Slip distribution effect in spatial coulomb stress analysis (Case study: Palu earthquake on September 28, 2018)

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Abstract. On September 28, 2018, the Palu-Koro fault released the accumulated stress that caused the earthquake. An earthquake with magnitude 7.5 caused large and massive damage around Palu. There were many aftershocks along the Palu-Koro fault. This research aims to calculate a model of spatial Coulomb stress based on this event to find a correlation between mainshock and the aftershocks. The slip distribution was used as an input of the spatial stress Coulomb modeling to increase the accuracy. We use the Teleseismic Body-Wave Inversion method to calculate slip distribution along the fault plane. As a result, this earthquake was generated by the Palu-Koro fault movement with Mw 7.48, strike 350°, dip angle 67°, and rake -9°. There are three asperity zones along the fault plane located in the north and southern parts of the fault plane. The location of the most energy discharge is in the south asperity zone of the fault plane model with a maximum slip value of 1.65 meters. The spatial Coulomb stress change of this event shows that aftershocks concentration are in areas experiencing increased stress after the earthquake.

1. Introduction

The source mechanism is a study to improve a better understanding of earthquake sources and detailed knowledge of the rupture process, which can be used to analyze earthquake sources [7]. Determination of the source mechanism using a waveform taken from a local station (near-source) still has a high level of noise due to the heterogeneity of the upper mantle structure. Kikuchi and Kanamori [1] developed a Teleseismic Body-Wave Inversion method to obtain an interpretation of the slip distribution, asperity, and orientation of the fault plane.

Seismic energy radiation caused by the source mechanism process can be interpreted using Coulomb stress. In Coulomb stress method, an earthquake can be modeled as a slip distribution in a uniform elastic half-space medium [3]. The direction of seismic energy radiation can be modeled properly in Coulomb stress analysis. Therefore, it is necessary to analyze the slip distribution using the inversion method of teleseismic waves and Coulomb spatial stress from the earthquake on September 28, 2018 in Palu. This research conduct to explain the source mechanism, slip distribution, and Coulomb spatial stress, as well
as validate the distribution of aftershocks that occurred after the release of energy in the Palu earthquake on September 28, 2018.

Previously, the research of Coulomb Stress changes due to the Palu earthquake on September 28, 2018 has been conducted by Utaminingtyas [12]. The parameters of the hypocenter location, strike, dip, slip, rake, and magnitude was used by Utaminingtyas [12] to model the fault plane based on the Wells-Coppersmith equation. From the calculation of Coulomb spatial stress changes with a fault area of 134.13 x 26.83 km, it was found that about 78.2% of the aftershocks that occurred were in the stress zone. In contrast to the Utaminingtyas [12], this study uses a fault plane model with slip distribution resulting from the Teleseismic Body-Wave Inversion method to improve the accuracy of Coulomb spatial stress change modeling.

2. Data and Methods

Figure 1. Distribution of seismic station locations within 30-90 ° from the earthquake source whose waveform data is used in slip distribution modeling.

This research is a case study that discusses and analyzes the source mechanism, slip distribution, and Coulomb stress from the Palu earthquake of September 28, 2018. This research consists of 2 stages, namely modeling the slip distribution and calculating Coulomb stress. The method used in slip distribution modeling is the teleseismic body wave inversion method from Kikuchi and Kanamori [2]. Then, the results of the slip distribution are used to calculate Coulomb spatial stress change. This process has done using the Coulomb 3.3 program from USGS (United States Geological Survey) [8].

The 2018 Palu earthquake waveforms used in this study were acquired from the database of IRIS (Incorporated Research Institutions for Seismology). The seismogram component used in this study is the Z component of the broadband seismometer. We collected the waveforms from the seismic stations with a distance of 30 ° - 90 ° from the earthquake source to get the teleseismic waveforms data. The seismic station distribution shows in figure 1.

3. Result and Discussion

3.1. Slip Distribution Model

The results of the inversion processing of teleseismic waveform data in figure 2 show the moment rate, focus mechanism, and slip distribution of the Palu earthquake source on September 28, 2018. The seismic velocity structure model used is the default program Jeffreys-Bullen velocity model, while the rupture velocity used is 5 km/hour. The source time function model used is the triangle model, with the assumption that the rock will immediately break after the stress energy has accumulated to a certain level.

The results of the inversion process obtained a focus mechanism that is similar to the initial input. From these results, it can be seen that the type of fault from the September 28, 2018 Palu earthquake was strike-slip with strike parameters of 350 °, dip 67 °, and rake -9 °. Besides, the seismic moment value \( M_0 \) is 0.210E21 Nm or equivalent to the moment magnitude (Mw) of 7.48. The length of the moment rate or source duration which is the result of the convolution of the slip velocity and the expansion of the rupture area, is 60 seconds from 15th to 75th seconds. Within 60 seconds of the rupture duration, there are two peak energy moments in the 40th and 50th seconds.
Figure 2. The final result from inversion. (a) moment rate function. (b) focal mechanism. (c) Slip distribution. (d) Slip distribution projected on the map. Asterisk indicated the initial breakpoint.

The results of the earthquake source mechanism obtained from this study are similar to the results issued by several worldwide institutions, such as the GFZ (Geo Forschungs Zentrum), USGS, BMKG (Badan Meteorologi, Klimatologi, and Geofisika), and Global CMT (Centroid Moment Tensor). The beachball produced by GFZ, USGS, BMKG, Global CMT, and this study show that the 2018 Palu earthquake source was a horizontal displacement with a left-lateral direction. Based on the epicenter location and the focal mechanism, this earthquake is associated with the Palu-Koro fault which divides Palu City in a north-south direction with a relative strike-slip type of sinistral (left-lateral) movement [13]. It is also supported by the fact that the 2018 Palu earthquake was a shallow depth earthquake [4].

The estimation of the area of the fault area takes references from several previous studies [5] [6] [10]. The results of the slip distribution show that the dominant earthquake slip is pointing to the left of the fault plane model with a maximum slip of 1.65 m. In figure 2c, it can be seen that 3 asperity zones that broke during the Palu earthquake on September 28, 2018. Based on this figure, it can also be seen that the location of the asperity zone is to the north and south of the hypocenter point with two asperity zones in the south and one asperity zone located to the north of the hypocenter. Figure 2d shows the projection of the slip distribution model in figure 2c onto the map. Based on the modeling results, the rupture process in the fault plane is preceded by an initial break or hypocenter indicated by an asterisk. Then move south to break the two zones of asperities and to the north solve one zone of asperity. The maximum slip in the Palu earthquake is in the southern part of the fault plane model. The asperity zone located in the southern part of the fault plane correlates with the location of the strongest damage in Palu City.

These results are also consistent with several studies that have been carried out, including the previous results [5] [6] [10] [11]. The comparison of the slip distribution model from those study showed in the table 1. The similarity of the slip distribution model of this study with these studies is the pattern of the aspherical zone and the location of the highest slip. Although using different data and methods, the results of the slip distribution pattern show that the aspherical zone pattern is mostly in the southern part of the fault model, while the location of the highest slip is around Palu Bay. However, these studies have differences in the maximum slip value. This difference is estimated due to differences in the data and input parameters used. The maximum slip value obtained in this study is not much different from the results of USGS [11] which obtained a maximum slip value of 1.8 meters. Meanwhile, the results of other studies show that the maximum slip varies from 2 to 8 meters at most. When compared with USGS [11], this study uses a single fault model and does not take into account the surface rupture in the earthquake source modeling. However, UGSG [11] does not only use teleseismic waveform data but also combined with SH waveform data and long-period surface wave data.
Meanwhile, Okuwaki [5] also uses teleseismic waveform data, single fault models, and a maximum rupture velocity of 5 km/s. However, the number of teleseismic waveform data and calculating the surface rupture is likely to be the cause of the maximum slip value reaching 4.25 meters. The surface rupture that appears in several locations in Palu City is estimated to cause the maximum slip calculation to be high. It also can be seen in the results of study by Socquet [6] and Ulrich [10] which make surface rupture data from satellite images for the main data. The use of this satellite image data results in the maximum slip estimates by Socquet [6] and Ulrich [10] of 5 meters and 8 meters, respectively.

| Parameter | Okuwaki (2018) | USGS (2018) | Socquet (2019) | Ulrich (2019) | This study |
|-----------|----------------|-------------|----------------|--------------|------------|
| Data      | 46 Z teleseismic P waveforms | • 40 teleseismic broadband P waveforms | Insar: Landsat Sentinel-2 ALOS-2 | Combine: Insar + Physic based model + teleseismic | 22 Z teleseismic P waveform |
| Velocity Model | Crust 1.0 | (1D) Crust 2.0 | - | T. Yudistira Crustal Velocity Model of Sulawesi + PREM | (1D) Jeffreys-Bullen |
| Geometry Model | Single fault | Single fault | Multiple fault | Multiple fault | Single fault |
| Max Vr    | 5 km/s | 4 km/s | 4 km/s | 5 km/s | 5 km/s |
| Plane Model | 240 km x 30 km (5 x 5 Subfault) | 200 km x 30 km | 42 x 7 Subfault | 200 km strike | 220 km x 32 km (10 x 8) subfault |
| Mo        | 3.2 x 10^20 Nm | 2.5 x 10^{17} Nm | 3.4 x 10^{20} Nm | | 2.1 x 10^{20} Nm |
| Surface Rupture Input | Yes | No | Yes | Yes | No |
| Max slip | 4.25 meter | 1.8 meter | Strike slip 5 meter Dip slip 2 meter | 8 meter | 1.65 meter |

3.2. Spatial Coulomb Stress Model
Coulomb spatial stress modeling due to the Palu earthquake on September 28 2018 was processed using the results of the slip distribution model. Parameters used in Coulomb stress modeling include strike, dip, rake, slip, depth, epicenter coordinates, magnitude, length and width of the fault plane model, net slip, and rake per net slip. Another input used is the friction coefficient, with a value of 0.4 for the strike-slip fault type [8]. Initial break modeling in the Coulom stress model uses a fault center with the hypocenter point in the middle of the fault plane. The calculation of the area of the fault plane is assumed to be an isotropic homogeneous rectangular area. The fault plane model is made along 220 km × 32 km which is divided into 22 grid boxes with the strike direction and 4 grid boxes with the dip direction. The size per grid is 10 km × 8 km in the direction of strike and dip, respectively. Furthermore, in each grid box, the net slip and rake values of the grid points in the fault plane model are entered in the previous process.
Figure 3 shows the changes in the spatial Coulomb stress caused by the Palu earthquake on September 28, 2018. Areas in red indicate an increase in Coulomb stress while the blue ones indicate a Coulomb stress decrease. The width of the stress change area is the result of the influence of magnitude. The greater the magnitude of an earthquake, the larger the area of Coulomb stress changes. The pattern of increasing Coulomb stress value which is dominated at each end of the fault is caused by the relatively sharp dip angle and the slip direction which tends to be parallel to the strike direction. The results of the Coulomb stress change plot resulted in 12 areas that experienced an increase and decrease in Coulomb stress. In addition to being at the ends of the fault model, the increase in Coulomb stress is also spread over several areas above the fault plane model, this is probably because the input used in this study is a fault plane model with slip distribution.

Different from previous research by Utaminingtyas [12], changes in Coulomb stress results from this study are more dominated by stress reduction areas both in the east and west of the fault area. Meanwhile, Utaminingtyas [12], which does not use slip distribution inputs, shows that the eastern area of the fault area has increased stress while the west part is dominated by a stress reduction zone. Differences also exist in the zones of increased stress with a small area around the fault plane due to variations in the length and direction of the slip along the fault plane. The use of uniform length and slip direction values in Utaminingtyas [12] causes the absence of stress-increasing zones with this small area.

When an area experiences increased stress, the area has the potential to experience an earthquake triggered by a previous earthquake. Seismic activity triggering is a process where changes in stress activity caused by an earthquake can cause or slow down seismic activity in the surrounding area. In the 2018 Palu earthquake, there were a total of 573 aftershocks that occurred between September 28, to November 21, 2018 [12]. To compare the relationship between the spatial distribution of changes in Coulomb stress and aftershocks, the aftershocks parameter that was relocated by Utaminingtyas [12] used hypoDD method.

In figure 3, which shows an overlay of the epicenter location of aftershocks with the distribution of Coulomb stress changes, it can be seen that the concentration of aftershocks tends to be in the northwest hypocenter area and the southern part of the fault plane model. The concentration of aftershocks in the southern part of the fault plane model correlates with an increase in Coulomb stress, which is consistent with previous studies [9] [14]. Although these aftershocks are outside the main fault plane, they are also potentially triggered by changes in stress caused by major earthquakes [14]. Meanwhile, the aftershocks in the northwest of the hypocenter were seen in the stress reduction zone. This discrepancy is thought to be due to the simplification of the fault plane model using only a single fault. This study has not yet accommodated a more complex multi-fault model as in the research of Socquet [6]. Based on Socquet
[6] who analyzed surface deformation using satellite data, the rupture of the Palu September 28, 2018 earthquake had a turn to the northwest after the hypocenter so that it is estimated that the area of concentration of aftershocks is still in the fault plane.

4. Conclusions
The Palu earthquake of 28 September 2018 which had a magnitude of Mw 7.48 was a left-lateral strike-slip fault with a strike parameter of 350 °, dip 67 °, and rake -9 °. Based on the results of the slip distribution, three asperity zones occurred during the Palu earthquake on September 28, 2018. One asperity zone is in the north of the fault plane model and two are in the southern part of the fault plane model. The greatest energy release zone is in the southern asperity zone with a maximum slip value of 1.65 meters. Compare to the other studies, this slip distribution model result is similar to various approaches although using minimum data. This study also confirms that the calculation of the maximum slip requires a surface rupture input. Some studies that use surface rupture data generate higher maximum slip than those that only use seismic data.

The results of the Coulomb spatial stress of the Palu 28 September 2018 earthquake showed an increase in the dominant stress in the northern and southern ends of the fault plane model. Also visible are several areas above the fault plane model that experience increased stress. The concentration of aftershocks in the area of increased stress in the outer part of the fault plane model is estimated to be due to the triggering of an earthquake by the main Palu earthquake on September 28, 2018. Meanwhile, for aftershocks that are still in part of the fault plane model, it is estimated that they are still a series of releases of main earthquake energy.

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