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Fumiaki Kimata, Endra Gunawan, Yusaku Ohta,
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Evaluation of the 2012 Indian Ocean Coseismic Fault Model in 3-D Heterogeneous Structure based on Vertical and Horizontal GNSS Observation

Cecep Pratama[1, a)] Takeo Ito[1] Takao Tabei[2] Fumiaki Kimata[3] Endra Gunawan[4] Yusaku Ohta[5] Tadashi Yamashina[2] Irwandi Nurdin[6] Didik Sugiyanto[6] Umar Muksin[6] Nazli Ismail[6] Irwan Meilano[7]

[1]*Graduate School of Environmental Studies, Nagoya University*
D2-2(510), Furo-cho, Chikusa-ku, Nagoya-shi, Aichi, JAPAN 464-8601
[2]*Department of Applied Science, Faculty of Science, Kochi University*
2-5-1 Akebono-cho, Kochi-shi, Kochi, JAPAN 780-8520
[3]*Tono Research Institute of Earthquake Science Applied Science*
1-63 Akiyocho-cho, Yamanouchi, Mizunami-shi, Gifu, JAPAN 509-6132
[4]*Graduate Research on Earthquake and Active Tectonics, Bandung Institute of Technology*
Jalan Ganesha 10, Bandung, West Java, INDONESIA 40132
[5]*Graduate School of Science, Tohoku University*
6-3 Aramaki Aza-Aoba, Aoba-ku, Sendai JAPAN 980-8578
[6]*Faculty of Physics, Syiah Kuala University*
Jalan Syech Abdurrauf no 3, Banda Aceh, Aceh, INDONESIA 23111
[7]*Faculty of Earth Sciences and Technology, Bandung Institute of Technology*
Jalan Ganesha 10, Bandung, West Java, INDONESIA 40132

[a)] Corresponding author: cecep@seis.nagoya-u.ac.jp

Abstract. Lack of observation network in the vicinity of oceanic intraplate earthquake lead the estimation of coseismic fault slip with high uncertainty. Satriano et al. [2] and Wei et al. [3] found NNE trending left-lateral slip as the primary features. In another hand, Yue et al. [4] and Hill et al. [5] proposed WNW trending right-lateral faults structure as the main characteristic. Here, we investigate the coseismic fault model that could explain the coseismic offset both vertical and horizontal in a 3-D heterogeneous earth structure. We constructed finite element model that include three-dimensional velocity structure, topography/bathymetry, spherical-earth and subducting slab. In this study, we employed scaling slip to adjust slip amount and total seismic moment. Instead of original slip amount, we preserve seismic moment as a basis comparison. Based on vertical and horizontal observation data, WNW trending right-lateral fault could fit better than NNE trending left-lateral fault. The present study demonstrates best-fit calculation using scaling slip optimized to the horizontal or vertical observation lead the both fault model worsen the misfit of vertical or horizontal component, respectively. This result analysis indicates a trade-off between vertical and horizontal component and reflects the importance of revisiting the fault slip modeling incorporating vertical and horizontal data equally.

INTRODUCTION

The first quarter in 2012, a great oceanic intraplate earthquake known as Indian Ocean earthquake struck 400 km offshore Sumatra. The earthquake sequence occurred in extremely complex conjugate faults consisting at least three fault planes for the first shock [2], [3], [4], [5] as shown in Figure 1a. However, those conclusions of fault

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model have several essential different characteristics. In the case of the 2012 Indian Ocean earthquake, previous studies suggest difference on coseismic fault slip orientation and the largest faulting. Initially, the complex conjugate fault has been found to be NNE trending left-lateral fracture zones as the main features with dominant deep slip [2], [3] (Figure 1c). On the other hand, WNW trending right-lateral faults structure was greater slip has been found with dominant shallow slip [4], [5] (Figure 1d).

Previous studies [6] and [7] investigate the best-fit coseismic model using horizontal component of GNSS data with the assumption of homogeneous half-space and layered spherical-earth model, respectively. However, those studies reached different conclusions of the best-fit coseismic model. Pratama et al. [1] reported systematic effect of model simplification. Simplification such as half-space model or homogeneous earth structure may affect the result [1]. Here, we improved the investigation using 3-D heterogeneous earth model based on horizontal and vertical GNSS data which never been included in the last analysis. In this study, we focus on the established two-fault model that significantly differs each other. The fault model hereafter in this paper will be stated as Wei Model [3] and Hill Model [5].

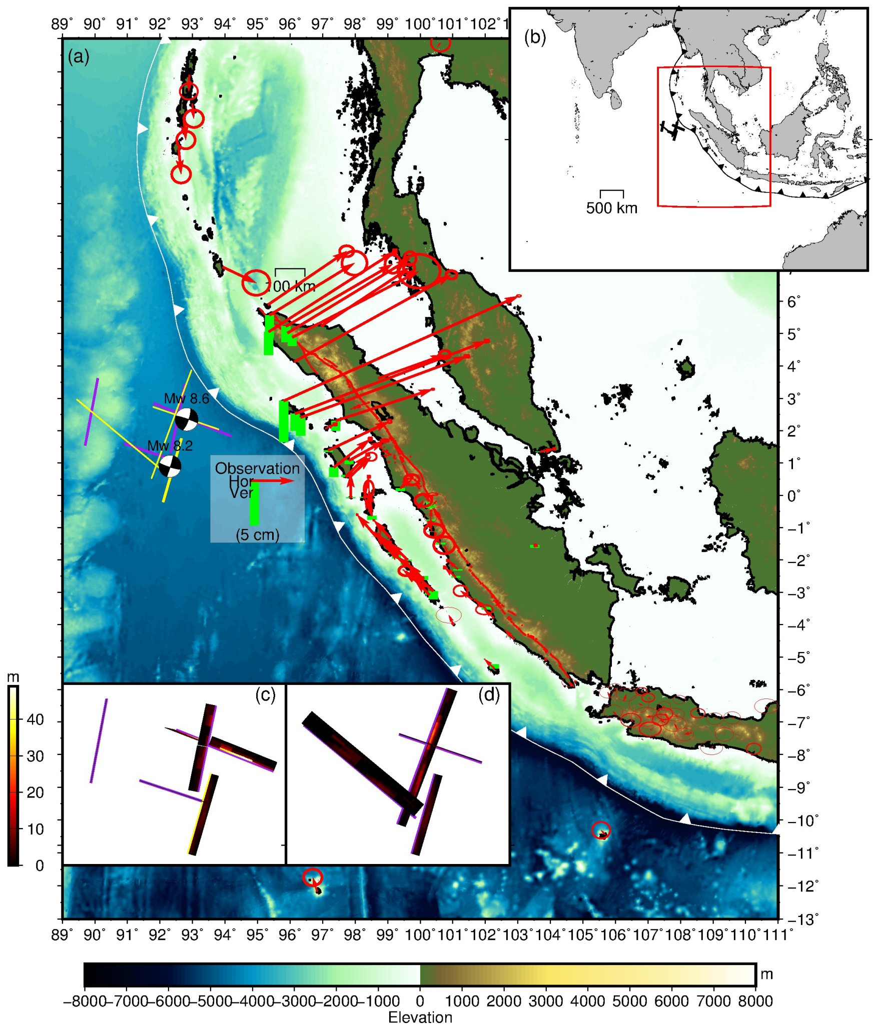


FIGURE 1. (a) Red arrows and green bar indicate observed horizontal and vertical GNSS data, respectively. Purple line and yellow line shows different fault trace of Wei Model and Hill Model, respectively. Red lines in Sumatra Island are Great Sumatra Fault while white line with triangle represents Sunda Trench. Surface topography and bathymetry are based on Becker et al. 2009, (b) Interest area, (c) Fault slip distribution of Hill Model (d) Fault slip distribution of Wei Model.

DATA AND METHODS

Observation Data

We compiled GNSS site position based on daily solution taken from previous studies [5], [6], [7], [9], [10], [11]. Total of observation data is 100 stations that include mid-field and far-field permanent GNSS site from several networks. The 100 stations consist of 200 offset for horizontal and 34 offset for vertical. Because clear vertical offset only seen on Mid-field network (Figure 1a). Mid-field network (<500 km site-to-source distance) consist of AGNeSS (Aceh GNSS Network for the Sumatran fault system), SuGAr (Sumatran GPS Array), and InaCORS (Indonesian Continuously Operating Reference Stations). Meanwhile, far-field network consist of SuGAr, InaCORS, IGS (International GNSS Service) and Nicobar-Andaman Island Network.

We obtained clear landward displacement and subsidence in northern Sumatra as shown in Figure 1a. In the northern part, the Nicobar-Andaman Island network observed southward. Meanwhile, in the southern part, the SuGAr and InaCORS network observed northward. Those deformation exhibited strike slip characteristic mechanism.

Coseismic Fault Model

Coseismic fault model that tested in this study was reported by [3] and [4]. We summarized the main differences of both fault models as shown in Table 1. Wei et al. [3] reported fault model for the mainshock Mw 8.6 and the largest aftershock Mw 8.2. Meanwhile, Hill et al. [4] only inferred fault model for the mainshock Mw 8.6. Since the provided horizontal and vertical GNSS data was a daily solution, we modified fault model from [4] with additional fault plane for Mw 8.2 based on [3] (we found that the offset based on the largest aftershock Mw 8.2 is significant).

Uniform slip scaling was used to adjust the fault model in three-dimensional heterogeneous structure. The uniform slip scaling means that we multiply each slip distribution with a scalar as a factor that controls the slip magnitude. In addition, we used this scaling to analyze trade-off between horizontal and vertical component.

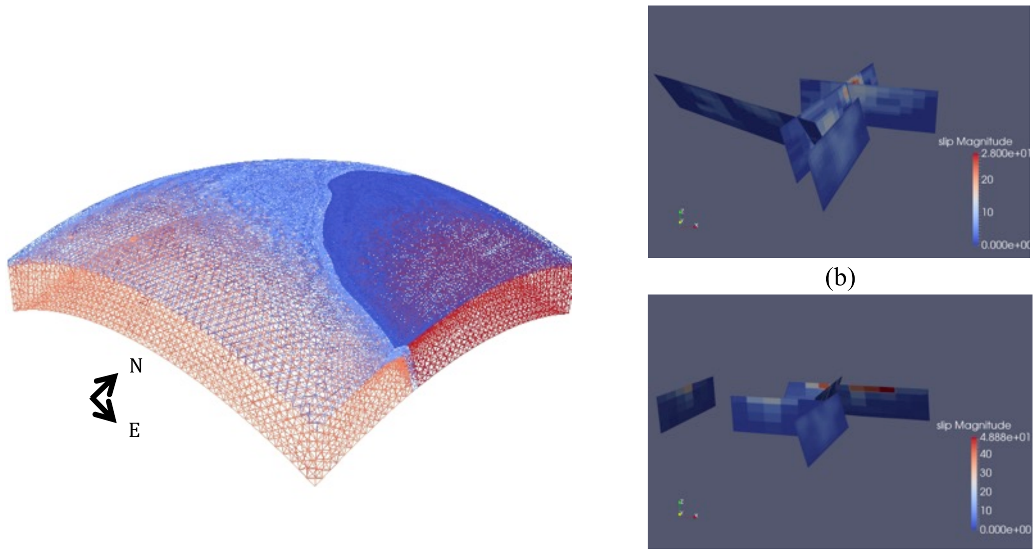
TABLE 1. Coseismic fault model characteristic for Wei model and Hill model

Parameter	Wei Model	Hill Model
Main Orientation	NNE	WNW
Number of Fault Plane (Mw8.6)	3	6
Maximum Coseismic Slip Amount	28 m	48 m
Dominant Depth Slip	Deep	Shallow
Original Seismic Moment	13×10^{21} N m	12×10^{21} N m
Original Data Constraint	Regional, teleseismic	Regional, teleseismic, 1-Hz GPS data

Finite Element Model

The meshed geometry model incorporate subducted elastic slab, earth curvature and three dimensional velocity structures. A detailed explanation of the model and boundary condition could be found in separate publication [1], [10]. We fixed the oceanic lithosphere thickness as 75 km from seafloor [10]. The finite element mesh is shown in Figure 2a.

We carried out finite element method using PyLith code from Computational Infrastructure for Geodynamics (https://geodynamics.org/cig/software/pylith) with fault interface using domain decomposition method [12], [13]. In this model, we simulate kinematic slip to produce surface displacement at each site and compare the calculation offset to observation offset. Figure 2b and Figure 2c shows slip distribution from Wei model and Hill model in three-dimensional view, respectively.



(a) (b) (c)

FIGURE 2. Finite Element Mesh, which has buried fault in the center of the geometry. (a) Spherical-Earth finite element model with the dark blue and dark red color indicates continental lithosphere and asthenosphere, respectively. Concurrently, the light blue and light red color represents oceanic lithosphere and asthenosphere, respectively. The three-dimensional view of Wei model (b) and Hill model (c).

RESULT AND DISCUSSION

Model and Observation Evaluation Criteria

We used separate root mean square for each component to accommodate different size of data. So, for every GNSS station, we used horizontal *i* and vertical *n* to evaluate the calculation offset *Cal* and observation offset *Obs* as following

$$Misfit = \sqrt{\frac{1}{I}\sum_{i=1}^{I}\left(Obs_{hor,i} - Cal_{hor,i}\right)^2} + \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(Obs_{ver,n} - Cal_{ver,n}\right)^2}$$

Grid search of scaling slip was used to evaluate model and observation offset. We calculated coseismic model using scale from 0.3 to 1.7 with 0.1 intervals.

We calculate both models with original slip distribution. At this moment, we found that Wei model slightly better fit than Hill model. Wei model predict better the vertical but large horizontal component than Hill model as shown in the table 2. Since we used three-dimensional heterogeneous structure, we estimate the total seismic moment to compare with the original seismic moment based on previous studies. Wei model gives significant lower total seismic moment. We obtained 9.8×10^{21} N m while the original total seismic moment is 13×10^{21} N m [3]. The difference is more than the seismic moment for the Mw 8.2 which is 2-3 × 10^{21} N m.

Horizontal and Vertical GNSS Data Effect in Evaluation

Preserve the Original Moment based on Previous Studies

The elastic modulus gives a significant contribution to the offset magnitude while the effect of the variation is less significant [1], [15]. In that sense, to compare the both model properly, we should calculate the fault model that reflect the original seismic moment. We tried to match the original moment with scaling slip. Wei model and

Hill model need to scale up to 1.33 and 1.09 times from the original slip (Tabel 2), respectively. For both models, horizontal misfits are lessening slightly but the vertical misfits are worsening more significant than horizontal misfit. The total misfit suggests Hill model predict better than Wei model for both horizontal and vertical observation. Coseismic offset based on Hill model estimate a slightly underestimate horizontal observation but overestimate vertical observation (Figure 3b). However, Wei model produce overestimate coseismic offset for both horizontal and vertical component (Figure 3a).

Gunawan et al. [7] have been investigated numerous coseismic models in a layered spherical earth model [16]. They showed that Hill model is a best model based on the original slip distribution. They also have tested using the half-space model [14] and found Hill model had worsen misfit than in a layered spherical earth. In addition, Maulida et al. [6] using half-space model found the Hill model have the largest misfit. A first potential problem in those studies is the evaluation derived without verification of the total moment magnitude of each fault model. A second potential problem that those studies only constrained by horizontal component where the vertical component gives a significant contribution with the opposite sense as shown in table 2. Hence, the best-fit model would be depending on the assumption of earth parameter such as elastic modulus, model geometry and the data constraint. Based on a complete GNSS component and a consistent total seismic moment, we found the Hill model is the best-fit fault model for the 2012 Indian Ocean earthquake.

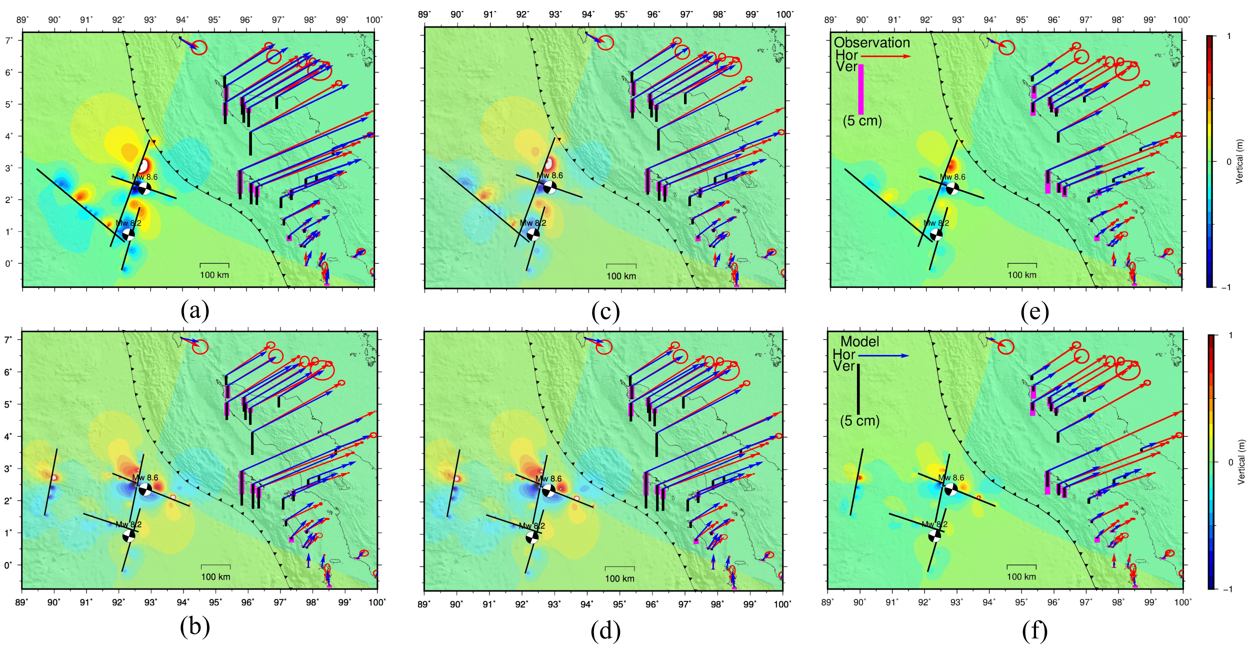


FIGURE 3. Coseismic pattern and best fit with several criteria. We preserve the original seismic moment based on the model for (a) Wei Model and (b) Hill Model. Best fit based on horizontal data only for (c) Wei model and (d) Hill model. Best fit based on vertical data only for (e) Wei model and (f) Hill model.

Scaled Slip to Fit Horizontal or Vertical Components of GNSS Observation

Vertical component is a new data to analyze where previous studies do not have. First, we tested both fault model to lessen the horizontal misfit by scaled the coseismic slip to fit horizontal component (Figure 3c-d). We obtained the vertical offset is overestimate and vertical misfit getting worst (Table 2). Secondly, we lessen the vertical misfit by scaled the coseismic slip to fit the vertical component (Figure 3e-f). We obtained the horizontal offset is underestimate and horizontal misfit went larger. This trade-off shows significant contribution of vertical component where had only small weight (about 20%) compared to horizontal component in previous GNSS based source inversion [5]. In addition, 3-D heterogeneous structure may play important role in vertical component. Incorporation of equal weight of vertical offset in the mid-field area for source inversion analysis using 3-D heterogeneous structure may change the coseismic slip distribution and maximum slip magnitude.

Wei model changes in Figure 3a-c-e correspond with scale of 0.6, 1.17 and 1.33. The maximum interval of those scales is about 0.73. Besides, the maximum interval of scale for Hill model in Figure 3b-d-f is about 0.64 (1.14 minus 0.5). This may indicates that changing of a shallow slip magnitude (Hill model) is slightly more sensitive to the vertical component than changing of a deep slip magnitude (Wei model).

TABLE 2. Evaluation of each model compared to observation data

Fault Model	Optimized to	Misfit			Scale Factor	Total Moment* (N m)
		Hor.	Ver.	Total		
Wei Model	Original Slip	26.19	10.56	36.75	1	9.8×10^{21}
Hill Model	Original Slip	23.94	13.04	36.98	1	11.04×10^{21}
Wei Model	Original Moment	26.01	15.06	41.07	1.33	13.04×10^{21}
Hill Model	Original Moment	22.74	14.63	37.37	1.09	12.03×10^{21}
Wei Model	Horizontal	23.56	12.77	36.33	1.17	11.47×10^{21}
Hill Model	Horizontal	22.48	15.54	38.02	1.14	12.59×10^{21}
Wei Model	Vertical	46.78	7.48	54.26	0.6	5.88×10^{21}
Hill Model	Vertical	51.59	7.16	58.75	0.5	5.52×10^{21}

*Removed Mw 8.2 seismic moment

In postseismic studies, different coseismic model will produce different pattern of coseismic stress change and possibly change the relative contribution of different postseismic mechanisms [19]. Thus, maintaining the model in a consistent manner is important to justify the result and minimizes uncertainty. The consistent model will have similar assumption of the model between coseismic and postseismic analysis as has been demonstrated by Freed et al. [20]. Otherwise, verification of the appropriate coseismic model in postseismic modeling is indispensable process.

The limitation of evaluation for coseismic fault model in this study is using coseismic offset as a constraint. The coseismic offset only represent one day offset. However, postseismic rate have a longer daily solution where it is controlled by viscosity and coseismic stress change. There is no rigorous investigation of scaling slip effect on postseismic modeling while have been used in numerous postseismic studies [17], [18]. Further research need to clarify the effect of coseismic stress change pattern due to uniform slip changing.

CONCLUSION

We have been demonstrated the evaluation of the 2012 Indian Ocean fault model based on coseismic offset for both horizontal and vertical component of GNSS observation. Despite of limitation of our analysis only involve coseismic offset, based on our result we conclude that

- Hill model is a best-fit model based on horizontal and vertical component in an appropriate total seismic moment using three-dimensional heterogeneous spherical earth.
- Vertical component has significant trade-off with horizontal component. Hence, this component is indispensable to include on source inversion study in term of equal weight. This study reflects the importance of re-visiting and re-considering vertical component on coseismic slip inversion analysis.
- For further research, we consider to continue our analysis to investigate comprehensively based on postseismic signal. In addition, scaling factor analysis shows that both fault slip model are slightly larger than the original slip distribution. This result should be investigated for postseismic modeling because the stress pattern produced by original slip distribution might be different than the scaled fault slip.

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