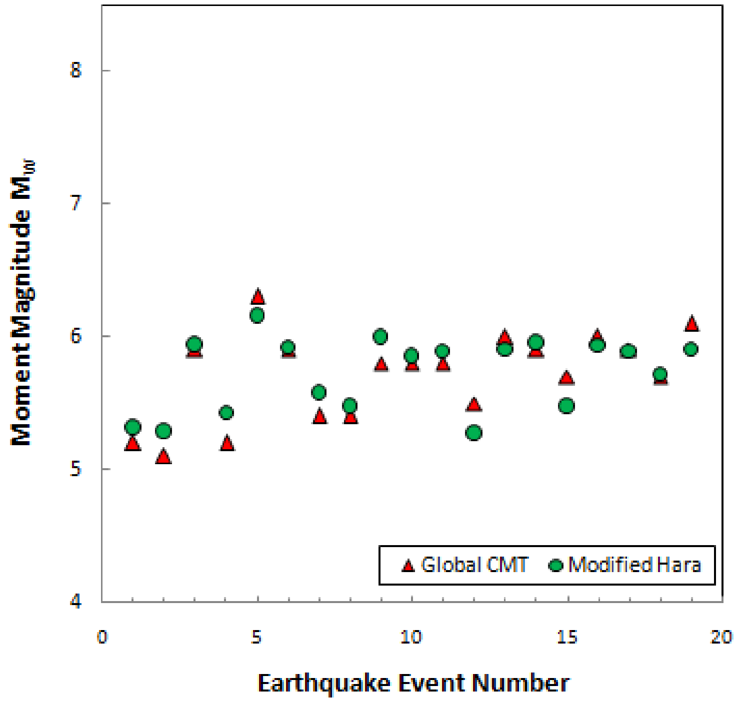


Figure 5 Comparison of M_W: Extended Hara model and the Global CMT catalog

6. CONCLUSION

The main findings of this study are as follows: Hara's model (2007) overestimates M_W to be less than 7.0 compared with the Global CMT catalog. The mean and standard deviation of the difference between Hara's model and the Global CMT catalog are 1.50 and 0.18, respectively.

The extended Hara model was developed with the use of the same basic equation, and the resulting coefficients are $\alpha = 0.538792$, $\beta = 0.783840$, $\gamma = 0.242616$, and $\delta = 4.929095$. The mean and standard deviation of the difference between the extended Hara model and the Global CMT catalog are 0.01 and 0.14, respectively.

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