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Seismic hazard identification around Surabaya City, East Java, Indonesia: a preliminary result based on the June 2023 Mojokerto earthquake

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Abstract - An earthquake was felt in the Mojokerto area, East Java (Indonesia) with a magnitude of M 4.4. This area has a low seismicity level according to the latest earthquake catalog. In this paper, we conduct a study to determine the direction of fault movement in the area, using data from BMKG seismic sensors with a distance of less than 250 km. The moment tensor inversion results show that the Strike/Dip/Rake values at each nodal plane are 257/88/4 and 167/86/175. To determine the direction of fault movement, we prefer a strike of 167 degrees for this earthquake, following the direction of deformation around the area from the northeast of Java Island. From the results of the moment tensor solution and the history of seismicity that has occurred in the area around Surabaya, it can be shown that the city of Surabaya is a city that is close to seismic activity, although it tends to have small activity, this needs to be considered considering that Surabaya is one of the cities with the highest population density in Indonesia. Further research needs to be done related to disaster vulnerability around the city of Surabaya. From the results of the source mechanism and seismicity in the Surabaya area it can be concluded that the Surabaya area has a disaster risk, there needs to be further research that discusses the local footprint effects of soil in the area in the Surabaya area. This research is needed for further discussion of the possibility of disasters in the Surabaya area.

Keywords: earthquake, moment tensor, source analysis, Surabaya

1 Introduction

On June 19, 2023, an earthquake occurred in the Mojokerto area (East Java) with a magnitude of M 4.4. This earthquake had a depth of 14 km (Badan Meteorologi Klimatologi dan Geofisika/BMKG). The East Java region, especially Mojokerto and Surabaya, is an area with a low seismicity level according to the latest BMKG catalog. This is evidenced by earthquake data from BMKG for three years, from 2020 to early 2023, totaling ~64 events with a maximum magnitude (Mmax) of 6.5 and a minimum magnitude (Mmin) of 2.2, the region only experienced that many earthquakes. The area around East Java is flanked by the Surabaya segment of the Kendeng Fault which runs from west to north of Java. And, the Bali Basin fault, which starts from the east of Java to the island of Bali (Figure

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1), an inactive fault actually holds a large potential for earthquakes because there has been no release of energy.

Surabaya is one of the cities with the highest population density in Indonesia. Although earthquakes rarely occur around Surabaya, the tectonic conditions and history of seismicity in the area require a study of the fault mechanisms around the area in order to reduce disaster risk and know the tendency of the direction of fault motion in the area.

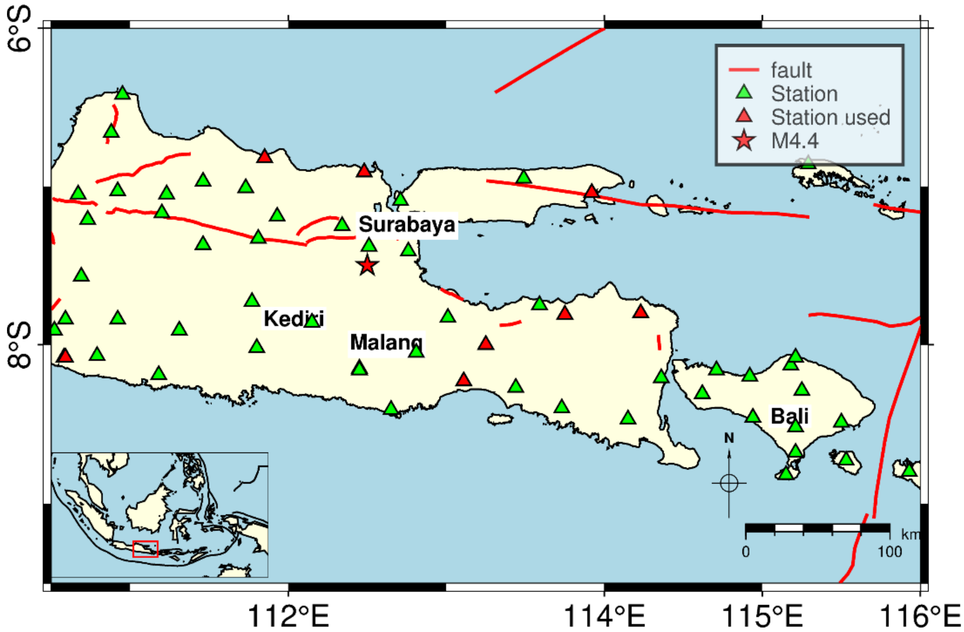

Fig. 1. Tectonic setting of Eastern Java with the crustal fault (red lines) taken from Indonesia's 2017 Earthquake Source and Hazard Map. The red star is the mainshock epicenter of the 2023 Mojokerto earthquake according to BMKG. Green triangles show the BMKG seismic stations; Red triangles show the seismic station used in the moment tensor inversion.

In this study, we conducted seismicity and source mechanism analysis including moment tensor inversion of the 2023 Mojokerto earthquake that had been felt by population in the Surabaya City, the major city in East Java. We utilized BMKG seismic data to conduct the methodology. Our result will help in seismic hazard identification in East Java that may affect Surabaya City. Our result is necessary for seismic hazard analysis in the East Java region.

2 Material and Method

One way to know the characteristics of the source of an earthquake is by knowing the moment of force acting on the fault plane, this moment of force will be easier to know by assuming that the earthquake is a point, then there are nine pairs of forces, the nine pairs of forces are then made into a 3 x 3 matrix, where the matrix describes the moments acting on each axis, because of the law of conservation of momentum, the nine pairs of forces that work can be reduced to six pairs of forces [1]–[4]. These six pairs of forces can be found using linear inversion. Then the known force pairs can be used to find the fault plane components, namely strike, dip, and rake. Besides, these force pairs can also be used to obtain moment magnitudes. The data used in this study to find the six pairs of forces is waveform data from BMKG seismic stations with a radius of less than 250 km (**Fig 2.).**

There are two inversion methods used to determine the moment tensor of an earthquake, namely frequency domain and time domain. In this study, the Time Domain Inversion Solution is used because it is more popular and faster because it does not need to convert waveforms to the frequency domain [5]. This program was later developed into the Python programming language known as the

MTTime program [6]. In this study, to reduce the effect of surface waves, a bandpass filter with a period of 20-40 s is used. Then to calculate the green function, a computer seismology program with Fortran language is used [7], [8], with a crustal velocity model 1.0 which is based on gravity data every 1 degree, this velocity model is an update with better resolution than the crustal velocity model 2.0 [9].

Then to find out the vibrations caused by the earthquake, we used peak ground acceleration (PGA) analysis, by identifying the distribution of stations less than <100 Km from the epicenter. This analysis is carried out per component so that later 3 components are obtained, namely north south, west east, and vertical[10].

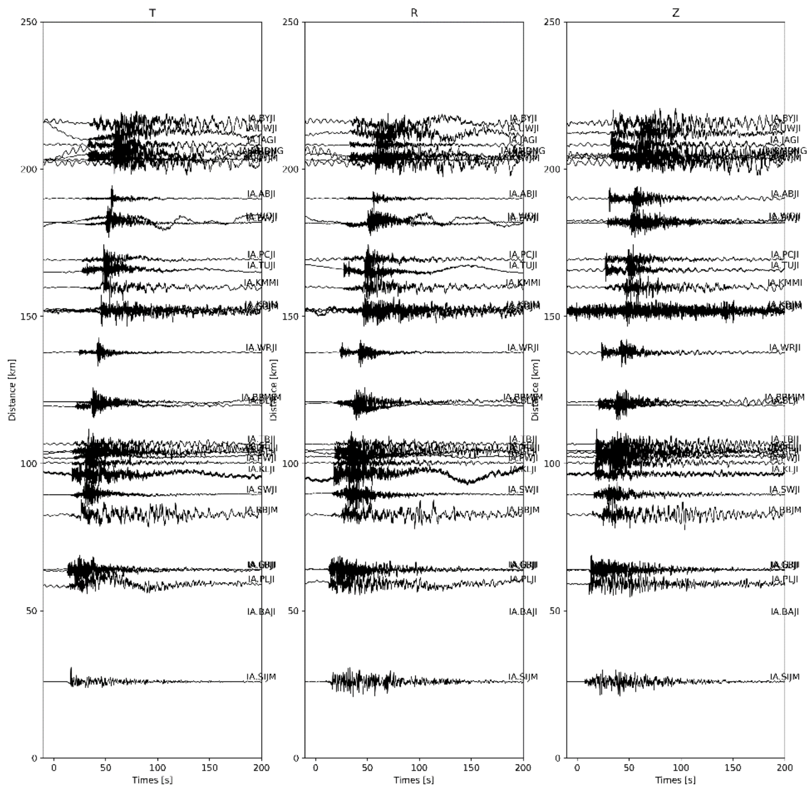

Fig. 2. Waveforms from stations at a certain distance from the epicenter. Earthquake data that has been reoriented from ZNE to ZRT. It can be seen that some stations have poor data, such as KLJI.

3 Result and Discussion

The results were obtained by using all stations at a radius of <250 km. get the enlargement source mechanism is strike-slip, but in this case, the Variation Reduction (VR) value is still low, which is less than <45% (Figure 3B). VR is the result of the calculation between synthetic data obtained from inversion results and observation data. Low VR can indicate the level of quality data used in this case the orientation of the sensor [11], in this case it can be seen that the PRJI sensor gets a VR minus result of almost 200 due to missorientation, because the data obtained VR < 45%, a filter is performed by eliminating stations with VR < 45%, so that the total stations used are 8 stations with VR values > 45% (Fig. 3C). The results of waveform fitting at each station show results that are quite consistent with the synthetic data (Fig. 3A).

The inversion results show that the strike/dip/rake values in each model plan are 257/88/4 and 167/86/175. To determine the direction of fault movement, researchers chose to strike 167 in this earthquake, in accordance with the direction of deformation around the area from the northeast where this northeast direction is obtained based on the results of GPS measurements, actually, this direction is influenced by the southern Java subduction zone and western Sumatra subduction [12]–[14] while judging from the dip slope this fault is a pure strike-slip fault.

The peak ground acceleration (PGA) results of the three components (Figure 4) show that the largest acceleration is located at the WGJM sensor, with an acceleration of 0.21 m/s2 in the east-west component, followed by the north-south component, and finally the vertical component. this acceleration can describe the amount of energy radiated when the sensor records an earthquake [15]. the value of the three components can actually provide an idea of the orientation of movement on the fault plane. these results are associated with the inversion results of the moment tensor and the direction of deformation in eastern Java.

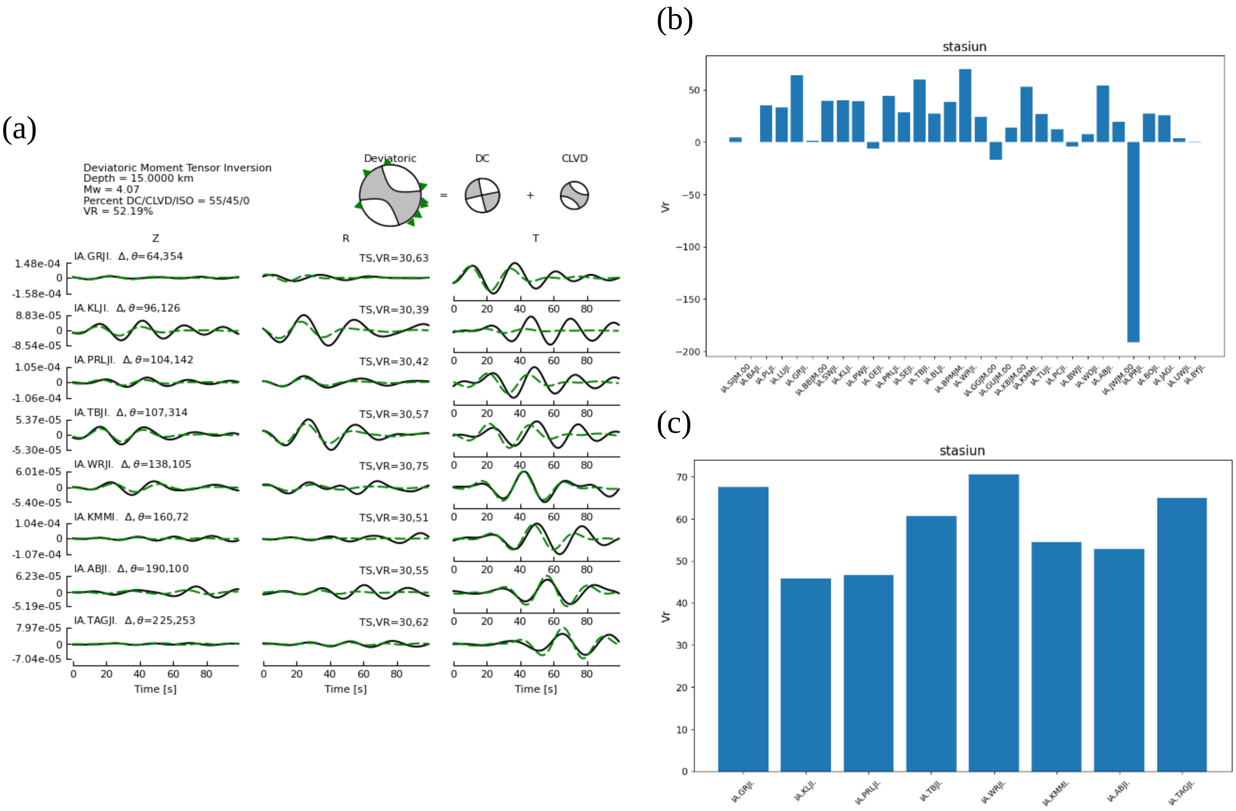

Fig. 3. a) Waveform fitting from a filtered station. It was found that the variation reduction value was above 45%. b) The reduced variation value for each station with a radius of less than 250 km from the epicenter. c) The result of reduced variations from stations that have been filtered.

Table 1. Max PGA in WGJM Sensor

MAX PGA (M/S^2)		
East	North	Vertical
0.21	0.11	0.04

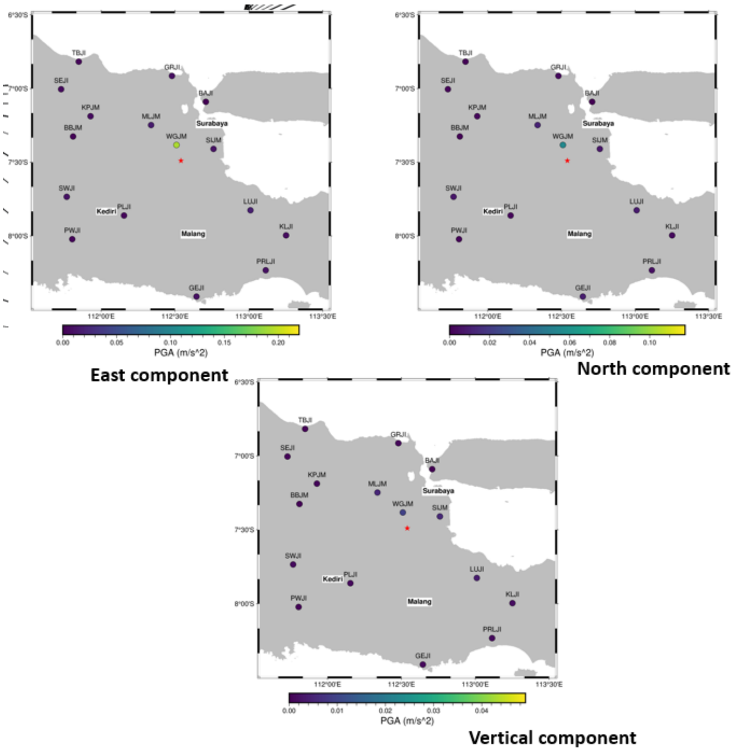

Fig. 4. Peak ground acceleration results of the three components at sensors with a radius of less than 100 km from the epicenter.

Based on the results of the moment tensor and PGA analysis, it is known that this earthquake event was caused by a force that also caused deformation in eastern Java. Based on the history of seismicity that occurred over the past 2 years, it is known that there were two earthquakes (**Table 2**), both of these earthquakes had magnitudes > 4 but had different epicenters where the first earthquake was located east of Surabaya, and the second earthquake was located in southern West Java. the first earthquake had a trust fault mechanism. these two earthquakes produced MMI III in Surabaya, MMI III itself is like vibration when a large transportation truck passes.

Table 2. The earthquake was felt in Surabaya and its surroundings

Date	Magnitude (M)	Depth (km)	Perceived intensity
Jan 15, 2022	4.1	14	III MMI in Juanda, East Surabaya and North Surabaya. II MMI in Sumenep
Jan 19, 2023	4.4	10	III-IV in Mojokerto, III in Pasuruan, Suarabaya, Lamongan, and Gresik, II-III in Sidoarjo, II in Malang

Geologically, Surabaya is an area that has sedimentary soil types, consisting of mud deposits, sand deposits, and alluvial deposits whereas areas that have sedimentary soil types tend to have soft and medium soil characteristics [16], [17].

From the results of the moment tensor, PGA analysis, history of earthquakes, and geological studies occurring in the area around Surabaya, it can be seen that the 4.1 earthquakes in Mojokerto had a strike-slip mechanism, with the highest land surface contact being in the west-east component, the city of Surabaya is a city that has seismic activity even though tends to have little activity, with geology dominated by soft and temperate soils. However, this needs to be taken into account considering that Surabaya is one of the cities with the highest population density in Indonesia. Further research is needed regarding disaster vulnerability around the city of Surabaya, especially the effect of local footprints in the Surabaya area on earthquakes around that area.

4 Conclusion

Based on the results of moment tensor analysis, PGA analysis, the history of earthquakes in the last two years, and the geology of the Surabaya area, it can be concluded that Surabaya is an area with low potential for seismic disasters, earthquake sources in the area are dominated by thrust faults and strike-slip faults. However, geologically, the Surabaya area is an area with soft and moderate soil conditions which, if an earthquake occurs, can experience amplification. There is a need for further research regarding the factors that cause amplification in Surabaya and any areas that have the potential for earthquake disasters and secondary disasters after an earthquake such as land. landslides and liquefaction.

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