Analysis of Aftershocks Distribution of the June 16, 2010 Yapen Earthquake Based on Stress Changes on the Fault Plane.

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On June 16, 2010, an earthquake (Mw 7.0) occurred on the north of the Papua island close to Yapen island. The area of earthquake source has been well identified due to the activity of faults which are formed by collision of four minor plates. The source mechanism of the June 16, 2010 Yapen earthquake was strike-slip fault type with two nodal planes. Determination of the actual fault plane of nodal planes is important for a detailed study of seismotectonics and earthquake risk assessment. In this study, we relocated the mainshock and aftershocks by using the Double-Difference algorithm, and analyzed the stress changes by using the Coulomb stress method on the study area. Furthermore, the determination of the actual fault plane was obtained by using the H-C method (Hypocenter-Centroid method). We used earthquake data from the Meteorology Climatology and Geophysics Agency (BMKG) and the Global Harvard Centroid Moment Tensor (CMT Global Harvard). Study results show that the relocated aftershock distribution lies close to the increase in stress coseismic area. The increase in stress coseismic area occurred at the nodal plane II as the actual fault plane. This results proved that the aftershock distribution was correlated to the actual fault plane.

1. Introduction
Indonesia is one of the earthquake prone countries because of high tectonic activity. There are three major plates and nine minor plates that collided by each other around Indonesian region. These collision zones act as earthquake sources. Papua region is one of the tectonic complex zones in Indonesia. The region is located among four minor plates namely Sunda, Pacific, Philippine Sea, and Australia plates, respectively (figure 1a) [1]. Due to these tectonic conditions, the occurrence of earthquake is very susceptible. On June 16, 2010 the big earthquake struck Yapen and Waropen districts in Papua region (see figure 1b). Furthermore, the earthquake caused the significant damages and made cracks on the ground trending to direction of 310-350 degree based on BMKG survey.

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Figure 1. (a) Regional tectonic features in the Indonesia region, especially Papua region [1]. (b) Red star shows the epicenter of the June 16, 2010 Yapen earthquake. The beach ball shows the focal mechanism from the Harvard CMT (Nodal plane I, strike 241°, dip 82°, slip -10° & nodal plane II, strike 332°, dip 80°, slip -172°).

The traces of cracks on the ground represent the direction of the earthquake strike. Knowledge of the earthquake strike can be obtained from aftershocks distribution and coseismic stress in changes [2,3,4,5,6,7]. The aftershocks distribution is also correlated with coseismic stress in changes of the earthquake. The purposes of this study are to determine the actual fault plane based on the patterns of aftershocks distribution and to analyze coseismic stress in changes of the June 16, 2010 Yapen earthquake. Based on these results, we succeeded to improve earthquake hazard assessment in the Papua region.

2. Data

In this study, 98 events were used to relocate the aftershocks M ≥ 3 from 13 stations of BMKG broadband seismometer network (figure 2). We used the Global CMT data to calculate the stress distribution of coseismic and to determine the actual of fault plane.

Figure 2. The distribution of 13 stations BMKG broadband seismometer network are marked by yellow triangles. The mainshock and aftershock of the June 16, 2010 Yapen earthquake are marked by red circles.
3. Theory and Methodology

3.1 Double-Difference Algorithm
In this study, we relocated the aftershocks using Double-Difference algorithm. This method can repair a velocity model as an input in processing, and make the relocation more sense than pre-relocation data [8,9]. The basic calculation is based on travel time between two earthquakes distance which is shorter than the earthquakes-station distance [10].

\[ \frac{\partial t^i_k}{\partial m} \Delta m^i - \frac{\partial t^j_k}{\partial m} \Delta m^j = d^i_j \]  

(1)

Or rewritten as follows:

\[ \frac{\partial t^i_k}{\partial x} \Delta x^i + \frac{\partial t^i_k}{\partial y} \Delta y^i + \frac{\partial t^i_k}{\partial z} \Delta z^i + \Delta t^i - \frac{\partial t^j_k}{\partial x} \Delta x^j + \frac{\partial t^j_k}{\partial y} \Delta y^j + \frac{\partial t^j_k}{\partial z} \Delta z^j - \Delta t^j = d^i_j \]  

(2)

where \( \Delta m^i \) is the change of relative hypocenter parameters \( \Delta x^i, \Delta y^i, \Delta z^i, \) and \( \Delta \tau^i \) for events i and j. \( \partial t^i_k \) is the travel time of earthquake wave \( i \) to the \( k \) station. \( d^i_j \) is residual of the observed and calculated events \( i \) and \( j \) which are recorded by the same station \( k \). \( \partial \) is the partial derivatives, \( m \) is the component of the slowness vector. Equation (2) is combined for all of pairs of earthquakes that is solved by linier matrix equation:

\[ WGm = Wd \]  

(3)

with \( G \) explains a matrix of size \( M \times 4N \) (\( M \), number of double-difference observations; \( N \), number of events), \( d \) is matrix of \( d^i_j \) which its size is \( M \times 1 \), \( m \) is a matrix of model perturbation of \( \Delta m \) with the size \( 4N \times 1 \), and \( W \) is a diagonal matrix which serves as weight each equation. The algorithm is applied in a packet program namely HypoDD developed by Waldhauser [10].

3.2 Coulomb Stress
We investigated whether the aftershocks are triggered by mainshock by calculating Coulomb stress distribution, \( \Delta \text{CFF} \). It can be represented as follows [2,3,4].

\[ \Delta \text{CFF} = \Delta \tau - \mu \Delta \sigma \]  

(4)

where \( \Delta \text{CFF} \) is a critical Coulomb failure stress, \( \Delta \tau \) is the changes of shear stress related to the slip distribution, \( \mu \) is an effective coefficient of friction related to pore fluid and normal stress change, and \( \Delta \sigma \) is the changes of normal stress, respectively. Coulomb failure stress \( \Delta \text{CFF} \) indicate that a rock will reach a limit to failure [2]. Coulomb failure stress can explain the behavior of stress released due to mainshock, and influence the surrounding area to generate aftershocks. The Coulomb stress changes are displayed into maps by using Coulomb 3 software (USGS) developed by Toda S [11].

3.3 H-C Method
In this study, we identified the fault plane of the June 16, 2010 Yapen earthquake by using the H-C method. The method analyze the geometrical configuration of the Hypocenter (H), Centroid (C), and the moment–tensor solution in Nodal Plane I (NP I) and Nodal Plane II (NP II) [7]. Furthermore, it can investigate the actual fault plane by determining the appropriate location of hypocenter to one of the both nodal planes, and the shortest distance of hypocenter to both nodal planes.
4. Result and Discussion

In this study, we relocated the aftershocks of the June 16, 2010 Yapen earthquake. Most of the aftershocks were located in northwest of mainshock. In lateral, the pattern of relocated aftershocks distribution was almost similar with of pre-relocated one. The pre-relocated pattern in depth showed that the aftershocks were occurred at shallow depth, meanwhile the relocated aftershocks were moved deeper part more than 10 km in depth. (figure 3 and figure 4). The difference of depth between pre-relocated and relocated aftershocks indicated that the relocated hypocenter depth depend on electing the pair of hypocenter in calculating. The elected hypocenter pair should have the shortest distance.

![Figure 3](image1)

**Figure 3.** (a) The initial hypocenter location (BMKG). The line of A-A', and B-B' are cross section lines, respectively. (b) Cross-sections of aftershocks distribution in the depth.

![Figure 4](image2)

**Figure 4.** (a) The hypocenter location relocated by using hypoDD. (b) Cross sections of aftershock distribution in the depth.

We calculated the stress changes of mainshock in order to investigate whether the aftershocks were generated by mainshock (figure 5). In Figure 5, the distribution of Coulomb stress shows that there are the increased stress zone at the end of rupture marked by warm color, 0-0.5 bar. This pattern indicates that the aftershocks would be expected to occur in and around this area. It is proven that there are many aftershocks occurred in and around the increased stress zone i.e. in NP II. Meanwhile aftershocks distribution is not represented by the stress in the depth because of the uncertainties vertically. We
applied the H-C method to analyze the actual fault plane of the June 16, 2010 Yapen earthquake. Figure 6 shows the position of hypocenter of the June 16, 2010 Yapen earthquake. The solution demonstrated that the hypocenter is closer to the NP II, 13.86 km than to NP I, 38.99 km. So, NP II is the actual fault plane of the June 16, 2010 Yapen earthquake.

**Figure 5.** The upper panel shows the Coulomb stress change and vertical cross section A-B (in bars) of nodal plane I and the lower panel represents the nodal plane II.
Figure 6. Centroid fault plane is in the middle of the intersection between nodal plane I and II. Mainshock is represented by blue star. NP I is marked by red square. NP II is marked by green square. Because the hypocenter is not located appropriately on the one of both nodal plane, the actual fault plane is obtained by determination the shortest distance of hypocenter-nodal plane i.e. NP II (NP I = 38.99 km & NP II = 13.86 km).

5. Conclusion
The relocated aftershock distribution lies close to the increased stress zone. The area of coseismic stress increase was occured in the NP II as the actual fault plane of the June 16, 2010 Yapen earthquake. Moreover, the H-C method shows that the strike direction of actual fault plane is agreement with field observation.

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