Rupture directivity and fault plane determination from analysis of rupture duration using broadband $P$-waves of the September 2018 $M_w$ 7.5 Palu, Indonesia earthquake

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Abstract. The aim of this study is to determine earthquake rupture directivity and fault plane of the 28 September 2018 $M_w$ 7.5 event in Palu, Indonesia. The data used in the current study were all acquired from broadband seismograms recorded by a network of 56 seismic stations. The method included analysis of rupture duration, where $T_{dur}$ was calculated using the vertical component of $P$-waveforms downloaded from IRIS site at http://ds.iris.edu/wilber3/find_event. For all stations involved in the $T_{dur}$ calculations, the largest distance between the epicenter and the corresponding station was estimated to be 40° from the azimuth station. The direction of the rupture indicated fault plane geometry of the source. The rupture directivity was found to be at azimuth 179°, in good agreement with the Palu Koro Fault azimuth. The finding implies that the direction of the earthquake rupture passed below the sea surface of Palu Bay, which could be the main source of the tsunami.

Keywords: rupture directivity; rupture duration; fault plane; tsunami source

1. Introduction
Tsunamis are classified into propagating surface waves in the ocean due to the release of endogenous energy from inside the Earth through mechanisms of tectonic earthquakes, submarine landslides, or volcanic eruptions [1]. It is widely known that large tsunamis associated with submarine strike-slip earthquakes are very rare but are possible to occur. Oceanic strike-slip faults may in common induce small tsunamis owing to the lack of huge amounts of potential energy release for vertical deformation of the seafloor [2, 3].

However, Palu-Koro faulting zone crossing most regions in Sulawesi Island is a strike-slip fault in a complex tectonic region, able to allow adequate vertical subsurface deformation. This strike-slip system may include complicated fault geometries, such as non-vertical faults and arches. This can lead to complex fracture dynamics producing a variety of pattern shifts during fractures, which can trigger tsunamis [4, 5]. The 28 September 2018 tectonic earthquake with a magnitude of $M_w$ 7.5 occurring around the Palu-Koro was speculated to be the cause for a submarine landslide. In turn, this geological
phenomenon was suspected to generate devastating tsunamis in Palu and Donggala, the most severe disaster among three simultaneous catastrophes (earthquake, tsunami, liquefaction) in the regions.

As an undersea earthquake may potentially induce a tsunami wave, studies focusing upon fault or source parameters and characterizing tsunamis have become important. These parameters include rupture directivity and fault plane. Research upon rupture directivity was carried out by [6], providing a way to calculate the direction of the rupture using short-period broadband signals from two pairs of seismic stations. If the duration of the signal directed by particular station is smaller than that recorded by the pairing station, then it can be interpreted that the direction of the rupture goes to that station.

Current research [7] conducted investigation into the use of tsunami parameters for tsunami early warning application during the first 4 minutes after the main shock. The results demonstrated that of 300 Indonesian earthquakes none of which produced a false warning. Rupture duration \( T_{\text{dur}} \) is useful to test whether the primary source of the tsunami on 28 September 2018 is caused by seismic energy or landslides. In addition, there is also a study conducted by [8] reporting that if an event has a mainly unilateral rupture, the pulse width observed on seismograms will vary depending on the angle between the rupture directivity and the takeoff vector to the station.

In this study, we determine rupture directivity and fault plane geometry of the 28 September 2018 earthquake using analysis of rupture duration. Furthermore, the determination of the rupture directivity and the fault plane geometry of the source was confirmed by travel time data of tsunami inundation recorded by local tide gauges around Palu Bay.

### 2. Method

Analysis of earthquake rupture duration starts from its basic definition as follows. It is the difference between the time it takes for a rupture to move along its length and the amount of time completed for the wave to propagate from the source to a particular point. This definition is mathematically written as follows,

\[
T_{\text{dur}} = \frac{L}{V_r} - \frac{L}{V_p} \cos \theta
\]

(1)

where \( T_{\text{dur}} \) is, by definition, the duration of the rupture, \( L \) is the length of the rupture, \( V_r \) is the speed of the rupture, \( V_p \) is the wave phase speed, and \( \theta \) is the angle between the station and the fault azimuth. The directivity of the rupture can be indirectly determined from Eq. (1). In particular, when \( \theta \) is zero \( T_{\text{dur}} \) takes a minimum value [8].

In practice, rupture duration \( T_{\text{dur}} \) was estimated in Eq. (2) from determination of travel time delays of \( P \)-wave arrivals for 90% (\( T^{0.9} \)), 80% (\( T^{0.8} \)), 50% (\( T^{0.5} \)), and 20% (\( T^{0.2} \)) values of the corresponding maximum [9] according to relations as follows,

\[
T_{\text{dur}} = (1 - w)T^{0.9} + wT^{0.2}
\]

\[
w = [(T^{0.2} + T^{0.5})/2 - 20]/40s
\]

(2)

(3)

where \( T^{0.9} < T_{\text{dur}} < T^{0.2} \). For local earthquakes, high-frequency analysis of the vertical component of broadband seismograms were applied whereas regional and teleseismic events were bandpass-filtered at frequency ranges of 1-5 Hz.

Detailed steps of algorithm used in \( T_{\text{dur}} \) estimates include (1) preparing raw data from the vertical component of broadband seismogram in a SAC format; (2) applying 4-poles and the 1-5 Hz Butterworth bandpass filter to obtain the high-frequency, vertical component of seismic velocity for each station used; (3) converting the high-frequency, vertical-velocity seismogram into velocity-squared envelopes to acquire root-mean-square (rms) amplitudes; (4) picking arrival times of \( P \)-waves automatically at the high-frequency, vertical-velocity seismogram; (5) determining time delays with respect to the \( P \)-wave arrivals for 90% (\( T^{0.9} \)), 80% (\( T^{0.8} \)), 50% (\( T^{0.5} \)), and 20% (\( T^{0.2} \)) measured from the maximum value observed; (6) calculating rupture duration \( T_{\text{dur}} \) for each station using both Eqs. (2) and (3) where \( 0 \leq w \leq 1 \) was applied; and (7) plotting \( T^{0.9} \), \( T^{0.8} \), \( T^{0.5} \), \( T^{0.2} \) and \( T_{\text{dur}} \) at the high-frequency seismogram.
To determine $T_{\text{dur}}$, data were downloaded from IRIS site at http://ds.iris.edu/wilber3/find_event. The distance between the epicenter and the farthest station was measured at 40° from the azimuth station from 0° to 360°. A total of 56 seismic stations were then used for data collection in the form of vertical component of $P$-waves from broadband seismogram.

3. Result and Discussion

To estimate the direction of the earthquake rupture on 28 September 2018, data were collected from 56 seismic stations having the closest azimuth whose value is 1.82° to the station that has the furthest azimuth value of 356.83°, from the 56 stations each calculated value of rupture duration $T_{\text{dur}}$.

![Figure 1](image.png)

**Figure 1.** Simple graph showing relationship between rupture duration $T_{\text{dur}}$ with azimuth seismic stations that record broadband seismic waveforms from the source.

The blue dots in Fig. 1 are rupture duration data given by azimuth positions of all stations involved. The red curved line is a corresponding fitting curve for the data. It is clear from Fig. 1 that 2 wave crests and 1 wave troughs appear, meaning that a high average $T_{\text{dur}}$ is found at azimuth 1.82° to 6.89° and 255.84° to 356.83°, whereas a low average $T_{\text{dur}}$ is observed at azimuth ranging from 140.33° to 193.28°. It is also clearly observed that the lowest value of $T_{\text{dur}}$ is calculated to be 10.8 s at azimuth 179°. This smallest value of $T_{\text{dur}}$ is interpreted as the direction of the rupture [6, 8, 10].

If the duration of the rupture of the signal recorded by the station is smaller than the signal recorded by the other station, then it can be interpreted that the direction of the rupture goes to that station. In the case of the 28 September 2018, the direction of the rupture moved in the direction of the azimuth 179°, which means that it almost coincides with the Palu-Koro Fault zone (Fig. 1b). Thus, the direction of the rupture passes through the underwater segment of the Palu Bay, where according to [11] there are maximum wave heights at two gauge stations, namely Pantoloan (within Palu Bay) and Mamuju (outside Palu Bay), measured to be 380 cm and 24 cm, respectively. This is consistent with the work of [12] confirming that the tsunami induced by the 28 September 2018 event was largely localized within Palu Bay. Thus, estimate of rupture direction and its implication in this study are in good agreement with previous work of [7] and [12], clarifying a seismic earthquake for the event.

4. Conclusions
Based on the rupture directivity estimate, where the rupture moves to the direction of azimuth of 179°, it can be concluded that the rupture passes under Palu Bay corresponding to a maximum tsunami wave height recorded. The result of the rupture direction was confirmed by field data of tsunami inundation, local bathymetry and topography.

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