The waveform inversion of mainshock and aftershock data of the 2006 M6.3 Yogyakarta earthquake

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Abstract

This research was examines the focal mechanism associated with the mainshock and three aftershocks of the magnitude 6.3 Yogyakarta earthquake on May 27, 2006. This study, therefore, aims to provide a clearer answer on the source mechanism of the earthquake, which has been debated. Data were obtained from the mainshock and aftershock sources, on June 8, 9, and 16, 2006. The mainshock and three aftershocks were used to conduct waveform inversion by calculating the Green's functions through the extended reflectivity method of the near-field and the far-field signal component. The mainshock's focal mechanism has a strike, dip, and range angle of 243.40° , 77.50° , and -28.30° , respectively.

Furthermore, the mainshock is not a pure strike-slip as previously hypothesized. The focal mechanism for the aftershock earthquake source on Mw 4.4, obtained on June 8, had a strike, dip, rake, and variance of 192.20° , 29.70° , -48.30° and 0.22, respectively. This aftershock had a different segment from the mainshock event and those obtained on the 9 and 16 of June with the same type of faulting as the mainshock with variance values of 0.195 and 0.243. These results showed that the mainshock of May 27, 2006, activated the aftershock on June 8, with a different type of fault.

Keywords: mainshock; aftershock; inversion; moment tensor; extended reflectivity; near-field

1. Introduction

In the early hours of May 27, 2006, at approximately 05.54 local times, an earthquake struck the city of Yogyakarta. Based on the Agency for Meteorology, Climatology, and Geophysics of Indonesia (BMKG) stated that the earthquake had a magnitude of $M_w=6.3$, centered at 8.030E and 110.320 S, with a depth of 11.87 km at the southeast of the city of Yogyakarta as shown in figure 1. It was declared the deadliest shallow earthquake in Indonesia (BMKG, 2006). This earthquake destroyed most of the infrastructure in the region of Yogyakarta and Klaten, Central Java Province. The reports by the National Development Planning Agency (BAPPENAS) in cooperation with the Yogyakarta Special Region Government (DIY), Central Java Provincial Government, and international partners in 2006 stated that the Yogyakarta earthquake killed more than 5000 people, with 38,000 injured, 423,000 evacuated, and 156,000 buildings destroyed (Bappenas, 2006).

Earthquake focal mechanism is used to obtain valuable information on the source parameters such as magnitude, fault orientation, and stress field. This instrument varies from several agencies such as Indonesia Meteorology Climatology and Geophysics (BMKG, 2006), United States Geological Survey (USGS, 2006), National Earthquake Information Center (NEIC, 2006), Kandilli Observatory and Earthquake Research Institute (KOERI, 2006), European Mediterranean Seismological Center (EMSC, 2006), and Institute de Physique du Globe de Paris (IPGP, 2006).

Debates on the source of the Yogyakarta earthquake is still in progress. Most researchers believe that the earthquake did not originate from the geological fault along the Opak's river, because the aftershock was distributed 10-15 km on the east side (Walter et al., 2007, Wulandari et al., 2018). Some researchers also believe that the earthquake has

reactivated some minor faults on the east side of the Opak fault (Budiman et al, 2019, Irham et al, 2014). Saputra et al. (2018), stated that the Opak river consists of 56 faults with a maximum displacement of 2.93 m. Meanwhile, the results obtained by Nakano et al., (2006) also had a different focal mechanism, as shown in figure 1. According to studies, several factors influence this difference, such as the lack of a seismometer network of BMKG's, which existed before 2006. This led to differences in the level of location accuracy, source depth, and fault orientation (Ma and Eaton, 2011, Saunders et al, 2016).

Figure 1: The focal mechanism from several agencies. The red star depicts the location of the epicentre. The black and white beachball colour depicts the mechanism of focus, while the purple dotted line is the Opak fault, which is located to the east.

The parameters of the earthquake sources from various institutions are shown in Table 1. Majority concluded that the epicenter is on the east side of the Opak fault which also indicates consistency by the aftershock distribution (Walter et al., 2008).

70

71 Table 1: Parameters of Yogyakarta earthquake from various agencies (Elnashai et al.,
72 2006)

Agencies	Event Time (WIB)	Depth (km)	Magnitude			Epicentre	
			M _b	M _s	M _w	Latitude (S)	Longitude (E)
BMKG	5:54:01	11.87	5,9			-8.03	110.32
USGS	5:53:38	12.5			6.3	-7.96	110.44
Global CMT	5:54:05	21.7	6.0	6.3	6.4	-8.03	110.54
NEIC	5:54:01	28			6.5	-8.00	110.28
IPGP	5:53:52	15			6.6	-8.00	11.3
KOERI	5:53:52	20			6.2	-8.00	110.8
EMSC	5:53:58	10			6.4	-8.04	110.39

73

74 Kawazoe and Koketsu, (2010) determined the focal mechanism of the Yogyakarta
75 earthquake using the waveform inversion method. They compared the inversion with the
76 observed data using the CRUST2.0 velocity model (Bassin et al., 2000) as well as the
77 left-lateral strike-slip and reverse dip-slip. Nakano et al. (2006) examined that the focal
78 mechanism dominated by strike-slip. Similar results were obtained by Abidin et al., 2009
79 through the Global Positioning System (GPS) data. The result showed that the horizontal
80 coseismic displacement took place around Bantul and Yogyakarta in the south and
81 southwest direction, with the focal mechanism in the form of left-lateral strike. Tsuji et al.
82 (2009) stated that coseismic displacement and strike-slip along the fault plane also
83 reverses on the east side, which experiences upward displacement. Several studies show
84 that there are different opinions regarding the source mechanism of the Yogyakarta
85 earthquake.

86 Therefore, the paper aims to ascertain the type of faulting based on the main event and
87 three aftershocks with magnitudes $M_w \geq 4$. It further characterizes the relationship
88 between the mainshock and aftershock. This research was conducted through the

calculation of moment tensor inversion based on the matching between observed and synthetic waveform.

2. Data and Methods

Data associated with the waveform were obtained from the Incorporated Research agencies for Seismology (IRIS) i.e. XMIS, SBJI, TNG, JCJI, BJI, KMMI, and DNP stations. These data were freely downloaded through the IRIS data services website (<http://ds.iris.edu>), with the distribution of IRIS and BMKG networks for all stations shown in Figure 2. The waveform data for the aftershock were obtained from the non-permanent seismometer installed by Universitas Gadjah Mada in cooperation with the GFZ, Potsdam, Germany. It consists of ten stations with three component sensors, as shown in figure 3. The experiment found approximately 524 aftershock events that are relocated and plotted to visualize the spatial distribution, as shown in Figure 2.

This study, processed the largest magnitude aftershock ($M_w \geq 4$) from M_w 4.4 June 8, M_w 4.1 June 9, and M_w 4.0 June 16, 2006. Analysis of the three aftershocks focal mechanism is used to determine the consistency of the fault direction caused by the mainshock.

Figure 2: BMKG networks consists of six stations, namely SBJI, TNG, JCJI, BJI, KMMI, and DNP. Meanwhile, the IRIS networks use XMIS stations. The blue box is the

distribution location of the GFZ non-permanent station (red inverted triangles) as well as the mainshock and aftershock epicentre locations. The yellow star in the blue box depicts the epicentre of the Yogyakarta earthquake mainshock. The black and white colour beachball is the main focal mechanism of the USGS.

105

106 The waveform is corrected from its instrument response using the Fortran code
 107 developed by Yagi (2006). The mainshock waveform is windowed with a data length of
 108 100 seconds starting 5 before the arrival time of the P-wave. Furthermore, the aftershock
 109 waveform data is windowed with a length of 50 seconds before the P-wave arrival time.
 110 The same filtering parameters used in previous studies, as shown in Table 2, is used to
 111 match the observation and synthetic waveform with the smallest variance value. The
 112 variance is the comparison between the observation and the synthetic waveform
 113 calculated using equation (1) (Yamanaka and Ishida, 1996; , Ito et al., 2004).

$$114 \quad \text{Var} = \sum_j \left[\frac{\left(u_j^{\text{obs}}(t_i) - u_j^{\text{cal}}(t_i) \right)^2}{\left(u_j^{\text{obs}}(t_i) \right)^2} \right] \quad 1$$

115 with U_j^{obs} observations waveform at each j station, U_j^{cal} calculations waveform at each j
 116 station each at time t .

117 The best inversion models are obtained by calculating the moment tensor inversion,
 118 which is iterated at the appropriate resampling time value from 0.1 seconds to 10
 119 seconds.

120 Table 2: Limits of the frequency range used in several studies.

Research	Frequency (Hz)	Length of Data (seconds)	Sampling Time (seconds)
Nakano et al. (2006)	0.01-0.02	250	0.5
Suardi (2009)	0.01-0.03	80	0.5
Yagi (2003)	0.0-0.5	120	0.25
Mikumo and Yagi (2003)	0.05-0.5	60	0.25

Kuge (2003)	0.04-0.2	80	0.5
Miyatake et al. (2004)	0.1-0.5	60	0.25

In this study, the calculation of the Green's function utilized five velocity models, namely: AK135 (Kennett et al., 1995), CRUST2.0 (Bassin et al., 2000), PREM (Dziewonski and Anderson, 1981), Jeffreys-Bullen (Jeffreys and Bullen, 1940), and Koulakov et al., 2007. Calculation of the correct Green's function tends to produce a good estimate of the subsurface velocity model. The predetermined velocity model and grid search models are used in the next stage to determine the depth of the hypocenter. The grid search method applied for hypocenter depth ranges from 1 km to 25 km. In addition, the depth of the hypocenter was determined both for the mainshock and aftershocks.

The main equation for this calculation is shown in equation 2, which describes the vertical component of the observation waveform at each j station as follows:

$$u_j = \sum_{q=1}^5 \iiint_v G_{jq}(t - \tau, x, y, z) dV + e_0 \quad 2$$

where G_{jq} is a green function of time t , and τ is a unit step from the source positions of x, y , and z . M_q is the moment tensor element, v is the volume of the earthquake source space, q is the number of free components for the second pair selected, and e_0 is the observation error. The focal mechanism represents a point source model. Equation (2) can be simplified into a vector shape to form equation (3).

$$d_j = G(T(t), x_c, y_c, z_c)_j m + e_j \quad 3$$

where $T(t)$ is the source time function in the source centroid, and x_c, y_c, z_c , d , and e_j are data vector errors with N-dimensions. M represents the five dimensions of the parameter model vector, and G is the $N \times 5$ coefficient matrix.

The solution to the above matrix equation is determined by the least square method when the observation waveform and the convolution of the Green's function with the time function of the source are known. The calculation of Green functions for near-field data uses the extended reflectivity method developed by Kohketsu (1995) and Yagi (2006).

3. Results

3.1. Mainshock event

At the initial stages, the filter parameter and time were determined by sampling the trial and error using the grid search method. The best bandpass filter range for mainshock and aftershock is 0.01 - 0.05 Hz, and 0.1 - 0.3 Hz, respectively.

Figure 3: The grid search method between time sampling and the value of the variance of the waveform fitting displacement results for several velocity models. The blue, red, yellow, green, and brown colour beachball indicates the AK135, CRUST2.0, Jeffreys Bullen, Koulakov, and PREM velocity models.

Figure 3 shows the beachball variations for each velocity model and time sampling variation. The time sampling with the smallest variance value of each velocity model is 0.5. The slightest grid search process of 0.234 was also obtained using the Koulakov velocity model. The results used to determine the focal mechanism through the grid

search method using a range filter of 0.01 to 0.2 Hz and some velocity models, as shown in Figure 4. The hypocenter depth with this grid search method through iterations between 1 - 25 km provides a depth step variation.

Figure 4: Depth variation for each velocity model, namely the AK135, CRUST2.0, Jeffreys-Bullen, Koulakov, and PREM.

The selection of filters with a frequency of 0.01-0.04 Hz on the mainshock provides stable results using the Koulakov, Jeffrey-Bullen, and PREM velocity models. In contrast, CRUST2.0 and AK135 provide unstable inversion model. At frequencies of 0.01 to 0.02 Hz with the CRUST2.0 velocity model, and PREM gives a stable inversion model, while AK135, JB, and Koulakov are not stable. At frequencies of 0.01 - 0.08, the velocity models of Koulakov, PREM, and JB are stable while CRUST and AK135 are not stable. At frequencies of 0.01 - 0.33, the stable result is given by the velocity models of JB, Koulakov, and PREM, while AK135 and CRUST2.0 are unstable. From these results, the smallest variance values and the most stable result is the Koulakov velocity model.

Figure 4 shows that the grid search method determines the focal mechanism of the mainshock based on the depth variation for each velocity model. A good fit between

172 the observation and the synthetic waveform was obtained when the hypocenter is located
 173 at the depth of 12 km with a variance of 0.247.

Figure 5: The fitting of the displacement waveform between observation with the synthetic waveform from the Yogyakarta earthquake mainshock recorded by BJI, JCJ, TNG, SBJI, KMMI and XMIS stations. The blue and red lines are the observation and synthetic waveforms, respectively.

174
 175 Figure 5 shows the waveform fitting with Koulakov velocity model. It shows the
 176 fitting of displacement between the observation and synthetic waveforms of the
 177 mainshock from BJI, JCJ, TNG, SBJI, KMMI and XMIS stations, at a good variance value
 178 0.247.

179

180 Figure 6 shows the beach ball focal mechanism based on the inversion model. The fault
 181 parameters obtained are strike 340.10, dip 62.40, and rake -165.80 for the first nodal
 182 solution and strike 243.40, dip 77.50 and rake -28.30 for the second. The magnitude of
 183 the moment produced by this model is 0.2808 E+19 (Nm), which corresponds to the
 184 moment magnitude Mw=6.2.

185 3.2. Aftershocks

186 The result of the aftershock focal mechanism is shown in Figure 7. Overall, the results
 187 based on the waveform fittings have quite small variance values of 0.218, 0.195, and
 188 0.243, respectively.

189

a)

Figure 7: Waveform fitting for the aftershock recorded on 8, 9, and 16 June 2006. The blue and red colours are the observation, and synthetic waveforms, respectively. a) The waveform fitting for aftershock on June 8 using PAL, KRI, NGL, PEL, WAN and WON stations. b) The waveform fitting for aftershock on June 9 using KRI, NGL, PAL, PEL, RAT and TRI stations. c) The waveform fitting for aftershock on June 16 using BOG, KARA, WON, NGL, PAL, PEL and RAT stations.

Table 3 shows a variation on the fault plane types of aftershock for the 8, 9, and 16 of June 2006. The typical dip-normal was the type of faulting used on June 8, while the strike-slip fault dominated June 9, and 16. The magnitude has a similar result with the catalogue from International Seismological Center (ISC) i.e., $M_w=4.4$, $M_w=4.1$ and $M_w=4.0$ for the 8, 9, and 16 June respectively. The variance value obtained from the inversion is shown in Table 3.

Table 3: Parameter of aftershock sources obtained in determining the focal mechanism

Date (June)	Seismic Moment	Depth (km)	Nodal Plane 1 (strike, dip, rake)	Nodal Plane 2 (strike, dip, rake)	P Axis		T Axis		Variance
					Azimuth	Plunge	Azimuth	Plunge	
8	0.2636E +16, M_w 4.2	15	192.2 ⁰ , 29.7 ⁰ , - 48.3 ⁰	326.5 ⁰ , 68.3 ⁰ , - 110.8 ⁰	25	61	72	21	0.2178
9	0.2531E +17, M_w 4.1	11	153.4 ⁰ , 69.1 ⁰ , 175.6 ⁰	245 ⁰ , 85.9 ⁰ , 20.9 ⁰	197	12	291	18	0.1949
16	0.2342E +16, M_w 4.1	6	87.2 ⁰ , 60.7 ⁰ , 36.9 ⁰	197.4 ⁰ , 58.4 ⁰ , - 144.9 ⁰	211	1	322	1	0.2432

The results of the aftershock moment tensor inversion is shown in Table 3 and serves as the basis for examining the consistency of the fault plane caused by the mainshock. The beachball solution from this inversion is shown in Figure 8.

4. Discussion

The focal mechanism model for the mainshock and aftershock of the Yogyakarta earthquake suggest that the Opak's river fault was not the source (Fukuoka et al., 2006; Diambama et al., 2019; and Nakano, et al., 2006). The gravity study in the Yogyakarta earthquake zone by Irham et al., 2014 also supported this result. Irham et al. (2014) stated that the Siluk fault located at 10 km to the east of the Opak river fault was the main source of Yogyakarta earthquake.

The focal mechanism obtained in this study corresponds to the determination of the focal mechanism by USGS. Initial calculations showed that the fault plane comprises the NE-SW left-lateral strike-slip mechanism. Previous studies are consistent with the location of the aftershock cluster with hypocenter differences spread at a depth of 8-15 km. The focal mechanism obtained is the earthquake rupture on the surface, thereby leading to deformation. The focal mechanism also showed that the geometry of the fault is not straight and appear bent at the southern end with a stretch-like image on the Opak River. The difficulty faced in determining the focal mechanism is due to the direction of the LOS, which is perpendicular to the fault traces, thereby, making it difficult to distinguish the direction of the strike-slip. Tsuji et al. (2009) stated that the coseismic displacement had a reverse component besides the strike-slip along the fault plane, while the east side experienced an upward movement.

225

226 Figure 8 shows the results of the moment tensor inversion of mainshock and aftershock.
 227 The fault parameters obtained from this model is similar to the USGS report. This showed
 228 that the fault source is a strike slip fault with a normal component compared to USGS that
 229 defined it as a pure strike-slip fault. Based on the inversion of the aftershock fault
 230 parameter on June 8, there is a different focal mechanism than the mainshock, which is
 231 dip-normal slip, and it is assumed to be a new earthquake source. The aftershock fault
 232 on June 9 and 16 have similarities with the strike-slip fault.

233

Figure 9 shows the focal mechanism of moment tensor inversion calculations from our study and the solution performed by USGS. The comparison parameters are shown in Table 4.

Table 4: Mainshock source parameters obtained in determining the focal mechanism

Source Parameter by	Seismic moment	Depth (km)	Nodal Plane 1 (strike, dip, rake)	Nodal Plane 2 (strike, dip, rake)	P Axis		T Axis	
					Azimuth	Plunge	Azimuth	Plunge
USGS	4.22E+25, Mw 6.3	21.7	323 ⁰ , 77 ⁰ , -176 ⁰	232 ⁰ , 86 ⁰ , -13 ⁰	187	12	278	7
This study	0.1893E+19, Mw 6.2	20.0	323.7 ⁰ , 65 ⁰ , -162.7 ⁰	234.6 ⁰ , 74.7 ⁰ , -28.1 ⁰	185	12	278	6

The results used to determine the mainshock and aftershock focal mechanism for the Yogyakarta earthquake on May 27, 2006, showed the consistency on June 9 and 16, 2006. However, there were different patterns of the mainshock and aftershock focal mechanism on June 8, 2006. The aftershock of June 8, 2006, is strongly suspected of being the epicentre that triggered the Yogyakarta earthquake. Further analysis including a full waveform inversion based on earthquake modelling is needed in the area of study to support these findings.

5. Conclusions

This study suggests that the mainshock of Yogyakarta 2006 earthquake has a focal mechanism of dip-normal strike-slip fault. The aftershock focal mechanism for June 8 showed a different fault plane characteristics with the mainshock, while those of 9 and 16 had the same fault direction, which is dominantly in strike-slip type. This research shows that the Yogyakarta earthquake has complex fault characteristics caused by the activation of minor faults on the east side of the Opak River. However, these results need further assignment, especially in relation to a significant velocity contrast between the western and eastern parts of the Opak's river fault.

Author Contributions: HS prepared the initial draft article and its analysis, while W corrected, weighed, and analyzed the results. In addition, IS performed data curation, acquisition, and examined the results. WS reviewed, edited, visualized, and analyzed the results. All authors have read and agreed to the published version of the manuscript.

Acknowledgment: The authors are grateful to Lembaga Pengelola Dana Pendidikan (LPDP) for funding this doctoral program, as well as to BMKG, IRIS, and GFZ for providing the required waveform data and parameters related to earthquake. The authors also wish to express their profound gratitude to Prof. Yuji Yagi, for developing the script for moment tensor inversion applied in this research. Universitas Gadjah Mada also supported the

study through the Doctoral Program of Physics at the Faculty of Mathematics and Natural Sciences.

Conflicts of Interest: The authors declare no conflict of interest.

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