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The M6.3 Yogyakarta Earthquake of May 27, 2006 Source Mechanism Using Teleseismic Body Wave Inversion

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ABSTRACT:Teleseismicbody wave inversion has been used to determine the source parameters of the Yogyakarta earthquake on May 27, 2006. Until now, it is suspected that the Yogyakarta earthquake was caused by the Opak's fault with a strike-slip fault mechanism. However, some field evidence and previous research indicate that the type of fault caused by the earthquake is not a pure strike-slip. This study aims to prove andt o determine the characteristics of the Yogyakarta earthquake using teleseismic body wave inversion. In this study, we use the vertical (Z) component of teleseismicbody wave data from the IRIS data repository. The distance between the station and the source used in this study is about 30°– 90°.For modelling purposes, we used a point source and finite fault source. The moment tensor inversion for the point source mechanism find the fault parameters have a strike 232°, dip 86°, and rake -13°, withaseismic moment of 0.581E + 19 Nm (equivalent with Mw = 6.3, moment magnitude). The depth of the source is 12 km, with the variance of the observed and synthetic wave form is 0.36.The finite fault mechanism gives a parameter for the source with a strike216°,dip 54°,andrake-31° having aseismic moment of 0.246E+20Nm and the source depth of 12 km. The variance was 0.26. The type of fault obtained from this modeling is a normal fault, with a source duration of about 60seconds. The asperity obtained from this inversion has three asperities zones, located in the north, south, and the dip direction of the hypocenter. The maximum slip occurs at the third asperities, which is in the direction of the dip. The maximum energy occurs in the dip direction so that the dominant direction of movement of the fault is a dip. From this study it is concluded that the main cause of the Yogyakarta earthquake was not the Opak fault,but a fault on the east side of the Opak's river fault.

KEYWORDS: Asperity, finite fault source, normal fault, point source, strike-slip, teleseismic.

I.INTRODUCTION

On early morning May 27, 2006, there was an earthquake with a magnitude of 6.3 centered at the South East of the Yogyakarta City, Indonesia. The earthquake that occurred that morning destroyed the infrastructure of the Special Region of Yogyakarta (DIY) and parts of Central Java Province. This earthquake was recorded as the deadliest shallow ground-centred earthquake and killed more than 5,900 people. Kawazoe and Koketsu (2010) conducted a study on the rupture process of the Yogyakarta earthquake source using near field body wave inversion [8]. The velocity model used to calculate the Green's function resulted from the Crust 2.0 [20]. This study obtained two asperities zones which are located close to the hypocenter. Kawazoe and Kotetsu concluded that the Yogyakarta earthquake generated from two different sub-events. The same results were obtained by [11]. Yagi analysed the Yogyakarta earthquake source rupture process using near-field data. The results show that the Yogyakarta earthquake has two asperities zones which are located to the south and north of the hypocenter, therefore, they concluded that the earthquake is resulted from avery complex tectonic condition. To the East of the Opak fault, it is found about 32 faults identified through a Structure from Motion (SfM) analysis and field analysis [14]. One of the evidences of the fault that it was a normal fault with the largest offset, which is about 2.39 m. This condition is reinforced by the results of the aftershock distribution that has been relocated. The results show that the distribution of the aftershock plotted to the surface has various specific patterns. The Yogyakarta earthquake activated minor faults on the eastern side of the Opak fault [1,19]. It was still being debated whether the Yogyakarta earthquake originated from the Opak's river fault or other minor faults in the

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surrounding. The same research conducted by [16], [2], [18] using the aftershock distribution analysis. The result was the aftershock distribution spread to the east of the Opak fault of about 10-15 km. Therefore they believe that the Yogyakarta earthquake did not originate from the Opak fault, but came from a fault that has not been clearly identified until now [19].

From geological study,the Opak Fault is located between the central and eastern parts, while the central and western parts are bounded by the Progo fault. The geological structure of the central part of Yogyakarta is known as a graben structure with a deep basement of Middle Miocene rock formation. The issued epicenter location of the Yogyakarta earthquake was to the east of the Baturagung slope, South-East of Yogyakarta. Liliane et al., 2012 stated that the Opak fault has a normal type of fault that traverses north-south along the Opak river [9,12]. Based on core data, several normal faults were also found across the city of Yogyakarta in an east-west direction [4]. Kali Ngalang and Kali Widoro are evidence of the Opak fault turning into normal faults after the Pliocene [15]. This study aims to model the Yogyakarta earthquake source mechanism to identify in detail how the Yogyakarta earthquake occurred.

The method used in this study is teleseismic body wave inversion. The source mechanism is obtained to obtain source characteristic information through seismograms. The source mechanism is obtained to determine the fault plane of the source rupture process that occurs. The difference between the research conducted by Kawazoe and Koketsu[8] with this study is that the data used in this study has a better station configuration. The velocity model used to calculate the Green function in this study is Jeffrey's Bullen (J.B.) [5] that supposed to get a better results than previous studies.

II. DATA AND METHOD

This study used the teleseismic body wave inversion method developed by [6]. This inversion program is to obtain the focal mechanism through a moment tensor inversion and source rupture process. The results obtained from the moment tensor inversion calculation in the form of magnification parameters are used for input to obtain the source rupture process in the form of slip distribution in a fault plane.The data used in this research is available from the Incorporated Research Institutions for Seismology (IRIS) web page. The distance between the source and the station is distributed between 30^{o}– 90^{o}. The number of stations used in this study is 21 stations. The station distribution sed in this study can be seen in Figure 1.

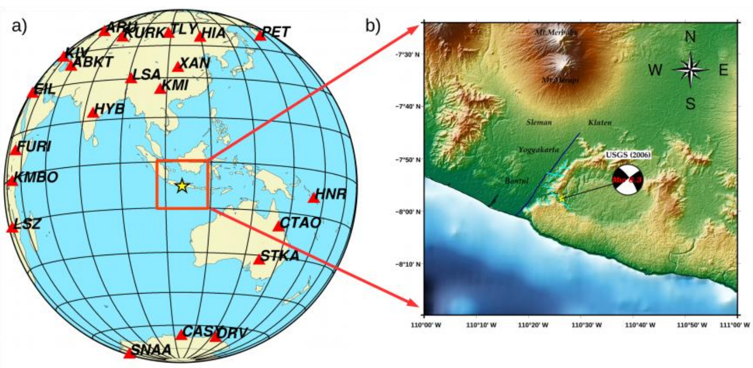

Fig 1: Configuration of station distribution and location of the research area. a) Configuration of the station which is given the red triangle symbol. The yellow star in the red box is the epicentre of the Yogyakarta earthquake mainshock. b) The location of the study area, the dark blue line is the Opak fault, while the light blue lines are minor faults around the fault. The black and white focal ball is the focus mechanism for the Yogyakarta earthquake issued by the United States Geological Survey (USGS).

Previous information about the position of the earthquake source is from UGSG and used as the input data for the inversion program. The earthquake epicentre was first relocated using seiscomp3 software from GeoforschungsZentrum (GFZ Potsdam). The use of teleseismic body wave seismogram is to reduce the influence of local geological effects as the high frequency will be weakened by the medium that the waveform passes throughthe station. The advantage of using teleseismic body waves is their low-frequency signal, making it easier to interpret the

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source mechanism [6]. Teleseismic waveform data used in this study is only the vertical component (Z). An example of the raw data used in this study can be seen in Figure 2.

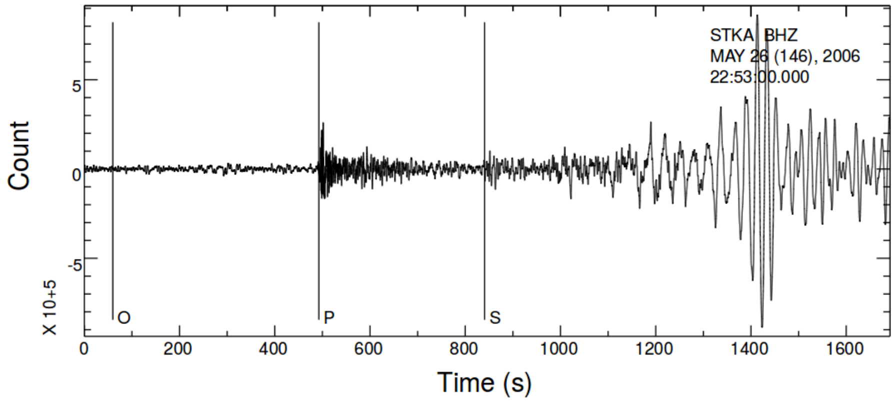

Fig 2: Example of teleseismic body wave at station KMI (See Fig. 1). The O, P, and S notations on the vertical line are the origin time, arrival time of the P wave, and arrival time of the S wave, respectively.

The next data processing stage after the data is prepared is to determine the frequency used for filtering. The frequency band used in this study were 0.01 - 0.1 Hz. The calculation of the Green's function is calculated using Jeffrey's Bullen (J.B.) velocity model. The source time function used in the moment tensor calculation is a simple triangle function. The source time function is selected to estimate the rupture time at the source starting from the initial rupture break. The results of this calculation will obtain a synthetic waveform that is compared with the observed waveform. The comparison value between synthetic waveform and observation waveform is in the form of variance value. The smallest variance is the best result from the inversion calculation. These results produce a source mechanism that is considered a point source. The source elements at each grid point are represented as synthetic waveforms. The synthetic waveform equation that represents the moment tensor at each point is:

$$y_j(t;p) = \sum_{n=1}^{n_b} a_n w_{jm}(t;p) \qquad 1$$

where $y_j(t;p)$ is the synthetic waveform at the time function (t) at the station (j). The Green's function is denoted by $w_{jm}(t;p)$, while (p) shows the onset time and position of the slip distribution. Coefficients a_n and p parameters determined by the least square criterion [7]:

$$\nabla = \sum_{j=1}^{n_s} \int \left[x_j(t) - \sum_{n=1}^{n_b} a_n w_{jn}(t;p)\right]^2 dt = min \qquad 2$$

and with the grids search method for p to maximise the function of the correlation between the observed and synthetic waveforms

$$\Psi(p) = \frac{\sum_{j=1}^{n_s} \int [x_j(t) y_j(t;p)] dt}{\sum_{j=1}^{n_s} \int [x_j(t)]^2 dt} \qquad 3$$

where n_s is the number of seismograms used in[7].

The process of determining the slip distribution in the fault plane is obtained from the inversion results with the assumption that the fault plane is a grid. Each grid point has its own slip time. Rupture time starts from the first point of the initial break. The fault plane at each sub faults point has a slip distribution spatially and temporally. The slip vector direction is represented as the slip direction. The equation describing slip distribution in a fault plane is shown in equation 4.

$$\nabla \dot{u}_i(x,t) = \sum_{j=1}^{j} p^j \hat{u}_t^j(t) \phi^j(x) f^j(x,t) \qquad 4$$

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where $\hat{u}_t^j(t)$ is a unit vector that is representing the slip direction. The slip direction is a function of time and always parallel to the fault plane. The spatial basis function is denoted$\phi^j(x)$ and \$ $f^j(x,t)$ is the slip time function. An integral is carried out in equation 4 for $t = \infty$ so that the final result of the slip distribution is formulated as:

$$\nabla \dot{u}_i(x,t) = \sum_{j=1}^{j} p^j \hat{u}_t^j \phi^j(x) \quad 5$$

The determination of the area of the fault is based on the Well and Coppersmith equation [17]. The determination of the fault area greatly determines the results of the slip and asperity distribution. Well and Coppersmith divided the empirical relationship equation based on the type of fault, namely strike-slip, reverse fault, and normal fault.

III. RESULT AND DISCUSSION

Before we determined the source mechanism of the Yogyakarta earthquake, first, we must determine the source mechanism and location of the sub-events, and with the constraint, all sub-events have the same source time function. The source time function is represented as a simple triangular function. The determination of the source mechanism and location of the sub-events in the $(\tau - l)$ diagrams are based on equations (2) and (3). First, all of the sub-events are placed at points on the grid$(\tau - l)$. After being calculated based on equation (3), a correlation between $(\tau - l)$ is obtained, is the resulting mechanism which is then plotted at the grid points in the $(\tau - l)$ diagram. An image showing the relationship between $(\tau - l)$ at the grid points in the plane can be seen in Figure 3.

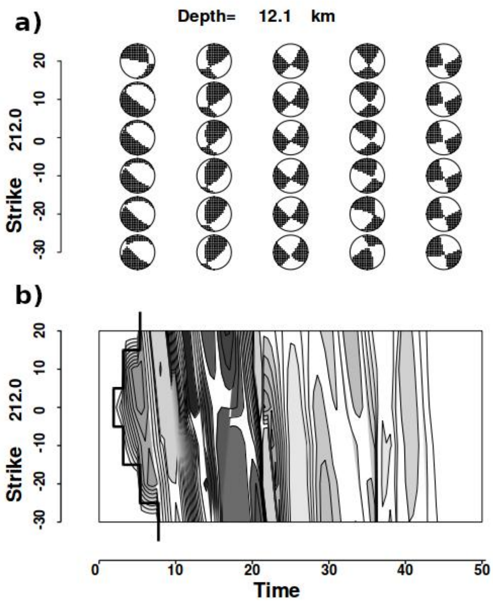

Figure 3a shows a contour map depicting the τ correlation function in the $(\tau - l)$ plane on the basis of the double-couple mechanism. The contour pattern on the stairs is the front of the rupture with a velocity of 4 km/s. We assume that there are no sub-events located in front of the rupture front. Figure 3b shows the best fit double-couple placed at grid points 20 km in space and 30 seconds in time. The final results are shown in Figure 4.

The results of this study are divided into two, first, the result of moment tensor inversion and the source rupture process in the form of slip distribution in the fault plane: and second the earthquake epicentre and depth information based on the results of the mainshock relocation. The results of the moment tensor inversion can be seen as in Figure 4 and Figure 5.

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A. Point Source

Figure 4 shows the moment tensor inversion at the point source. The resulting parameter of the Yogyakarta earthquake on May 27, 2006, is the seismic moment of 0.581E + 19 Nm or equivalent to Moment Magnitude, Mw = 6.3. The fault plane parameters obtained were strike 212^{o}, dip 32.5^{o}, and rake -39^{o}, with a source depth of 12.5 km. The type of fault resulting from this inversion is a normal fault. This type of fault has a different result than that issued by the USGS. The fault plane parameters issued by the USGS are strike 232^{o}, dip 86^{o}, and rake -13^{o}. The comparison of the observed waveform and the inversion synthetic waveform can be seen in Figure 5.

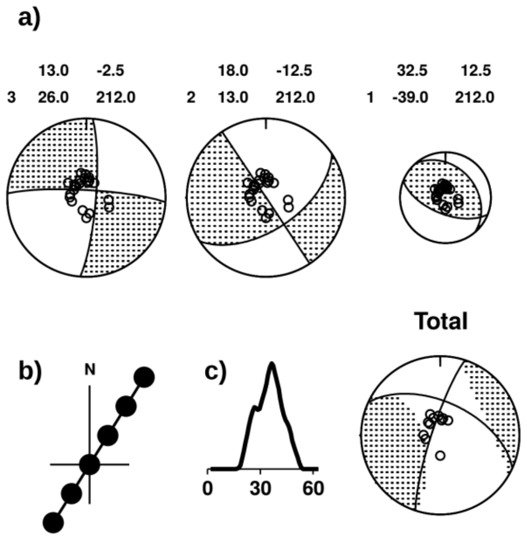

Fig 4: Mainshock moment tensor inversion results. a) The focal ball resulting from the inversion at several different depths, the focal beachball resulting from this inversion is a total focal ball. b) Strike the fault plane calculated from the North direction. c) Functions of the moment rate and source duration.

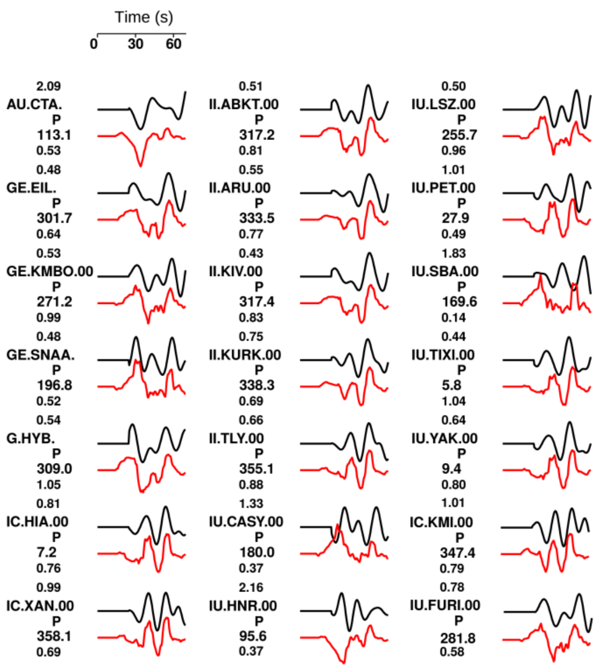

Fig 5: Comparison of the observed waveform (black colour) and synthetic waveform (red colour) from the point source inversion result, the waveform length is 70 seconds. The numbers next to each waveform are the station name and the maximum amplitude of each waveform.

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The comparison of observed waveforms and synthetic waveforms has the smallest variance value from several results, namely with a value of 0.36. The moment tensor inversion calculation is very much determined from the velocity model, the input hypocentre parameters, and the quality of the waveform data.

The fault plane area is determined from Well and Coppersmith calculations and seen from the aftershock distribution. The length and width of the fault area used in this study are 89 km strike length and 37 km dip width. The fault plane area is divided into subfaults. The fault area is divided into 13 × 6 subfaults, with the subfault plane dimensions 7.5 × 7.5 km. Selection of the number of subfaults strikes and dips based on trial and error to get the correct fault plane, based on the comparison of the observed and synthetic waveform from the variance value. The results of teleseismic body wave inversion calculations with a finite fault source can be seen in Figure 6 and Figure 7.

B. Finite Fault Source

The coseismic slip distribution of the inversion of the teleseismic body wave shown in Figure 5 is the best result from the iteration. The resulting earthquake source parameters were strike 216^o, dip 54^o, and rake -31^o. The variance value of this inversion result has a smaller value than the point source inversion. The seismic moment resulting from the inversion is 0.246E + 20 Nm or its equivalent value with Mw = 6.3. The source depth obtained from the inversion is 12 km. The fault type is a normal fault with a source duration of 60 seconds. Teleseismic body wave inversion shows only the spatial slip distribution. The slip distribution is projected orthogonally onto the surface plane. The results of the inversion show that the Yogyakarta earthquake had scattered asperities along the fault plane. Based on the results of the inversion in Figure 5, it appears to have three asperities zones (weak zones). The Asperity is to the north and south of the hypocenter, and in the direction of the dip. Hypocenter or first initial break does not occur in the asperity zone. The greatest energy of released earthquakes is not at the initial break, but in the maximum asperity zone [10]. The maximum asperity zone is in the strike direction of the hypocenter. The direction of the slip vector is seen almost aligned with the fault plane to the north of the hypocenter. The resulting slip movement direction includes bilateral rupture, which is moving from the south of the hypocenter, then moving north and stopping in the dip direction [3]. The greatest maximum energy is seen above the fracture plane of the hypocenter, which is 0.28 m, indicating strong shaking to occur on the surface. [16] have proven that the zone affected by the Yogyakarta earthquake that is most severely located to the west of the Opak fault. To the south of the hypocenter, the slip vector shows the direction of the dip and has a high slip movement. The rock structures that are above the hypocenter and in the northern part have a weaker structure than those in the middle of the fault plane.

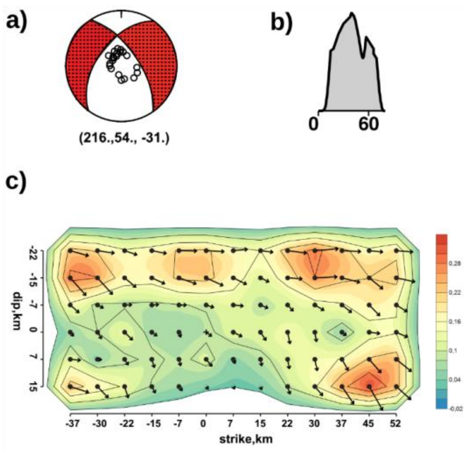

Fig 6: The distribution of the coseismic slip for the Yogyakarta earthquake on May 27, 2006, based on the inversion of teleseismic body waves. a) Beach ball. b) Functions of the moment rate and source duration. c) The distribution of the slip in the fault plane, the arrow is the direction of the slip vector, the yellow star is the hypocenter of the earthquake.

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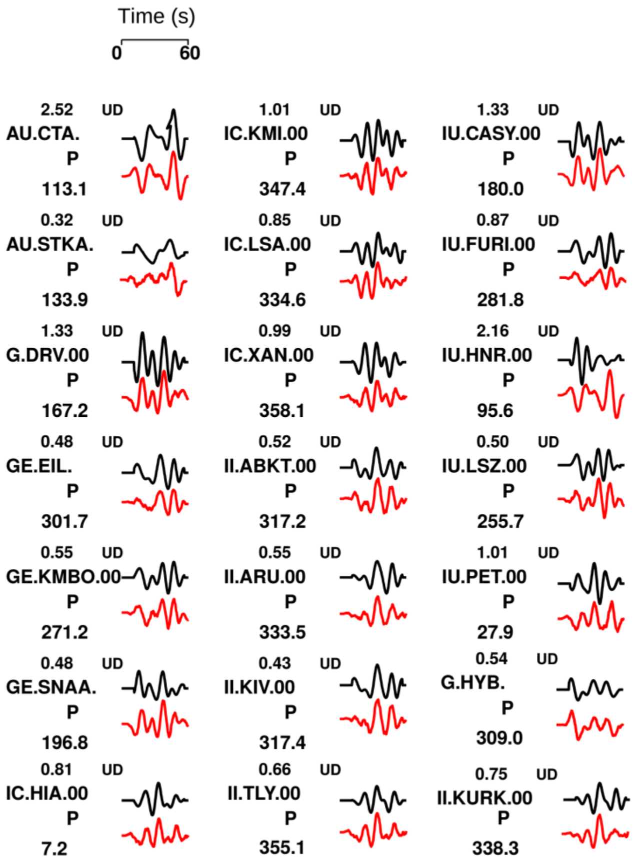

Fig 7: Comparison of the observed waveform (black colour) and synthetic waveform (red colour) from the inversion result with the finite fault source, the waveform length is 70 seconds. The numbers next to each waveform are the station name and the maximum amplitude of each waveform.

Validation of the inversion results in the form of source mechanism parameters to obtain finite fault parameters due to the Yogyakarta earthquake can be seen from the fitting of the observation waveform with synthetic waveforms. The comparison between the observed waveform and the synthetic waveform can be seen in Figure 7.
The variance value of the ratio between the observed waveform and the synthetic waveform is 0.26. The variance value resulting from this inversion is quite small, and it can be seen from Figure 7 that it has almost the same shape between the observed waveform and the synthetic waveform. So that this result is the best result of inversion, and illustrates the results of the source rupture process modelling from this inversion result quite well.

IV. CONCLUSSION AND FUTURE WORK

From the results of the teleseismic body wave inversion with a point and a finite fault source, the Yogyakarta earthquake on May 27, 2006, had a normal fault type. The source as a point obtained fault parameters that are almost the same as the source as the finite fault. The results of the inversion of the source as a point obtained the fault parameters with strike of 32^{o}, dip 86^{o}, and rake -13^{o}, with a seismic moment of 0.5 1E + 19 Nm (equivalent to Mw = 6.3) and a source depth of 12 km. The variance based on the comparison of the observed and synthetic waveforms is 0.36. While the results of the source inversion with a finite fault model resulting a strike of 216^{o}, dip 54^{o}, and rake -31^{o} and the seismic moment of 0.246E+20 Nm (equivalent to Mw = 6.3), with a source depth of 12 km. The variance was 0.26. The slip distribution resulting from this inversion has three asperities zones. The asperity zone is in the north, south and dip direction from the hypocenter. The maximum slip is in the third asperity, namely in the dip direction. The other two parameter are in the strike direction causing energy to accumulate at the top, causing a strong vibration on the

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Earth's surface. The distribution of the damage was also seen to be in the west of the Opak fault, proving that the energy released reached the surface. To interpret a source in the form of a finite fault, it is very suitable to use teleseismic body wave data because it has a low frequency content, but it is not recommended for interpreting the characteristics of a point source. The data needed and suitable for interpreting the source as a point source is a data close to the source. Further suggestion is to use a combination of near-field data and teleseismic body wave data for a more complete analysis.

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CONFLICT OF INTEREST: The authors declare no conflict of interest.

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