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Hijrah Saputra

Universitas Gadjah Mada

Wahyudi Wahyudi

Universitas Gadjah Mada

Iman Suardi

Sekolah Tinggi Meteorologi Klimatologi dan Geofisika

Ade Anggraini

Universitas Gadjah Mada

Wiwit Suryanto (✉ ws@ugm.ac.id)

Universitas Gadjah Mada <https://orcid.org/0000-0002-6275-7880>

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

Hijrah Saputra¹, Wahyudi Wahyudi¹, Iman Suardi², Ade Anggraini¹, and Wiwit
Suryanto^{1*}

¹*Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas
Gadjah Mada, Yogyakarta, 55281 Indonesia*

²*The Agency for Meteorology, Climatology, and Geophysics of Indonesia, Jakarta
10720 Indonesia*

*Correspondence: ws@ugm.ac.id

Abstract

This study comprehensively investigates the source mechanisms associated with the mainshock and aftershocks of the Yogyakarta earthquake of magnitude $M_w = 6.3$ on May 27, 2006. Therefore, this study is to provide a more precise answer to the controversial source mechanism. This study uses moment tensor inversion to obtain fault plane parameters and joint inversion to obtain spatial and temporal slip distributions during an earthquake. The coseismic slip distribution is overlaid with the relocated aftershock distribution to see the stress field variations around the tectonic area of the study. Moment tensor inversion uses near-field data, and joint inversion uses near-field and teleseismic body wave data. The data is filtered by trial and error using a bandpass filter with frequency pairs and velocity models from several previous studies. The green's function for moment tensor inversion calculated using the extended reflectivity method and joint inversion computed using the Kikuchi and Kanamori methods. In this study, we apply the Akaike Bayesian Information Criterion (ABIC) method to obtain more stable inversion results. The results of the mainshock and aftershock moment tensor inversion show different fault types. The mainshock fault types are strike-slip and dip-normal types, while the 8th aftershock is of the same type as the mainshock, while the 9th and 16th June are strike slips. The joint inversion results show two asperities. The maximum slip is 0.78 m, with the first asperity 10 km south of the mainshock and the second asperity 10 km north

of the mainshock. The obtained source parameters are total seismic moment $M_0 = 0.4311E + 19$ (Nm) or $M_w = 6.4$, with a source depth of 12 km and a source duration of 28 seconds. Slip distribution overlay with aftershock distribution shows compatibility. The type of focus mechanism that results from this joint inversion is the oblique.

Keywords: mainshock; aftershock; inversion; moment tensor; near-field; teleseismic; joint inversion

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 $M_w=6.3$, centred at 8.003E 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 source mechanism used to obtain valuable information on the source parameters such as magnitude, fault orientation, stress drop, and source process. 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; and 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; and 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 the figure. According to studies, several factors influence this difference, such as the lack of seismometer networks of BMKG, which existed before 2006. It led to a difference in the level of location accuracy, source depth, and fault orientation (Ma and Eaton, 2011; and Saunders et al., 2016).

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

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

Agencies	Event Time (WIB)	Depth (km)	Magnitude			Epicenter	
			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

77

78 Kawazoe and Koketsu (2010) determined the focal mechanism of the Yogyakarta
79 earthquake using the waveform inversion method. They compared the inversion with the
80 observed data using the CRUST 2.0 velocity model (Bassin et al., 2000) as well as the
81 left-lateral strike-slip and reverses dip-slip. Nakano et al. (2006) examined the focal
82 mechanism dominated by strike-slip. Similar results obtained by Abidin et al., 2009
83 through the Global Positioning System (GPS) data. The result showed that the horizontal
84 coseismic displacement took place around Bantul and Yogyakarta in the south and
85 southwest direction, with the focal mechanism in the form of left-lateral strike. Tsuji et al.
86 (2009) stated that coseismic displacement and strike-slip along the fault plane also
87 reverses on the east side, which experiences upward displacement. Several studies show
88 that there are different opinions regarding the source mechanism of the Yogyakarta
89 earthquake.

90 Therefore, this study has two main purposes. That is, moment tensor inversion used to
91 determine the type of expansion based on the mainshock and the three aftershocks M_w
92 > 4 . The second purpose is to obtain a model of the Yogyakarta source by knowing the
93 distribution of cosmic slips in space and time using the joint inversion method. The
94 calculation of moment tensor inversion and joint inversion based on the fit between the
95 observed and synthetic waveforms with the smallest variance.

96 **2. Data and Methods**

97 **2.1. Moment tensor inversion mainshock and aftershocks**

98 **2.1.1. Data**

99 The data used for the mainshock moment tensor inversion obtained from the Incorporated
100 Research Agency for Seismology (IRIS). Meanwhile, aftershocks data obtained from the
101 Geofon and EIDA Data Archives. These data downloaded through the IRIS data services

website (<http://ds.iris.edu>) and (<http://eida.gfz-potsdam.de/webdc3>), respectively. Distribution of IRIS and BMKG networks for all stations shown in Figure 2. The aftershock waveform data used for the distribution of aftershocks from 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 2. The experiment found approximately 524 aftershocks events that are relocated and plotted to visualize the spatial distribution, as shown in Figure 2. The aftershocks data plotted are research data from Wulandari et al. (2018). Mainshock data relocated using the SeisComP3 program, while distribution aftershocks data relocated using the NonLinLoc method.

2.1.2. Method

The waveform corrected from its instrument response using the Fortran code developed by Yagi (2006). The mainshock waveform is windowed with a data length of 100 seconds, starting 5 seconds before the arrival time of the P-wave. Furthermore, the aftershock waveform data is windowed with a length of 50 seconds starting 5 seconds before the P-wave arrival time. The filters used in this data processing for mainshock and aftershock did by trying out some of the filters used in the previous research, which shown in Table 2 and Table 3. The filter and velocity model selection based on the smallest variance value. The variance is the comparison between the observation and the synthetic waveform calculated using equation (1) (Yamanaka and Ishida, 1996; Ito et al., 2004).

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

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

Optimal inversion model obtained by computing a moment tensor inversion that iterates at appropriate resampling time values from 0.1 to 10 seconds.

128 Table 2: Limits of the frequency range used in several studies for mainshock.

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
Mikumo and Yagi (2003)	0.05-0.4	60	0.25
Yagi (2003)	0.01-0.4	120	0.25
This study	0.01-0.05	100	0.5

129

130 Tabel 3: Limits of the frequency range used in several studies for aftershocks

Research	Frequency (Hz)	Length of Data (seconds)	Sampling Time (seconds)
Pinar A et al. (2007)	0.05-0.1	50	0.2
Kasemsak S (2017)	0.03-0.15	50	0.1
Miyatake et al. (2004)	0.1-0.5	60	0.25
This study	0.1-0.3	50	0.5

131

132 In this study, we are applying the grid search method to determine the depth of the
 133 hypocenter in each frequency range with a bandpass filter. The waveform is converting
 134 from velocity to displacement using a sampling time of 0.2 seconds - 10 seconds and
 135 calculating the green function using several velocity models. The grid search method
 136 applied for hypocenter depth ranges from 1 km to 25 km. Also, the depth of the hypocenter
 137 was determined both for the mainshock and aftershocks. The calculation of the green's
 138 function utilized five velocity models, namely: AK135 (Kennett et al., 1995), CRUST2.0
 139 (Bassin et al., 200), PREM (Dziewonski and Anderson, 1981), JB (Jeffreys-Bullen, 1940),
 140 and Koulakov (Koulakov et al., 2007). Some of the velocity structure models used in this

study shown in Table 4. Calculation of the green's function tends to produce a good estimate of the subsurface velocity model.

Table 4. The seismic velocity model used in this study.

Velocity Model	Vp (km/s)	Vs (km/s)	Density (10 ³ kg/m ³)	Thicknees (km)	Qp	Qs
AK135	1.65	1.00	2.00	3.3	160	80
	5.80	3.20	2.60	10	250	150
	6.80	3.90	2.92	18.0	400	200
	8.04	4.48	3.60	0.0	600	250
CRUST2.0	2.92	2.44	1.01	2.09	150	50
	7.34	6.00	3.50	2.72	250	100
	13.96	6.60	3.80	2.86	400	200
	25.00	7.10	3.90	3.05	600	300
PREM	5.80	3.20	2.60	3.0	250	150
	6.80	3.90	2.90	15.0	400	200
	8.11	4.4	3.38	24.4	600	250
	8.08	4.47	3.38	71.2	600	300
JB	5.57	3.36	2.65	15.0	250	150
	6.50	3.74	2.87	18.0	400	200
	8.10	4.68	3.30	0.0	650	280
Koulakov	4.60	2.64	2.50	3.0	200	100
	5.30	3.05	2.65	5.0	250	150
	6.30	3.62	2.85	8.0	400	200
	7.00	4.02	2.95	8.0	450	200
	7.45	4.28	3.20	0.0	500	250

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

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

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 the observation error. The focal mechanism represents a point source model. Equation (2) can be simplified into a vector shape to form equation (3).

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

can be rewritten equation (3) into vector form, namely:

$$d = \begin{bmatrix} u_{ud}(t_1) \\ u_{ud}(t_2) \\ \vdots \\ u_{ns}(t_1) \end{bmatrix}, G = \begin{bmatrix} G_{ud}^{m_1}(t_1) & G_{ud}^{m_2}(t_1) & \dots & G_{ud}^{m_5}(t_1) \\ G_{ud}^{m_1}(t_2) & G_{ud}^{m_2}(t_2) & \dots & G_{ud}^{m_5}(t_2) \\ \vdots & \vdots & \ddots & \vdots \\ G_{ns}^{m_1}(t_1) & \vdots & \vdots & G_{ud}^{m_5}(t_2) \end{bmatrix}, m = \begin{bmatrix} m_1 \\ m_2 \\ m_3 \\ m_4 \\ m_5 \end{bmatrix} \quad 4$$

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 x 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). The source time function used to determine the moment tensor solution. The slip rate function is applied to waveform data with a simple triangular function.

2.2. Joint Inversion

2.2.1. Data

We download 16 teleseismic waveform body wave data (P and S waves), the vertical components recorded on the IRIS-DMC station downloaded via the page (<http://ds.iris.edu>). Teleseismic data from The International Federation of Digital Seismograph Networks (FDSN). The selected data has a high signal-to-noise ratio and covers a good azimuth range. The source and station distances used have a range of 30°

– 90°. The teleseismic station configuration can be seen in Figure 3 (a). Meanwhile, near-field data downloaded for free from the page (<http://eida.gfz-potsdam.de/webdc3>). Near-field data uses the BMKG station network, and the configuration can be shown as in Figure 3 (b). The configuration of body wave teleseismic data and near-field data can be seen in Figure 3.

The teleseismic data used for this wave inversion calculation consists of 12 stations. Teleseismic body wave data windowed with a data length of 90 seconds, 5 seconds before the P wave, filtered with a bandpass filter in the frequency range 0.008 - 0.1 Hz, and converted to displacement with a sampling time of 0.5 seconds. Whereas near-field data uses 14 components from 5 broadband seismometer stations, four stations from the BMKG network namely TNG, BJI, KMMI and DNP, and one station from the IRIS-DMC network, namely the XMIS station. Near-field data is windowed with a data length of 180 seconds, 5 seconds before the P wave, filtered using a bandpass filter with a frequency range of 0.05 - 0.15 Hz, then converted to displacement with a sampling time of 0.5 seconds. When the first P wave arrives at each seismogram, it manually picked using the help of the Seismic Analysis Code (SAC) program.

2.2.2. Method

The method used to determine the rupture process of the Yogyakarta earthquake source uses the equation from Yagi et al. (2004) developed from the Yoshida equation, 1992. This equation represents the rupture process as a temporal, spatial slip distribution in the fault plane. The wave received by the station is the observed waveform at each station j given as in equation 5.

$$W_j^{obs}(t_i) = \sum_{mnlk} X_{mnkl} g_{mnkj}(t_i - (l-1)\tau - T_{mn}) + e_j \quad 5$$

Where X_{mnkl} is the slip component at each mn sub faults and each l^{th} time change, $g_{mnkj}(t)$ is the basic seismic wave green function of the point source with slip units on each mn sub faults. T_{mn} is the basic function of the start time for each sub faults, while e_j is a gaussian error with the variance σ_j . The calculation of the green function used for

teleseismic data is the Kikuchi and Kanamori (1991) method. The velocity model seismic used for the calculation of the green data near-field and teleseismic functions is Koulakov and Jeffreys Bullen (JB), respectively, as shown in Table 3.

We apply the numerical method to the standard waveform inversion scheme so that we obtain a more objective source model (Harzell and Heaton, 1983; Yoshida, 1992). The inversion calculation used in this research is the inversion code developed by Yagi et al. (2004). This method represents the rupture as a slip distribution over time and space in a fault plane. The initial model of the fault plane determined from the area distribution of the fault plane. Papazachos et al. 2004 can also use to calculate slip lengths and areas. The fault plane divided into $M \times N$ sub faults with the length and width of the sub faults d_x and d_y , respectively. The slip rate function on each sub-default determined from a simple triangular series of functions for the length of the dislocation time (rise time) τ .

Equation (5) can be simplified into vector form as follows:

$$Y_j = A_j \times + e_j \quad 6$$

Where A_j is a matrix with the dimensions of the number of data points at each station n_j $\times$ the number of model parameters N_j .

Changing the number of model parameters will make a solution unstable because a small change in data will make a big difference in that solution. So that to produce a stable inversion, this study also applies to smooth limits to the slip distribution over time and space.

For seismic wave analysis using observational data has two constraints, namely spatial and temporal, to obtain the best calculation of model parameters by minimizing the number of residuals squared S , determined by the equation: $S(\times, \sigma_j, \sigma_t, \sigma_d) = \sum_j \frac{1}{\sigma_j^2} \|y_j -$

$$A_j \times \|^2 + \frac{1}{\sigma_t^2} \|T_x\|^2 + \frac{1}{\sigma_d^2} \|D_x\|^2 \quad 7$$

Where $\mathbf{T}$ is the matrix of $N_1 \times N_a$ ($N_1 = MNLK$), and $\mathbf{D}$ is the matrix of $N_2 \times N_a$ ($N_2 = MNK$), MNK is slip component K^{th} on the sub faults MN^{th} and timestep L^{th} , while N_a the model parameter.

The least-square method is applied to determine the best estimate of the model parameters by providing the value of the covariance σ (Jackson and Matsuura, 1985). The values of σ_t and σ_d cannot be determined directly but can select from the quality of the data. The values of σ_t and σ_d are objectively using Akaike's Bayesian Information Criterion (ABIC) method (Akaike, 1980). This ABIC equation has also used by Fukuhata (2003; 2004). The ABIC equation to get the optimal value is:

$$ABIC(\mathbf{x}, \sigma_t, \sigma_d) = N \log S(\mathbf{x}, \sigma_j, \sigma_t, \sigma_d) - \log \left\| \frac{1}{\sigma_t^2} \mathbf{T}^t \mathbf{T} + \frac{1}{\sigma_d^2} \mathbf{D}^t \mathbf{D} \right\| + \log \left\| \sum_j \frac{1}{\sigma_j^2} \mathbf{A}_j^t \mathbf{A}_j + \frac{1}{\sigma_t^2} \mathbf{T}^t \mathbf{T} - \frac{1}{\sigma_d^2} \mathbf{D}^t \mathbf{D} \right\| + C \quad 8$$

Where N is the total number of observed equations, and the value of C is constant. In this study, the grid search method applied to obtain the optimal values of σ_t and σ_d . This study also uses the non-negative least squares (NNLS) method to solve the least-squares problem with a positive constraint on the model parameters.

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3. Results

3.1. Moment tensor inversion of mainshock event

The mainshock source mechanism is determined by the grid search method using various frequency ranges and velocity models, as shown in table 2 and table 4. The results can show as in Figure 4. Converting the velocity waveform to displacement using a sampling time of 0.1 second - 10 seconds, to be able to choose a stable result.

251

252 Figure 4 shows the beachball variations for each velocity model and time sampling
253 variation. The time sampling with the smallest variance value of each velocity model is
254 0.5 seconds, and frequency is 0.01 – 0.05 Hz. The 0.5 second sampling time is very
255 stable with the five velocity models. Sampling times above 1 are precarious. Frequencies
256 with low variance found at low frequencies, 0.01 to 0.05 Hz. A velocity model that can
257 describe the subsurface structure of the study area is the Koulakov velocity model with a
258 sampling time of 0.5 seconds and a frequency of 0.01 to 0.05 Hz. The minimum variance
259 value for this grid search method is 0.234, which shown by comparing observed and
260 synthetic waveforms, as shown in Figure 5. The parameter of the Yogyakarta seismic
261 source on May 27, 2006, is the moment 0.2808×10^{19} (Nm) is equivalent with moment
262 magnitude $M_w=6.2$. The fault parameters obtained for Nodal 1 are strike 353.7° , dip 43.4° ,
263 and slip -126° , and Nodal 2 are strike 218.7° , dip 56.2° , and slip -61° , and the hypocenter
264 is 12 km.

265

266 The results of the moment tensor inversion from near-field data for the mainshock are
267 shown by Nodal 2 with the type of faulting, namely, strike-slip and dip-normal. The
268 depiction of this faulting type can be depicted as a beachball, as shown in figure 6.

269

270 **3.2. Moment tensor inversion of aftershocks event**

271 The aftershock mechanism determined in the same way as the mainshock. The method
272 used is a grid search method in previous studies using various velocity models and
273 frequency ranges. The velocity models and frequency ranges used to determine the
274 aftershocks mechanism are shown in Tables 3 and 4, respectively. The aftershock
275 reversal results for June 8, 9, and 16 can be seen in Figure 7, respectively. Figure 8 and
276 Figure 9. Convert the waveform velocity to displacement using a sampling time of 0.2 to
277 10 seconds.

278

Figure 7, Figure 8, and Figure 9 are images of beachball variations from the results of the grid search method to obtain the aftershock source mechanism for June 8, 9, and 16, respectively. These graphs show as a function of time sampling and variance for each model. The speed and range of the bandpass filter are as shown in Table 2. The sampling time of 1 second and above for the aftershock on June 8, 9, and 16 in the five velocity models have the same trend, namely the focal ball and unstable variance values. As for the sampling time of 0.5 seconds, the aftershock on June 8, 9, and 16 was very stable. The very stable variance value of the five velocity models used is the Koulakov velocity model. The Koulakov velocity model is very representative of the subsurface structure of the study area. For the five velocity models and aftershocks on June 8, 9, and 16, the lowest dispersion frequency was 0.1-0.3 Hz. The smallest variance values for the aftershock on June 8, 9, and 16 were 0.2178, 0.1949, and 0.2432, respectively. The parameters of the inversion result of the aftershock source can be seen in Table 5.

In Figure 10, we show the fitting shape of the observed waveform and the synthetic waveform displacement of the Yogyakarta earthquake aftershock on May 27 2006, namely June 8, 9 and 16. The resulting waveform fitting is the best result from the grid search process.

Table 5 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, as shown in Figure 11. The variance value obtained from the inversion shown in Table 5.

Tabel 5: Parameter of source mechanism of the aftershock Yogyakarta earthquake 8, 9, and 16 June.

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, Mw 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, Mw 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, Mw 4.0	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

305

306 The results of the aftershock moment tensor inversion are shown in Table 5 and serve as
307 the basis for examining the consistency of the fault plane caused by the mainshock. The
308 beachball solution from this inversion shown in Figure 11.

309

310 Figure 11 shows the inversion result of the mainshock and aftershocks moment tensor.
311 The mainshock focal mechanism has a dip-normal strike-slip fault type. Meanwhile, the
312 focal mechanism of the 9 and 16 June aftershock has a different type from the mainshock,
313 namely the strike-slip. Meanwhile, the aftershock on June 8 has the same type as the
314 mainshock. There is a strong suspicion that the 9 and 16 June aftershocks originated
315 from a different fault plane than the mainshock. The fault type issued by USGS has a
316 predominantly strike-slip fault type.

317 3.3. Joint Inversion

318 We adopt Akaike's Bayesian Information Criterion (ABIC) to get more objective parameter
319 results (Akaike, 1980). The calculation of the green function for teleseismic body waves
320 uses the method from Kikuchi and Kanamori's (1991), while for near-field data uses the
321 method developed by Kohketsu (1985).

322 3.3.1. Fault model

323 The fault model used in this study uses the Hazkel finite fault model, which assumes that
324 there is no change in the slip angle along the rupture and that the faulting occurs in a
325 single fault plane. The fault dimensions are essential to know to obtain detailed global

features of the fault plane and coseismic rupture of an earthquake. Seismic traces in the fault plane can be used to estimate the extent of the fault plane. Mapping the distribution of the Yogyakarta earthquake aftershock from several previous studies shows the area of the Opak fault plane, namely 28 km long and 15 km wide (Walter et al., 2008; Anggraini, (2913). Meanwhile, according to the Papazachos et al. (2004) equation, it is known that the length of the fault plane is 30 km and the width of the fault plane is 20 km. The initial model of the fracture area used in this study divided into two stages, namely, stage 1 and stage 2. The division of the fault plane into two parts is to obtain the area of the fault plane that corresponds to the actual area of the Opak Fault. The fault plane on stage 1 with a strike length of 32.5 km and a dip width of 15 km, which divided into several sub faults, namely 15 x 6 sub faults. The length of each sub faults is 2.5 km. The dimensions of the fault plane on stage 2 are smaller than stage 1, namely the length strike 17.5 km x dip width 15 km. The fault plane divided into several sub-defaults, namely 7 x 6 sub faults. The hypocenter position used will be the result of relocation from the mainshock released by USGS using the software sesicomp3. The fault plane model used in this study can see, as shown in Figure 12. The velocity model used to calculate teleseismic body wave data is Jeffreys Bullen (JB). Meanwhile, the near-field data calculation uses five velocity models, as shown in table 4. The JB velocity model for teleseismic data is varied into four near-field data rate models to obtain the smallest variation.

The rupture velocity is set to equal the maximum shear wave velocity to save computation time. The maximum velocity used is the shear wave velocity from Koulakov et al., which is 4.6 km / s. The waveform data for implementing the slip-rate function uses a simple triangular function sequence with a rise time of 1 second. Dislocation time and rupture propagation for each sub faults used to determine slip-rate function duration. Hypocenter depth using the grid search method has carried out by calculating the mainshock moment tensor inversion. Fault plane parameter and the depth of the hypocenter obtained on mainshock moment tensor inversion calculation used as the initial input parameters for the calculation of joint inversion.

3.3.2. Source Rupture Process

The rupture of the Yogyakarta earthquake source process on May 27, 2006, was the result of a joint inversion. Figure 13 is the result of the joint inversion of the Yogyakarta earthquake, namely the earthquake source mechanism, the moment rate function, and the coseismic slip distribution. The focal mechanism resulting from the inversion joint inversion has similarities to the initial input. The resulting fault parameters were strike 217.6° , dip 56° , and slip -53° (Figure 13a). The source duration of moment rate function length is 28.5 seconds (Figure 13b). The total seismic moment produced is $M_0 = 0.4311E + 19$ (Nm) or $M_w = 6.4$ (Figure 13b), which has the same thing that was released by USGS, namely $M_0 = 0.422E + 25$ (Nm) or $M_0 = 6.3$. The energy moment released at the 6th second after the first initial break. The total slip vector produced is 0.78 m (Figure 13d). The slip movement has an NS direction from the hypocenter point then moves in an SW direction towards the surface and moves in a dip direction at the 15th second to the end. The Yogyakarta earthquake fault type is more dominant dip-normal than strike-slip (Figure 13c).

Figure 14a shows a series of snapshots of the Yogyakarta earthquake dislocation distribution to the surface area from 0 to 28 seconds. It can seem that the change in dislocation occurs not at the initial break, but the 3rd second. It is moving southward until the eighth second as far as 10 km. Then the dislocation movement moves northward for 20 km until the 12 second. The 15th second the slip movement is seen moving in the direction of 15 km until the last second. The maximum slip that occurs is 0.72 m 10 km north of the hypocenter. The first asperity zone is 10 km south of the hypocenter and the second asperity zone is 10 km south of the hypocenter (Figure 13.c). Figure 14b illustrates the slip rate of snapshots per second. The average rupture speed was 4 m / s.

Figure 15 shows the comparison of the observed waveform (in blue) with the synthetic waveform (in red) displacement for near-field data (Figure 15a) and body wave teleseismic data (Figure 15b). The variance value of observed waveform fittings with synthetic waveforms is 0.3412. This value is still quite large, even if seen from the

waveform fitting, it is quite good at the beginning of the arrival of the P wave. The limited quality of the signal recorded by the teleseismic station is also a factor in the variance value. Magnitude 6.3 earthquakes are less well recorded at long-range stations and are also affected by layer inhomogeneity. The limited azimuthal coverage of near-field data can also affect the quality of this inversion calculation. The near-field and teleseismic data are not very good quality, but these results show a fairly good resolution quality. This result is one of the advantages of simultaneous inversion of near-field and teleseismic data using ABIC optimization (Akaike, 1980). Therefore, the obtained variance values are the best results from the joint inversion results.

Figure 16 illustrates the distribution of the Yogyakarta earthquake coseismic slip overlaid with the distribution of the relocated aftershock. This figure can explain the aftershock distribution pattern with the coseismic slip distribution. The distribution of the aftershock distribution lies at a high enough slip. This pattern shows that they are in the same fault plane, but the pattern that located on the west has a different pattern. The difference in this pattern thought to originate from different fault planes. If we look at the results of the previously produced aftershock moment tensor inversion on June 9, they have a different type of fault. The differences in these fault types indicate the complexity of the faults in the study area.

4. Discussion

The results of moment tensor inversion obtained using near-field data on the main earthquake and aftershock in Yogyakarta on May 27, 2006. The resulting mainshock fault source parameters were strike 218.7° , dip 56.2° , and slip -61° . This fault parameter shows that the fault type caused by the Yogyakarta mainshock is oblique. These results have also confirmed several research results which state that the type of fault caused by the Yogyakarta mainshock is not pure strike-slip but has a dip-normal component. Kawazoe and Koketsu (2010) in their research, said that the type of earthquake source mechanism has two types, namely left-lateral strike-slip faulting and reverse dip-slip faulting. In

conclusion, according to Kawazoe and Koketsu, the source mechanism that occurs can have two different fault segments.

Meanwhile, Tsuji et al. (2009) stated that there was a movement in the direction of the fault line on the east side along the Opak fault line. These results confirm the results of the joint inversion, from the slip distribution in Figure 11c, showing that at the 15th second, there is a slip shift towards the dip. The most significant slip also occurred at the second Asperity at 0.72 m.

Moment tensor inversion calculations for the 8, 9, and 16 June aftershock using temporary near-field data also performed. Fault source parameters for the 8, 9, and 16 June aftershocks show the complexity of the Opak fault (Budiman et al., 2019; Saputra et al., 2018, Anggraini, 2013). The fault types for the 8th aftershock were dip-normal, the 9th and 16th June were the strike-slip (Table 5). These results show that the Yogyakarta earthquake mainshock has activated several active faults on the eastern side of the Opak fault (Anggraini 2013; Budiman et al., 2019; Irham et al., 2014).

This research has also conducted to determine the rupture process of the Yogyakarta earthquake source on May 27, 2006, using joint inversion. The result is the earthquake source mechanism, the moment rate function, and the coseismic slip distribution. The focal mechanism resulting from this inversion is similar to that of the mainshock moment tensor inversion. The resulting fault parameters are strike 217.6° , dip 56° , and slip -53° . The results of this inversion show the consistency obtained from the moment tensor inversion with the joint inversion. The fracture type obtained from this inversion result is dip-normal, with a smaller slip than the moment tensor inversion. Yagi (2006) in the research of Ohsumi and Baba (2007), shows that the rupture that occurred due to the Yogyakarta earthquake had two stages. The first stage as the first subevent with directions southwest to northeast and then the second stage as the second subevent. The results of this joint inversion also obtained two weak zones, located 10 km south of the hypocenter as the first Asperity and 10 km to the north as the second Asperity. Kawazoe and Koketsu (2010) also identified two zones of violence near the hypocenter and in the southwest. So that Kawazoe and Koketsu (2010) suspect it came from two different events. These results have also confirmed the aftershock moment tensor

inversion, where the fault types for the 9 and 16 June aftershock have different types, so that there may have been reactivation of several minor faults on the east side of the Opak fault (Anggraini 2013; Walter et al., 2008; Saputra et al., 2018; Budiman et al., 2018).

The distribution of the coseismic slip, overlaid with the relocation of the aftershock distribution (Figure 15), shows that the aftershock spread out parallel to the Opak fault. To the west of the Opak fault distribution, there is another pattern. This pattern thought to originate from different fault segments, and these results can confirm the results of the aftershock moment tensor inversion on June 9 and 16 which thought to originate from a different fault segment with the mainshock fault plane.

5. Conclusions

We have calculated the moment tensor inversion of the mainshocks and aftershocks, and the inversion of the joint inversions to obtain a more comprehensive model of the Yogyakarta May 27, 2006, earthquake source. The first thing to do is to get the exact Yogyakarta earthquake source mechanism using the mainshock waveform inversion. The source parameters obtained are used as input to perform joint inversion calculations. Mainshock source parameter obtained by dip-normal strike-slip type. To get a stable inversion result in the joint inversion method, we adopt the ABIC method (Akaike, 1980). In this joint inversion, we can obtain information on the distribution of the coseismic slip in the rupture area. The slip distribution obtained is bilateral rupture. Generally, the direction of slip distribution propagates along the fault plane in the strike direction, then moves and ends in the dip direction. The direction of the slip distribution spreads from the hypocenter point to the south for 10 km then moves north for 20 km then moves towards dip-normal. The source of the Yogyakarta earthquake that resulted from this research can conclude from the Opak fault, which reactivated the minor fault on the east side of the Opak fault. The source of the Yogyakarta earthquake strongly suspected of having come from two different sources, such as those obtained from the mainshock and aftershock moment tensor inversion and the results of joint inversion calculations.

Author Contributions: HS initiated the research idea, prepared the initial draft article and its analysis, while W corrected, weighed, and analyzed the results. Besides, IS provided critical comments, performed data curation, acquisition, and examined the results. AA added supporting data and supervision. WS reviewed, edited, visualized, and analyzed the results. All authors have read and agreed to the published version of the manuscript.

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Competing interests

We declare that we have no competing professional or personal interests that might have influenced the performance or presentation of the work described in the manuscript.

Availability of data and materials

The data is maintained by the Agency of Meteorology, Climatology and Geophysics of Indonesia and will be available upon requests to the Agency.

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651 Caption Figures:

652 Figure 1: Focal mechanisms of several agencies. The yellow star represents the location
653 of the epicentre. The black and white shoreline colour indicates the focus mechanism,
654 while the dark blue line is the Opak fault, and the light blue line is the minor fault scattered
655 east of the Opak fault.

656

657 Figure 2: BMKG networks consists of six stations, namely SBJI, TNG, JCJI, BJI, KMMI,
658 and DNP. Meanwhile, the IRIS networks use XMIS stations (red inverted triangles). The
659 red box is the distribution location of the GFZ. Non-permanent stations (red triangles)
660 consists of ten stations, namely PEL, TRI, RAT, KARA, PAL, BOG, WAN, NGL, KRI, and
661 WON. The yellow star in the red box depicts the epicentre of the Yogyakarta earthquake
662 mainshock. The black and white colour beachball is the main focal mechanism of the
663 USGS. The small red circle east of the Opak fault is the aftershocks distribution that has
664 relocated.

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666 Figure 3: Near-field data station configuration and body wave teleseismic data. (a). The
667 station configuration for the body wave teleseismic data given a red inverted triangle
668 symbol. The number of body wave teleseismic data used is 12 stations. The distance of
669 the teleseismic data station to the source is 300 - 900. The yellow star in the pink box is
670 the epicentre position and the near-field station configuration. (b). Configure a near-field
671 data station marked with a red inverted triangle symbol. The yellow star is the epicentre
672 of the Yogyakarta earthquake mainshock. The station-to-source distance for near-field
673 data is $0^{\circ} - 5.5^{\circ}$.

674

675 Figure 4: The grid search method to get the best solution of the mainshock focal
676 mechanism as a function of time sampling and variance for each of the speed and range
677 bandpass filter models as shown in Table 2. The blue, yellow, red, brown and green colour
678 beachball indicates the filtering used by Nakano, Suardi, Mikumo, Yagi, and in this study,

respectively. The velocity model used are: (a). AK135, (b) CRUST, (c). PREM, (d). JB and (e). Koulakov.

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. The value above the waveform is the maximum amplitude of the observed waveform

Figure 6: Focal mechanism of the inversion model using Koulakov's velocity model illustrated by a green colour beach ball.

Figure 7: The grid search method to get the best solution of the focal aftershock mechanism on June 8 as a function of time sampling and variance for each model speed and bandpass filter range as shown in Table 2. The blue, yellow, red, brown and green colour beachball indicates the filtering used by Pinar, Kasemsak, Miyatake, and in this study, respectively. The velocity model used are: (a). AK135, (b) CRUST, (c). PREM, (d). JB and (e). Koulakov.

Figure 8: The grid search method to get the best solution from the focal mechanism of the June 9 aftershock as a function of time sampling and variance for each of the velocity models and bandpass filter ranges as shown in Table 2. The blue, yellow, red, brown and green colour beachball indicates the filtering used by Nakano, Suardi, Mikumo, Yagi, and in this study, respectively. The velocity model used are: (a). AK135, (b) CRUST, (c). PREM, (d). JB and (e). Koulakov.

Figure 9: Grid search method to get the best solution from the focal mechanism of aftershock on June 16 as a function of time sampling and variance for each velocity model and several frequencies used. The blue, yellow, red, brown and green colour beachball indicates the filtering used by Nakano, Suardi, Mikumo, Yagi, and in this study, respectively. The velocity model used are: (a). AK135, (b) CRUST, (c). PREM, (d). JB and (e). Koulakov.

Figure 10: Waveform fitting for the aftershock recorded on 8, 9, and 16 June 2006. The blue and red colours are 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 is fitting for aftershock on June 9 using KRI, NGL, PAL, PEL, RAT and TRI Stations. c) The waveform is fitting for aftershock on June 16 using BOG, KARA, WON, NGL, PAL, PEL and RAT stations.

Figure 11: Result of determining the mainshock and aftershock focal mechanism for the Yogyakarta earthquake on May 27 2006. The focal mechanism of the mainshock and aftershock is represented in green, while the red colour small circle indicates the distribution.

Figure 12: The assumed fault plane used in the joint inversion calculation. The black line is the assumption of the fault plane at stage 1, while the green line is the assumption of the fault plane at stage 2. Yellow stars and red circles are the distribution of epicentre locations and aftershock relocations. Green beachball is the focal mechanism of the inversion mainshock.

Figure 13: Results of the joint inversion of the Yogyakarta earthquake on May 27 2006. (a) The focal mechanism of the Yogyakarta earthquake. (b) Functions of the moment rate

and source duration. (c) The distribution of the coseismic slip vector, the yellow star is the hypocenter position; the colour of the contour represents the size of the slip dislocation. At the same time, the white dots are the position of the Asperity zone (d) The graph of the dislocation in the asperity zone against time.

Figure 14: Series of snapshots projected orthogonally onto the surface plane. (a) distribution of dislocations per second, from 0 seconds to 28 seconds. (b) Distribution of the slip rate per second from 0 seconds to 28 seconds. The yellow star is the epicentre of the mainshock.

Figure 15: Comparison of the observed and synthetic waveforms. The blue waveform is the observed waveform, and the red waveform is the synthetic waveform. The value above the waveform is the maximum amplitude value of each waveform. (a) Near-field data. (b) Teleseismic body wave.

Figure 16: Distribution of seismic slip on May 27, 2006, in Yogyakarta plotted on the surface of the map The yellow star is the epicenter of the main shock. The small red circle is the distribution of the aftershock relocation locations. Green focus ball is a reverse focus mechanism.

Figures

Figure 1

Focal mechanisms of several agencies. The yellow star represents the location of the epicentre. The black and white shoreline colour indicates the focus mechanism, while the dark blue line is the Opak fault, and the light blue line is the minor fault scattered east of the Opak fault.

Figure 2

BMKG networks consists of six stations, namely SBJI, TNG, JCJI, BJI, KMMI, and DNP. Meanwhile, the IRIS networks use XMIS stations (red inverted triangles). The red box is the distribution location of the GFZ. Non-permanent stations (red triangles) consists of ten stations, namely PEL, TRI, RAT, KARA, PAL, BOG, WAN, NGL, KRI, and WON. The yellow star in the red box depicts the epicentre of the Yogyakarta earthquake mainshock. The black and white colour beachball is the main focal mechanism of the USGS. The small red circle east of the Opak fault is the aftershocks distribution that has relocated.

Figure 3

Near-field data station configuration and body wave teleseismic data. (a). The station configuration for the body wave teleseismic data given a red inverted triangle symbol. The number of body wave teleseismic data used is 12 stations. The distance of the teleseismic data station to the source is 300 - 900. The yellow star in the pink box is the epicentre position and the near-field station configuration. (b). Configure a near-field data station marked with a red inverted triangle symbol. The yellow star is the epicentre of the Yogyakarta earthquake mainshock. The station-to-source distance for near-field data is $0^\circ - 5.5^\circ$.

Figure 4

The grid search method to get the best solution of the mainshock focal mechanism as a function of time sampling and variance for each of the speed and range bandpass filter models as shown in Table 2. The blue, yellow, red, brown and green colour beachball indicates the filtering used by Nakano, Suardi, Mikumo, Yagi, and in this study, respectively. The velocity model used are: (a). AK135, (b) CRUST, (c). PREM, (d). JB and (e). Koulakov.

Figure 5

The fitting of the displacement waveform between observation with the synthetic waveform from the Yogyakarta earthquake mainshock recorded by BJI, JCJ, TNG, SBJ, KMMI and XMIS stations. The blue and red lines are the observation and synthetic waveforms, respectively. The value above the waveform is the maximum amplitude of the observed waveform

Figure 6

Focal mechanism of the inversion model using Koulakov's velocity model illustrated by a green colour beach ball.

Figure 7

The grid search method to get the best solution of the focal aftershock mechanism on June 8 as a function of time sampling and variance for each model speed and bandpass filter range as shown in Table 2. The blue, yellow, red, brown and green colour beachball indicates the filtering used by Pinar, Kasemsak, Miyatake, and in this study, respectively. The velocity model used are: (a). AK135, (b) CRUST, (c). PREM, (d). JB and (e). Koulakov.

Figure 8

The grid search method to get the best solution from the focal mechanism of the June 9 aftershock as a function of time sampling and variance for each of the velocity models and bandpass filter ranges as shown in Table 2. The blue, yellow, red, brown and green colour beachball indicates the filtering used by Nakano, Suardi, Mikumo, Yagi, and in this study, respectively. The velocity model used are: (a). AK135, (b) CRUST, (c). PREM, (d). JB and (e). Koulakov.

Figure 9

Grid search method to get the best solution from the focal mechanism of aftershock on June 16 as a function of time sampling and variance for each velocity model and several frequencies used. The blue, yellow, red, brown and green colour beachball indicates the filtering used by Nakano, Suardi, Mikumo, Yagi, and in this study, respectively. The velocity model used are: (a). AK135, (b) CRUST, (c). PREM, (d). JB and (e). Koulakov.

Figure 10

Waveform fitting for the aftershock recorded on 8, 9, and 16 June 2006. The blue and red colours are 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 is fitting for aftershock on June 9 using KRI, NGL, PAL, PEL, RAT and TRI Stations. c) The waveform is fitting for aftershock on June 16 using BOG, KARA, WON, NGL, PAL, PEL and RAT stations.

Figure 11

Result of determining the mainshock and aftershock focal mechanism for the Yogyakarta earthquake on May 27 2006. The focal mechanism of the mainshock and aftershock is represented in green, while the red colour small circle indicates the distribution.

Figure 12

The assumed fault plane used in the joint inversion calculation. The black line is the assumption of the fault plane at stage 1, while the green line is the assumption of the fault plane at stage 2. Yellow stars and red circles are the distribution of epicentre locations and aftershock relocations. Green beachball is the focal mechanism of the inversion mainshock.

Figure 13

Results of the joint inversion of the Yogyakarta earthquake on May 27 2006. (a) The focal mechanism of the Yogyakarta earthquake. (b) Functions of the moment rate and source duration. (c) The distribution of the coseismic slip vector, the yellow star is the hypocenter position; the colour of the contour represents the size of the slip dislocation. At the same time, the white dots are the position of the Asperity zone (d) The graph of the dislocation in the asperity zone against time.

Figure 14

Series of snapshots projected orthogonally onto the surface plane. (a) distribution of dislocations per second, from 0 seconds to 28 seconds. (b) Distribution of the slip rate per second from 0 seconds to 28 seconds. The yellow star is the epicentre of the mainshock.

Figure 15

Comparison of the observed and synthetic waveforms. The blue waveform is the observed waveform, and the red waveform is the synthetic waveform. The value above the waveform is the maximum amplitude value of each waveform. (a) Near-field data. (b) Teleseismic body wave.

Figure 16

Distribution of seismic slip on May 27, 2006, in Yogyakarta plotted on the surface of the map. The yellow star is the epicenter of the main shock. The small red circle is the distribution of the aftershock relocation locations. Green focus ball is a reverse focus mechanism.