Moment tensor analysis using regional and temporary deployment 2008 data for Sumatran active fault zone earthquakes

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Abstract. The purpose of this study is to determine the focal mechanisms of the earthquakes through moment tensor inversion of seismograms derived from local events in Sumatran fault zone. We use ISOLA software for data processing which is widely used to estimate the source parameters from local events. We retrieve seismogram data from three selected local events recorded by ZB temporary deployment and BMKG-GEOFON networks. The inversion results reveal that the deformation style around this fault zone is dominated by strike slip motion with shallow focal depths. These results are also consistent with regional active tectonics revealed by other geophysical and geological studies.

1. Introduction

The active deformation of Sumatra region is mainly dominated by the oblique subduction of Indo-Australian plate underneath the Eurasian plate. This oblique subduction provides a strike-slip shear. This shear is accommodated mostly by Sumatran fault zone (figure 1). The Sumatran fault zone is classified as trench-parallel strike-slip fault system with 1900-km long from Andaman Sea to Sunda strait across Sumatra forming Bukit Barisan, Sumatran mountainous range [1]. The slip rates of the fault vary from 6 mm/yr in the southern-end to around 27 mm/yr along the equator [2-4]. The increase of these slip rates might be related to the clockwise rotation of the subducted Indo-Australian plate. Several destructive earthquakes have occurred on this fault system and many of them have not been well documented. In general, Natawidjaja [5] suggests that a major earthquake have occurred once in every 5 year along this fault zone.

A large number of studies have been conducted on this area from global scales to local scale to characterize the geometry of the fault [1-5]. In 2008, the temporary network was deployed as part of the Sumatra segmentation and aftershock project [6, 7] and recorded many events originating from the Toru fault [1], the name of one segment in the Sumatran fault. In the past, this segment has generated an earthquake with magnitude larger than 6, the Pahae Jahe earthquake in 1984 [1]. To contribute for improving our understanding about the fault geometry, we analyze moment tensor solutions from full waveform inversion techniques to get the focal mechanisms of the earthquakes generated around this fault. In general, information about focal mechanism is documented at Global
Centroid Moment Tensor (GCMT) catalogue. However, for this area only few of the events are available on the catalogue (usually only earthquakes with magnitude greater than 5). The previous focal mechanism study using regional network has been conducted based on this catalogue in this area. This study has similar result in which the events analyzed show strike-slip fault types.

Thus, the availability of new local data obtained from the temporary network in this area allows us to analyze moment tensor of the events that are not stated in CMT catalogue. By studying moment tensor inversion, we are able to understand the source parameter including the fault plane solution and the scalar moment. This information is important in revealing the physical process generating the earthquake in this zone.

2. Data Observation and Methods
In this study, we used local earthquakes data located around Sumatran fault zone and recorded by GEOFONE-IA and ZB temporary deployment 2008 networks. The study used three events that have magnitude greater than 4 (Mw < 4). This selection is needed in order to assure that the events are recorded by many seismic stations as well as to provide seismogram with good signal to noise ratio. The epicenter location, depth and magnitude of the events are shown in table 1. We inspected manually the seismogram data to assure the data quality. To compute the focal mechanism of these events, we performed moment tensor inversion method using ISOLA package [8, 9]. This program inverts full waveforms of an earthquake using linear inversion to obtain the moment tensor solution. Prior to the inversion process, the seismograms are corrected from the instrument response and then converted into displacement data. The discrete wavenumber technique [10] is applied to calculate the Green's Function for the synthetic displacement on each station using the Hesling-Santosa(H-S) velocity model as displayed in table 2 [11-13]. On the last stage, the linear inversion process of the three component seismograms provides the moment tensor solutions related to the six parameters of focal mechanisms [14]. The eigenvectors of moment tensors give strike, dip and rake angles as well as the scalar moment of the earthquake (figure 2). To assess the quality of the solution, we used the
variance reduction value (VR) showing the relation between the observed and calculated waveforms. In ISOLA, we also considered the values of double-couple (DC), space time variability (STVAR), condition number and focal mechanism variability (FMVAR) as described in [9].

Table 1. The parameters of events used in this study.

| Event | Date      | Origin time | Lat  | Lon  | Depth (km) | Mw |
|-------|-----------|-------------|------|------|------------|----|
| 1     | 2008-05-22| 18:57:57.90 | 1.731| 99.135| 15.4       | 4.4|
| 2     | 2011-06-14| 00:08:32.49 | 1.831| 99.225| 17         | 5.4|
| 3     | 2013-07-11| 17:16:28.00 | 1.820| 99.170| 20.1       | 5  |

Figure 2. An example of moment tensor solution using ISOLA package for event 2.

Table 2. H-S crustal model [9, 10, 11] used for the inversion in ISOLA.

| No | Vp (km/s) | Depth (km) | Vs (km/s) | Density (g/cm³) | Qp | Qs |
|----|-----------|------------|-----------|-----------------|----|----|
| 1  | 2.31      | 0.0        | 1.300     | 2.500           | 300| 150|
| 2  | 4.27      | 1.0        | 2.400     | 2.900           | 300| 150|
| 3  | 5.52      | 2.0        | 3.100     | 3.000           | 300| 150|
| 4  | 6.23      | 5.0        | 3.500     | 3.300           | 300| 150|
| 5  | 6.41      | 16.0       | 3.600     | 3.400           | 300| 150|
| 6  | 6.70      | 33.0       | 4.700     | 3.400           | 300| 150|
| 7  | 8.00      | 40.0       | 4.760     | 3.500           | 1000|500 |
3. Results and Discussion

We have inverted full waveforms of three events located in the Sumatran fault zone using ISOLA with various frequency bands ranging between 0.03-0.08 Hz for each event. Table 3 and 4 show the moment tensor solutions and fundamental focal mechanisms of the events obtained from the moment tensor inversion. The variance reduction and best fitting mechanism are well constrained with acceptable values of other quality criteria (STVAR, FMVAR and CN). The variance reductions (VR) showing the fitting between the synthetic seismogram and the observed one (figure 3) are acceptable above 60 %. These values are also supported by small condition numbers. The condition number (CN) shows the reliability of the inversion calculated from the configuration of the source-station, frequency range and the velocity model. The high and small CN then indicate ill- and well-posed inverse problems, respectively. It is important to note that large and small values of the variance reduction and condition number rely on the application, Sokos and Zahradnik [9] suggest that the low value of CN is less than 10, and the high value of VR is higher than 60 %. Furthermore, all solution of focal mechanism shows good DC values. The DC value represents how close the earthquakes from the double couple mechanism, as the interpretation of the non-DC solutions may cause problematic interpretation for the tectonic events [15]. Other indicators (STVAR and FMVAR) also indicate acceptable solutions of the inversions. STVAR is defined as space-time resolution, and FMVAR is measured the minimum rotation between two focal mechanisms. Sokos and Zahradnik [9] suggest that the most reliable solutions are those with small index of both FMVAR and STVAR. Comparing with the other references about moment tensor solution obtained from other agencies for the same events (GCMT catalogue) shown in figure 4, we also observe that our solutions are comparable.

In general, our solutions obtained for the moment tensor inversion of the earthquakes at Sumatran fault zone are consistent with the tectonic framework of Sumatra region. The focal mechanisms suggest that the predominant focal mechanism on the study area is strike slip with depth less than 15 km. A previous seismicity study [7] based on the earthquake distribution and topography identifies highly localized strain related to the fault activities at depth less than 15 km. This previous study also suggests that the fault zone in this area is a strike-slip duplex system with complex structure, as most seismic activities are found at the two main bounding fault traces suggested by Sieh and Natawidjaja in [1].

| Event | M_{d33} | M_{d11} | M_{p22} | M_{d31} | M_{p3} | M_{p12} | Exp (Nm) |
|-------|---------|---------|---------|---------|--------|---------|----------|
| 1     | 1.942   | -9.934  | 7.993   | -0.693  | 3.841  | 3.744   | 15       |
| 2     | 0.086   | -1.190  | 1.104   | -0.284  | 0.735  | 0.657   | 17       |
| 3     | -0.335  | -1.022  | 1.357   | 0.242   | -0.044 | 2.205   | 16       |

Table 3. The moment tensor solutions of the events obtained by using ISOLA software.

| Event | Centroid depth (km) | Strike/Dip/Rake (°) | Mw | VR | DC (%) | CN | STVAR | FMVAR (°) |
|-------|---------------------|---------------------|----|----|--------|----|-------|-----------|
| 1     | 14                  | 324/78/158          | 4.6| 0.67| 90.4   | 2.6| 0.01  | 20        |
| 2     | 11                  | 61/60/5             | 5.4| 0.69| 93     | 2.6| 0.05  | 13        |
| 3     | 14                  | 346/84/-177         | 4.9| 0.65| 76.7   | 2.3| 0.03  | 11        |

Table 4. The source parameters of the events in this study computed by ISOLA software.
Figure 3. An example of the fitting between the observed (black) and synthetic (red) seismograms for event 2. The blue numbers indicate the variance reduction and the grey waveforms are not used in the inversion.

Figure 4. The focal mechanisms of the events used in this research with their related locations. The black and red beach balls represent the solution derived from ISOLA full waveform inversion and Global CMT, respectively.
4. Conclusions
In this work, we have inverted the seismic waveforms to obtain the focal mechanism of the events located in the branch of the Sumatran fault zone. All the events show a strike slip solution with the hypocenter of the events less than 15 km depth. These results are in good agreement with a general tectonic setting of Sumatran Island and with the results of previous geophysical and geological studies. This work is a preliminary step in characterizing the geometry of the Sumatran fault zone. Therefore, future investigation is needed by involving a larger waveform data that contains, for example, the earthquakes with magnitude less than 4.

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