Duration magnitude estimate from local magnitude for moderate earthquakes in three provinces of Sulawesi

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Abstract. The primary aim of this study is to estimate earthquake duration magnitude \( M_D \) from local magnitude \( M_L \) for a set of seismo-tectonic events in North Sulawesi, Central Sulawesi, and West Sulawesi during 2008-2015 years. The data were collected from Webdc3, comprising datasets of magnitudes in the three regions of interest. The data were firstly used to develop corresponding local magnitudes, after which these magnitudes were analyzed to parameterize duration magnitude. Using a simple parametric equation (adopted from relevant work) directly linked \( M_D \) to \( M_L \), \( M_D = 1.05 M_L - 0.17 + c \) where \( c \) represented a correction factor, we found that the equation is applicable to moderate events considered with no significant difference in the calculated values whether or not \( c \) was used. For completeness, we compared the \( M_D \) values in the three provinces with \( M_W \) scales provided by the Global CMT catalogue as the reference. The results show that the obtained values of \( M_D \) are in good agreement with the magnitude reference of \( M_W \) within \( \pm 0.2 \) units in magnitude. The results suggest that empirical relations between \( M_D \) and \( M_L \) used here are appropriate for rapid and accurate magnitude determination to improve seismic hazard assessment in the three provinces.

1. Introduction
Hazard mitigation study associated with earthquakes involves a method of earthquake early warning that comprises conceptual methods and possible applications [1]. In this context, a physical quantity of importance differentiating a particular earthquake source from another is earthquake magnitude [2]. For regions that are vulnerable to seismo-tectonic hazards, such as Sulawesi Island as one of islands in the eastern Indonesian provinces, the problem of hypocenter relocation and magnitude determination was claimed vital due to tsunami potential in the regions [3]. In response to this, [4, 5] used broadband seismograms recorded by a network of local stations in Sulawesi to estimate accurate local magnitudes generated from data of \( P \)-wave dominant periods. Another important parameter related to the source is signal duration formerly introduced by [6] as a measure of a tsunami discriminant. This duration was then used by [7] to evaluate Indonesian tsunami early warning system.

The primary purpose of this study is to estimate earthquake duration size from possible quantities, including signal duration and local magnitude recorded by local seismic station networks surrounding the epicenter. The signal duration generated by Joko Tingkir, a software validated in [8] for use, can be used to determine duration magnitude but many seismologists [9, 10, 11] were particularly in favor of...
a direct scaling relation of duration magnitude and local magnitude, with which we are here concern. Thus, magnitude estimate using this scaling is crucial for earthquake early warning in Indonesia.

2. Experimental Methods
A total of 72 moderate earthquakes in majority recorded by a network of local seismic stations in North Sulawesi with all hypocenters at sea depth and magnitudes in the range of \(4.0 \leq M \leq 7.5\) during 2010-2015 previously examined by [4], along with other 50 local occurrences in Central Sulawesi and 37 local earthquakes in West Sulawesi previously explored by [5] having the same magnitude range as that occurred in North Sulawesi but recorded during 2008-2015 with hypocenters distributed below the seafloor and land at depth, were used in this study. Geographical positions of the three provinces are respectively \(0.25^\circ - 5.57^\circ\) N and \(123.12^\circ - 127.17^\circ\) E for North Sulawesi, \(2.37^\circ\) N – \(3.80^\circ\) S and \(119.37^\circ - 124.37^\circ\)E for Central Sulawesi, \(0.20^\circ - 3.63^\circ\) S and \(118.72^\circ - 124.90^\circ\) E for West Sulawesi. In all cases, most of the events considered are shallow sources of less than or equal to 100 km deep with moderate magnitudes (see figure 1).

![Figure 1](image-url)
2.1. Data collection
All considered events that occurred in the three regions of interest and their corresponding datasets of earthquake magnitudes were freely accessible as high-frequency broadband seismogram data from http://eida.gfz-potsdam.de/webde3/. Their associated magnitudes for each region were then obtained from the Global CMT catalogue at http://www.globalcmt.org/, where the magnitudes were considered as reference and were symbolized as $M_w$ in this study. Local magnitudes $M_L$ for all events used here were taken from [4] for North Sulawesi and from [5] for both Central Sulawesi and West Sulawesi.

2.2. Data analysis
The primary method used in this study was to develop a line of best fit with a correction, if necessary, using paired datasets of earthquake magnitudes given for each region of interest. Initially, we adopted techniques in [9, 10] using signal duration data (not provided here) to generate duration magnitude $M_D$ but found unclear relation between the resulting magnitude $M_D$ with respect to magnitude reference $M_w$ by the Global CMT catalogue. This included a small correlation coefficient for the regression line generated, leading to a failure in duration magnitude determination. Considering this failure, we used a different scale, similar to the one discussed in [11], where $M_D$ was directly linked to local magnitude $M_L$ from both [4] and [5]. Using this method, we estimated duration magnitude for the three provinces with an additional factor $c$ to take the effects of local sites and instruments into account and wrote it as $M_D = 1.05M_L - 0.17 + c$, adopted from [11]. During examination of this mathematical expression for the three provinces, we found $c$ to be negligible and hence we used $M_D = 1.05M_L - 0.17$ only to derive duration magnitude estimates $M_D$ from local magnitudes $M_L$ for this work.

3. Results and Discussions
The results of earthquake duration magnitude estimate for all events examined in the present study are detailed below and the corresponding discussions follow. This includes statistical analysis of the data obtained in each region. For reasons associated with epicentral distances between the epicenter and local stations positioned nearby the source in the three provinces, we strongly argue that the methods developed by [4, 5] relying on the dominant periods of P-waves for local magnitude estimates are not appropriate for this case. Signal, or more precisely earthquake rupture, duration is likely to be a good parameter to consider for teleseismic earthquakes rather than local events, as is the case here. Hence, we do not use techniques as in [4, 5] with rupture duration data for magnitude determination.

We then perform ‘trial and error’ to search for a possible scaling relation of duration magnitude and rupture duration, as also suggested by [9]. Using a modified scale of that proposed in [9] with no and with station corrections, we find duration magnitudes for the three provinces are mostly comparable with the references but are not well constrained for this case. We here argue from regression analysis that the signal duration data may provide a single linear relation to the duration magnitude but with small values of a correlation coefficient for the best fit in each region that lead to small confidence. This is perhaps an important step for redefinition of what is necessary for magnitude determination, whether or not signal duration is needed.

After failures in using rupture duration data for magnitude determination, we finally make progress by adopting the method discussed in [11]. This method claims in favor for scaling relations of moment magnitude $M_w$, duration magnitude $M_D$ and local magnitude $M_L$ for moderate events in North India with sizes in the range of 3.0 – 5.5. Having examined the scaling relations between the three measures of magnitudes and the differences in geological settings between regions of North India and Sulawesi that may be present, we propose $M_D = 1.05M_L - 0.17 + c$ where $c$ is largely influenced by local effects. We examine carefully for all events and find that $c$ plays no important role as it is on the order of $10^{-3}$, hence negligible, meaning that the $c$ factor in the proposed scaling is insensitive to local stations at relatively short distances. This argument is supported by [10, 11], claiming that no significant change in the best-fit lines of linear regression is present when the correction factor is further added. We then use $M_D = 1.05M_L - 0.17$ to estimate duration magnitudes from local magnitudes for moderate events examined in the current study.

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We may also argue here that values of $M_D$ obtained from the scaling relation, $M_D = 1.05M_L - 0.17$, are adequately accurate and rapid for magnitude determination. This is sensible as local magnitudes $M_L$ are accurately determined with respect to the magnitude references $M_W$, as suggested by [4, 5]. Thus, we may expect linear regression of $M_D$ versus $M_W$ for the datasets given with a relatively large value of $R^2$ for the best fits obtained. Shown below in figure 2, plots of $M_D$ versus $M_W$ for the provinces of North Sulawesi, Central Sulawesi, and West Sulawesi.

Figure 2. Plots of duration magnitudes $M_D$ obtained from the scaling relation of $M_D = 1.05M_L - 0.17$, where $M_L$ is the local magnitudes derived from previous work [4, 5] with respect to the references measured in $M_W$ by the Global CMT catalogue for North Sulawesi in reds (a), Central Sulawesi in blues (b) and West Sulawesi in greens (c). Note that black-solid lines are lines of linear regression for each province (generated by datasets of $M_D$ and $M_W$) and black-dotted lines denote ‘virtual-events’ that would have equal magnitudes measured in both $M_D$ and $M_W$.

It is seen from figure 2 that at least two features of primary importance can be extracted, regarding the distribution of duration magnitudes $M_D$ with respect to the references $M_W$. For the three provinces, the majority of the data, in particular events with $4.0 \leq M \leq 6.0$, collapses into a likely single equation of the best fit generated, $M_D = 1.05M_L - 0.17$ with the large correlation coefficient, $R^2 > 0.83$. Further, all the duration magnitude estimates $M_D$ are insignificantly different from the reference magnitudes $M_W$ as these estimates are consistent with the references with the calculated standard deviations of only 0.20 for North Sulawesi, 0.19 for central Sulawesi, and 0.17 for West Sulawesi (or in general of up to 0.20 for North Sulawesi, 0.19 for central Sulawesi, and 0.17 for West Sulawesi (or in general of up to...
0.2 to one decimal place). The same value of standard deviation was also reported by [4, 5] for local magnitude determination based on the dominant period of P-waves in the three provinces. However, some points representing events with relatively large sizes of $M > 6.0$ are overestimated by this scaling, relatively compared with the references. This finding suggests that the scaling relation between duration magnitude and local magnitude adopted from [11] and used here seems appropriate for moderate events only with magnitudes of up to 6.0, after which magnitude estimates are generally larger than expected (compared with the reference provided by the Global CMT catalogue). This is not surprising as the local magnitude scale fits only to the moment magnitude of up to 6.5 in size [12]. With increasing sizes, the local magnitude estimates are systematically deviated from the references.

4. Conclusions
This study aims to estimate duration magnitude $M_D$ from local magnitude $M_L$ for moderate events in North Sulawesi, Central Sulawesi, and West Sulawesi during 2008-2015. The local magnitudes were firstly analyzed to parameterize magnitudes based on rupture duration but providing unclear relations. Following the method developed by [11], we use a simple equation which directly connects $M_D$ to $M_L$, that is, $M_D = 1.05M_L - 0.17$ to estimate the duration magnitudes from their corresponding local sizes for all moderate events in the regions of interest. We find small differences in corrections originated from site and instrument effects for the three provinces and therefore the corrections are unimportant. The results for $M_D$ scale are compared with magnitude reference $M_W$ from the Global CMT catalogue. Direct comparison between these values shows that $M_D$ estimates are consistent with those measured in $M_W$ within ± 0.2 units in size. This suggests that the relation of $M_D$ and $M_L$ used here are reliable for rapid and accurate magnitude determination to evaluate seismic hazards in the three provinces.

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