Supershear rupture of the 28 September 2018 Palu earthquake inferred from Empirical Green’s Function analysis

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Abstract. We deconvolved 22 teleseismic waveforms of Mw6.1 earthquake with Mw7.5 Palu earthquake to obtain Apparent Source Time Functions (ASTFs). Analysis of those ASTFs resulted rupture directivity, rupture length and rupture velocity of the earthquake. The main earthquake ruptured to N 227°E direction along 80 km away from the epicenter at an average speed of 4.5 km/s. The rupture velocity which is greater than local shear-wave velocity of 3.5 km/s indicated supershear characteristic of the earthquake. An ASTF of SNZO station was used to infer 1-D slip distribution of this earthquake. Based on this ASTF we calculated earthquake moment of 1.45 x 10²⁰ Nm that released in 30 seconds. The largest seismic moment released between 0-15 seconds and decreased before it stopped at 30 seconds. A Maximum slip of 8 meters occurred at a distance of 20 km to the south of the epicentre and decreased to around 4 meter near Palu City.

1. Introduction

Earthquake rupture speeds exceeding the shear-wave velocity have been reported for several shallow strike-slip earthquakes [1,2]. Palu earthquake was the one of supershear earthquake in the world that occur in Indonesia. This energetic earthquake have caused very strong ground motion as well as secondary hazard: landslide tsunami and severe liquefaction around Palu and Donggala, Central Sulawesi. Severe hazard caused by this earthquake should be related with their source rupture properties that was uncommon. This study is intended to understand source rupture properties of the Palu earthquake.

Source rupture properties of the earthquake commonly approached by seismic slip inversion method [3], seismic back projection [4] or slip inversion from GPS geodetic or remote sensing data [5]. In this study we used Empirical Green’s Function (EGF) deconvolution method [6]. By deconvolving the EGF seismogram with the main earthquake seismogram we obtained Apparent Source Time Functions (ASTFs) to infer rupture properties of Palu earthquake.

Rupture properties consist of rupture directivity, rupture velocity, and rupture length were important parameters to understand the physics an earthquake. Directivity of the rupture process is a parameter of the seismic source that plays an important role in generating of ground motions and thus in structural damage. Rupture velocity is an indicator that indicate whether the rupture were in slow, subshear, or supershear mode. Rupture length were also important parameter to calculate earthquake moment and the length of damaged area.

2. Data and Methods

We deconvolved the main earthquake with the Empirical Green’s Function (EGF) earthquake to obtain Apparent Source Time Function (ASTF). The main earthquake to be analyzed was Mw7.5
earthquake while the EGF earthquake was a foreshock of Mw6.1 located near the main earthquake. The EGF earthquake was chosen by considering their similar focal mechanism to make sure both have similar radiation pattern. Earthquake parameters of the main and EGF earthquake were listed in Table 1.

Table 1. Main and EGF earthquake parameters of BMKG which is used in this study.

| Earthquake | Magnitude (Mw) | M0 (Nm) | Depth (km) | Location (lat, lon) | ND1 (strike, dip, rake) | ND2 (strike, dip, rake) |
|------------|----------------|---------|------------|---------------------|------------------------|------------------------|
| Main       | 7.5            | 1.8 x 10^{20} | 15         | -0.22, 119.85       | 351°, 60°, -10°         | 87°, 81°, -148°        |
| EGF        | 6.1            | 9.7 x 10^{17} | 7          | -0.35, 119.83       | 3°, 80°, -3°            | 94°, 86°, -169°        |

Seismogram of the main and EGF earthquakes were derived from 22 broadband stations of the Global Seismic Network (GSN). We use teleseismic Rayleigh waves at epicentral distances between 55° and 125° for this analysis to get a clear Rayleigh phases without any other phases mixed as well as to avoid the effect of earthquakes centroid difference [7].

Seismograms has been windowed in the Rayleigh waves window, and seismograms initial time is based on the same phase velocity, corresponding to the arrival of Rayleigh waves at each station. Data has been bandpassed between 100 and 200 sec, and resampled to 1 second before deconvolution process were conducted.

We performed the deconvolution technique using waterlevel deconvolution approach [8] to obtain ASTFs of each seismic station. We used waterlevel parameter (alpha) of 0.01 to get a proper ASTFs signal. We measured the duration of the ASTFs for each station by calculating the duration from the point where the amplitude exceeds 15% of the maximum peak until the point where the amplitude drops below 15% of the maximum peak. We then fitted the ASTFs duration versus azimuth with the
calculated $\Delta t$ for different unilateral rupture scenarios in a grid-search procedure [9]. We calculated the rupture velocity using trial values between 3.0 - 5.0 km/s and changed the fault length from 50 to 150 km.

By using simple assumptions about the rupture, we can map the slip along the fault length using source time functions observed nearly perpendicular to the fault [10]. We assume that the rupture velocity $V_r$, was constant, and the dislocation time function is relatively uniform across the fault.

3. Results
The resulted ASTF from 22 teleseismic station are shown in Figure 2. The shortest ASTF duration occurred in CASY station with duration of 10 second and the longest one occurred in ADK station almost 80 second.

![Figure 2](image)

**Figure 2.** Apparent Source Time Functions (ASTF) from EGF deconvolution of teleseismic Rayleigh waves. The amplitude of ASTFs are normalized to their maximum value.

The plot of ASTF duration vs azimuth are shown in Figure 3. Five fault rupture scenario using $V_r$ 3.0, 3.5, 4.0, 4.5, and 5.0 km/second were used to calculate theoretical ASTF duration. By using this approach we concluded that the rupture propagated laterally to N227°E direction or the north-south direction. A fault scenario which showed a better fit compared to the other scenarios for rupture length of 80 km and rupture velocity 4.5 km/s. The resulted rupture length are comparable to empirical estimation of rupture dimension using scalling law [11]. According to the scalling law for Mw7.5 the rupture length were estimated to be 85 km. The rupture velocity which is greater than local shear wave velocity indicated supershear characteristic of the earthquake. Note that local shear wave velocity in the Crust 1.0 model ranges from 3.4 to 3.8 km/s at depths between 3 and 20 km [12], which cover the centroid depth of 15 km.
Figure 3. ASTF duration (black dots) fitted with calculated ASTF duration (colored curves) for the rupture scenario with different rupture velocity (Vr). The best fit scenario was for Vr = 4.5 km/s (black line), azimuth N 227°E, and fault length 80 km.

Since the rupture propagated to N227°E direction, the station that perpendicular to this direction have a special information on source rupture process. Therefore the ASTF of SNZO station (N137°E) was used to analyze Palu earthquake source rupture process. Based on this ASTF we calculated earthquake moment of $1.45 \times 10^{20}$ Nm that released in 30 seconds. Total earthquake moment calculated from this ASTF was a bit smaller than that calculated by moment tensor inversion in Table 1. A larger moment released between 0-15 seconds and decreased before it stopped at 30 seconds (Figure 4).

Figure 4. Moment rate function based on ASTF of SNZO station. Total earthquake moment are equal to the grey shaded area of $1.45 \times 10^{20}$ Nm.

We also calculated 1-D fault slip distribution using ASTF of the SNZO station. We use seismic moment of the EGF earthquake $M_0 = 9.7e+17$ Nm, assumed rigidity to be $\mu = 3 \times 10^3$ dyne/cm², and fault width is estimated to be 15 km based aftershock distributions. A 1-D slip distribution along the Palu fault are shown in Figure 5. The figure show that the earthquake ruptured up to 80 km from the epicentre to the south. A Maximum slip of 8 meters occurred at a distance of 20 km to the south of the epicentre and decreased to around 4 meter between 40 – 80 km to the south of the epicentre.
Figure 5. 1-D Slip distribution of the Palu Earthquake based on SNZO station. The earthquake ruptured up to 80 km from the epicentre to the south. The figure show maximum slip of 8 meters at a distance 20 km from the epicenter.

Unfortunately a 1-D slip distribution image resulted by this study did not cover slip distribution to dip direction. Yet this method was enough for a first degree estimation of earthquake source rupture properties. Severe damage and widespread liquefaction showed that the rupture should be shallow around Palu City. This is also supported by the direction of rupture that leads to S-SW (N227°E) while the fault plane is directed towards S-SE (N351°E). This means rupture propagates from a deep point in the north (15 km depth) to a more shallow point in the south (below 5 km depth). More over the propagation speed of rupture which is exceed the local shear velocity made additional effect to strong ground motion around the Palu city.

4. Concluding Remarks
The Empirical Green’s Function method has revealed source rupture properties of the Palu earthquake. The earthquake ruptured to N 227°E direction along 80 km away from the epicentre at an average speed of 4.5 km/s. The rupture velocity which is greater than local shear-wave velocity indicated super shear characteristic of the earthquake. The rupture propagation at a shallow depth at supershear velocity within weakly consolidated alluvial sediments in the basin resulted in widespread liquefaction and severe damage from shock-wave-induced ground shaking.

Based on an ASTF located perpendicular to rupture direction we calculated earthquake moment of $1.45 \times 10^{20}$ Nm that released in 30 seconds which is comparable to earthquake moment that was derived from moment tensor inversion. The largest seismic moment released between 0-15 seconds and decreased before it stopped at 30 seconds. This study were also imaged a 1-D slip distribution along 80 km length of the fault length. A Maximum slip of 8 meters occurred at a distance of 20 km to the south of the epicentre and decreased to around 4 meter between 40 – 80 km to the south of the epicentre or near Palu city.
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