DETERMINATION OF SLIP DISTRIBUTION OF THE 28 MARCH 2005 NIAS EARTHQUAKE USING JOINT INVERSION OF TSUNAMI WAVEFORM AND GPS DATA

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ABSTRACT

The large 28 March 2005 Nias earthquake (M_w 8.6) occured on megathrust of the Sumatra subduction zone and generated a small tsunami. We estimated the slip distribution of the 2005 Nias earthquake using joint inversion of tsunami waveforms and GPS data. We used 5 tide gauge stations around Indian Ocean and 9 GPS stations from Sumatran GPS array (SuGar) around Sumatra to perform the joint inversion. We assumed that the fault length was 300 km and the width was 150 km. To determined the slip distribution, we divided the ruptured area into 18 subfaults. The result shows that the maximum slip amount of 12.35 m was found below Nias Island. The large amount of the slip was located at intermediate (21 – 27 km) and deeper (> 27 km) depths. The large slip area of the 2005 Nias earthquake did not reach the Sumatra trench. The rupture area of the 2005 Nias earthquake was similar to that of the 1861 earthquake. The total seismic moment was calculated to be 1.06×10^{22} Nm (M_w = 8.6) by the slip distribution.

Keywords: Nias earthquake, Joint inversion, Slip distribution

1. INTRODUCTION

On 28 March 2005 at 16:09:36 UTC a large earthquake occured in the northern part of Nias Island. The Nias earthquake occured only three months after the Sumatra-Andaman earthquake, 26 December 2004 (M_w = 9.1). According to United States Geological Survey (USGS), the epicenter of the Nias earthquake was located at 2.074°N, 97.013°E and its depth was 30 km. The Harvard Centroid Moment Tensor (Harvard CMT) solutions estimated fault parameters as strike = 329° , dip = 7°, rake = 109° and seismic moment Mo = 1.1 x 10^{22} Nm (M_w = 8.6). Historical records of the last 300 years reveal an additional great interplate earthquakes near Nias Island in 1861 with a moment magnitude M_w 8.5 (Newcomb and McCann, 1987). Subarya *et al*. (2006) and Prawirodirdjo *et al*. (2010) estimated that the 2005 Nias earthquake ruptured approximately the same region as that of the 1861 earthquake.

A tsunami by the 2005 Nias earthquake was recorded by some tide gauge stations around Indian Ocean. Tsunami by the 2005 Nias earthquake hit on Nias Island and surrounding areas. The maximum tsunami elevation in Nias Island, Banyak Island, Simeuleu Island were 3.6 m, 3.5 m, and 4.2 m, respectively (Borrero *et al*., 2010). The 2005 Nias earthquake ruptured the plate interface which in some part is located beneath Nias Island. The vertical and horizontal displacements due to the earthquake on the Nias Island and surrounding area recorded by Sumatran GPS array (SuGar). We used the GPS data and the tsunami waveforms in a joint inversion to estimate the slip distribution of the 2005 Nias earthquake.

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2. OBSERVATION DATA

2.1 Tsunami Waveform and Bathymetry Data

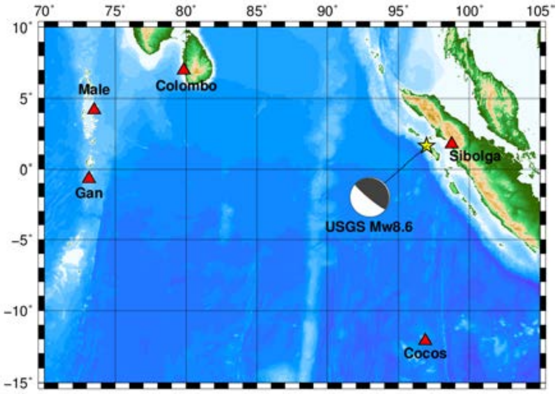

Figure 1. Epicenter of the 2005 Nias earthquake and location of available tide gauge stations.

In this study, we used 5 tide gauge stations in around Indian Ocean (Figure 1). We obtained the tide data for Sibolga station by digitizing a figure by Aydan *et al.*(2005) showing the record, and the tide data for Male, Gan, Colombo stations were obtained by digitizing figures by Liu and Wang (2005) showing the records, while the tide data for Cocos station we get from Australian Bureau of Meteorology (BoM). For bathymetry data, we used data from GEBCO (General Bathymetric Chart of the Oceans) provided by the British Oceanographic Data Centre (2012) with spatial grid interval 30’’ (~ 0.925 km).

2.2 GPS Data

The crustal deformation due to the 28 March 2005 Nias earthquake was recorded by GPS stations of SuGar. We used 9 SuGar GPS stations (Figure 2) which are: ABGS, SAMP, and UMLH on Sumatra Island; LEWK and BSIM on Simeuleu Island; LHWA on Nias Island; PSMK on Simuk Island; PBAI on Bais Island; and PTLO on Telo Island. The vertical and horizontal displacements at each GPS station were obtained from Kreemer *et al*. (2006).

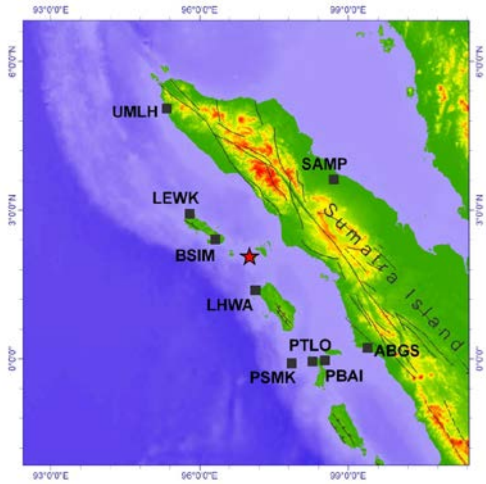

Figure 2. Location of GPS stations used in this study

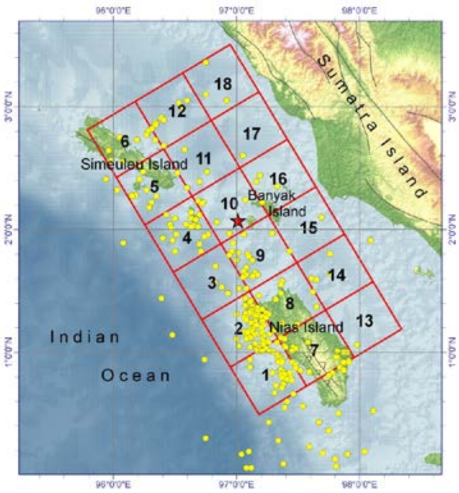

Figure 3. Location of 18 subfaults which are assumed for the 28 March 2005 Nias earthquake study

3. METHODS

3.1 Estimation of the Fault Plane

For the study of the Nias earthquake, we assumed a rupture plane with a length of 300 km and a width of 150 km by referring to the aftershock distributions. Then, for the purpose of estimating the slip distribution, we divided the fault plane into 18 subfaults with the size of 50 km x 50 km each (Figure 3). For the subfaults number 1 – 6 we used top depth of 15 km, for the subfaults number 7 – 12 we used top depth of 21 km, and subfaults number 13 – 18 we used top depth of 27 km. The focal mechanism of strike 329°, dip 7°, and rake 109°, obtained from Harvard CMT solution, was assumed for all the subfaults. We applied the Okada (1985) formula to compute the deformation on the ocean bottom for each subfault.

3.2. Numerical Tsunami Simulation

For the numerical calculation of tsunami simulation, we used the linear shallow-water theory in spherical coordinates. The computation area of this study is 15°S - 10°N and 70°E - 105°E (Figure 1). We used a nested grid method for the calculation of tsunami simulation. In this study we resampled GEBCO 30" to become 3 different spatial grid sizes: 135", 45" and 15". The linear shallow-water or the linear long-wave theory is given by the following equations (Johnson, 1998) :

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

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

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

where, φ is longitude, θ is colatitude (90° - latitude), f is the Coriolis coefficient, t is time, h is the water level, Q_φ and Q_θ are the flow flux along latitude and longitude 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 angular frequency of the earth's rotation. We applied the Courant-Friedrichs-Lewy (CFL) condition to checking the stability.

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

where Δx is spatial grid size. We used time step of 1 second to satisfy the CFL stability condition for finite difference computation.

3.3 Synthetic Vertical and Horizontal Displacements

In the slip distribution studies, GPS data can be used as a reference value for the surface deformation caused by the all subfaults. For the 2005 Nias earthquake, the observed vertical and horizontal displacements at each GPS SuGar station were obtained from Kreemer *et al*. (2006). Then, to obtained synthetic vertical and horizontal displacements at each GPS SuGar station from all subfaults we used Okada (1985) formula.

3.4 Inversion

Slip amount is very important because it is related to the seismic moment of the earthquake. Observed tsunami waveforms are expressed as a superposition of computed waveforms as follows (Satake, 1987) :

$$\mathbf{A}_{ij}\,(t)\,.\,\mathbf{x}_j = \mathbf{b}_i\,(t) \qquad (5)$$

where $\mathbf{A}_{ij}$ is the computed waveform, or Green's function at the i-th station from the j-th subfault, $\mathbf{x}_j$ is the amount of slip on the jth subfault and $\mathbf{b}_i$ is the observed tsunami waveform at the i-th station. To avoid a negative slip value, we applied non-negative least square method (Lawson and Hanson, 1974) for determining slip amount. The formula of the non-negative least square method is as follows :

$$\left[\mathbf{A}_{ij}(t).\mathbf{x}_j - \mathbf{b}_i(t)\right]^2 \rightarrow \text{minimum} \quad ;\, \mathbf{x}_j \ge 0 \qquad (6)$$

Because we also involved the GPS data for joint inversion, we modified Eq. (5) as follows :

$$\begin{bmatrix} \mathbf{ST}_{ij} \\ \mathbf{SG}_{ij} \end{bmatrix} . \mathbf{X}_j = \begin{bmatrix} \mathbf{DT}_i \\ \mathbf{DG}_i \end{bmatrix} \tag{7}$$

where $\mathbf{ST}_{ij}$ is the synthetic tsunami waveforms at station *i*-th from segment *j*-th, $\mathbf{SG}_{ij}$ is the synthetic vertical and horizontal displacements at station *i*-th from segment *j*-th, $\mathbf{x}_j$ is the slip amount at segment *j*-th, $\mathbf{DT}_i$ is the observation of tsunami waveforms at station *i*-th and $\mathbf{DG}_i$ is the observation of vertical and horizontal displacements at station *i*-th.

The spatial variation of fault slip must be smooth to some degree because of the finiteness in the fracture strength of actual rocks (Yabuki and Matsu'ura, 1992). We used the following objective function minimized in the inversion.

$$s(\mathbf{m}) = (\mathbf{d} - \mathbf{Gm})^{\mathrm{t}} \mathbf{E}^{-1} (\mathbf{d} - \mathbf{Gm}) + \alpha^2 \mathbf{m}^{\mathrm{t}} \mathbf{Hm} \tag{8}$$

where **d** is the observed tsunami waveforms and GPS data in the joint inversion, **G** is the Green's function containing the synthetic tsunami waveforms and synthetic vertical and horizontal displacements, **m** is the model parameter vector, α^2 is the smoothing factor, **H** is the smoothing matrix consisting of a Laplacian operator that spatially smooths the slip distribution and **E** is the measurement errors, which are assumed to be the covariance matrix of the data.

To obtain the optimal value of smoothing factor (α^2), the Akaike's Bayesian Information Criterion (ABIC) proposed by Akaike (1980) is used in this study.

$$ABIC(\alpha^2) = (N + P - M) \log s(\mathbf{m}) - P \log \alpha^2 + \log \left\| \mathbf{G}^{\mathrm{t}} \mathbf{E}^{-1} \mathbf{G} + \alpha^2 \mathbf{H} \right\| + C \tag{9}$$

where N is the total number of data points in the tsunami waveform and GPS data, P is number of the subfault, M is the number of model parameter and C is a constant.

The modified "delete-half" Jackknife method (Tichelaar and Ruff, 1989) was applied to estimate error. In this method, the inversion is repeated many times by deleting half the number of data randomly. The errors defined as the standard deviation are multiplied by a scale factor, K, where the formula of K is calculated as follows :

$$K = \left[(n - j - p + 1) / j \right]^{1/2} \tag{10}$$

where n is the total number of data points, j is the number of dropped data points and p is the number of the model parameters that can be assumed as the number of subfaults.

4. RESULTS AND DISCUSSION

The slip distribution (Figure 4a and Table 1) shows that the largest slip amount of 12.35 m was located at subfault 8 with depth between 21 km and 27 km. This subfault is located at below Nias Island. Figure 5a shows that the northwest part of Nias Island had uplift of around 3 m, Simeuleu Island and Banyak Island had uplift of around 2.5 m, while subsidence around 1 – 1.5 m occured in Sumatra Island. Graph of ABIC and smoothing factor are shown in Figure 5c.

The result of slip distribution calculation suggests that before the 2005 Nias earthquake occured, there was a locked zone in and around Nias Island. We have an assumption that the 2005 Nias earthquake was the recurrence of the 1861 event. The result of our slip distribution calculation is consistent with the result of Walker *et al.* (2005), Kreemer *et al.* (2006), and Konca *et al.* (2007), with a large amount of slip distributed in northern part of Nias Island, Simeuleu Island, and Banyak Island. The large slip area of the 2005 Nias earthquake did not reach the Sumatra trench.

Table 1. Slip amount of each subfault

Subfault Number	Slip Amount (meter)	Error (meter)
1	2.92	± 0.05
2	6.21	± 0.05
3	0.31	± 0.26
4	0.00	± 0.35
5	3.26	± 0.60
6	3.44	± 0.80
7	2.53	± 0.19
8	12.35	± 0.97
9	3.08	± 1.31
10	1.61	± 0.11
11	4.99	± 2.28
12	4.87	± 0.40
13	0.00	± 0.02
14	5.83	± 0.73
15	9.50	± 0.43
16	8.58	± 0.65
17	5.64	± 1.80
18	4.94	± 2.14

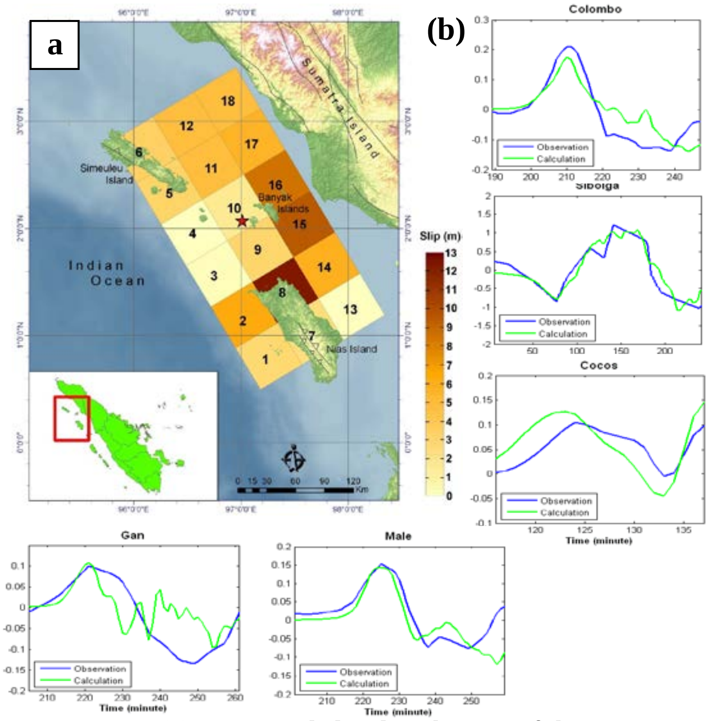

Figure 4. (a) Estimated slip distribution of the 2005 Nias earthquake determined by joint inversion of tsunami waveforms and GPS data. (b) Comparison of the observed (blue lines) and synthetic tsunami waveforms (green lines) computed from the calculated slip distribution.

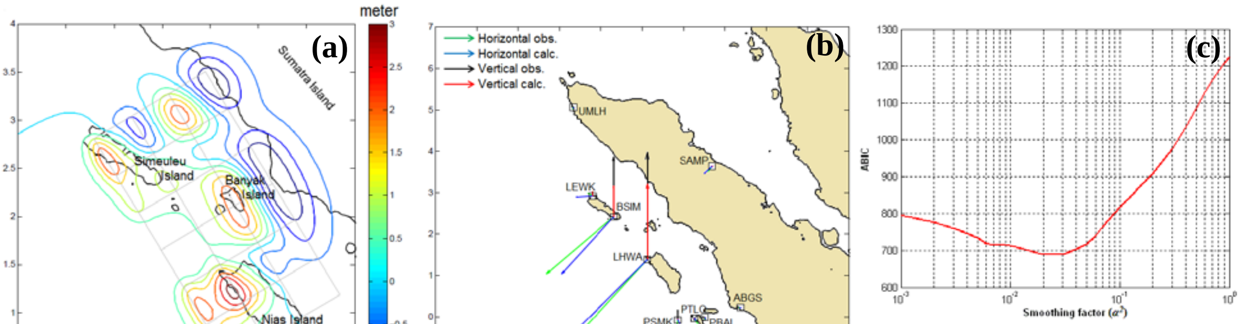

Figure 5. (a) Crustal deformation computed from the slip distribution. (b) Comparison of observed displacements (vertical and horizontal) and displacements calculated from the slip distribution (c) Values of ABIC plotted as a function of α^2, where the ABIC values are minimized at $\alpha^2 = 0.03$

In general, our comparison of observed and computed tsunami waveforms, as shown in Figure 4b, are consistent except for that of Gan station which has a large error compared with the other stations. We suppose this is because of resolution of the bathymetry data is low in the area of the Maldives Islands. Overall, for comparison of observed and computed displacements as shown in Figure 5b, the computed displacements (vertical and horizontal) explain the observed ones.

The total seismic moment calculated from these slip distribution is 1.06×10^{22} Nm (M_w = 8.6), with the assumed rigidity (Fujii and Satake, 2008) 4.0×10^{10} N/m^2 for subfaults number 1-12 (shallow and intermediate subfaults) and 7.0×10^{10} N/m^2 for subfaults number 13-18 (deeper subfaults). The result was slightly smaller than seismic moment of Harvard CMT solution and the seismic moment that was obtained using joint inversion of seismic wave and geodetic data by Konca *et al.* (2007). The result of moment magnitude was similar to the result of the Harvard CMT solution and Walker *et al.* (2005), but larger than moment magnitude that was obtained using GPS data by Kreemer *et al.* (2006).

5. CONCLUSIONS

The 28 March 2005 Nias earthquake was a large earthquake that occured in the megathrust of the Sumatra subduction zone. This earthquake generated a small tsunami with a maximum tsunami height of around 1.3 m recorded at closest tide gauge station (Sibolga). We have estimated the slip distribution of the 28 March 2005 Nias earthquake by using joint inversion of tsunami waveforms and GPS data. We assumed that the fault length was 300 km and the width was 150 km. The slip distribution shows that the large amount of the slip was located in the intermediate (21 – 27 km) and deeper (> 27 km) subfaults. The maximum slip amount was 12.35 m located at below Nias Island. The large slip area of the 2005 Nias earthquake did not reach the Sumatra trench. The rupture area of the 2005 Nias earthquake was similar with that of the 1861 earthquake. The slip distribution is consistent to the source model that were obtained by teleseismic wave (Walker *et al.*, 2005), GPS data (Kreemer *et al.*, 2006) and joint inversion of seismic wave and geodetic data (Konca *et al.*, 2007). The total seismic moment calculated by the slip distribution was 1.06×10^{22} Nm (M_w = 8.6).

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