TSUNAMI SOURCE STUDY OF THE 2010 MENTAWAI EARTHQUAKE FROM TSUNAMI WAVEFORM INVERSION AND INSAR ANALYSIS

Gian Ginanjar* **Supervisor: Yuichiro TANIOKA ****
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ABSTRACT

The source process of the 2010 Mentawai Tsunami is estimated by using tsunami waveforms at a DART station and tide gauge stations around the Indian Ocean. The inversion results show that the major slip region for the October 25 2010 Mentawai earthquake is located near epicenter. The slip amount near the epicenter is about 1.3 to 2.5 m, and the slip amount around the trench is about 1.8 m. The seismic moment calculated from the slip distribution is 1.07 x 10^{21} Nm (moment magnitude Mw= 8.0), larger than that obtained from seismic inversion. However, comparison of the measured tsunami heights at Mentawai islands region with the calculated maximum coastal tsunami heights from slip distribution shows that the simulated tsunami heights is underestimated the measured tsunami heights at Mentawai islands region.

The distribution of aftershocks and the area of dominant slip in the slip distribution model from tsunami inversion suggest that the event ruptured up-dip from the point of nucleation (hypocenter) and very near the trench. Such near-trench rupture supports that this earthquake was a "tsunami earthquake".

The fringes calculated from InSAR data show one cycle of color corresponding to 2 pi radians phase change. The one color cycle of 2 pi radians phase change would correspond to 2.8 cm of displacement along the radar line of sight (LOS) for South Pagai island of Mentawai islands region. The amount of displacement in the direction of the line of sight calculated from tsunami inversion is also estimated to be one color cycle of 2 pi radians phase change.

Keywords: 2010 Mentawai earthquake, Tsunami source, Tsunami waveform inversion, Tsunami earthquake, Slip distribution, InSAR.

1. INTRODUCTION

An earthquake with moment magnitude (Mw) of 7.7 according to United States Geological Survey (USGS) or 7.2 (MwmB) according to BMKG, occurred at Mentawai region off west of Sumatera Island on October 25th 2010, at origin time of 14:42:22 UTC, in about 30 km west of Pagai Selatan, Mentawai - Sumatera Barat, Indonesia as shown in Figure 1. The epicenter is located at 3.61º S and 99.93º E with focal depth of 10 km according to BMKG, or 3.484º S and 100.114º E with focal depth of 20.6 km according to USGS.

The earthquake occurred near the trench on subduction zone where the Indo-Australian plate is subducting beneath the Sunda plate at oblique angle. The focal mechanism from the USGS's Wphase moment tensor solution shows that the earthquake has a thrust fault type mechanism system with strike of 326º, dip of 12º and slip of 101º. The earthquake occurred along the plate boundary between the Indo-Austalian plate and the Sunda plate. Large earthquakes that occurred near the trench

* Indonesian Agency for Meteorology, Climatology and Geophysics - BMKG (Badan Meteorologi, Klimatologi dan Geofisika) Indonesia.
** Institute of Seismology and Volcanology, Hokkaido University, Japan.

with thrust fault mechanisms which have low angle of dip and produced large tsunami but not so big of ground shaking are called tsunami earthquakes (Satake and Tanioka, 1999). The 2010 Mentawai earthquake is possibly this type of a tsunami earthquake

While any earthquakes that generate tsunamis can be classified as "tsunamigenic earthquake", the term "tsunami earthquake", hereafter TsE, is used for a special class of events that generate much larger tsunamis than expected from its seismic waves (Kanamori, 1972). For this Mentawai earthquake, the tsunami magnitude was Mt = 8.1, estimated by Abe formula using the tsunami wave heights from different tide gauge stations (Abe, 1989).

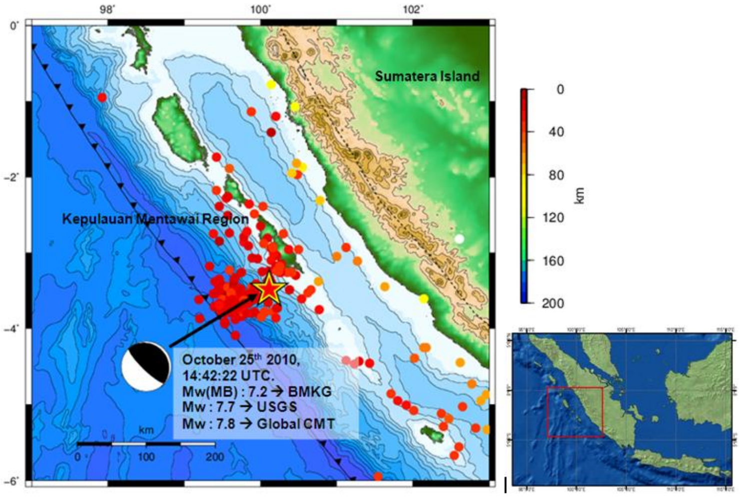

Figure 1. The Location of 2010 Mentawai earthquake

Other characteristic of TsE is "slow and long rupture processes of earthquakes" (Kanamori, 1972). For this Mentawai Earthquake, "the estimated duration is 109.7 s, and considering the low amplitude and long duration, which are the characteristics of TsE, the event is likely to be a tsunami earthquake" (Hara, 2010).

2. OBSERVATION DATA

2.1 Tsunami Waveform Data

The tsunami was recorded by many tide gauge stations around the Indian Ocean and by a DART (Deep-ocean Assessment and Reporting of Tsunamis) buoy deployed in the deep sea ocean between Indonesia and Australia (Table 1).

These tide gauge and DART buoy records include ocean tides, therefore the ocean tides need to be removed to get the tsunami waveforms. First, ocean tides approximation should be made by fitting a polynomial function, then removed from the original records at all tide gauge and DART stations.

Table 1. Tide Gauge Stations and a Dart Buoy station

Station Name	Latitude (°)	Longitude (°)
Cocos	-12.1167	96.8919
Colombo	6.95	79.85
Denis_Island	-3.8	55.6667
Hanimadhoo	6.7667	73.1667
Padang	-0.95	100.3667
Pt_Louis	-20.15716	57.5043
Reunion	-20.92	55.28
Rodrigues	-19.68024	63.42119
Seblat	-3.224167	101.5994
Telukdalam	0.554	97.822
Tanahbala	-0.53	98.5
Trinconmalee	8.5637	81.1996
D56001	-13.985	110.005
Enggano	-5.3461	102.2781

2.2 Tsunami Runup Data

From november 5 to 10, the "JICA (Japan International Cooperation Agency) – JST (Japan Science and Technology Agency) Indonesia Multi-disciplinary Hazard Reduction from Earthquakes and Volcanoes in Indonesia" organized several teams to conduct a post tsunami survey with several different focuses of survey. Thirty-eight measurements of tsunami height range from 2.5 to 9.3 m, but mostly 4 to 7 m. The tsunami inundation was more than 300 m at three locations. The tsunami deposits, mostly coarse to medium sand and 5 to 26 cm in thickness, were sampled along transects at three locations (Satake et al., 2011).

2.3 InSAR Data

To detect the ground displacement on the Pagai Island of Mentawai Islands region near the source area, this study conduct an InSAR analysis by using the satellite data of the ALOS/PALSAR, launched in 2006 and operated by the Japan Aerospace Exploration Agency (JAXA), which has an L-band sensor with wavelength of 23.6 cm.

For processing of the level-1.0 SAR data to bobtain Interferogram SAR (InSAR), we used a free software package called GMTSAR: An InSAR Processing System Based on Generic Mapping Tools (Sandwell et al., 2011). An InSAR data of the South Pagai Island-Mentawai Islands region is obtained as shown in Figure 2.

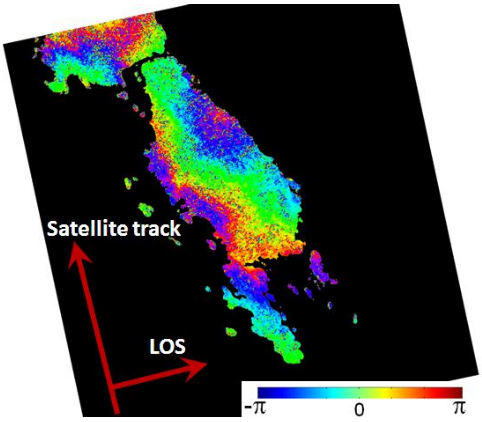

Figure 2. InSAR data of Mentawai Islands with 6 months of time spans shown displacement in line of sight (LOS) direction.

The PALSAR data pair used in the InSAR analysis are from Desember 30 2010 as master image and from June 29 2010 as slave image, with ascending flight direction and perpendicular baseline (Bperp) is -323.09.

3. METHOD

3.1 Source Area from Tsunami Arrival Times

This study first estimate the tsunami source area from the observed tsunami travel time, by making an inverse refraction diagram. This technique calculates the initial wavefronts through back projection of tsunamis from tide gauge stations towards the source (e.g., Fujii and Satake, 2006). The tsunami source is well constrained by the travel time after we made a little adjustment for Cocos's travel time because we believe that poor bathymetry data in shallow coastal area around Cocos Island is responsible for poor constraints that need to be adjusted. Figure 3 shows the green circle indicates the constraint area for the source, black lines indicate estimated initial wavefronts from the observed tsunami arrival times, while yellow line shows the adjusted travel time for the Cocos.

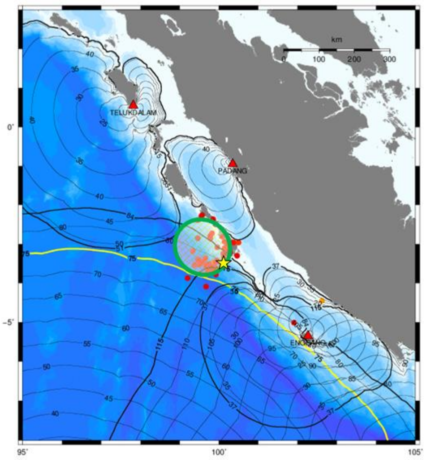

Figure 3. Inverse refraction diagrams for the 2010 Mentawai tsunami.

For this study 15 subfaults located within the aftershock area are assumed (Figure 4). The length and width are 50 km × 50 km for each subfault. The focal mechanisms of all the subfaults are strike of 326º, dip of 12º and slip of 101º from the USGS's Wphase moment tensor solution. The top depths of the subfaults were assumed to be 5, 15.4 and 25.8 km for shallow, middle and deep subfaults, respectively.

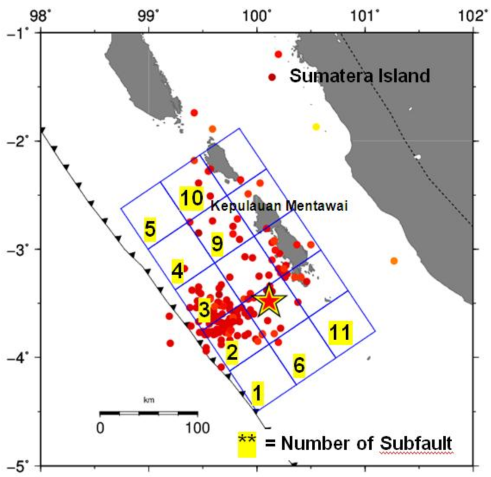

Figure 4. Fifteen assumed subfaults located within the aftershock area.

3.2 Numerical Tsunami Simulation

The computational area ranges from 52°E to 113°E and from 25°S to 10°N. We used a bathymetry grid data from General Bathymetric Chart of the Oceans (GEBCO) 30 arc-second grid data and resampled it to 1 arc-minute grid size for far field data, and for near field the GEBCO 30 arc-second merged with nautical charts of Padang-Bengkulu-Nias-Mentawai and resampled the merged grid with 15 arc-second grid size.

The linear shallow water or linear long wave theory is given by the following equations (Johnson, 1999):

$$\frac{\partial h}{\partial t} + \frac{1}{R\, sin\, \theta}\left[\frac{\partial}{\partial \theta}(Q_\theta \sin\theta) + \frac{\partial Q_\varphi}{\partial \varphi}\right] = 0 \qquad (1)$$

$$\frac{\partial Q_\varphi}{\partial t} = -fQ_\theta - \frac{gd}{R\sin\theta}\frac{\partial h}{\partial \varphi} \qquad (2)$$

$$\frac{\partial Q_\theta}{\partial t} = -fQ_\varphi - \frac{gd}{R}\frac{\partial h}{\partial \theta} \qquad (3)$$

, where φ is longitude, θ is colatitudes (90º $-$ latitude), f is the Coriolis coefficient, t is time, h is the water level, Q_φ and Q_θ are the flow flux along longitude and latitude axes, respectively, g is the gravitational acceleration, and d is the water depth. The Coriolis coefficient is given by $f = 2\Omega cos\theta$, where Ω is the angular frequency of the Earth's rotation. Computational time step of 3 s for far field and 1 s for near field are chosen to satisfy Courant-Friedrichs-Lewy (CFL) stability condition that is expressed by the following equation:

$$\Delta t \le \frac{\Delta x}{\sqrt{2gd}} \qquad (4)$$

, where Δt and Δx are temporal and spatial grid lengths, d is the maximum still water depth in a computation region. The physical meaning of the stability condition is that the time step Δt must be equal or smaller than the time required for the wave to propagate in the spatial grid size Δx.

3.3 Inversion

The fault plane is divided into 15 small subfaults and the deformation on the ocean bottom is computed for each subfault with a unit amount of slip. Using this displacement field as the initial condition, tsunami waveforms are computed by a finite-difference method using actual bathymetry.

The observed tsunami waveforms are expressed as superposition of the computed waveforms as follows:

$$A_{ij}(t)x_j = b_i(t) \qquad (5)$$

where A_{ij} is the computed waveforms, or Green's functions, at the i-th station from the j-th subfault, x_j is the amount of slip on the j-th subfault, and b_i is the observed tsunami waveform at the i-th station (Sateke and Kanamori, 1991).

The Akaike's Bayesian information criterion (ABIC) proposed by Akaike (1980) is used to determine the optimal value of the smoothing factor (α^2).

3.4 Displacement in Line of Sight (D_{LOS})

The relationship between LOS displacement and displacement components on the ground is expressed as follows (Hanssen, 2001):

$$D_{LOS} = d_h \cos(\phi - \xi) \sin(\theta) + d_v \cos(\theta) \quad (6)$$

where D_{LOS} is a LOS displacement, d_h is the horizontal displacement, d_v is the vertical displacement, ξ is the azimuth of the perpendicular to the satellite track, ϕ is the azimuth of the displacement, and θ is the off-nadir angle.

4. RESULTS AND DISCUSSION

4.1 Slip Distribution Determined by the Tsunami Waveform Inversion

The slip distribution inverted from the tsunami waveform data is shown in Figure 5(a). The optimal value of smoothing factor (α^2) that minimizes the value of ABIC is 0.5 (Figure 5(d)). According to the inversion result the major slip region is located near the epicenter with maximum slip amount of 2.5 m. The seismic moment calculated from this slip distribution is 1.0705 x 10^{21} Nm that corresponds to moment magnitude of 7.9531 (M_w= 8.0) by assuming a rigidity of 4 x 10^{10} Nm^{-2}. The comparison of tsunami waveforms are shown in Figure 5(c) and the comparison with the tsunami height from field survey in Mentawai island region is shown in Figure 5(b).

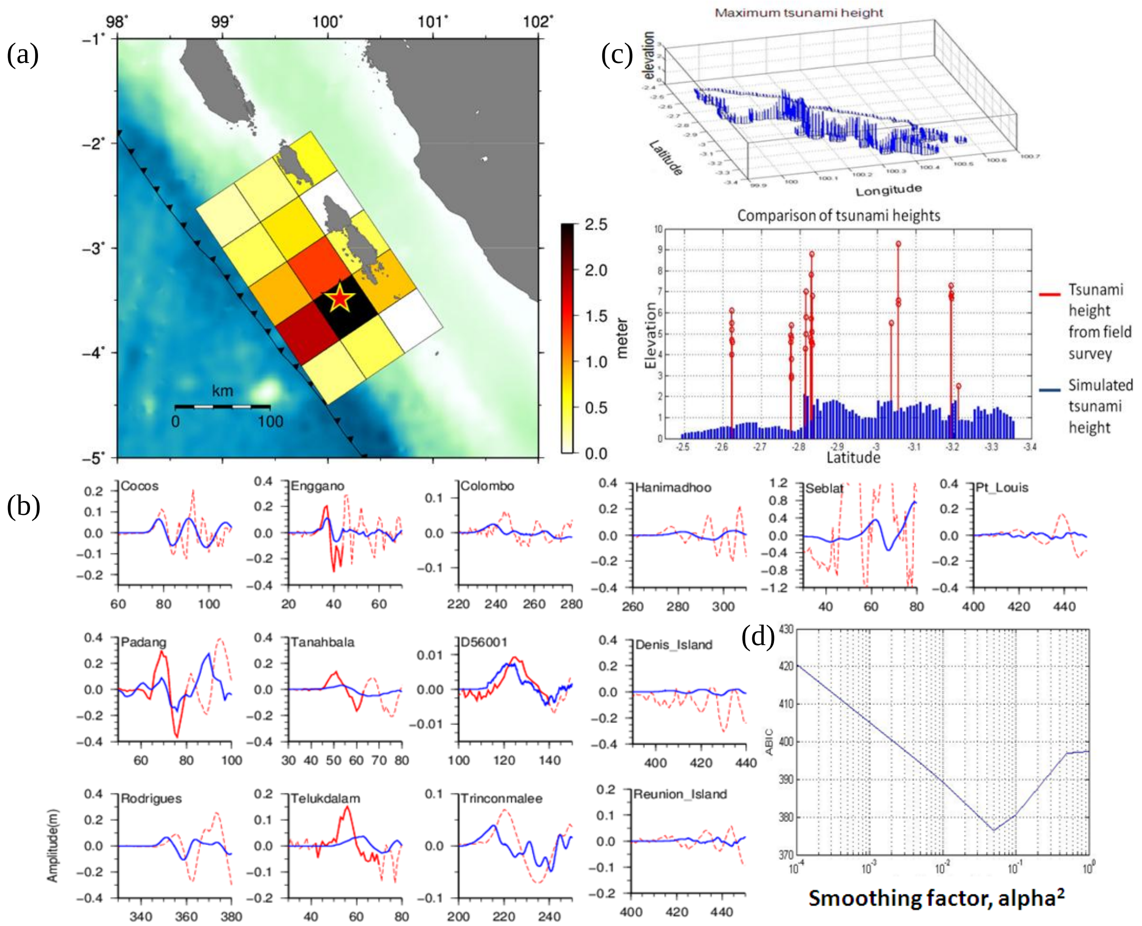

Figure 5. (a) Slip distribution of the 2010 Mentawai earthquake estimated from tsunami waveform data. (b) Observed tsunami data and synthetic tsunami from the inversion, where observed tsunami records are shown in red (dashed line is original records and solid line is cut-data for inversion) and synthetic tsunami waveforms are shown in blue. (c) Simulated coastal tsunami heights and comparison between simulated tsunami height and tsunami height data from field surveys (Satake et al., 2011). (d) Values of ABIC plotted as a fucntion of α^2, in which the minimized ABIC is at $\alpha^2 = 0.5$.

4.2 D_{LOS} Model Predicted from the Tsunami Inversion Result

The fringes for calculated D_{LOS} model generally shows the same pattern with the fringes by InSAR data that also show one cycle of color corresponding to 2 pi radians phase change (Figure 6). The one color cycle of 2 pi radians phase change, if interpreted as ground displacement, would correspond to 2.8 cm of displacement along the radar line of sight.

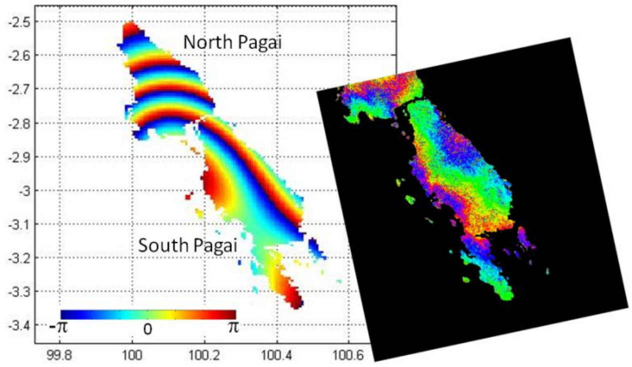

Figure 6. DLOS model (left) and InSAR data (right)

5. CONCLUSIONS

The 2011 Mentawai earthquake is an example of a rare slow-source tsunami earthquake, with Mw=7.7, tsunami magnitude of Mt=8.1, and slow rupture duration of 109.7 s. The slip amount near the epicenter is about 1.3 to 2.5 m, and the slip amount around the trench is about 1.8 m.

The seismic moment calculated from the slip distribution is 1.0705 x 10^{21} Nm corresponding the moment magnitude of 7.9531 (Mw 8.0), larger than that obtained using seismic inversion. However, the simulated tsunami heights are underestimated at Mentawai islands region.

The distribution of aftershocks and the area of dominant slip in the slip distribution model from tsunami inversion suggest that the event ruptured up-dip from the point of nucleation (hypocenter) and very near the trench. Such near-trench rupture supports that this earthquake was a "tsunami earthquake".

The displacement LOS model determined from tsunami inversion generally shows the same pattern with the fringes by InSAR data that also show one cycle of color corresponding to 2 pi radians phase change. The one color cycle of 2 pi radians phase change would correspond to 2.8 cm of displacement along the radar line of sight (LOS) for South Pagai island of Mentawai islands region.

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