A possible opak fault segment that caused the 2006 mw 6.3 yogyakarta earthquake and its future implication

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Abstract. On May 26th, 2006, the Mw 6.3 earthquake devastated the Yogyakarta region in a shallow strike-slip mechanism. Previous studies suggest the 2006 Yogyakarta earthquake aligned with the Opak river fault. However, several studies reported the aftershock distribution occurred along the eastward side of the Opak river fault strike. Those discrepancies may indicate two possibilities. First, the Opak river fault has an eastward dipping fault. Second, there are unidentified fault lines rather than Opak river fault. In this study, we investigated the fault segment that was responsible for the 2006 earthquake. We estimated the fault length based on seismic moment release assuming rigidity, fault depth, and coseismic displacement are 30 GPa, 12.5 Km, and 1 m, respectively. Therefore, we investigated the two possible scenarios using multi-years and recent Global Navigation Satellite System (GNSS) network developed by the Department of Geodetic Engineering, Universitas Gadjah Mada. The GNSS observation suggests the 2006 Yogyakarta earthquake occurred on the unidentified fault rather than has an eastward dipping fault. The estimated fault length is only 9.2 Km segment. Hence, the present study implies that other fault segments might not have released the accumulated stress and may become large earthquakes in the future.

1. Introduction
Source of the damaging earthquakes in the Yogyakarta region are mostly from the tsunamigenic earthquake in the Subduction zone or the shallow earthquake along the populated area. Our understanding of seismic hazard in Yogyakarta was mainly centered in the Java subduction zone where historical tsunami have occurred [1]. However, active crustal structures in the Yogyakarta region remain poorly understood. One of the cases that still intriguing is which fault segment and its length contribute to the Mw 6.3 Yogyakarta earthquake. The identified fault source plays an important role in constructing a suitable monitoring method and gives an insight into other active faults that potentially rupture in the near future.

To investigate the fault segment that ruptures during the earthquake, we can evaluate the coseismic slip distribution from GNSS offset data (e.g. [2]). Unfortunately, there is no available precise offset record since previous studies [3] may contain bias due to the effect of the long interseismic period. Instead of coseismic offset data, in this study, we evaluate the possible fault segment considering interseismic GNSS velocities and aftershock distribution. The relocated aftershock distribution of the 2006 Yogyakarta earthquake [4] shown in Figure 1 provides beneficial information about its possible segment. This study investigates the fault segment that was related to the 2006 Yogyakarta earthquake assuming the kinematic slip of earthquake rupture should be similar to an interseismic slip.
2. Methods
We used the Global Navigation Satellite System (GNSS) network developed by the Department of Geodetic Engineering, Universitas Gadjah Mada. Observation of ten GNSS sites around the Opak fault has been carried out periodically from 2013 to 2018 [5]. In order to obtain the deformation rate, the data were processed using GAMIT/GLOBK 10.7 [6] and refer to International Terrestrial Reference Frame 2008 (ITRF2008) [7].

The velocities and standard errors from with respect to ITRF2008 were translated to the Sundaland block effect to make it appropriate for tectonic discussion. We transform the velocity from ITRF2008 into ITRF2000 prior to Sundaland block translation defined by Simon et al. [8]. In addition, those velocities may be affected by postseismic deformation due to the 2006 Yogyakarta earthquake. Moving average filter was applied to obtain the long-wavelength feature that active in the study region. Therefore, this technique can be used to separate long-wavelength deformation and short-wavelength deformation. The equations of this filter were written as follows:
\[
\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}
\]  

Where \( \bar{y} \) is the moving average of horizontal velocities, \( y_i \) is the observed horizontal velocities, and \( n \) is the amount of the GNSS site around the Opak fault. After we estimate the local velocities using a moving average filter (Figure 2), we then estimate the fault parallel velocities. The fault parallel velocities could be used to indicate the relative motion between the assumed block with respect to the fault segment.

![Figure 2](https://example.com/f2.png)

**Figure 2.** Blue lines and cyan lines indicate Opak river fault and another possible segment that ruptured due to the 2006 Yogyakarta earthquake, respectively. Red vectors show horizontal velocities while purple bars denote uplift.

### 3. Results and Discussion

We evaluate the plausible scenario of the 2006 Yogyakarta earthquake, assuming the epicenter and relocated aftershock distribution shown in Figure 1. The first possibility, we evaluate the observed short-wavelength of GNSS data assuming the earthquake occurred at the Opak river fault with eastward dipping fault (Figure 3a). However, we observed right-lateral strike slip motion rather than left-lateral, which is inconsistent with the left-lateral coseismic slip mechanism. The second possibility, we evaluate
the observed GNSS velocities assuming the earthquake ruptured at the unidentified fault on the eastern side of the Opak river fault. Thus, we observed left-lateral strike slip motion, which is similar to the kinematic of the coseismic slip. The second possibility is physically reasonable since most previous studies suggest interseismic and coseismic motion will show a similar tendency (e.g. [9]).

**Figure 3.** Fault trace and vectors description the same as Figure 1. (a) First possibility shows right-lateral fault, (b) The second possibility shows left-lateral fault.

Based on the second scenario where we found the unmapping fault, we calculate the length of this segment using the equation below.

\[
M_w = \left(\frac{2}{3}\right) \log M_o - 6.06
\]  

where

\[
M_o = \mu AS
\]

We assumed the rigidity (\(\mu\)) and coseismic slip (S) are 30 GPa and 1 meter, respectively. Since A is a surface area consists of length and depth, we assumed the depth of the earthquake to estimate the fault length. The depth of the earthquake sourced from the USGS catalog is 12.5 km. Therefore, we estimate the fault length is about 9.2 Km. In addition, based on Centroid Moment Tensor (CMT) catalog, the depth is 21.7 km. Thus, we obtain a shorter fault length of about 5.3 Km.

We estimate the maximum magnitude of earthquake potential assuming the rest of the Opak river fault ruptures at the same time. Using equation (2) and (3) with the estimated source depth, we obtain a maximum Mw 6.8. The estimated magnitude would bring a catastrophic disaster if the people of Yogyakarta do not become aware and prepared to mitigate the risk.
Figure 4. Fault trace and vectors description the same as Figure 1. The black square indicates the Opak river fault that assumed to be locked if the unidentified segment (blue line) length is 5.3 Km.

4. Conclusions
Our observation data suggest an unidentified active fault eastern side of the Opak fault, which is responsible for the 2006 Yogyakarta earthquake. The unidentified fault length is between 5 to 9 Km. The estimated length of unidentified active fault implies a potential future earthquake with a maximum magnitude of 6.8 (Mw). Seismic source inversion is necessary to reduce uncertainty in focal depth and clarify the fault location. Our moving average filter may contain postseismic deformation due to the 2006 Yogyakarta, therefore we intend to evaluate the coseismic source inversion based on postseismic deformation in further study.

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