Teleseismic body wave inversion in determining rupture process of Sumbawa doublet earthquake, November 25th, 2007

P N Ratna¹, A R Gusman² and A D Nugraha³

¹Department of Geophysical Engineering, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jalan Ganesa No.10, Bandung, West Java, Indonesia 40132
²Institute of Geological and Nuclear Sciences Limited (GNS Science), New Zealand
³Global Geophysics Research Group, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jalan Ganesa No.10, Bandung, West Java, Indonesia 40132

E-mail: putrinatari78@gmail.com

Abstract. The rupture patterns of the Sumbawa doublet earthquake that occurred on November 25th, 2007 was estimated using teleseismic body wave inversion. The first event occurred at 16:02:18 UTC with epicenter at 8.292°N and 118.37°E, short after this, the second event occurred at 19:53:08 UTC with epicenter at -8.224°N and 118.467°E. For each event, teleseismic body wave data were retrieved from the Incorporated Research Institutions for Seismology – Data Management Center (IRIS-DMC). The waves were windowed for 70 s which started at 20 s before the P-wave arrival, band-pass filtered between 0.01 and 0.1 Hz and then integrated into a displacement with a sampling time of 0.5 s. The Green's function is calculated using the Kikuchi and Kanamori method. The fault geometry is based on the earthquake parameters of the Global Centroid Moment Tensor solution. Strike and dip for first event were 88° and 23°, respectively and those for the second event were 87° and 25°, respectively. The seismic moment (Mo) estimated by the inversion for the first event is 0.617x10¹⁹ Nm or equivalent to moment magnitude (Mw) 6.46 with source duration of approximately 55 s. While for the second event, the seismic moment is estimated to be 0.644x10¹⁹ Nm (Mw 6.47), with slightly longer source duration. The inversion for both events provided a similar slip pattern. The rupture propagated along the dip direction, and the maximum slip occurred near the hypocenter region. The maximum slip amount for first event and second event were 1.43 m and 1.48 m, respectively.

1. Introduction
On November 25, 2007, at 16:02 UTC, an earthquake with a moment magnitude (Mw) of 6.5 occurred in the Sumbawa Island. Four hours later, a second earthquake of same magnitudes shook the same region. These earthquakes caused 3 people died, 45 people were injured and several buildings were severely damaged. International Seismological Center (ISC) determined that the epicenter for the first event was -8.292°N and 118.37°E at a shallow depth of 20 km. For the second event, earthquake occurred in -8.224°N and 118.467°E at shallower depth of 18 km (figure 1). Both earthquakes occurred with the same mechanism (thrust faulting). The characteristic between those earthquakes indicated that that was a doublet earthquake [1] [2].
The area of this study is located in Sumbawa Island, West Nusa Tenggara. This area is included in the Mediterranean mountain route located adjacent to the subduction zone. The subduction occurred between the Indo-Australian Plate and the Eurasian plate. The movement of the Indo-Australian plate infiltrated under the Eurasian plate was estimated to have a speed of 7 cm per year. The movement of the plate led to tectonic structures that characterized the subduction system, namely Benioff-zone, ocean trench, outer arc ridge, outer arc basin, and volcanic arc as shown in figure 2. These causes Sumbawa to become an area that has an earthquake vulnerability from the south [3].

In addition, Sumbawa is also highly prone to earthquakes from the north. This is caused by the tectonic structure of back arc thrust. This structure stretches from the Bali Sea to the Flores Sea parallel to Sumbawa Island in the form of fault segments. The back arc thrust structure indicated subduction polarity reversal due to the difficulty of subducting the buoyant continental margin of Australia [4]. The activity of this structure is quite active as evidenced by many tectonic earthquakes with shallow hypocenter characteristics and relatively large magnitudes. Based on the data, most of the strong earthquake to the devastating earthquake that shook Sumbawa is caused by the activity of this back arc thrust.

2. Data and Method

2.1 Data
The data used in this study are earthquake waveform on November 25, 2007 obtained from Incorporated Research Institutions for Seismology (IRIS) in SEED format. The format must be converted to SAC in the inversion process. Data were taken from 22 teleseismic stations as shown in figure 3. The selected station was a station that has a distance between 30° - 100° from the epicenter to avoid complex earth structures. In addition, the station was also spread over the azimuth range -180° - 180° from the source to provide a good azimuthal coverage. This study used P wave and SH wave. Instrument responses were removed from the original recording. In addition, waveforms were windowed for 70 second, starting 20 second before the P-wave arrival, band-pass filtered between 0.01 and 0.1 Hz and then integrated into a displacement with a sampling rate of 0.5 second. The Green’s function is calculated using the Kikuchi and Kanamori [5] [6] method.
2.2 Method

The earthquake rupture process is determined using the iterative deconvolution method developed by Kikuchi and Kanamori [5] [6]. Earthquake source is modelled as a series of double-couple point sources. It is assumed that all the point sources have the same fault mechanism and time history. Each point source is specified by moment tensor, onset time, and location. Then moment tensor ($M_n$, where $n = 1, \ldots, N_b$) is represented by a linear combination of elementary moment tensor defined by Kikuchi and Kanamori [8]. In double couple case, the number of the elementary tensors, $N_b$, varies from two to five, with the constraint of vanishing trace and determinant.

Each point source is iteratively determined by the least squares method. Green's function or synthetic wavelet for elementary moment tensors in layered structure is calculated for this purpose. The structure at the source and receiver site model [9] is used to compute Green’s function. The structure is shown in table 1.

| Table 1. Structures |
|---------------------|
| $\alpha$ (km/s) | $\beta$ (km/s) | $\rho$ (g/cm$^3$) | $H$(km) |
| Source structure | 1.5 | 0.0 | 1.02 | 1.11 |
| | 2.2 | 0.78 | 2.0 | 1.3 |
| | 6.0 | 3.5 | 2.72 | 4.3 |
| | 6.6 | 3.8 | 2.86 | 6.48 |
| | 7.1 | 3.9 | 3.05 | 10.79 |
| | 7.99 | 4.44 | 3.3 | 0 |
| Receiver structure | 5.8 | 3.46 | 2.45 | 20 |
| | 6.50 | 3.85 | 2.71 | 15 |
| | 8.04 | 4.49 | 3.3 | 42.5 |
| | 8.05 | 4.5 | 3.3 | 0 |
| Structure on PP bounce points | 6.5 | 3.85 | 2.71 | 15 |
The source points were defined as the number of \( n_x \) in the x directions and \( n_y \) in the y direction with the spaces of \( \Delta x \) and \( \Delta y \) [10]. In this case, the fault plane is formed from \( n_x \cdot n_y \) grid covering the area \( n_x \cdot n_y \cdot \Delta x \cdot \Delta y \). Let \( x_j(t) \) denote the observed waveform and \( w_{jn}(t;p) \) denote the Green’s function (synthetic wavelet) due to \( n^{th} \) elementary moment tensor \( M_n \), where \( p \) is a parameter that collectively represents the onset time and the location of the subevent. The synthetic waveform \( y_j(t;p) \) due to a moment tensor

\[
M_{ij} = \sum_{n=1}^{N_b} a_n M_n
\]  

is given by

\[
y_j(t;p) = \sum_{n=1}^{N_b} a_n w_{jn}(t;p)
\]

The coefficient \( a_n \) and the parameter \( p \) are determined with the least squares criterion [11]:

\[
\Delta = \sum_{j=1}^{N_s} \int [x_j(t) - y_j(t;p)]^2 \, dt = \min
\]

and the correlation function between the observed and synthetic waveforms is maximized with a grid search for \( p \):

\[
\Psi(p) = \frac{\sum_{j=1}^{N_s} [x_j(t)y_j(t;p)]dt}{\sum_{j=1}^{N_s} [x_j(t)]^2 dt}
\]

where \( N_s \) is the number of seismograms used.

3. Result and Analysis

3.1 Inversion Parameter

The fault area for first and second event of 48x24 km\(^2\) is created according to aftershock distribution area within 12 days after the mainshock (figure 1). This fault plane is divided into 16x8 grids of 3x3 km\(^2\) each. The length of the fault is in the same direction as the strike while the width is in the direction of the dip.

The solution of focal mechanism is taken from Global Centroid Moment Tensor. For first event, strike, dip and rake are 88°, 23°, and 103° respectively, while for the second event are 87°, 25°, and 100°. The focal mechanism is set at a depth of 30 km for first event and 25 km for second event.

The rupture sequence for first and second event, divided into several subevents, has a source time function defined as a series of 10 triangular functions with a 4.0 second rise time and 4.0 second offset time. The optimum rupture velocity is 2.0 km/s and the rigidity surrounding the fault plane is assumed 40 GPa. All these parameters are obtained after going through grid search and trial and error.

3.2 Source Rupture Process

3.2.1 First Event. The inversion results for first event are shown figure 4. Figure 4(a) shows that the earthquake focal mechanism is a thrust faulting, with strike, dip, and rake were 88°, 23°, and 104°. The distribution of the slip (figure 4(c)) indicated the rupture was propagating along the dip direction from
the hypocenter to the shallower part. Maximum slip occurs near the hypocenter of 1.43 meters while in the other parts, slips vary from 0.01 to 1.21 meters. The resulting slip distribution focused around the center region. Long slips also occurred at the edge of the fault plane. The presence of slip release signifies the release of stress. In other words, before the earthquake, the fault plane containing strong patches under stress. Knowledge of this zone is very important because it can show the heterogeneity of the fault plane and usually a large earthquake occurs in this zone.

Moment rate function (figure 4(b)) shows that the total seismic moment (Mo) released is 0.617x10^19 or equivalent to the magnitude of Mw 6.46. The energy is released for more than 50 seconds that can be divided into three segments. The first energy release occurs in 5 seconds after the earthquake occurs with maximum amplitude. Then, the second and the third energy release within 6 to 47 seconds. The amplitude of the energy released is much smaller than the first.

3.2.2 Second Event. Inversion results for the second event are shown in figure 5. Figure 5(a) illustrated that the focal mechanism was similar with the first event with strike, dip, and rake were 87°, 25°, and 102° respectively. Slip distribution indicated that the rupture propagated mainly along the dip from the hypocenter to a shallower region. The maximum slip was longer than the first event which was 1.48 meters near the hypocenter. For other parts, slips vary from 0.01 to 1.25 meters.

Just as before, the slip distribution (figure 5(c)) focused on the center but shifted towards the northeast. According to moment rate function (figure 5(b)), 0.644x10^19 Nm (Mw6.47) energy was released over a period 55 second during the earthquake. The majority of energy was released within 5 second after the earthquake initiated. Then, additional energy released within 50 second with a very small amplitude.

The variance resulting from the comparison between observational and synthetic waveforms for both events is nearly the same. For first event, variance was 0.4888 while the second event was 0.4429 (figure 6). This results in the amount of energy released which generated by the inversion inconsistent with the ISC’s report.
4. Conclusion
The inversion yielded similar results for the doublet earthquake occurring in Sumbawa. Based on the inversion parameter, both earthquake had similar characteristics. The resulting slip distribution has the same direction that is focused on the center region and have same shape. Slips also occurred on the edge of fault plane. According to the inversion, it can be estimated that the energy released by the first event is a stress stored in the plane. The stress stored has not been released all by the first event. Therefore, the stress was again released in the form of energy from the second earthquake so that the slip zone of the second event was an extension of the first event. It is supported by the inversion results that both earthquakes shared the same fault plane.

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Figure 6. Comparison between observed (black line) and synthetic waveforms (red line). (a) 1st event, (2) 2nd event.

(a) (b)