Investigating the Mainshock and Aftershock of the May 2006 Earthquake in Central Java for Aerothropolis Development at Yogyakarta International Airport

Hijrah Saputra[1], Rian Amukti[2], Sugeng Purwo Saputro[3], Mochamad Aryono Adhi[4], Ahmad S Pohan[5], Sismanto Sismanto[6], Budi Eka Nurcahya[6], Richard Lewerrisa[7], and Sorja Koesuma[8]

[1]Airlangga University
[2]Center of Geological Disaster, National Research & Innovation Agency
[3]National Research and Innovation Agency (BRIN)
[4]Department of Physics, Faculty of Mathematics and Natural Sciences, Semarang State University
[5]Department of Physics, Faculty of Mathematical and Science, Andalas University
[6]Universitas Gadjah Mada
[7]Universitas Papua
[8]Universitas Sebelas Maret

March 9, 2023

Abstract

Research on the analysis of the source mechanism of the mainshock and aftershock events of the May 27, 2006, Yogyakarta earthquake, which is thought to have originated from the Opak fault and analysis of receiver function data to model the subsurface velocity P of the Central Java subsurface, to obtain a geological form model of the Opak fault. This research aims to support the development of the Yogyakarta Aerothroppolis area in terms of disaster analysis. The data used in this study are remote Teleseismic receiver function data from the MERAMEX station installed in 2004, and data for the Bantul earthquake event and its aftershock event in 2006. The results obtained from the analysis are that the Yogyakarta area is shaped like a half-graben close to Yogyakarta International Airport. The fault that separates the western part of Yogyakarta is still not identified. Based on the results of the rupture process analysis of the source along the Opak fault plane, some zones have not yet released their energy. The distribution of aftershocks due to the mainshock on 27 May 2006 is spread around the Opak fault, which is heading North-South, and West-East, which is thought to have activated the minor fault to the east of the Opak fault. The opak fault rupture area can be analyzed to have a Low Anomaly velocity P value from the receiver function data and is the same as the aftershock event obtained.

Investigating the Mainshock and Aftershock of the May 2006 Earthquake in Central Java for Aerothropolis Development at Yogyakarta International Airport

Hijrah Saputra[1*], Rian Amukti[2*], Sugeng P Saputra[3], Mochamad Aryono Adhi[4], Ahmad S Pohan[5], Sismanto[6], Budi Eka Nurcahya[7], Richard Lewerissa[8], Sorja Koesuma[9]

[1]Affiliation for author 1. Postgraduate School, Universitas Airlangga, Surabaya

[2]Affiliation for author 2. Center of Geological Disaster, National Research & Innovation Agency (BRIN)

[3]Affiliation for author 3. Research Center for Geological Resources, National Research and Innovation Agency (BRIN)

[4]Affiliation for author 4. Department of Physics, Faculty of Mathematics and Natural Sciences, Semarang State University

[5]Affiliation for author 5. Department of Physics, Faculty of Mathematical and Science, Andalas University, Jl. Universitas Andalas Limau Manis Pauh, Padang, 25163, Indonesia

[6]Affiliation for author 6. Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia

[7]Affiliation for author 7. Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia

[8]Affiliation for author 8. Department of Physics, Faculty of Mathematics and Natural Sciences, Papua University, Manokwari, Papua Barat 98314, Indonesia

[9]Affiliation for author 9. Department of Physics, Faculty of Mathematics and Natural Sciences, Sebelas Maret University

Corresponding author: Hijrah Saputra (hijrah.saputra@pasca.unair.ac.id); Rian Amukti (rian.amukti87@gmail.com)

Key Points:

- Analysis of source mechanisms of mainshock and aftershock events of May 27, 2006, earthquake in Yogyakarta, Central Java.
- Use of receiver function data to model the subsurface velocity P and obtain a geological form model of the Opak fault.

- Research aimed at supporting the development of the Yogyakarta Aerothropolis area in terms of disaster analysis.

Abstract

Research on the analysis of the source mechanism of the mainshock and aftershock events of the May 27, 2006, Yogyakarta earthquake, which is thought to have originated from the Opak fault and analysis of receiver function data to model the subsurface velocity P of the Central Java subsurface, to obtain a geological form model of the Opak fault. This research aims to support the development of the Yogyakarta Aerothropolis area in terms of disaster analysis. The data used in this study are remote Teleseismic receiver function data from the MERAMEX station installed in 2004, and data for the Bantul earthquake event and its aftershock event in 2006. The results obtained from the analysis are that the Yogyakarta area is shaped like a half-graben close to Yogyakarta International Airport. The fault that separates the western part of Yogyakarta is still not identified. Based on the results of the rupture process analysis of the source along the Opak fault plane, some zones have not yet released their energy. The distribution of aftershocks due to the mainshock on 27 May 2006 is spread around the Opak fault, which is heading North-South, and West-East, which is thought to have activated the minor fault to the east of the Opak fault. The opak fault rupture area can be analyzed to have a Low Anomaly velocity P value from the receiver function data and is the same as the aftershock event obtained.

Keywords: Rupture, aftershock, receiver function, opak fault, aerothropolis.

Plain Language Summary

This study analyzes the source mechanism of the main earthquake and its aftershocks that occurred on May 27, 2006, in Yogyakarta, Indonesia, believed to have originated from the Opak fault. The researchers used receiver function data to model the Central Java subsurface velocity P and obtained a geological form model of the Opak fault. The study aimed to support the development of the Yogyakarta Aerothropolis area in terms of disaster analysis. The results showed that the Yogyakarta area is shaped like a half-graben close to Yogyakarta International Airport. The fault that separates the western part of Yogyakarta has not yet been identified. The distribution of aftershocks due to the mainshock was spread around the Opak fault, which is heading North-South and West-East, and it is thought to have activated the minor fault to the east of the Opak fault. The study also found that the Opak fault rupture area can be analyzed to have a low anomaly velocity P value from the receiver function data and is the same as the aftershock event obtained. This study provides valuable information for disaster analysis in the Yogyakarta Aerothropolis area.

1 Introduction

Yogyakarta is an area that has its uniqueness and charm, so many tourists come, both local and foreign. This has a positive impact on regional growth. The area around the airport, with many business activities or commercial services, is the basis for forming the aerotropolis area concept (Kasarda, 2016). This concept was developed in the Yogyakarta International Airport area to increase business competitiveness which will have an impact on the community's economy so that it will have a large effect (Sumarata, 2021). This condition is supported by proper planning, including security from the threat of disaster.

Yogyakarta is not only a popular tourist destination but also an area that is prone to earthquake disasters due to its location on the active tectonic plate. According to the National Disaster Management Agency (BNPB), Yogyakarta has a high seismic hazard level, with 21 active faults identified in the region (BNPB, 2021). Therefore, proper disaster risk management is crucial in aerotropolis planning to minimize the potential impact of earthquakes on the community's economy and livelihoods. This can be achieved through a comprehensive analysis of the earthquake risk, including the identification of vulnerable areas and the implementation of appropriate measures to mitigate the risk. In addition, community participation and awareness-raising programs should be incorporated into the disaster risk management plan to ensure the sustainability of the aerotropolis area development. By considering the earthquake risk and implementing appropriate measures, the aerotropolis area in Yogyakarta can develop sustainably and contribute to the economic growth of the region while ensuring the safety and well-being of the local community.

The principles of aerotropolis planning consist of regional spatial structure, distance, zoning, land use, designation of the main functions of the area, integration, and connectivity (Kurniawan, 2016; Yujin, 2013; Wang, 2013; Greis, 2011). To find out good spatial planning in aerotropolis planning, an in-depth analysis of disasters in the area is also needed (Surya et al., 2020). Both seasonal disasters, such as floods and tornadoes, and large, unpredictable disasters, such as volcanoes, earthquakes, and tsunamis (Ammon et al., 2006). Therefore, this research was conducted to support one side of the earthquake disaster, which can be analyzed from many events around the area (Kuncoro et al.,2020.

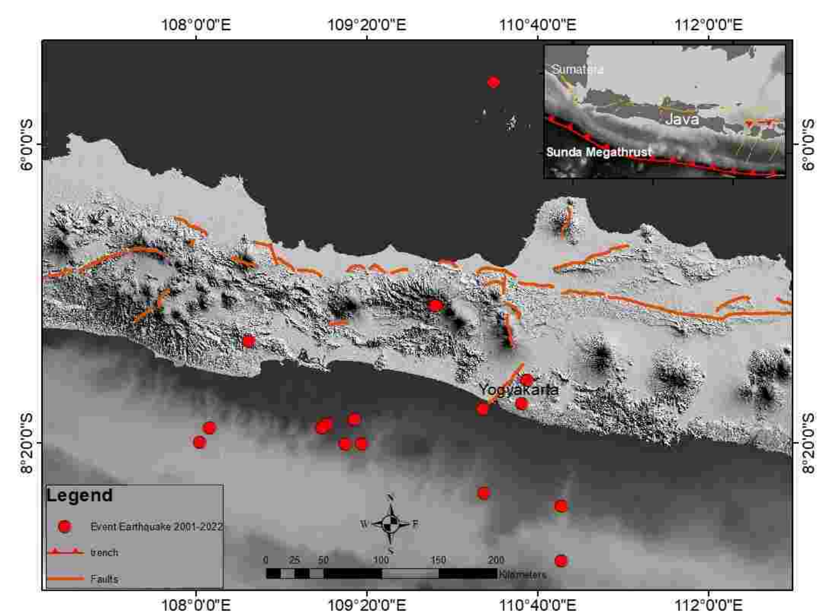

Figure 1. Earthquake distribution map for 2001-2022 around Central Java and Yogyakarta. The red circle is the mainshock distribution that has been relocated. The brown lines are the distribution of faults spread across Java island.

The feasibility study has succeeded in reconstructing the source model in detail and analyzing the source mechanism and the rupture process of the May 27, 2006, Yogyakarta earthquake by knowing the coseismic process and the seismotectonic characteristics of the study area. So by knowing the physical characteristics of the May 27, 2006, Yogyakarta earthquake, we can understand the destructive nature of the earthquake, so it can be used as a guide for earthquake mitigation, especially the Yogyakarta earthquake (Saputra et al., 2021). However, to obtain information on the source mechanism and phenomenon of May 27, 2006, Yogyakarta earthquake, it is recommended to use other earthquake data. So that a more detailed analysis of the mechanism of the source and the process of earthquake rupture in the research area will be obtained so that the characteristics of the Opak fault will be known in more detail, especially after 2020, Yogyakarta International Airport, which is located in Temon District, Kulon Progo Regency, has been operating. The airport area will be built with the Aerotropolis concept in its development. In the Yogyakarta Regional Regulation number 5 of 2019 concerning the 2019-2039 Regional Spatial Plan for the Special Region of Yogyakarta, the development of the Temon-Prambanan Area is projected to become one of the province's strategic areas from an economic point of view. One form is the development of the aerotropolis area. Aerotropolis can increase economic growth in a country or region (Peoples, 2014). The concept of the Yogyakarta aerotropolis with a radius of about 15 km from the airport (Syaifuddin et al., 2021).

This research aims to analyze the physical characteristics and the source mechanism of the May 27, 2006, Yogyakarta earthquake. The urgency of this study is to provide a better understanding of the destructive nature of the earthquake and to provide guidance for earthquake mitigation, especially in the Yogyakarta region. The results of this study can also provide important information for the development of the aerotropolis area around Yogyakarta International Airport. Understanding the seismotectonic characteristics and potential risks of earthquakes in the area is crucial for ensuring the safety and sustainability of the airport and the surrounding region. Additionally, this research can contribute to the advancement of earthquake science and the development of effective strategies for disaster risk reduction.

2 Materials and Methods

2.1 Receiver function data

The method used in this study is the aftershock relocation method to determine the aftershock event in the 2006 earthquake that occurred to obtain a rupture zone (Saputra, 2021). The relocation method was conducted using the hypoDD code (Waldhauser and Ellsworth, 2000) and the double-difference algorithm (Zhang et al., 1889). This event data is combined with the subsurface velocity model data resulting from the Receiver Function method (Figure 2) using the MERAMEX network installed in 2004 (Amukti, 2019). The MERAMEX network is a dense seismographic network that consists of 24 broadband and short-period seismometers, covering an area of approximately 200 km radius around the study area. The subsurface structure is then analyzed using the tomographic inversion method, which allows for a more detailed study of the subsurface velocity structure and can provide insight into the characteristics of the active fault in the study area.

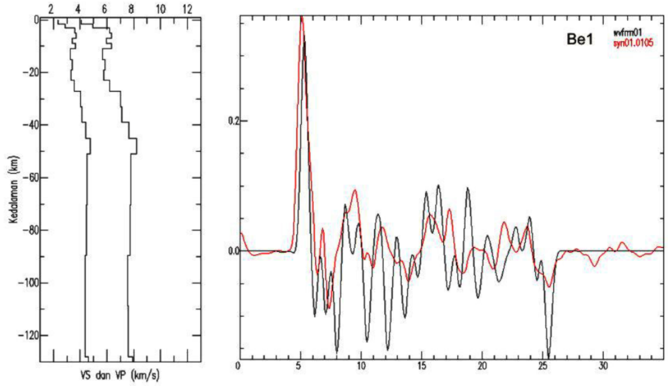

Figure 2. Example of receiver function data

2.2 Aftershocks data

This study also uses relocated aftershock data obtained from temporary seismometers installed after the 2006 Yogyakarta mainshock. In this analysis, the study employs the aftershock relocation method to determine the precise location of each aftershock event and reduce uncertainty in earthquake location determination.

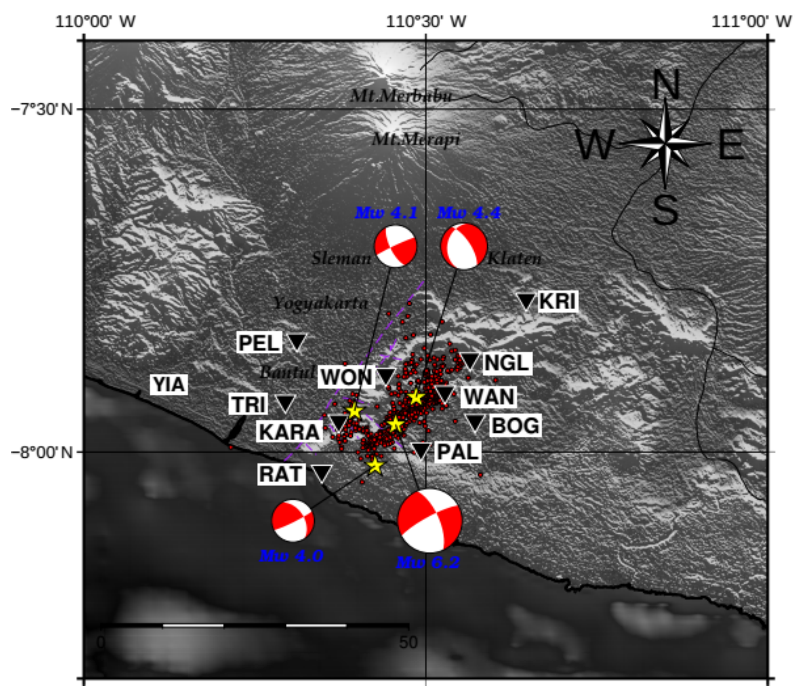

Figure 3. Distribution of relocated aftershocks taken from temporary seismometer recordings. The red circle is the relocation aftershock distribution. The grey triangles are seismometers. The red and white focal ball is the mainshock and aftershock issued by the USGS.

Figure 3 shows the enlargement between the mainshock and the three aftershocks, namely on June 8, 9 and 16, which had different types of displacement. This shows the complexity of the faults around the Opak fault. The results of the mainshock rupture process analysis in the study of Saputra et al. (2021) show two weak zones and can be seen from the distribution of aftershocks scattered around the asperity zone (weak zone). Between the weak zones, there is a seismic gap, indicated as a zone that has not yet released its energy.

3 Data

This study utilized the earthquake aftershock location method to determine the aftershock events of the 2006 earthquake in order to obtain the fault zone. The location method was performed using the hypoDD code (Waldhauser & Ellsworth, 2000) and the double-difference algorithm (Zhang et al., 1889). The earthquake data was combined with subsurface velocity model data generated from the Receiver Function method (Figure 2) using the MERAMEX network installed in 2004 (Amukti, 2019). The MERAMEX network is a dense seismograph network consisting of 24 broad-band and short-period seismometers covering an area of about 200 km radius around the study area. The subsurface structure was then analyzed using the tomographic inversion method, which allows for a more detailed study of the subsurface velocity structure and provides insights into the characteristics of active faults in the study area.

The aftershock data was also used in this study, obtained from temporary seismometers installed after the main earthquake in Yogyakarta in 2006. In this analysis, the study used the earthquake location method to determine the precise location of each aftershock event and reduce uncertainty in determining the earthquake location. Figure 3 shows the enlargement between the main earthquake and three aftershocks on June 8, 9, and 16, which have different displacement types. This indicates the complexity of faults around the Opak fault. The results of the faulting process analysis in the main earthquake by Saputra et al. (2021) show the presence of two weak zones, which can be seen from the distribution of aftershocks scattered around the asperity zone (weak zone). Between the weak zones, there is a seismic gap, which is indicated as a zone that has not yet released its energy.

In this study, the Receiver Function method was used to generate the subsurface velocity model, which was then combined with the aftershock location data to obtain insights into the characteristics of active faults in the study area. The tomographic inversion method was used to obtain more detailed information about the subsurface structure. In addition, the earthquake location method was also used to determine the precise location of each aftershock event, which helps in understanding the complexity of faults around the Opak fault. The results of this study show the presence of two weak zones and a seismic gap between the weak zones. These results can provide important information for understanding the potential earthquake hazards in the region.

4 Results, or a descriptive heading about the results

4.1 Analysis of the earthquake source rupture process

Analyzing the earthquake source rupture process is critical to seismological research, as it helps understand the mechanisms that trigger earthquakes. In this study, the researchers used the finite fault inversion method to analyze the earthquake source rupture process of the Yogyakarta earthquake. The results showed that the rupture process was a unilateral propagation from the southwest to the northeast. Moreover, the fault length was approximately 28 km, and the maximum slip was estimated to be around 1.4 meters. The results are crucial in improving our understanding of the characteristics of the Yogyakarta earthquake and provide valuable information for developing effective earthquake mitigation strategies.

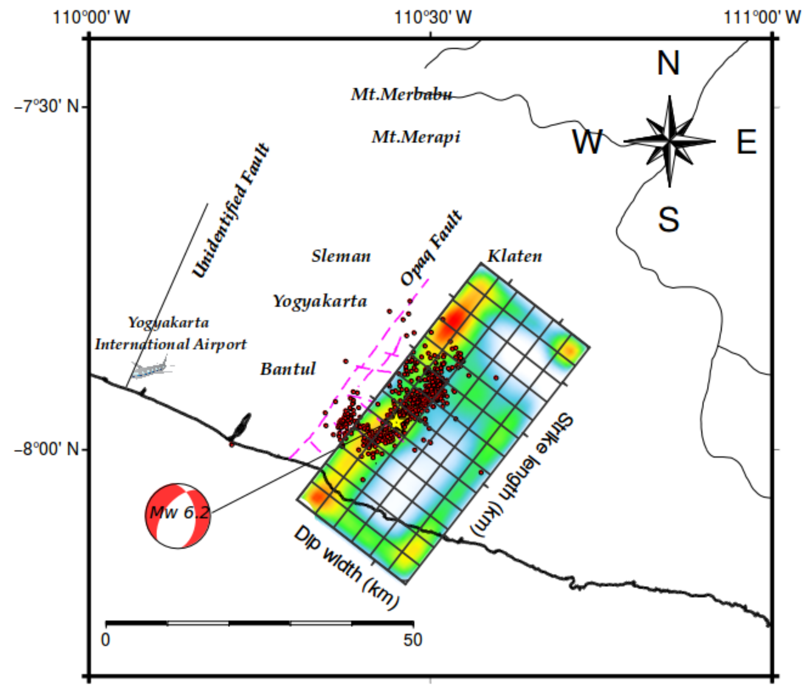

Figure 4. The results of the analysis of the rupture process of the Yogyakarta earthquake on May 27, 2006, show the slip distribution from the opaque fault plane. The rectangular contour is the distribution of slip on the opaque fault plane. The red colour circle is the aftershock distribution. The yellow star is the Yogyakarta earthquake mainshock, resulting from a joint inversion research by Saputra et al. (2021). The purple dotted line is an opaque fault, and on the east side of the main fault, there are several minor faults. The black line is the boundary of the graben zone, where the fault has not been identified. The red and white focal ball results from a joint inversion calculation from Saputra et al. 2021 study (modification from Saputra et al. Research, 2021).

Figure 4 shows the coseismic slip distribution of the May 27, 2006, Yogyakarta earthquake along the opaque fault plane overlaid with the aftershock distribution, which is the result of research by Saputra et al. (2021). The aftershock distribution pattern converges in the area of maximum slip. The concentration of slip that collects in the aftershock zone area indicates that there is a continuous release of energy (Sykes, 2021). In the middle of the slip zone, there is a seismic gap that shows the behaviour of the fault. The asperity zone is very important to know as a basis for the initial analysis of earthquake hazards (Corbi et al., 2017; Lay et al., 1981; Abercrombie et al., 2001). If you look at the displacement pattern between the mainshock and aftershock, as shown in Figure 2, it is quite clear that the displacement pattern is different. So it can be concluded that the source of the earthquake came from a different fault area. This shows the complexity of the Opak fault. The slip distribution pattern shown in Figure 3 also shows that there is a white colour in the middle of the Opak fault plane. This indicates that this zone is a zone that has not yet released its energy, one day, it can trigger other fault fields around the main opaque fault. Several earthquake events that occurred after 2006 are still widely distributed around the Opak fault. On the western fault boundary, it can be seen that there is a weak field that has not yet released energy. This boundary is very close to the location of Yogyakarta International Airport.

4.2 Receiver function data

The receiver function method is used to model the subsurface with teleseismic earthquake events (Amukti, 2019). Figure 5 shows the distribution of MERAMEX stations which were installed in 2004 with a black triangle symbol, the Bantul earthquake aftershock event in 2006 with a red circle symbol, and also the Jogjakarta International Airport, which is coloured in a green circle.

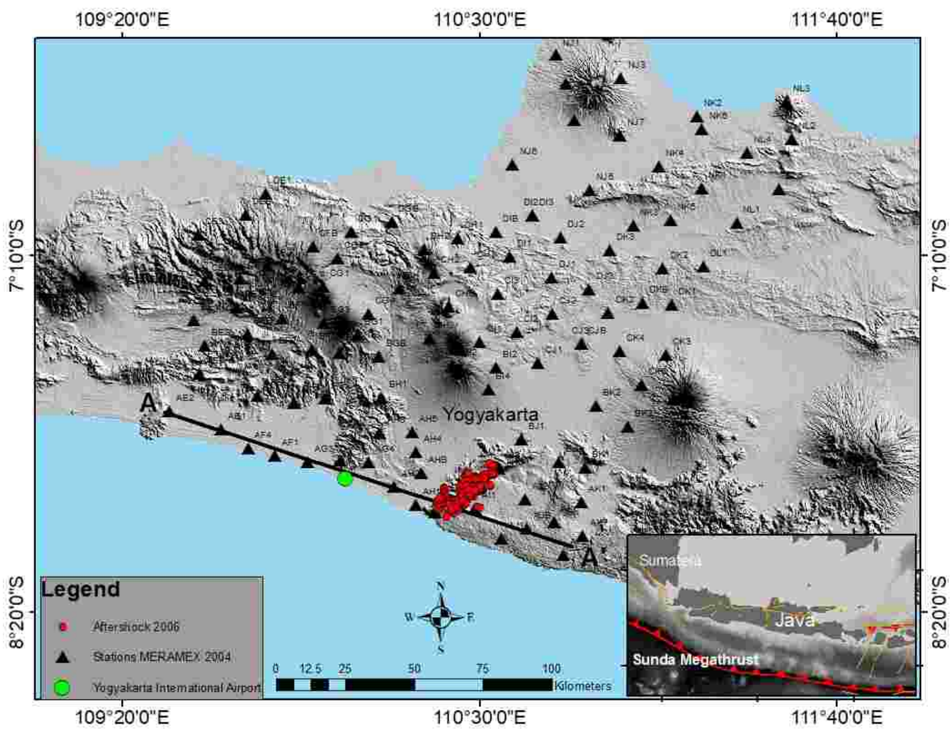

Figure 5. Aftershock distribution of the 2006 Yogyakarta earthquake recorded from the Meramex station installed in 2004. The red circles are the distribution of aftershocks. The black triangle is the distribution of Meramex stations. The red and yellow lines on the map index are subduction zones and local faults on the mainland, respectively. The black line is the velocity (Vp) model slice from A-A.'

The velocity (Vp) results from the receiver function method are modelled to obtain an overview of the subsurface slices between points A to A' as shown in Figure (6). The aftershock event is seen at a depth of 5-20 Km and is located in the Low-Velocity Anomaly model. To view laterally, a velocity model is created at a depth of 11 km (Figure 6).

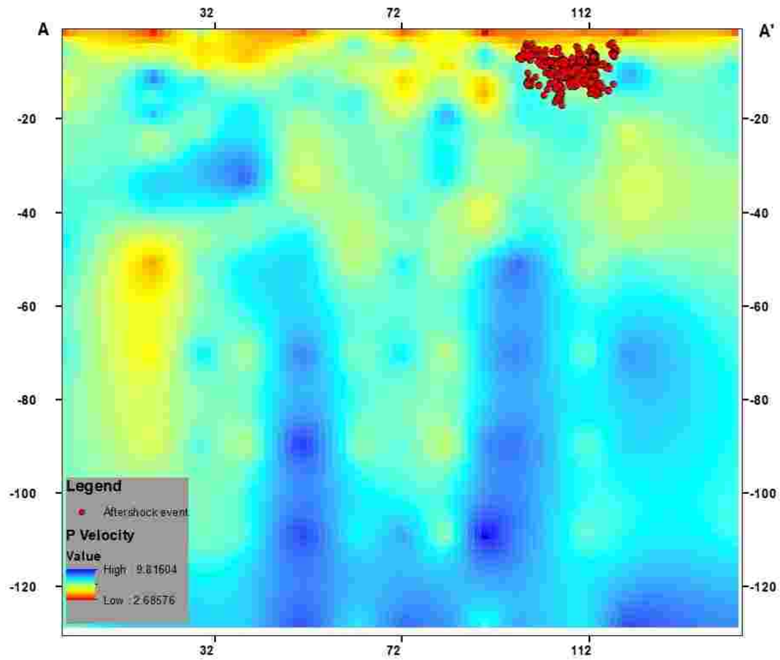

Figure 6. Model Velocity (Vp) of the Receiver Function and combined with the aftershock event data on the A-A slice. The red circle is the aftershock distribution of the depth function.

Figure 7 shows the distribution of P waves in Central Java with a depth of 11 Km. If further analyzed, it will be seen the distribution of P waves which have high speeds of up to 8 Km/s, will form fragments (Amukti, 2019). These results explain that there is a fault in central Java known as the Maratus zone, which continues from Borneo Island to Java Island. This analysis is based on previous research conducted by Wakita (2000), Smith et al. l (2005), Hall and Sevastjanova (2012), Haberland et al. (2014), and Wölbern and Rümpker (2015). Figure 7 also shows that the Velocity P model and aftershock data have a relationship, where the aftershock event is right in the low anomaly area of velocity in the area around the Opak fault.

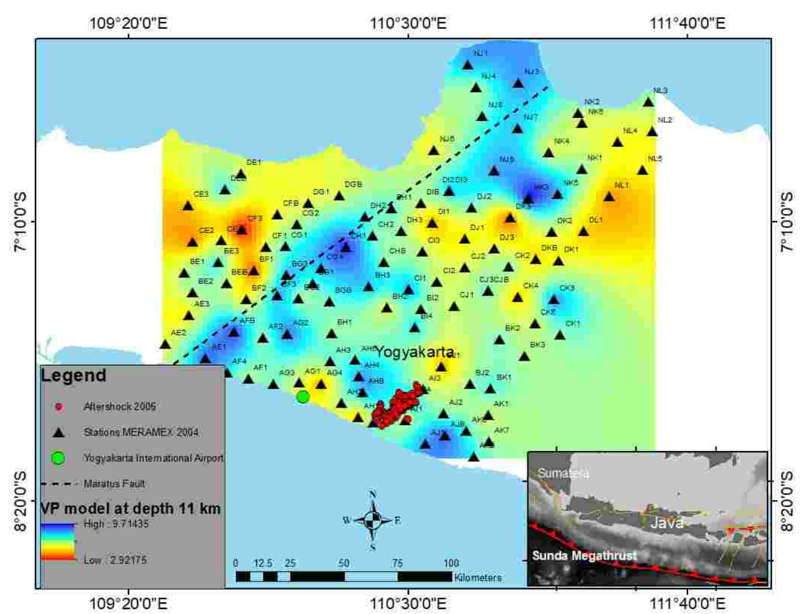

Figure 7. Model velocity (Vp) combined with the aftershock event at a depth of 11 Km. The red circle is the relocated aftershock distribution. The black triangle is the distribution of Meramex stations. The green circle is the international position of Yogyakarta airport.

Another interesting thing is that right below Yogyakarta International Airport has a low anomaly velocity as well, so a more detailed analysis and interpretation is needed in this area, so a 3-dimensional model was made (Figure 7).

Figure 8 shows a reconstructed 3-dimensional model of the Receiver Function and Aftershock Event, and a geological model is created that can explain this situation. The opaque fault is seen in the low-velocity anomaly, but from the aftershock event data, it is explained that the ruptured fault does not persist in the Opak fault but is more to the east and has a curved shape. To the north of the Opak fault, there is the Mataram fault which was confirmed by the National Earthquake Center in 2022.

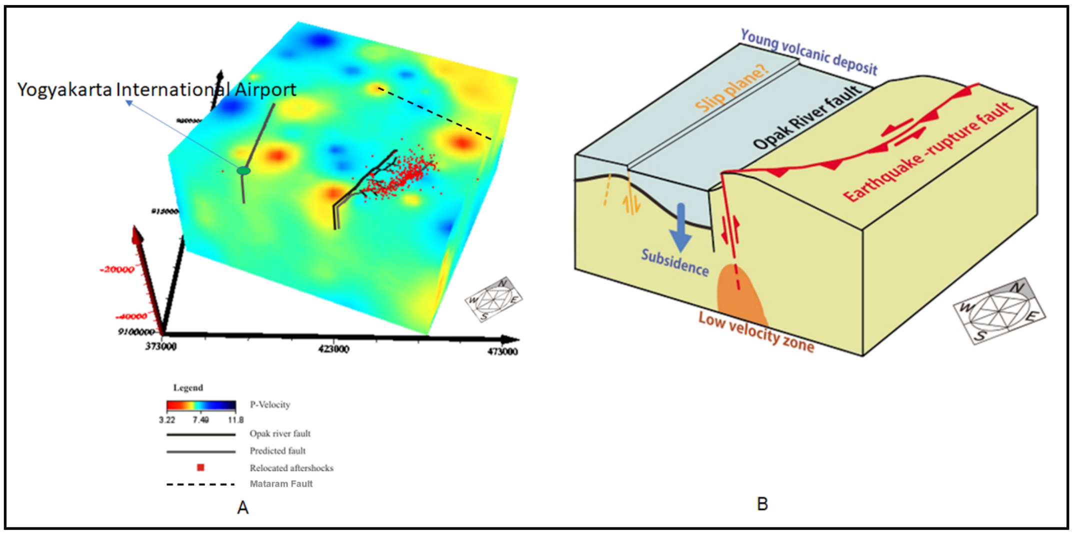

Figure 8. 3D Model Reconstruction. A. It is a 3-dimensional model of the data velocity (Vp) receiver function. B. It is a geological model interpretation image of the Opak Fault.

What is interesting is that to the west, there is a low-speed anomaly that can be interpreted as a prediction of aircraft errors/slips, and this anomaly is right under the construction of the Yogyakarta International Airport (Figure 8. a). However, this still needs to be confirmed with other geophysical research methods such as the Gravity, Electromagnetic and geological observation accuracy surveys in the field.

On May 26, 2006, at 22:54 UTC, Yogyakarta was rocked by an earthquake. Many scientists debate the sources and mechanisms of how earthquakes occur. The opinion most often expressed by scientists is the source of the earthquake originated from the Opak fault activity. The German Task Force (GTF), together with the Seismological Division of the Meteorological and Geophysics Agency (BMG), undertook the installation of a seismic station around the Opak Fault to record aftershock events (Walter et al, 2008). The recording results show that the epicentres of the aftershocks were not aligned along the Opak River Fault but 10 km further to the east (Walter et al., 2008).

Tsuji et al. (2009) observed the Yogyakarta earthquake with SAR interferometry. His research results show that surface deformation occurred 10 km east of the Opak River Fault which is suspected as the source of the May 2006 event. He modelled a schematic diagram of the relationship between the earthquake fault, the Opak River Fault, and subsidence in young volcanic deposits. The conclusion from the model is that the earthquake displacement has a reverse slip component in addition to a strike slip along the eastern oblique fault plane.

In order to prove this, this research conducted modelling of the P wave velocity structure in the area around the Opak River Fault using MERAMEX data which was installed in 2004, and the Yogyakarta earthquake occurred in 2006. To analyze the Opak Fault, we added aftershock data from Anggraini (2014) and Saputra (2021).

Geologically, the Opak Fault is an active fault with a long continuity (almost North-South), and its movement is controlled by subduction in the southern part of Java Island. Its position, which is near the surface and intersects urban areas, makes this Fault very dangerous (during an earthquake) because it has a direct impact on humans.

The Opak Fault is a fault that has an oblique (horizontal-vertical) movement (Saputra et al., 2021). This oblique movement is indeed common in faults with wide dimensions to accommodate the large energy. It moves in a sinistral direction and is followed by the rising east block. However, when viewed from the surface, this Fault is not clearly visible because it has been covered by young volcanic deposits.

Apart from the Opak Fault, right below the location of YIA Airport, there is also an "unidentified" fault. This Fault is thought to still be part of the Opak Fault, with the shape of the Fault almost resembling a half-graben. To the north of the Opak Fault, there is the Mataram fault which was confirmed by the National Earthquake Center in 2022. The Opak Fault and the faults around it are very likely to be found because it is estimated that the Opak Fault is on the continental boundary line at the age of the Oligocene-Miocene (Susilohadi, 2020).

5 Conclusions

Therefore this research was conducted to support one side of the earthquake disaster aspect, which can be analyzed from many events that have occurred around the area. This data shows that the area around Yogyakarta experienced a major earthquake in 2006, which caused many fatalities. The feasibility study has succeeded in reconstructing the source model in detail and analyzing the source mechanism and the rupture process of the May 27, 2006, Yogyakarta earthquake by knowing the coseismic process and the seismotectonic characteristics of the study area. So that a more detailed analysis of the mechanism of the source and the process of earthquake rupture in the research area will be obtained so that the characteristics of the Opak fault will be known in more detail, especially after 2020, Yogyakarta International Airport, which is located in Temon District, Kulon Progo Regency, has been operating.

The method used in this study is the aftershock relocation method to determine the aftershock event in the 2006 earthquake that occurred to obtain a rupture zone (Saputra, 2021), then this event data is combined with the subsurface velocity model data resulting from the Receiver Function method (Figure 2) with using the MERAMEX network which was installed in 2004 (Amukti, 2019). Figure 4 shows the coseismic slip distribution of the May 27, 2006, Yogyakarta earthquake along the opaque fault plane overlaid with the aftershock distribution, which is the result of research by Saputra et al. (2021). This indicates that this zone is a zone that has not yet released its energy, one day, it can trigger other fault fields around the main opaque fault. Figure 5 shows the distribution of MERAMEX stations which were installed in 2004 with a black triangle symbol, the Bantul earthquake aftershock event in 2006 with a red circle symbol, and also the Jogjakarta International Airport, which is coloured in a green circle. Figure 8 shows a reconstructed 3-dimensional model of the Receiver Function and Aftershock Event, and a geological model is created that can explain this situation. Opaque faults are seen in the low-velocity anomaly, but from the aftershock event data, it is clear that the ruptured fault is not exactly at the opaque fault but rather to the east and with a curved shape. What is interesting is that to the west, there is a low-velocity anomaly which can be interpreted as a predicted fault/slip plane, and this anomaly is right under the construction of the Yogyakarta International Airport. To prove this, in this study, a P-wave velocity structure modelling was carried out in the area around the Opak River Fault using MERAMEX data installed in 2004 and the Yogyakarta earthquake occurred in 2006.

Acknowledgments

The authors want to express our sincere gratitude to the funding agency "Riset Kolaborasi Indonesia" for the financial support provided for this research. We also appreciate IRIS, BMKG, and GFZ for providing the waveform data used in this study. Our special thanks go to all authors namely: RK, SPS, MAA, APS, S, BEN, RL, and SK for their contribution in critical comments, performing data curation, and acquisition, examining the results and editing the draft article. Lastly, we thank the Postgraduate School of Airlangga University and BRIN for providing facilities and support throughout this research project.

Open Research

Data Availability Statement

The Agency of Meteorology, Climatology, and Geophysics of Indonesia maintained the data, which was available upon request. Maps were created using Generic Mapping Tools (GMT) version 6 (Wessel et al., 2019a, 2019b), licensed under LGPL version 3 or later, available at https://www.genericmapping-tools.org/.

References

Deng, A., & Stauffer, D. R. (2006), On improving 4-km mesoscale model simulations. *Journal of Applied Meteorology and Climatology*, *45*(3), 361–381. doi:10.1175/JAM2341.1.

Abercrombie, R.E., Antolik, M., Felzer, K. and Ekström, G. (2001) The 1994 Java Tsunami: Slip over a Subducting Seamount. Journal of Geophysical Research, 106, 6595-6607. https://doi.org/10.1029/2000JB900403.

Anggraini, A., 2014. The 26 May 2006 Yogyakarta earthquake, aftershocks and interactions, PhD Thesis, Uneversitaet Postdam, 107p.

Amukti, R., Yunartha, N. A., Anggraini, A., & Suryanto, W. (2019). Modeling of the earth's crust and upper mantle beneath central part of Java Island using receiver function data. *AIP Conference Proceedings*, *2194*. https://doi.org/10.1063/1.5139736.

Ammon, C.J., Kanamori, H., Lay, T. and Velasco, A.A. (2006) The 17 July 2006 Java Tsunami Earthquake. Geophysical Research Letters, 33, L24308.

Corbi, Fabio & Funiciello, Francesca & Brizzi, Silvia & Lallemand, S. & Rosenau, Matthias. (2017). Control of asperities size and spacing on seismic behavior of subduction megathrusts: Asperities and Megathrust Seismicity. Geophysical Research Letters. 44. 10.1002/2017GL074182.

Greis, N. P. (2011). The Aerotropolis, The Key to Global Competition in the 21st Century.

Haberland, C., Bohm, M., Asch, G., 2014. Accretionary of the crust of Central and East Java revealed by local earthquake travel-time tomography, Journal of Asian Earth Sciences 96, 297-295.

Hall, R., Secastjanova, I., 2012. Australian crust in Indonesia, Australian Journal of Earth Sciences 29, 827-844.

Ingo Wölbern, and Georg Rümpker., 2015. Crustal thickness beneath Central and East Java (Indonesia) inferred from P receiver functions. Journal of Asian Earth Sciences 115, 69-79.

Kasarda, J. D. (2016). Aerotropolis. West Sussex UK: John Wiley & Sons Press, 1-8.

Kuncoro, A.W., Kusuma, Y., Prasetya, G.S., & Pramitasari, A.A. (2020). Review of the Yogyakarta earthquake and damage to the tourism sector. E3S Web of Conferences, 156(01003).

Kurniawan, S. J. (2016). Perwujudan/Implementasi Konsep Interaksi AerotropolisBerbasis Tata Ruang di Indonesia. *Jurnal Perhubungan Udara*, *42*(4), 195–202.

Lay, Thorne & Kanamori, Hiroo. (1981). An Asperity Model of Large Earthquake Sequences. Earthquake prediction: an international review. 579-592. 10.1029/ME004P0579.

Peoples, J. (2014). *The Economics Of International Airline Transport* (J. Peoples, Ed.; First edition, Vol. 4). Emerald.

Syaifuddin, M., Purnomo, E. P., Salsabila, L., Fathani, A. T., & Mitra Adrian, M. (2021). Development of Aerotropolis in Kulon Progo with Green Infrastructure Concept. *IOP Conference Series: Earth and Environmental Science*, *837*(1). https://doi.org/10.1088/1755-1315/837/1/012014.

Saputra, H., Wahyudi, W., Suardi, I., Anggraini, A., & Suryanto, W. (2021). The waveform inversion of mainshock and aftershock data of the 2006 M6.3 Yogyakarta earthquake. *Geoscience Letters*, *8*(1). https://doi.org/10.1186/s40562-021-00176-w.

Smith, H., Hall, R., Hamilton, J., Kinny, P., 2005. East Java : Cenozic Basins, Vocanoes and Ancient Basement, Proceedings, Indonesian Petroleum Association, IPA05-G-045.

Surya, B., Hadijah, H., Suriani, S., Baharuddin, B., Fitriyah, A. T., Menne, F., & Rasyidi, E. S. (2020). Spatial Transformation of a New City in 2006– 2020: Perspectives on the Spatial

Dynamics, Environmental Quality Degradation, and Socio— Economic Sustainability of Local Communities in Makassar City, Indonesia. Land, 9(9), 324.

Susilohadi. (2020). Shallow Seismic Atlas of Madura Strait and Bali Sea. Pusat Penelitian dan Pengembangan Geologi Kelautan.

Sumarata, R. obertias O., Manaf, M., & Syafri, S. (2021). Konsep Pengembangan Aerotropolis di Bandara Internasional Sultan Hasanuddin Makassar. *Urban and Regional Studies Journal*, *3*(2), 60–69. https://doi.org/10.35965/ursj.v3i2.672.

Sykes, L. (2021) Decadal Seismicity Prior to Great Earthquakes at Subduction Zones: Roles of Major Asperities and Low-Coupling Zones. *International Journal of Geosciences*, **12**, 845-926. doi:10.4236/ijg.2021.129046.

Tsuji, T., Yamamoto, K., Matsouka, T., Yamada, Y., Onishi, K., Bahar, A., Milano, I., Abidin, Z.H., 2009. Earthquake fault of the 26 May 2006 Yogyakarta earthquake observed by SAR interferometry, E-Letter Earth Planets Space, 61, e29-e32, 2009.

Wakita, K., 2000. Cretaceous accretionary-collision complexes in central Indonesia, Journal of Asian Earth Sciences 18, 739-749.

Waldhauser, F., & Ellsworth, W. L. (2000). A double-difference earthquake location algorithm: Method and application to the Northern Hayward Fault, California. Bulletin of the Seismological Society of America, 90(6), 1353-1368. https://doi.org/10.1785/0120000006.

Walter, R.T., Wassermann, J., and Behr, Y., Anggraini, A., Gunther, E., Sobiesiak, M., Grosser, H., Wetzel, -U.H., and Milkereit, C., Sri Brotopuspito, K, J.P., Harjadi, P., and Zschau, J., 2008. The 26 May 2006 magnitude 6.4 Yogyakarta earthquake south of Mt. Merapi volcano: Did lahar deposits amplify ground shaking and thus lead to the disaster?, Geochemistry Geophysics

Geosystems An Electronic Journal Of The Earth Sciences, Q05006, doi10.10292007GC001810, ISSN : 1525-2027.

Wang, Ying & Chou, Chien-chang & Yeo, Gi-tae. (2013). Criteria for Evaluating Aerotropolis Service Quality. The Asian Journal of Shipping and Logistics. 29. 395–414. 10.1016/j.ajsl.2013.12.006.

Yujin, Li & Zhiyong, Zhang. (2013). Technical Methods of Comprehensive Transportation Plans in the Airport Economic Zone-taking Xiaogan Airport Economic Zone as a Case. Procedia - Social and Behavioral Sciences. 96. 10.1016/j.sbspro.2013.08.024.

Zhang, H, Clifford H. Thurber; Double-Difference Tomography: The Method and Its Application to the Hayward Fault, California. *Bulletin of the Seismological Society of America* 2003;; 93 (5): 1875–1889. doi: https://doi.org/10.1785/0120020190

Investigating the Mainshock and Aftershock of the May 2006 Earthquake in Central Java for Aerothropolis Development at Yogyakarta International Airport

Hijrah Saputra[1*], Rian Amukti[2*], Sugeng P Saputra[3], Mochamad Aryono Adhi[4], Ahmad S Pohan[5], Sismanto[6], Budi Eka Nurcahya[7], Richard Lewerissa[8], Sorja Koesuma[9]

[1]Affiliation for author 1. Postgraduate School, Universitas Airlangga, Surabaya

[2]Affiliation for author 2. Center of Geological Disaster, National Research & Innovation Agency (BRIN)

[3]Affiliation for author 3. Research Center for Geological Resources, National Research and Innovation Agency (BRIN)

[4]Affiliation for author 4. Department of Physics, Faculty of Mathematics and Natural Sciences, Semarang State University

[5]Affiliation for author 5. Department of Physics, Faculty of Mathematical and Science, Andalas University, Jl. Universitas Andalas Limau Manis Pauh, Padang, 25163, Indonesia

[6]Affiliation for author 6. Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia

[7]Affiliation for author 7. Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia

[8]Affiliation for author 8. Department of Physics, Faculty of Mathematics and Natural Sciences, Papua University, Manokwari, Papua Barat 98314, Indonesia

[9]Affiliation for author 9. Department of Physics, Faculty of Mathematics and Natural Sciences, Sebelas Maret University

Corresponding author: Hijrah Saputra (hijrah.saputra@pasca.unair.ac.id); Rian Amukti (rian.amukti87@gmail.com)

Key Points:

- Analysis of source mechanisms of mainshock and aftershock events of May 27, 2006, earthquake in Yogyakarta, Central Java.
- Use of receiver function data to model the subsurface velocity P and obtain a geological form model of the Opak fault.

- Research aimed at supporting the development of the Yogyakarta Aerothropolis area in terms of disaster analysis.

Abstract

Research on the analysis of the source mechanism of the mainshock and aftershock events of the May 27, 2006, Yogyakarta earthquake, which is thought to have originated from the Opak fault and analysis of receiver function data to model the subsurface velocity P of the Central Java subsurface, to obtain a geological form model of the Opak fault. This research aims to support the development of the Yogyakarta Aerothropolis area in terms of disaster analysis. The data used in this study are remote Teleseismic receiver function data from the MERAMEX station installed in 2004, and data for the Bantul earthquake event and its aftershock event in 2006. The results obtained from the analysis are that the Yogyakarta area is shaped like a half-graben close to Yogyakarta International Airport. The fault that separates the western part of Yogyakarta is still not identified. Based on the results of the rupture process analysis of the source along the Opak fault plane, some zones have not yet released their energy. The distribution of aftershocks due to the mainshock on 27 May 2006 is spread around the Opak fault, which is heading North-South, and West-East, which is thought to have activated the minor fault to the east of the Opak fault. The opak fault rupture area can be analyzed to have a Low Anomaly velocity P value from the receiver function data and is the same as the aftershock event obtained.

Keywords: Rupture, aftershock, receiver function, opak fault, aerothropolis.

Plain Language Summary

This study analyzes the source mechanism of the main earthquake and its aftershocks that occurred on May 27, 2006, in Yogyakarta, Indonesia, believed to have originated from the Opak fault. The researchers used receiver function data to model the Central Java subsurface velocity P and obtained a geological form model of the Opak fault. The study aimed to support the development of the Yogyakarta Aerothropolis area in terms of disaster analysis. The results showed that the Yogyakarta area is shaped like a half-graben close to Yogyakarta International Airport. The fault that separates the western part of Yogyakarta has not yet been identified. The distribution of aftershocks due to the mainshock was spread around the Opak fault, which is heading North-South and West-East, and it is thought to have activated the minor fault to the east of the Opak fault. The study also found that the Opak fault rupture area can be analyzed to have a low anomaly velocity P value from the receiver function data and is the same as the aftershock event obtained. This study provides valuable information for disaster analysis in the Yogyakarta Aerothropolis area.

1 Introduction

Yogyakarta is an area that has its uniqueness and charm, so many tourists come, both local and foreign. This has a positive impact on regional growth. The area around the airport, with many business activities or commercial services, is the basis for forming the aerotropolis area concept (Kasarda, 2016). This concept was developed in the Yogyakarta International Airport area to increase business competitiveness which will have an impact on the community's economy so that it will have a large effect (Sumarata, 2021). This condition is supported by proper planning, including security from the threat of disaster.

Yogyakarta is not only a popular tourist destination but also an area that is prone to earthquake disasters due to its location on the active tectonic plate. According to the National Disaster Management Agency (BNPB), Yogyakarta has a high seismic hazard level, with 21 active faults identified in the region (BNPB, 2021). Therefore, proper disaster risk management is crucial in aerotropolis planning to minimize the potential impact of earthquakes on the community's economy and livelihoods. This can be achieved through a comprehensive analysis of the earthquake risk, including the identification of vulnerable areas and the implementation of appropriate measures to mitigate the risk. In addition, community participation and awareness-raising programs should be incorporated into the disaster risk management plan to ensure the sustainability of the aerotropolis area development. By considering the earthquake risk and implementing appropriate measures, the aerotropolis area in Yogyakarta can develop sustainably and contribute to the economic growth of the region while ensuring the safety and well-being of the local community.

The principles of aerotropolis planning consist of regional spatial structure, distance, zoning, land use, designation of the main functions of the area, integration, and connectivity (Kurniawan, 2016; Yujin, 2013; Wang, 2013; Greis, 2011). To find out good spatial planning in aerotropolis planning, an in-depth analysis of disasters in the area is also needed (Surya et al., 2020). Both seasonal disasters, such as floods and tornadoes, and large, unpredictable disasters, such as volcanoes, earthquakes, and tsunamis (Ammon et al., 2006). Therefore, this research was conducted to support one side of the earthquake disaster, which can be analyzed from many events around the area (Kuncoro et al.,2020.

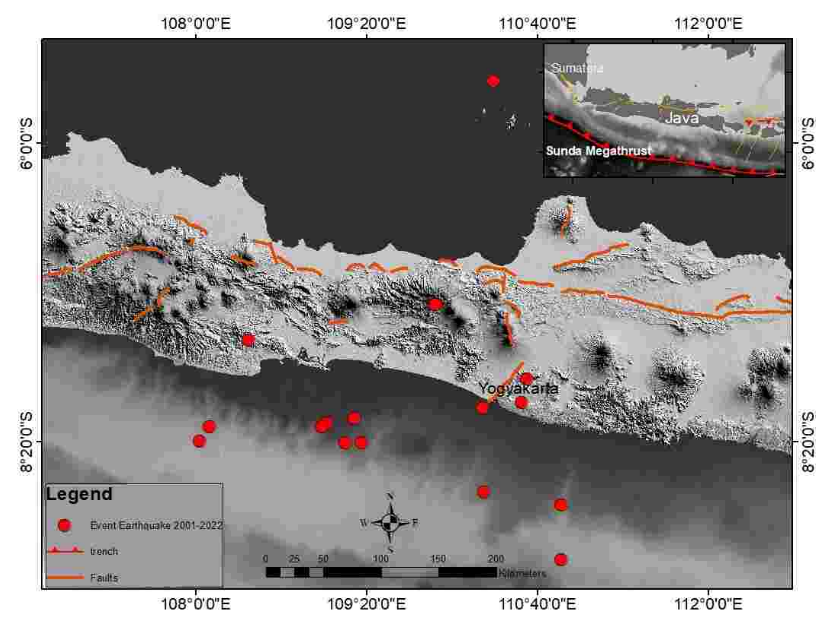

Figure 1. Earthquake distribution map for 2001-2022 around Central Java and Yogyakarta. The red circle is the mainshock distribution that has been relocated. The brown lines are the distribution of faults spread across Java island.

The feasibility study has succeeded in reconstructing the source model in detail and analyzing the source mechanism and the rupture process of the May 27, 2006, Yogyakarta earthquake by knowing the coseismic process and the seismotectonic characteristics of the study area. So by knowing the physical characteristics of the May 27, 2006, Yogyakarta earthquake, we can understand the destructive nature of the earthquake, so it can be used as a guide for earthquake mitigation, especially the Yogyakarta earthquake (Saputra et al., 2021). However, to obtain information on the source mechanism and phenomenon of May 27, 2006, Yogyakarta earthquake, it is recommended to use other earthquake data. So that a more detailed analysis of the mechanism of the source and the process of earthquake rupture in the research area will be obtained so that the characteristics of the Opak fault will be known in more detail, especially after 2020, Yogyakarta International Airport, which is located in Temon District, Kulon Progo Regency, has been operating. The airport area will be built with the Aerotropolis concept in its development. In the Yogyakarta Regional Regulation number 5 of 2019 concerning the 2019-2039 Regional Spatial Plan for the Special Region of Yogyakarta, the development of the Temon-Prambanan Area is projected to become one of the province's strategic areas from an economic point of view. One form is the development of the aerotropolis area. Aerotropolis can increase economic growth in a country or region (Peoples, 2014). The concept of the Yogyakarta aerotropolis with a radius of about 15 km from the airport (Syaifuddin et al., 2021).

This research aims to analyze the physical characteristics and the source mechanism of the May 27, 2006, Yogyakarta earthquake. The urgency of this study is to provide a better understanding of the destructive nature of the earthquake and to provide guidance for earthquake mitigation, especially in the Yogyakarta region. The results of this study can also provide important information for the development of the aerotropolis area around Yogyakarta International Airport. Understanding the seismotectonic characteristics and potential risks of earthquakes in the area is crucial for ensuring the safety and sustainability of the airport and the surrounding region. Additionally, this research can contribute to the advancement of earthquake science and the development of effective strategies for disaster risk reduction.

2 Materials and Methods

2.1 Receiver function data

The method used in this study is the aftershock relocation method to determine the aftershock event in the 2006 earthquake that occurred to obtain a rupture zone (Saputra, 2021). The relocation method was conducted using the hypoDD code (Waldhauser and Ellsworth, 2000) and the double-difference algorithm (Zhang et al., 1889). This event data is combined with the subsurface velocity model data resulting from the Receiver Function method (Figure 2) using the MERAMEX network installed in 2004 (Amukti, 2019). The MERAMEX network is a dense seismographic network that consists of 24 broadband and short-period seismometers, covering an area of approximately 200 km radius around the study area. The subsurface structure is then analyzed using the tomographic inversion method, which allows for a more detailed study of the subsurface velocity structure and can provide insight into the characteristics of the active fault in the study area.

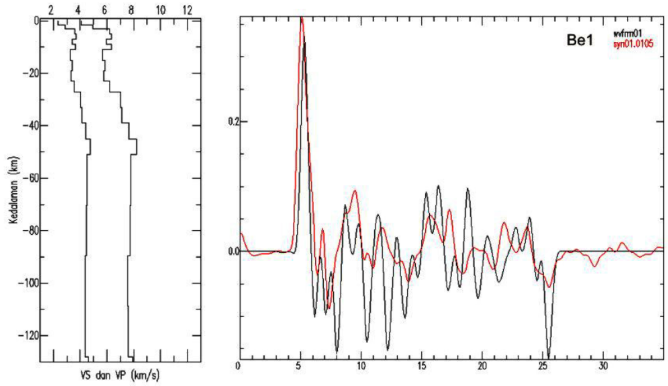

Figure 2. Example of receiver function data

2.2 Aftershocks data

This study also uses relocated aftershock data obtained from temporary seismometers installed after the 2006 Yogyakarta mainshock. In this analysis, the study employs the aftershock relocation method to determine the precise location of each aftershock event and reduce uncertainty in earthquake location determination.

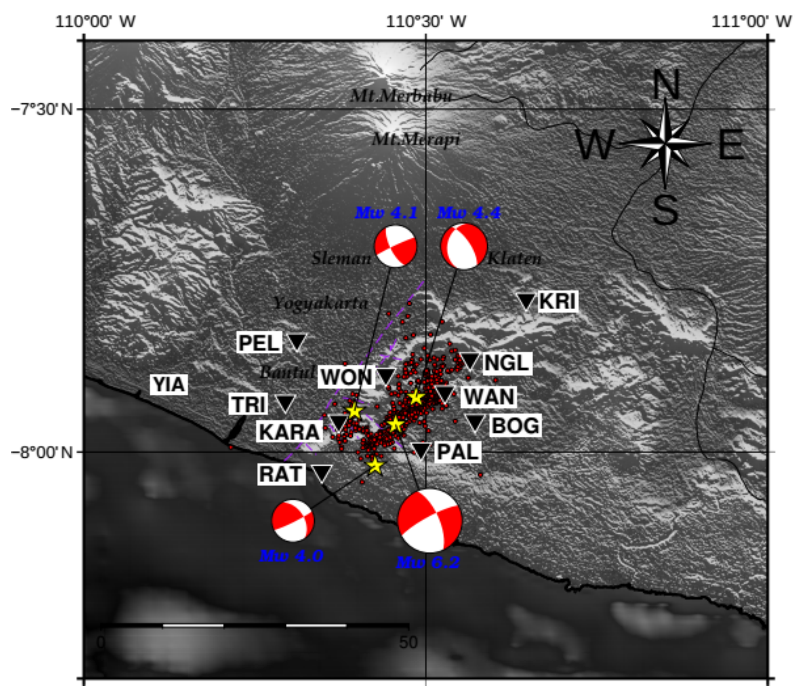

Figure 3. Distribution of relocated aftershocks taken from temporary seismometer recordings. The red circle is the relocation aftershock distribution. The grey triangles are seismometers. The red and white focal ball is the mainshock and aftershock issued by the USGS.

Figure 3 shows the enlargement between the mainshock and the three aftershocks, namely on June 8, 9 and 16, which had different types of displacement. This shows the complexity of the faults around the Opak fault. The results of the mainshock rupture process analysis in the study of Saputra et al. (2021) show two weak zones and can be seen from the distribution of aftershocks scattered around the asperity zone (weak zone). Between the weak zones, there is a seismic gap, indicated as a zone that has not yet released its energy.

3 Data

This study utilized the earthquake aftershock location method to determine the aftershock events of the 2006 earthquake in order to obtain the fault zone. The location method was performed using the hypoDD code (Waldhauser & Ellsworth, 2000) and the double-difference algorithm (Zhang et al., 1889). The earthquake data was combined with subsurface velocity model data generated from the Receiver Function method (Figure 2) using the MERAMEX network installed in 2004 (Amukti, 2019). The MERAMEX network is a dense seismograph network consisting of 24 broad-band and short-period seismometers covering an area of about 200 km radius around the study area. The subsurface structure was then analyzed using the tomographic inversion method, which allows for a more detailed study of the subsurface velocity structure and provides insights into the characteristics of active faults in the study area.

The aftershock data was also used in this study, obtained from temporary seismometers installed after the main earthquake in Yogyakarta in 2006. In this analysis, the study used the earthquake location method to determine the precise location of each aftershock event and reduce uncertainty in determining the earthquake location. Figure 3 shows the enlargement between the main earthquake and three aftershocks on June 8, 9, and 16, which have different displacement types. This indicates the complexity of faults around the Opak fault. The results of the faulting process analysis in the main earthquake by Saputra et al. (2021) show the presence of two weak zones, which can be seen from the distribution of aftershocks scattered around the asperity zone (weak zone). Between the weak zones, there is a seismic gap, which is indicated as a zone that has not yet released its energy.

In this study, the Receiver Function method was used to generate the subsurface velocity model, which was then combined with the aftershock location data to obtain insights into the characteristics of active faults in the study area. The tomographic inversion method was used to obtain more detailed information about the subsurface structure. In addition, the earthquake location method was also used to determine the precise location of each aftershock event, which helps in understanding the complexity of faults around the Opak fault. The results of this study show the presence of two weak zones and a seismic gap between the weak zones. These results can provide important information for understanding the potential earthquake hazards in the region.

4 Results, or a descriptive heading about the results

4.1 Analysis of the earthquake source rupture process

Analyzing the earthquake source rupture process is critical to seismological research, as it helps understand the mechanisms that trigger earthquakes. In this study, the researchers used the finite fault inversion method to analyze the earthquake source rupture process of the Yogyakarta earthquake. The results showed that the rupture process was a unilateral propagation from the southwest to the northeast. Moreover, the fault length was approximately 28 km, and the maximum slip was estimated to be around 1.4 meters. The results are crucial in improving our understanding of the characteristics of the Yogyakarta earthquake and provide valuable information for developing effective earthquake mitigation strategies.

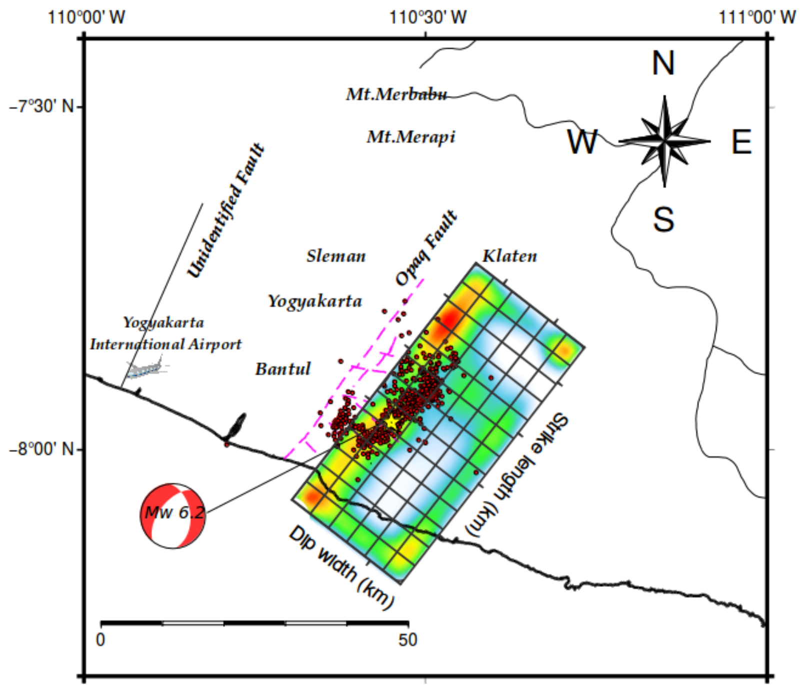

Figure 4. The results of the analysis of the rupture process of the Yogyakarta earthquake on May 27, 2006, show the slip distribution from the opaque fault plane. The rectangular contour is the distribution of slip on the opaque fault plane. The red colour circle is the aftershock distribution. The yellow star is the Yogyakarta earthquake mainshock, resulting from a joint inversion research by Saputra et al. (2021). The purple dotted line is an opaque fault, and on the east side of the main fault, there are several minor faults. The black line is the boundary of the graben zone, where the fault has not been identified. The red and white focal ball results from a joint inversion calculation from Saputra et al. 2021 study (modification from Saputra et al. Research, 2021).

Figure 4 shows the coseismic slip distribution of the May 27, 2006, Yogyakarta earthquake along the opaque fault plane overlaid with the aftershock distribution, which is the result of research by Saputra et al. (2021). The aftershock distribution pattern converges in the area of maximum slip. The concentration of slip that collects in the aftershock zone area indicates that there is a continuous release of energy (Sykes, 2021). In the middle of the slip zone, there is a seismic gap that shows the behaviour of the fault. The asperity zone is very important to know as a basis for the initial analysis of earthquake hazards (Corbi et al., 2017; Lay et al., 1981; Abercrombie et al., 2001). If you look at the displacement pattern between the mainshock and aftershock, as shown in Figure 2, it is quite clear that the displacement pattern is different. So it can be concluded that the source of the earthquake came from a different fault area. This shows the complexity of the Opak fault. The slip distribution pattern shown in Figure 3 also shows that there is a white colour in the middle of the Opak fault plane. This indicates that this zone is a zone that has not yet released its energy, one day, it can trigger other fault fields around the main opaque fault. Several earthquake events that occurred after 2006 are still widely distributed around the Opak fault. On the western fault boundary, it can be seen that there is a weak field that has not yet released energy. This boundary is very close to the location of Yogyakarta International Airport.

4.2 Receiver function data

The receiver function method is used to model the subsurface with teleseismic earthquake events (Amukti, 2019). Figure 5 shows the distribution of MERAMEX stations which were installed in 2004 with a black triangle symbol, the Bantul earthquake aftershock event in 2006 with a red circle symbol, and also the Jogjakarta International Airport, which is coloured in a green circle.

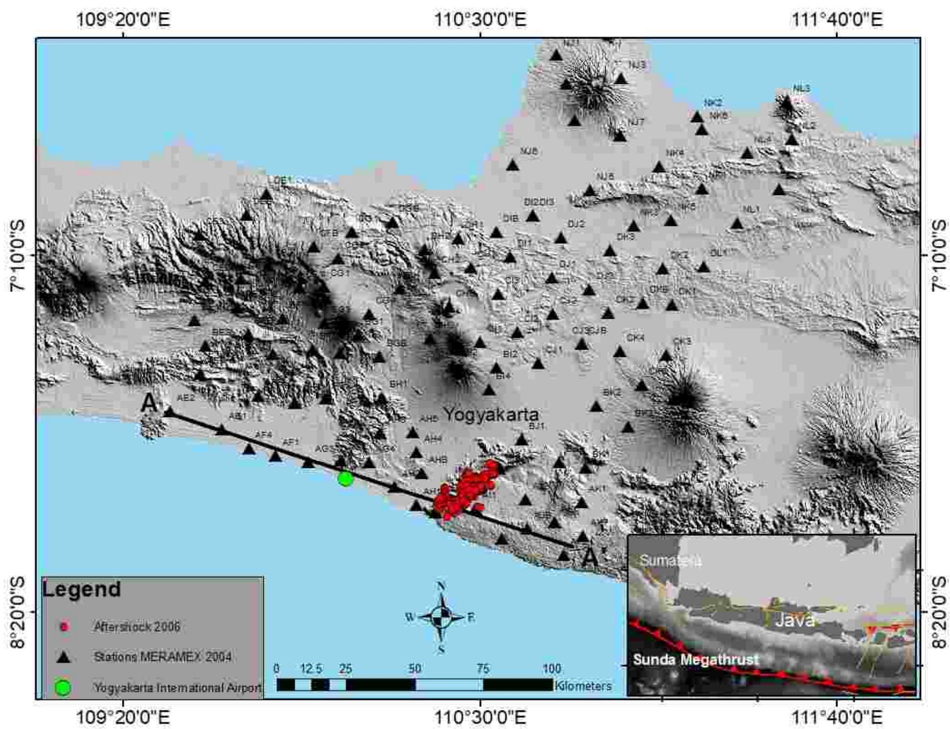

Figure 5. Aftershock distribution of the 2006 Yogyakarta earthquake recorded from the Meramex station installed in 2004. The red circles are the distribution of aftershocks. The black triangle is the distribution of Meramex stations. The red and yellow lines on the map index are subduction zones and local faults on the mainland, respectively. The black line is the velocity (Vp) model slice from A-A.'

The velocity (Vp) results from the receiver function method are modelled to obtain an overview of the subsurface slices between points A to A' as shown in Figure (6). The aftershock event is seen at a depth of 5-20 Km and is located in the Low-Velocity Anomaly model. To view laterally, a velocity model is created at a depth of 11 km (Figure 6).

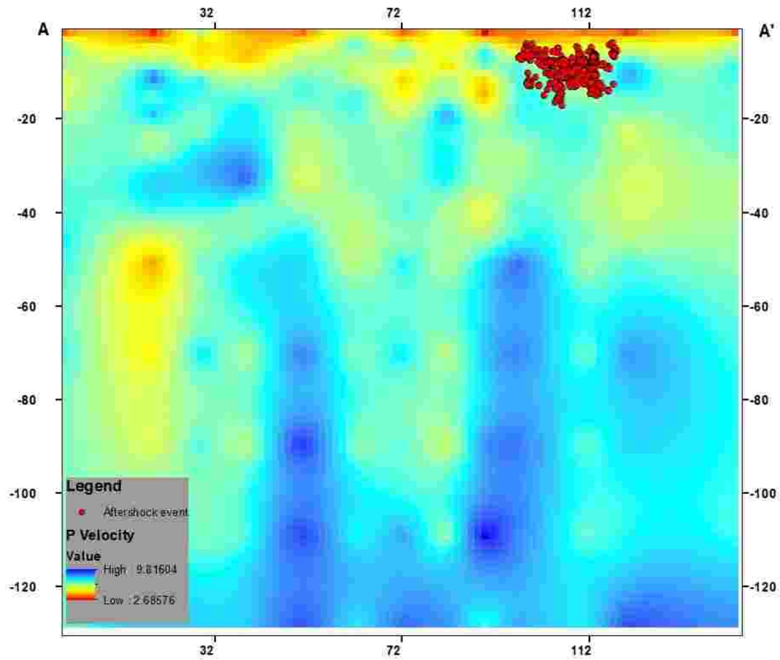

Figure 6. Model Velocity (Vp) of the Receiver Function and combined with the aftershock event data on the A-A slice. The red circle is the aftershock distribution of the depth function.

Figure 7 shows the distribution of P waves in Central Java with a depth of 11 Km. If further analyzed, it will be seen the distribution of P waves which have high speeds of up to 8 Km/s, will form fragments (Amukti, 2019). These results explain that there is a fault in central Java known as the Maratus zone, which continues from Borneo Island to Java Island. This analysis is based on previous research conducted by Wakita (2000), Smith et al. l (2005), Hall and Sevastjanova (2012), Haberland et al. (2014), and Wölbern and Rümpker (2015). Figure 7 also shows that the Velocity P model and aftershock data have a relationship, where the aftershock event is right in the low anomaly area of velocity in the area around the Opak fault.

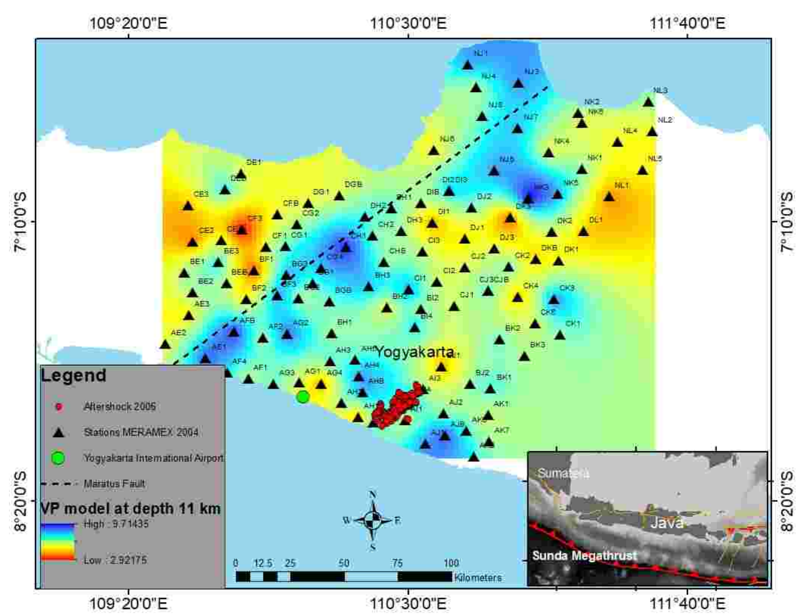

Figure 7. Model velocity (Vp) combined with the aftershock event at a depth of 11 Km. The red circle is the relocated aftershock distribution. The black triangle is the distribution of Meramex stations. The green circle is the international position of Yogyakarta airport.

Another interesting thing is that right below Yogyakarta International Airport has a low anomaly velocity as well, so a more detailed analysis and interpretation is needed in this area, so a 3-dimensional model was made (Figure 7).

Figure 8 shows a reconstructed 3-dimensional model of the Receiver Function and Aftershock Event, and a geological model is created that can explain this situation. The opaque fault is seen in the low-velocity anomaly, but from the aftershock event data, it is explained that the ruptured fault does not persist in the Opak fault but is more to the east and has a curved shape. To the north of the Opak fault, there is the Mataram fault which was confirmed by the National Earthquake Center in 2022.

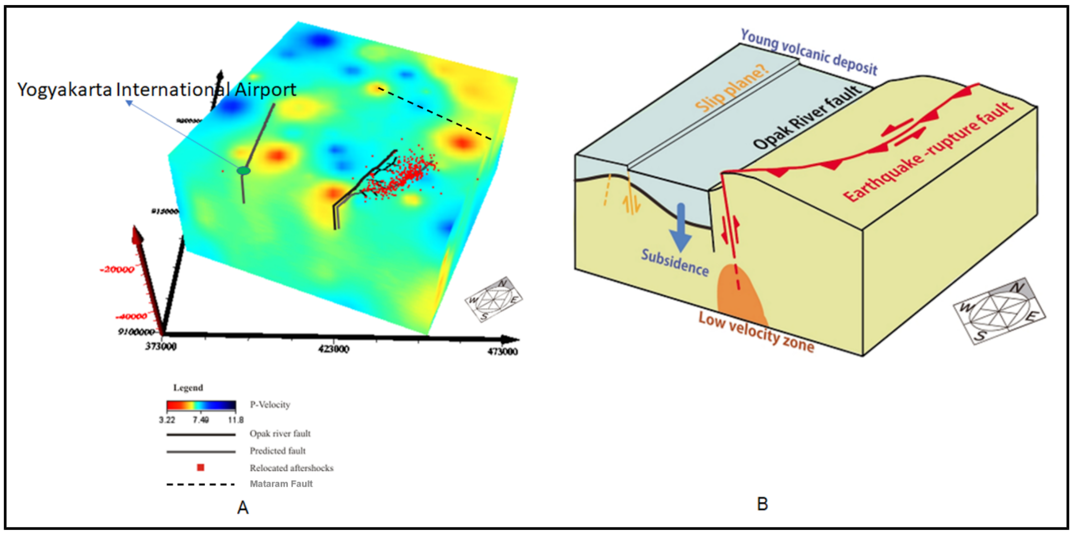

Figure 8. 3D Model Reconstruction. A. It is a 3-dimensional model of the data velocity (Vp) receiver function. B. It is a geological model interpretation image of the Opak Fault.

What is interesting is that to the west, there is a low-speed anomaly that can be interpreted as a prediction of aircraft errors/slips, and this anomaly is right under the construction of the Yogyakarta International Airport (Figure 8. a). However, this still needs to be confirmed with other geophysical research methods such as the Gravity, Electromagnetic and geological observation accuracy surveys in the field.

On May 26, 2006, at 22:54 UTC, Yogyakarta was rocked by an earthquake. Many scientists debate the sources and mechanisms of how earthquakes occur. The opinion most often expressed by scientists is the source of the earthquake originated from the Opak fault activity. The German Task Force (GTF), together with the Seismological Division of the Meteorological and Geophysics Agency (BMG), undertook the installation of a seismic station around the Opak Fault to record aftershock events (Walter et al, 2008). The recording results show that the epicentres of the aftershocks were not aligned along the Opak River Fault but 10 km further to the east (Walter et al., 2008).

Tsuji et al. (2009) observed the Yogyakarta earthquake with SAR interferometry. His research results show that surface deformation occurred 10 km east of the Opak River Fault which is suspected as the source of the May 2006 event. He modelled a schematic diagram of the relationship between the earthquake fault, the Opak River Fault, and subsidence in young volcanic deposits. The conclusion from the model is that the earthquake displacement has a reverse slip component in addition to a strike slip along the eastern oblique fault plane.

In order to prove this, this research conducted modelling of the P wave velocity structure in the area around the Opak River Fault using MERAMEX data which was installed in 2004, and the Yogyakarta earthquake occurred in 2006. To analyze the Opak Fault, we added aftershock data from Anggraini (2014) and Saputra (2021).

Geologically, the Opak Fault is an active fault with a long continuity (almost North-South), and its movement is controlled by subduction in the southern part of Java Island. Its position, which is near the surface and intersects urban areas, makes this Fault very dangerous (during an earthquake) because it has a direct impact on humans.

The Opak Fault is a fault that has an oblique (horizontal-vertical) movement (Saputra et al., 2021). This oblique movement is indeed common in faults with wide dimensions to accommodate the large energy. It moves in a sinistral direction and is followed by the rising east block. However, when viewed from the surface, this Fault is not clearly visible because it has been covered by young volcanic deposits.

Apart from the Opak Fault, right below the location of YIA Airport, there is also an "unidentified" fault. This Fault is thought to still be part of the Opak Fault, with the shape of the Fault almost resembling a half-graben. To the north of the Opak Fault, there is the Mataram fault which was confirmed by the National Earthquake Center in 2022. The Opak Fault and the faults around it are very likely to be found because it is estimated that the Opak Fault is on the continental boundary line at the age of the Oligocene-Miocene (Susilohadi, 2020).

5 Conclusions

Therefore this research was conducted to support one side of the earthquake disaster aspect, which can be analyzed from many events that have occurred around the area. This data shows that the area around Yogyakarta experienced a major earthquake in 2006, which caused many fatalities. The feasibility study has succeeded in reconstructing the source model in detail and analyzing the source mechanism and the rupture process of the May 27, 2006, Yogyakarta earthquake by knowing the coseismic process and the seismotectonic characteristics of the study area. So that a more detailed analysis of the mechanism of the source and the process of earthquake rupture in the research area will be obtained so that the characteristics of the Opak fault will be known in more detail, especially after 2020, Yogyakarta International Airport, which is located in Temon District, Kulon Progo Regency, has been operating.

The method used in this study is the aftershock relocation method to determine the aftershock event in the 2006 earthquake that occurred to obtain a rupture zone (Saputra, 2021), then this event data is combined with the subsurface velocity model data resulting from the Receiver Function method (Figure 2) with using the MERAMEX network which was installed in 2004 (Amukti, 2019). Figure 4 shows the coseismic slip distribution of the May 27, 2006, Yogyakarta earthquake along the opaque fault plane overlaid with the aftershock distribution, which is the result of research by Saputra et al. (2021). This indicates that this zone is a zone that has not yet released its energy, one day, it can trigger other fault fields around the main opaque fault. Figure 5 shows the distribution of MERAMEX stations which were installed in 2004 with a black triangle symbol, the Bantul earthquake aftershock event in 2006 with a red circle symbol, and also the Jogjakarta International Airport, which is coloured in a green circle. Figure 8 shows a reconstructed 3-dimensional model of the Receiver Function and Aftershock Event, and a geological model is created that can explain this situation. Opaque faults are seen in the low-velocity anomaly, but from the aftershock event data, it is clear that the ruptured fault is not exactly at the opaque fault but rather to the east and with a curved shape. What is interesting is that to the west, there is a low-velocity anomaly which can be interpreted as a predicted fault/slip plane, and this anomaly is right under the construction of the Yogyakarta International Airport. To prove this, in this study, a P-wave velocity structure modelling was carried out in the area around the Opak River Fault using MERAMEX data installed in 2004 and the Yogyakarta earthquake occurred in 2006.

Acknowledgments

The authors want to express our sincere gratitude to the funding agency “Riset Kolaborasi Indonesia” for the financial support provided for this research. We also appreciate IRIS, BMKG, and GFZ for providing the waveform data used in this study. Our special thanks go to all authors namely: RK, SPS, MAA, APS, S, BEN, RL, and SK for their contribution in critical comments, performing data curation, and acquisition, examining the results and editing the draft article. Lastly, we thank the Postgraduate School of Airlangga University and BRIN for providing facilities and support throughout this research project.

Open Research

Data Availability Statement

The Agency of Meteorology, Climatology, and Geophysics of Indonesia maintained the data, which was available upon request. Maps were created using Generic Mapping Tools (GMT) version 6 (Wessel et al., 2019a, 2019b), licensed under LGPL version 3 or later, available at https://www.genericmapping-tools.org/.

References

Deng, A., & Stauffer, D. R. (2006), On improving 4-km mesoscale model simulations. *Journal of Applied Meteorology and Climatology*, *45*(3), 361–381. doi:10.1175/JAM2341.1.

Abercrombie, R.E., Antolik, M., Felzer, K. and Ekström, G. (2001) The 1994 Java Tsunami: Slip over a Subducting Seamount. Journal of Geophysical Research, 106, 6595-6607. https://doi.org/10.1029/2000JB900403.

Anggraini, A., 2014. The 26 May 2006 Yogyakarta earthquake, aftershocks and interactions, PhD Thesis, Uneversitaet Postdam, 107p.

Amukti, R., Yunartha, N. A., Anggraini, A., & Suryanto, W. (2019). Modeling of the earth's crust and upper mantle beneath central part of Java Island using receiver function data. *AIP Conference Proceedings*, *2194*. https://doi.org/10.1063/1.5139736.

Ammon, C.J., Kanamori, H., Lay, T. and Velasco, A.A. (2006) The 17 July 2006 Java Tsunami Earthquake. Geophysical Research Letters, 33, L24308.

Corbi, Fabio & Funiciello, Francesca & Brizzi, Silvia & Lallemand, S. & Rosenau, Matthias. (2017). Control of asperities size and spacing on seismic behavior of subduction megathrusts: Asperities and Megathrust Seismicity. Geophysical Research Letters. 44. 10.1002/2017GL074182.

Greis, N. P. (2011). The Aerotropolis, The Key to Global Competition in the 21st Century.

Haberland, C., Bohm, M., Asch, G., 2014. Accretionary of the crust of Central and East Java revealed by local earthquake travel-time tomography, Journal of Asian Earth Sciences 96, 297-295.

Hall, R., Secastjanova, I., 2012. Australian crust in Indonesia, Australian Journal of Earth Sciences 29, 827-844.

Ingo Wölbern, and Georg Rümpker., 2015. Crustal thickness beneath Central and East Java (Indonesia) inferred from P receiver functions. Journal of Asian Earth Sciences 115, 69-79.

Kasarda, J. D. (2016). Aerotropolis. West Sussex UK: John Wiley & Sons Press, 1-8.

Kuncoro, A.W., Kusuma, Y., Prasetya, G.S., & Pramitasari, A.A. (2020). Review of the Yogyakarta earthquake and damage to the tourism sector. E3S Web of Conferences, 156(01003).

Kurniawan, S. J. (2016). Perwujudan/Implementasi Konsep Interaksi AerotropolisBerbasis Tata Ruang di Indonesia. *Jurnal Perhubungan Udara*, *42*(4), 195–202.

Lay, Thorne & Kanamori, Hiroo. (1981). An Asperity Model of Large Earthquake Sequences. Earthquake prediction: an international review. 579-592. 10.1029/ME004P0579.

Peoples, J. (2014). *The Economics Of International Airline Transport* (J. Peoples, Ed.; First edition, Vol. 4). Emerald.

Syaifuddin, M., Purnomo, E. P., Salsabila, L., Fathani, A. T., & Mitra Adrian, M. (2021). Development of Aerotropolis in Kulon Progo with Green Infrastructure Concept. *IOP Conference Series: Earth and Environmental Science*, *837*(1). https://doi.org/10.1088/1755-1315/837/1/012014.

Saputra, H., Wahyudi, W., Suardi, I., Anggraini, A., & Suryanto, W. (2021). The waveform inversion of mainshock and aftershock data of the 2006 M6.3 Yogyakarta earthquake. *Geoscience Letters*, *8*(1). https://doi.org/10.1186/s40562-021-00176-w.

Smith, H., Hall, R., Hamilton, J., Kinny, P., 2005. East Java : Cenozic Basins, Vocanoes and Ancient Basement, Proceedings, Indonesian Petroleum Association, IPA05-G-045.

Surya, B., Hadijah, H., Suriani, S., Baharuddin, B., Fitriyah, A. T., Menne, F., & Rasyidi, E. S. (2020). Spatial Transformation of a New City in 2006– 2020: Perspectives on the Spatial

Dynamics, Environmental Quality Degradation, and Socio— Economic Sustainability of Local Communities in Makassar City, Indonesia. Land, 9(9), 324.

Susilohadi. (2020). Shallow Seismic Atlas of Madura Strait and Bali Sea. Pusat Penelitian dan Pengembangan Geologi Kelautan.

Sumarata, R. obertias O., Manaf, M., & Syafri, S. (2021). Konsep Pengembangan Aerotropolis di Bandara Internasional Sultan Hasanuddin Makassar. *Urban and Regional Studies Journal*, *3*(2), 60–69. https://doi.org/10.35965/ursj.v3i2.672.

Sykes, L. (2021) Decadal Seismicity Prior to Great Earthquakes at Subduction Zones: Roles of Major Asperities and Low-Coupling Zones. *International Journal of Geosciences*, **12**, 845-926. doi:10.4236/ijg.2021.129046.

Tsuji, T., Yamamoto, K., Matsouka, T., Yamada, Y., Onishi, K., Bahar, A., Milano, I., Abidin, Z.H., 2009. Earthquake fault of the 26 May 2006 Yogyakarta earthquake observed by SAR interferometry, E-Letter Earth Planets Space, 61, e29-e32, 2009.

Wakita, K., 2000. Cretaceous accretionary-collision complexes in central Indonesia, Journal of Asian Earth Sciences 18, 739-749.

Waldhauser, F., & Ellsworth, W. L. (2000). A double-difference earthquake location algorithm: Method and application to the Northern Hayward Fault, California. Bulletin of the Seismological Society of America, 90(6), 1353-1368. https://doi.org/10.1785/0120000006.

Walter, R.T., Wassermann, J., and Behr, Y., Anggraini, A., Gunther, E., Sobiesiak, M., Grosser, H., Wetzel, -U.H., and Milkereit, C., Sri Brotopuspito, K, J.P., Harjadi, P., and Zschau, J., 2008. The 26 May 2006 magnitude 6.4 Yogyakarta earthquake south of Mt. Merapi volcano: Did lahar deposits amplify ground shaking and thus lead to the disaster?, Geochemistry Geophysics

Geosystems An Electronic Journal Of The Earth Sciences, Q05006, doi10.10292007GC001810, ISSN : 1525-2027.

Wang, Ying & Chou, Chien-chang & Yeo, Gi-tae. (2013). Criteria for Evaluating Aerotropolis Service Quality. The Asian Journal of Shipping and Logistics. 29. 395–414. 10.1016/j.ajsl.2013.12.006.

Yujin, Li & Zhiyong, Zhang. (2013). Technical Methods of Comprehensive Transportation Plans in the Airport Economic Zone-taking Xiaogan Airport Economic Zone as a Case. Procedia - Social and Behavioral Sciences. 96. 10.1016/j.sbspro.2013.08.024.

Zhang, H, Clifford H. Thurber; Double-Difference Tomography: The Method and Its Application to the Hayward Fault, California. *Bulletin of the Seismological Society of America* 2003;; 93 (5): 1875–1889. doi: https://doi.org/10.1785/0120020190