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# Assessing the Probability of Megathrust Earthquakes in Indonesia: A Review of Seismic Hazard Assessment and Mitigation Strategies

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**ABSTRACT**
This research addresses the probability of megathrust earthquakes occurring in Indonesia, which is an earthquake-prone region due to its position on the Pacific Ring of Fire. The background of this research emphasizes the importance of seismic hazard assessment to understand the likelihood and impact of such seismic events. The method used is a literature study, by analyzing various sources of information, including scientific journals and government reports, to evaluate mitigation strategies that have been implemented. The results and discussion show that while Indonesia has made progress in early warning systems and seismic hazard maps, challenges in risk communication and public awareness still need to be addressed. The conclusions of this study emphasize the need for improved mitigation strategies and disaster preparedness to reduce the risks associated with future large earthquakes and tsunamis.

**Keywords**: *Megathrust Earthquakes, Mitigation Strategies, Seismic Hazard*

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## INTRODUCTION

Indonesia, located on the Pacific Ring of Fire, is one of the most seismically active regions in the world, characterized by numerous megathrust earthquake sources. The country is home to 13 major megathrust segments, each with the potential to generate significant seismic events, including the devastating tsunamis that often accompany them (Librian et al., 2024). Understanding the probability of these megathrust earthquakes is crucial for effective disaster risk management and mitigation strategies. The concept of seismic hazard assessment involves evaluating the likelihood of earthquake occurrences and their potential impacts on communities and infrastructure. This assessment is essential for informing local governments and communities about the risks they face and for developing appropriate preparedness measures (Widiyantoro et al., 2024). By analyzing historical earthquake data and geological conditions, researchers can provide valuable insights into the probability of future megathrust events.

In recent years, the Indonesian government has made significant strides in improving its seismic hazard assessment capabilities. The establishment of the Tsunami Early Warning System (TEWS) and the development of detailed seismic hazard maps are examples of proactive measures taken to enhance public safety (BMKG, 2023). These initiatives aim to reduce the vulnerability of communities living in high-risk areas and to promote a culture of preparedness. Despite these advancements, challenges remain in effectively communicating seismic risks to the public. Misinformation and misunderstandings about the nature of megathrust earthquakes can lead to unnecessary panic or complacency (Rakuasa et al., 2022). Therefore, it is essential to convey accurate information about the potential for megathrust events and the importance of preparedness.

Mitigation strategies play a vital role in reducing the impact of megathrust earthquakes on society. These strategies include land-use planning, building codes, and community education programs that emphasize the importance of earthquake preparedness (Cipta et al., 2017). By integrating these strategies into local governance, Indonesia can enhance its resilience to seismic hazards. The role of local governments in implementing mitigation strategies cannot be overstated. They are responsible for enforcing building regulations, conducting public awareness campaigns, and coordinating emergency response efforts (Kunci, 2010). Collaboration between national and local authorities is essential for creating a comprehensive approach to earthquake risk management.

Furthermore, the concept of "seismic gaps"—areas that have not experienced significant earthquakes for an extended period—should be considered in seismic hazard assessments. These gaps can indicate regions that may be due for a major seismic event, highlighting the need for increased monitoring and preparedness efforts (Megawati et al., 2024). In conclusion, assessing the probability of megathrust earthquakes in Indonesia is a complex but necessary endeavor. By reviewing current seismic hazard assessment practices and mitigation strategies, this study aims to contribute to the ongoing efforts to enhance public safety and resilience in the face of inevitable seismic threats. Continued research and collaboration among stakeholders will be crucial in addressing the challenges posed by megathrust earthquakes in Indonesia.

## RESEARCH METHODOLOGY

This research uses the literature study method to evaluate the probability of megathrust earthquakes in Indonesia by reviewing various relevant sources of information, including scientific journals, government reports, and publications from relevant institutions such as the Geological Agency and BMKG. The data collection process involved identifying and analyzing previous studies that addressed seismic hazard assessment and mitigation strategies that have been implemented in Indonesia, as well as reviewing maps of disaster-prone areas and information on the “seismic gap”. Using this approach, the research aims to develop a comprehensive picture of the challenges and progress in megathrust earthquake risk management in Indonesia.

## RESULT AND DISCUSSION

### Learning from Japan

Japan's experience in dealing with earthquakes and tsunamis provides valuable lessons for Indonesia in terms of seismic hazard assessment and mitigation strategies. Japan has developed a culture of high earthquake awareness, where people actively monitor and record seismic activity, and implement an effective early warning system (CNN Indonesia, 2024). By utilizing advanced technology and engaging all levels of society in disaster mitigation education and training, Japan has successfully reduced disaster impacts and increased community resilience. Indonesia can adopt a similar approach by strengthening seismic literacy among the public, improving collaboration between the government and the community, and implementing a better early warning system to deal with potential megathrust earthquakes in the future. Some things to learn from Japan are:

1) They have a culture of always observing earthquake behavior since 1137 years ago (Hakuho Nankai Earthquake - Tsunami in 684)
2) Always mark, record the sequence of each earthquake activity very well.
3) The Japanese public does not easily forget disaster events, they even dig up the history of earthquakes and tsunamis to organize mitigation (Figure 1a).
4) Compact: The attention of state officials, scientists and the Japanese public to earthquake activity is very high (Figure 1b & 1c)
5) The public has very good earthquake and tsunami literacy -> not “shocked” and not “gumunan”/gaduh with information on earthquake potential, accept, not denial and always learn.
6) Strong determination in realizing concrete mitigation, aware with a strong belief that mitigation will save them (Figure 1c)


Figure 1a. The public always educates themselves and prepares concrete mitigation, 2b. Focus of the M7.1 Nankai Megathrust Earthquake, PM Kishida Cancels Overseas Visit, 2c. Warnings of a major earthquake in the Nankai Megathrust by seismologists are still valid for the Japanese people

### Earthquake Source Facts: Indonesia has 13 Megathrust Segmentations

Indonesia is situated in a highly seismic region, characterized by 13 distinct megathrust segmentations (Figure 2), each with varying magnitudes and historical earthquake activity (CNBC Indonesia, 2024). These segmentations, such as the Megathrust

Aceh-Andaman (M9.2) and Megathrust Nias-Simeulue (M8.7), highlight the potential for significant seismic events that can lead to devastating tsunamis. The historical data indicates that these areas have experienced major earthquakes in the past, underscoring the necessity for continuous monitoring and assessment of seismic hazards.

The presence of "seismic gaps" within these megathrust zones further complicates the risk landscape, as these areas have not experienced significant earthquakes for extended periods, potentially indicating a build-up of tectonic stress. This phenomenon necessitates the implementation of robust mitigation strategies, including public education, infrastructure resilience, and regulatory frameworks tailored to address the unique challenges posed by megathrust earthquakes. By understanding the seismic hazard landscape and preparing accordingly, Indonesia can better safeguard its population and reduce the socio-economic impacts of future seismic events.

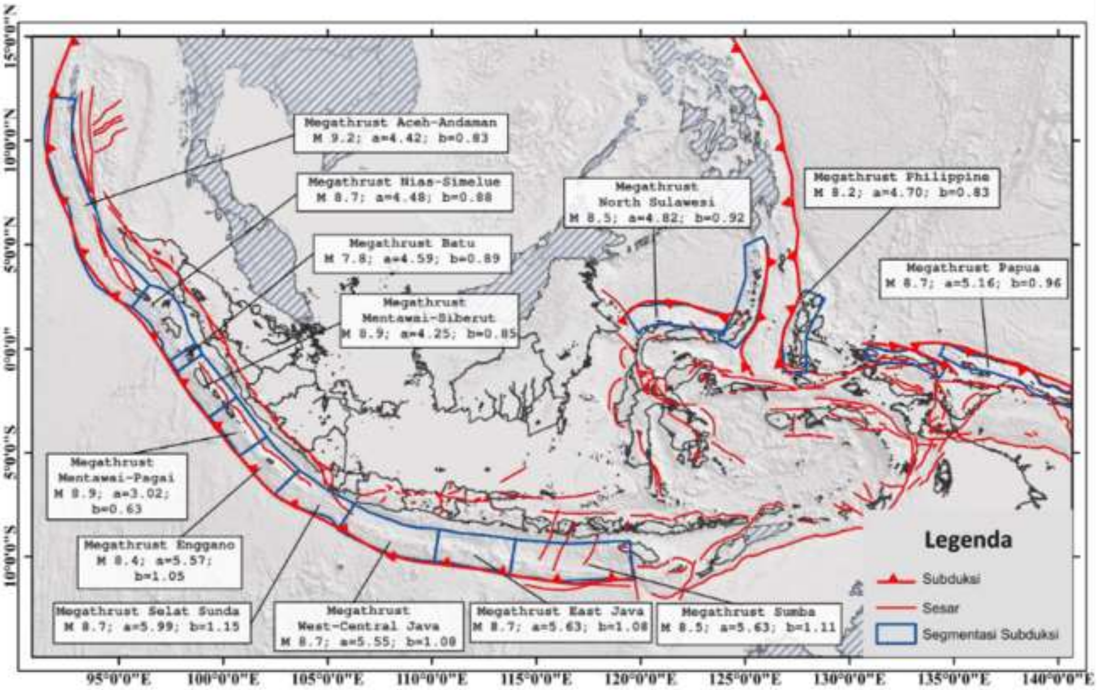

Figure 2. Map of Megathrust Earthquake Sources in Indonesia

Tectonically in Indonesia there are 13 Megathrust Zone earthquake source segmentations, namely:

1. *Aceh-Andaman Megathrust M9.2*

The Aceh-Andaman Megathrust (M9.2) is one of 13 megathrust zone earthquake source segmentations found in Indonesia tectonically. This segmentation is located in the Aceh and Andaman regions, with a potential earthquake magnitude of up to 9.2. Research shows that the Aceh-Andaman segment has a well-documented history of megathrust earthquakes, with records of major earthquakes in the past. However, other segments along the Indonesian megathrust zone, especially those south of Java, show potential seismic gaps that could trigger catastrophic events in the future. Historical data indicates that large earthquakes are rare in these regions, but the absence of event records does not mean the risk has disappeared, as the potential for significant seismic activity remains high due to ongoing tectonic processes.

*2. Nias-Simeulue Megathrust M8.7*

The Nias-Simeulue Megathrust (M8.7) is one of 13 earthquake source segments in Indonesia that has great potential to generate megathrust earthquakes. Located off the west coast of Sumatra, this segment is known for its significant seismic history, including large earthquakes that occurred in 2005 and 2006. Research shows that this segment has a high shear velocity and can release large amounts of energy, potentially causing destructive tsunamis in the surrounding area. In addition, analysis of the seismic gaps around this segment indicates that there is a possibility of large earthquakes in the future, which demands more attention in terms of disaster mitigation and strengthening the tsunami early warning system in the region. The tsunami modeling performed shows that in the event of a megathrust earthquake on this segment, the resulting tsunami could reach significant heights, adding to the urgency of increasing community preparedness against this seismic threat.

*3. Megathrust Batu M7.8*

The Batu Megathrust (M7.8) is one of 13 earthquake source segments in Indonesia that has great potential to generate megathrust earthquakes. Located off the west coast of Sumatra, this segment has been of interest due to its significant seismic history and potential to produce large earthquakes that can have widespread impacts. Data from the Meteorology, Climatology and Geophysics Agency (BMKG) shows that this segment has the possibility to release large seismic energy, which can cause destructive tsunamis. In addition, research shows that the Batu Megathrust has not experienced a major energy release in a long time, raising concerns of a megathrust earthquake in the near future. This calls for more attention in terms of disaster mitigation, including strengthening early warning systems and community preparedness for seismic threats that may occur in the region.

*4. Mentawai-Siberut Megathrust M8.9*

The Mentawai-Siberut Megathrust (M8.9) is one of the most significant megathrust segments in Indonesia, located off the west coast of Sumatra. The segment is approximately 200 km long and 200 km wide, with a slip rate of up to 4 cm per year, indicating an accumulation of seismic energy that could potentially produce large earthquakes. History records that megathrust earthquakes have occurred in this region in 1797 with a magnitude of 8.7 and in 1833 with a magnitude of 8.9. The long time span since the last event raises concerns about future large earthquakes, especially since both events show that this zone has the potential to release enormous energy. The Meteorology, Climatology, and Geophysics Agency (BMKG) warns that this condition creates a "seismic gap," where the region has not experienced a significant release of seismic energy for a long time, so the possibility of a megathrust earthquake in Mentawai-Siberut is a serious threat that needs to be watched by the community and the government in disaster mitigation efforts.

5. *Mentawai-Pagai Megathrust 8.9*

The Mentawai-Pagai Megathrust (M8.9) is one of the most significant megathrust segments in Indonesia, located off the west coast of Sumatra. This segment has the potential to produce large earthquakes with maximum magnitudes of up to 8.9, potentially causing destructive tsunamis. History records that this region has experienced large earthquakes in 1797 and 1833, suggesting that this segment has a recurring seismic pattern. However, the long time span since the last event raises concerns of significant energy accumulation in this zone, which could lead to future megathrust earthquakes. The Meteorology, Climatology and Geophysics Agency (BMKG) identifies this segment as a “seismic gap,” where there has been no major energy release for hundreds of years, increasing the risk of large, unpredictable earthquakes. Therefore, it is important to strengthen the early warning system and improve community preparedness against potential disasters that could be caused by seismic activity in Mentawai-Paga.

6. *Enggano Megathrust M8.4*

The Enggano Megathrust (M8.4) is one of the most significant megathrust segments in Indonesia, located off the west coast of Sumatra. With a potential maximum magnitude of up to 8.4, this segment is a major concern in seismic risk assessment. History shows that this region has the potential to generate large earthquakes that can cause tsunamis, given the accumulation of energy over many years without significant release. The Meteorology, Climatology and Geophysics Agency (BMKG) identified Enggano as part of a “seismic gap,” meaning that this segment has not experienced a major release of seismic energy for a long time, increasing the risk of future megathrust earthquakes. Further research is needed to better understand the seismic behavior of this segment and to develop effective mitigation strategies to protect the people living in this disaster-prone area, especially given the dense population along the west coast of Sumatra that could potentially be affected by the resulting earthquake and tsunami.

7. *Megathrust Sunda Strait - Banten M8.7*

The Sunda Strait-Banten Megathrust (M8.7) is one of the most important megathrust segments in Indonesia, located between the islands of Sumatra and Java. This segment has long been of interest to researchers and disaster mitigation agencies, such as the Meteorology, Climatology and Geophysics Agency (BMKG), as it is considered a “seismic gap” zone with the potential to produce large earthquakes. History records that this region has not experienced a significant earthquake for hundreds of years, with the last recorded major earthquake occurring in 1757. This delay in the release of seismic energy raises fears of a megathrust earthquake that could have far-reaching impacts, including the possibility of a destructive tsunami. BMKG warns that a potential earthquake in this segment is “just a matter of time,” making it important to improve disaster preparedness and mitigation in this high-risk area, including strengthening infrastructure and early warning systems to protect communities living nearby.

*8. Megathrust West Java - Central Java M8.7*

The West Java - Central Java Megathrust (M8.7) is one of the most important megathrust segments in Indonesia, located along the southern coast of Java. This segment has the potential to produce large earthquakes that can cause serious impacts, including tsunamis. According to the Meteorology, Climatology and Geophysics Agency (BMKG), this region is a zone of "seismic gap," where there has been no release of large seismic energy for hundreds of years, increasing the risk of future megathrust earthquakes. History shows that this segment has not experienced a significant earthquake for a long time, which makes scientists concerned about the accumulation of energy that could lead to a large earthquake. Research suggests that the potential maximum magnitude in this segment could reach 8.7, which could threaten the safety of people in coastal areas and beyond. Therefore, it is important to improve early warning systems and community preparedness to deal with potential disasters that could be caused by seismic activity in this segment.

9. *East Java Megathrust M8.7*

The East Java Megathrust (M8.7) is one of the megathrust segments that has great potential to produce powerful earthquakes in Indonesia, located along the southern coast of East Java. The segment is approximately 440 km long and 200 km wide, with a slip rate of up to 4 cm per year, indicating significant accumulation of seismic energy. History records that the region experienced a major earthquake in 1994 with a magnitude of 7.8, although the maximum potential that the segment can generate is 8.7. According to the Meteorology, Climatology and Geophysics Agency (BMKG), these conditions create fears of a megathrust earthquake that could cause a tsunami, especially as the segment is part of a wider active subduction zone. Research shows that this segment is also a "seismic gap," where there has been no major energy release for a long period, increasing the risk of future large earthquakes. Therefore, it is important for the government and communities to improve disaster preparedness and mitigation in this region to reduce possible impacts from intensified seismic activity.

*10. North Sulawesi Megathrust M8.5*

The Sumbe Megathrust (M8.5) is one of the significant megathrust segments in Indonesia, located off the southern coast of Sumatra. With a potential maximum magnitude of up to 8.5, this segment is a major concern in seismic risk assessment, especially since its seismic history shows that the region has not experienced a major earthquake for a long time. According to the Meteorology, Climatology and Geophysics Agency (BMKG), this creates a "seismic gap," where the accumulation of seismic energy could potentially result in a damaging megathrust earthquake in the future. Research shows that this segment has the potential to trigger tsunamis that can have widespread impacts on coastal areas, given the dense population in the region. Therefore, it is important to improve early warning systems and community preparedness, as well as strengthen infrastructure to mitigate the impacts that seismic activity on the Sumbe Megathrust may have.

*11. North Sulawesi Megathrust M8.5*

The North Sulawesi Megathrust (M8.5) is one of the most important megathrust segments in Indonesia, located along the northern coast of Sulawesi. With a potential maximum magnitude of up to 8.5, this segment is of interest in seismic risk assessment due to its seismic history which suggests that this region can produce large earthquakes with the potential to cause tsunamis. According to data from the Meteorology, Climatology and Geophysics Agency (BMKG), North Sulawesi is part of an active subduction zone that can trigger megathrust earthquakes, and has not experienced a major release of seismic energy in a long time, creating concerns about future catastrophic earthquakes. Research shows that the accumulated energy in this segment can lead to destructive earthquakes, making it important to improve early warning systems and community preparedness in the region. Therefore, a better understanding of the seismic behavior of the North Sulawesi Megathrust is necessary to develop effective mitigation strategies to protect people living in this disaster-prone area.

*12. Philippine Sea Plate Megathrust M8.2*

The Philippine Sea Plate Megathrust (M8.2) is one of the significant megathrust segments in Indonesia, located in the northeast region adjacent to the Philippine Sea Plate. With a potential maximum magnitude of up to 8.2, this segment is a major concern in seismic risk assessment, especially given its seismic history which shows that this region can trigger large earthquakes with the potential to cause tsunamis. According to the Meteorology, Climatology and Geophysics Agency (BMKG), the geological conditions around the Philippine Sea Plate Megathrust create an accumulation of seismic energy that could lead to damaging megathrust earthquakes in the future. Research shows that this segment is part of a broader subduction system, where interactions between tectonic plates can produce far-reaching earthquakes. Therefore, it is important to improve early warning systems and community preparedness around this region, as well as to strengthen infrastructure to reduce the impacts that may be caused by intensified seismic activity on the Philippine Sea Plate Megathrust.

*13. North Papua Megathrust (M8.7).*

The North Papua Megathrust (M8.7) is one of the megathrust segments that has great potential to produce powerful earthquakes in Indonesia, located along the northern coast of Papua. With a potential maximum magnitude of up to 8.7, this segment is of interest in seismic risk assessment due to its seismic history which suggests that this region can trigger large earthquakes with the potential to cause tsunamis. According to data from the Meteorology, Climatology and Geophysics Agency (BMKG), the geological conditions around the North Papua Megathrust create an accumulation of seismic energy that could lead to damaging megathrust earthquakes in the future. Research shows that this segment is part of a broader subduction system, where interactions between tectonic plates can produce far-reaching earthquakes. Therefore, it is important to improve early warning systems and community preparedness around this region, as well as to strengthen infrastructure to reduce the impacts that may be caused by intensified seismic activity on the Northern Papua Megathrust.

**Historical Facts about Java Earthquake & Tsunami, Evidence of Megathrust Threats**

The historical records of earthquakes and tsunamis in Java provide compelling evidence of the real and present threat posed by megathrust events in the region. Significant seismic events, such as the 1921 earthquake (M7.5) and the 2006 earthquake (M7.7), highlight the destructive potential of the megathrust zones along the southern coast of Java (Figure 3). These historical occurrences not only demonstrate the frequency of such events but also emphasize the need for comprehensive seismic hazard assessments to better understand the risks associated with megathrust earthquakes in this densely populated area (Wibowo et al., 2024).

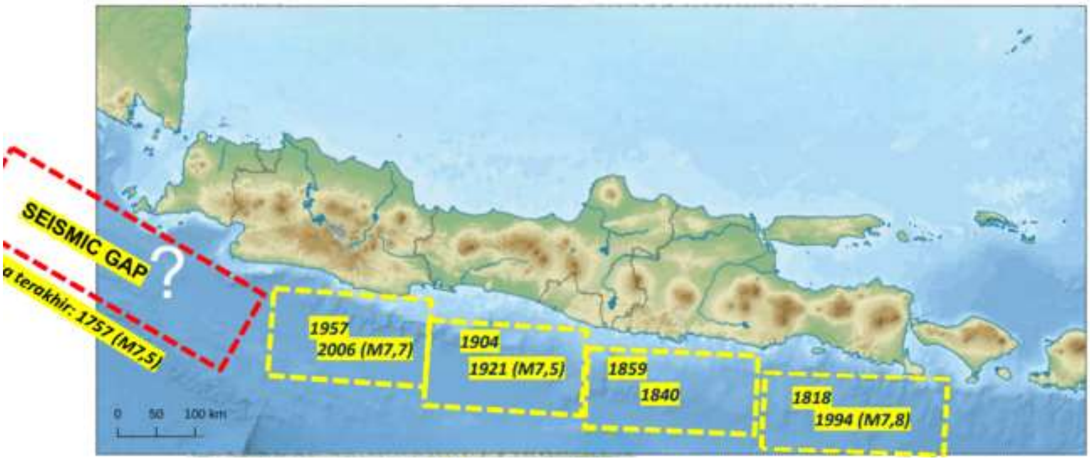


Figure 3. Java Island Seismic Gap

Moreover, the concept of "seismic gaps" in Java, where large earthquakes have not occurred for extended periods, raises concerns about the potential for future megathrust events. The absence of significant seismic activity in these gaps may indicate a build-up of tectonic stress, which could lead to catastrophic earthquakes in the future. This phenomenon underscores the importance of continuous monitoring and research to identify these gaps and develop effective mitigation strategies to minimize the impact of potential megathrust earthquakes on local communities (Wibowo et al., 2024).. In light of these historical facts, it is imperative for Indonesian authorities to prioritize disaster preparedness and public education regarding the risks associated with megathrust earthquakes and tsunamis. Implementing robust infrastructure, early warning systems, and community engagement initiatives can significantly enhance resilience against these natural disasters. By learning from past events and investing in proactive measures, Indonesia can better safeguard its population and reduce the socio-economic impacts of future seismic threats (Wibowo et al., 2024).

**Historical Facts about the Sumatra Earthquake & Tsunami, Proof that Megathrust is a Real Threat**

The historical record of earthquakes and tsunamis in Sumatra serves as a stark reminder of the real and imminent threats posed by megathrust events in this region. Notable seismic occurrences, such as the 2004 Aceh earthquake (M9.2) and the subsequent tsunami, resulted in catastrophic loss of life and widespread destruction, highlighting the devastating potential of megathrust earthquakes (Figure 4). These events have underscored the necessity for thorough seismic hazard assessments to understand the risks associated with the megathrust zones along the Sumatra subduction zone (Widiyantoro et al., 2024)

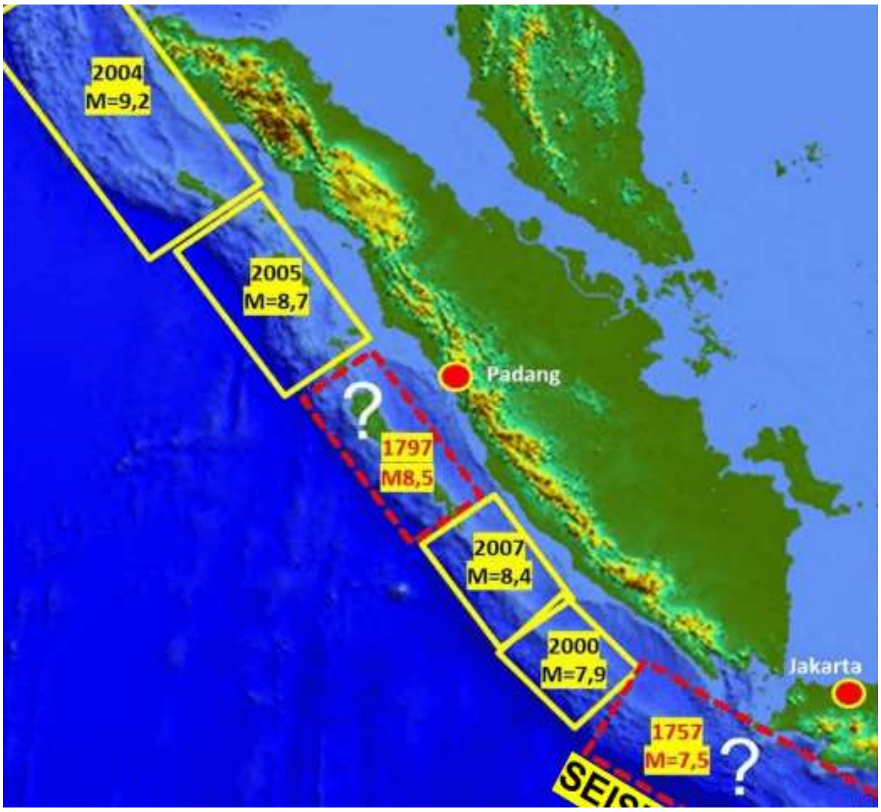

Figure 4. Seismic Gap of Sumatra Island

Additionally, the concept of "seismic gaps" in Sumatra, where significant earthquakes have not been recorded for extended periods, raises concerns about the potential for future megathrust events. The Mentawai-Siberut region, for instance, has experienced a seismic gap of 227 years, indicating a possible accumulation of tectonic stress that could lead to a major earthquake. This phenomenon emphasizes the importance of ongoing research and monitoring to identify these gaps and develop effective mitigation strategies to prepare for potential seismic threats.

In response to these historical facts, it is crucial for Indonesian authorities to enhance disaster preparedness and public awareness regarding the risks associated with megathrust earthquakes and tsunamis in Sumatra. Implementing comprehensive early warning systems, improving infrastructure resilience, and fostering community engagement initiatives can significantly reduce the impact of future seismic events. By learning from past experiences and investing in proactive measures, Indonesia can better protect its population and mitigate the socio-economic consequences of potential megathrust disasters (Widiyantoro et al., 2024).

**Don't Ignore the "Seismic Gap" Information: Because It's Real**

The concept of "seismic gap" is critical in understanding the seismic hazard landscape in Indonesia, particularly in regions prone to megathrust earthquakes (Figure 5). Seismic gaps refer to tectonically active areas that have not experienced significant earthquakes for extended periods, indicating a potential build-up of stress that could lead to future seismic events. Historical data, such as the 267-year gap in the southern Banten and Sunda Strait regions, reinforces the importance of recognizing these gaps as indicators of potential future megathrust earthquakes (Widiyantoro et al., 2020).

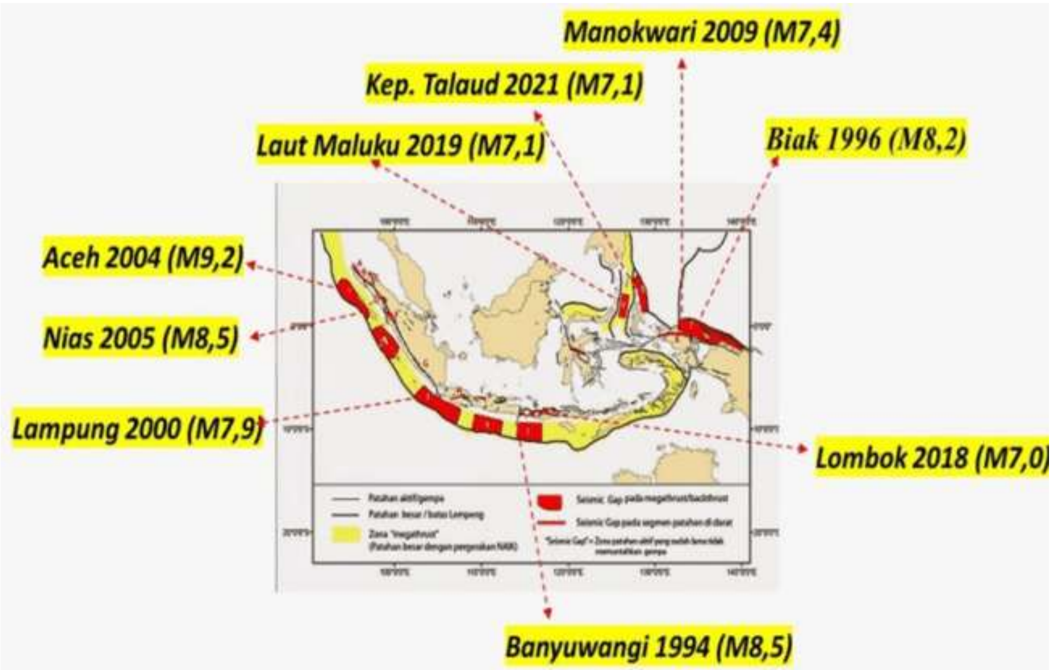


Figure 5. Seismic Gap in Indonesia

Ignoring the information regarding seismic gaps can lead to a false sense of security among communities living in these regions. The lack of recent seismic activity does not equate to safety; rather, it may suggest an increased risk of a significant earthquake occurring in the future. This understanding is crucial for effective risk communication and public awareness campaigns, as communities must be educated about the potential dangers associated with seismic gaps and the importance of preparedness measures (Widiyantoro et al., 2020). To mitigate the risks associated with seismic gaps, it is essential for Indonesian authorities to prioritize research and monitoring efforts in these areas. Implementing comprehensive seismic hazard assessments and developing targeted mitigation strategies can help reduce the socio-economic impacts of potential megathrust earthquakes. By acknowledging and addressing the realities of seismic gaps, Indonesia can enhance its resilience to future seismic threats and better protect its population from the devastating consequences of megathrust events .

## The Ultimate Earthquake Mitigation Solution: Realizing Earthquake Resistant Buildings

One of the primary solutions for mitigating the impacts of earthquakes in Indonesia is the implementation of earthquake-resistant building designs. Given the country's vulnerability to megathrust earthquakes, constructing buildings that can withstand seismic forces is essential for reducing casualties and property damage. Historical evidence, such as the stark contrast in casualties between the 2006 Yogyakarta earthquake, which resulted in over 6,000 deaths due to inadequate building standards, and the 2009 Suruga earthquake in Japan, which had only one fatality due to stringent building codes, underscores the importance of adopting robust engineering practices.

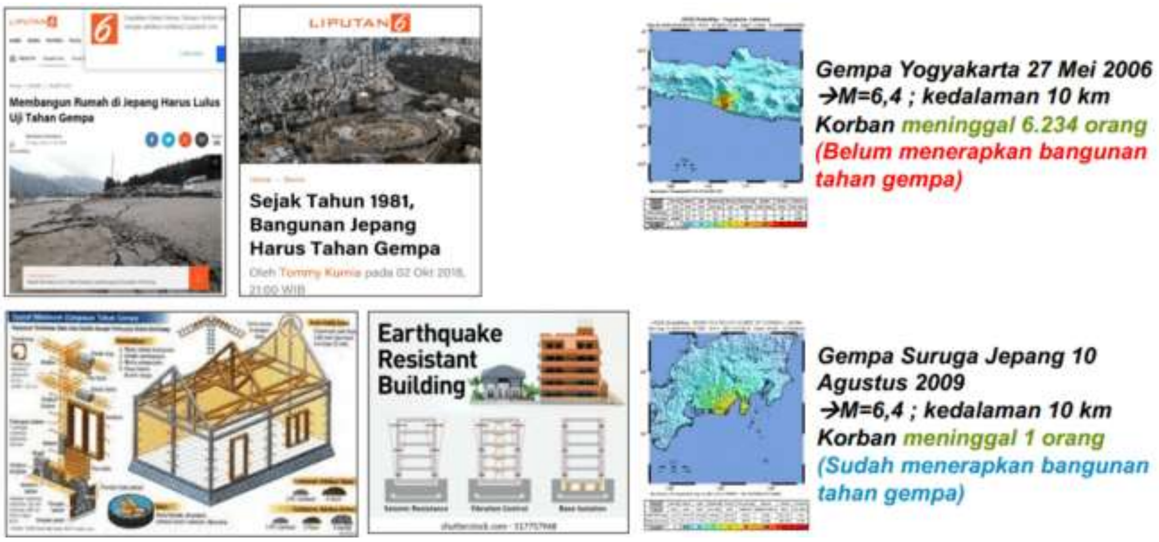


Figure 6. Earthquake Resistant Building

In addition to improving building codes, it is crucial to promote public awareness and education regarding earthquake preparedness and resilient construction practices (Figure 6). Engaging communities in understanding the importance of earthquake-resistant designs can foster a culture of safety and encourage compliance with building regulations. Workshops, training sessions, and public campaigns can empower individuals and local builders to prioritize seismic safety in their construction projects, ultimately leading to a more resilient built environment (Alwani & Adianto, 2021). Furthermore, collaboration between government agencies, engineering professionals, and local communities is vital for the successful implementation of earthquake-resistant infrastructure. Policymakers must ensure that regulations are enforced and that financial incentives are provided for retrofitting existing structures to meet modern seismic standards. By fostering a multi-stakeholder approach to earthquake mitigation, Indonesia can significantly enhance its resilience to future seismic events and protect its population from the devastating consequences of megathrust earthquakes.

**BMKG - Indonesia Tsunami Early Warning Ready to Provide Earthquake Information and Tsunami Early Warning**

The role of the Meteorology, Climatology, and Geophysics Agency (BMKG) in Indonesia is crucial for providing timely information on earthquakes and tsunami early warnings (Figure 7). With Indonesia's geographical location along the Pacific Ring of Fire, the risk of megathrust earthquakes and subsequent tsunamis is significant. BMKG's advanced monitoring systems and rapid data analysis capabilities enable the agency to issue alerts that can save lives and minimize damage by informing communities of impending threats (Harig et al., 2020).

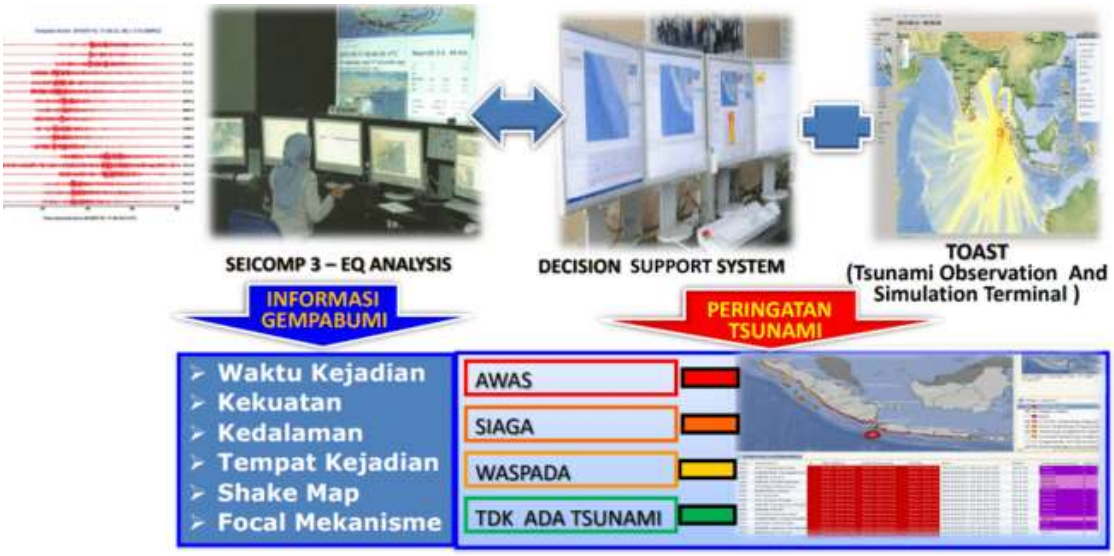


Figure 7. Earthquake Information Framework and Tsunami Early Warning from BMKG

BMKG employs a comprehensive approach to tsunami early warning, which includes real-time seismic data collection, analysis of earthquake parameters, and the dissemination of information to the public and local authorities. The agency utilizes a network of seismic stations and tsunami buoys to monitor seismic activity and ocean conditions, ensuring that alerts are based on accurate and up-to-date information. This proactive stance is essential for enhancing community preparedness and response to potential tsunami events, as timely warnings can significantly reduce casualties and property loss (Atika et al., 2019).

Moreover, public education and community engagement are vital components of BMKG's tsunami early warning system. By conducting outreach programs and simulations, BMKG aims to raise awareness about tsunami risks and the importance of adhering to early warning alerts. Empowering communities with knowledge and preparedness strategies fosters resilience and encourages individuals to take appropriate actions during emergencies, ultimately contributing to a more effective disaster response framework in Indonesia (Atika et al., 2019).

## End to end System Tsunami Early Warning

The end-to-end tsunami early warning system is a critical framework for enhancing Indonesia's preparedness against potential tsunami threats resulting from megathrust earthquakes (Figure 8). This system encompasses a comprehensive approach that includes monitoring, data analysis, alert generation, and effective communication to ensure timely warnings reach at-risk communities. By integrating advanced technologies such as seismic sensors, tsunami buoys, and satellite data, the system can rapidly assess seismic events and predict tsunami generation, thereby improving response times and reducing the risk of casualties (UNESCO, 2024).

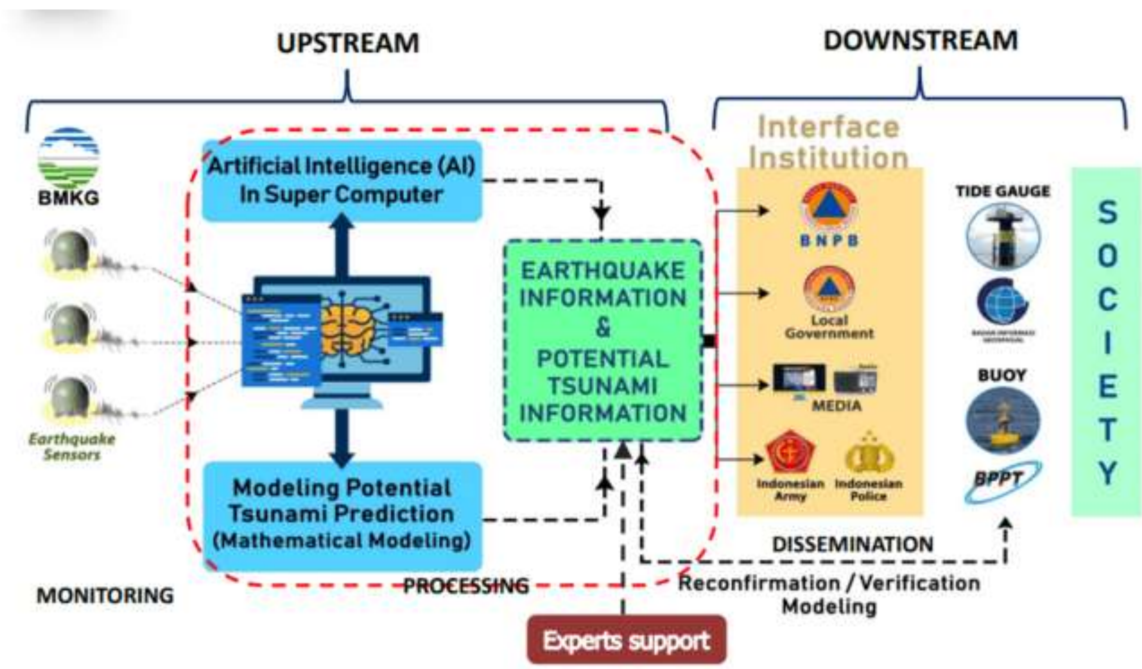


Figure 8. End to End System Tsunami Early Warning

A key component of the end-to-end system is the collaboration between various stakeholders, including government agencies, local authorities, and community organizations. This multi-faceted approach ensures that information flows seamlessly from data collection to public dissemination. Effective coordination among these entities is essential for maintaining the integrity of the warning system and ensuring that alerts are communicated clearly and promptly to the communities most at risk (Pusgen, 2017). Furthermore, continuous training and public education are vital for the success of the end-to-end tsunami early warning system. Engaging communities through drills, workshops, and informational campaigns helps to familiarize residents with the warning protocols and appropriate response actions during a tsunami event. By fostering a culture of preparedness and resilience, Indonesia can significantly enhance its capacity to respond to tsunami threats, ultimately safeguarding lives and minimizing the socio-economic impacts of such disasters (UNESCO, 2024).

## Modes of Dissemination of Earthquake Information and Tsunami Early Warning

The dissemination of information regarding earthquakes and tsunami early warnings is a critical aspect of disaster risk management in Indonesia, particularly given the country's susceptibility to megathrust events. Various modes of information dissemination, including SMS alerts, social media, and community radio, play a vital role in ensuring that timely and accurate warnings reach the affected populations (Figure 9). By utilizing multiple communication channels, authorities can enhance the likelihood that residents receive crucial information promptly, thereby improving their chances of taking appropriate protective actions (BMKG, 2021).


Figure 9. Dissemination Flow

Moreover, the effectiveness of these dissemination modes relies heavily on the integration of technology and community engagement. For instance, the use of mobile applications and automated alert systems allows for rapid communication of seismic events and tsunami warnings to a broad audience. However, it is equally important to engage local communities in understanding these systems, as familiarity with the warning protocols and the significance of alerts can significantly influence public response during emergencies. Additionally, continuous evaluation and improvement of dissemination strategies are essential to address the evolving needs of communities at risk. Regular drills and public education campaigns can help reinforce the importance of staying informed and prepared for potential seismic threats. By fostering a culture of awareness and readiness, Indonesia can enhance its resilience to earthquakes and tsunamis, ultimately reducing the impact of such disasters on its population and infrastructure (BMKG, 2021).

## Community-based Tsunami Mitigation - Earthquake and Tsunami Field School & BMKG Goes to school

Community-based tsunami mitigation through the Earthquake and Tsunami Field School and BMKG Goes to School programs is an important initiative in increasing community awareness and capacity towards earthquake and tsunami risks. The program aims to provide communities with knowledge and skills, so that they can be better prepared for disasters that may occur. By directly involving communities in the learning process, this initiative has the potential to create communities that are more resilient and responsive to disaster threats (Mukti & Aribowo, 2017). Through Sekolah Lapang activities, participants are taught about earthquake mechanisms, tsunami signs and appropriate evacuation steps. This knowledge is crucial, especially in disaster-prone areas, where a good understanding of the risks can reduce panic and improve the effectiveness of response in the event of a disaster. In addition, the BMKG Goes to School program also serves to bridge the communication between scientists and the community (Figure 10), so that the information conveyed is more easily understood and accepted by the community (Pusgen, 2017).


Figure 10. Community-based Tsunami Mitigation - Earthquake and Tsunami Field School & BMKG Goes to school

The success of community-based tsunami mitigation relies heavily on the support and collaboration between the government, educational institutions and community organizations. By building strong partnerships, these programs can be expanded and adapted to reach more communities and raise awareness of the importance of disaster mitigation. Thus, through continuous education and training, communities can be better prepared and able to reduce the risks posed by earthquakes and tsunamis (Rakuasa & Mehdila, 2023).

**Community-based Tsunami Mitigation - Tsunami Ready Community Program**

The Tsunami Ready Community program is a community-based tsunami mitigation initiative that aims to improve community preparedness and resilience to tsunami threats in Indonesia (Figure 11). Through the program, communities receive training and resources to develop evacuation plans, early warning systems and effective communication strategies. With international recognition from UNESCO, the program not only increased local awareness but also provided greater legitimacy and support for disaster mitigation efforts at the global level (Mukti & Aribowo, 2017).

The success of this program can be seen from BMKG's achievement in facilitating 10 communities in 10 districts to be recognized as Tsunami Ready Communities. This recognition indicates that the community has met certain criteria in tsunami preparedness, including the existence of an effective early warning system and active community participation in training and simulations. The program thus contributes to disaster risk reduction and increases the sense of security among people living in tsunami-prone areas (Pusgen, 2017).


Figure 11. Tsunami Ready Community Program

In addition, the Tsunami Ready Community program also encourages collaboration between the government, non-governmental organizations and communities in disaster mitigation efforts. By involving various parties, the program creates strong synergies in the development of more effective mitigation policies and practices. Through a community-based approach, it is hoped that tsunami awareness and preparedness can be continuously improved, so that communities can be better prepared to face the potential threats posed by megathrust earthquakes (Mukti & Aribowo, 2017).

## CONCLUSION

The conclusions of this study emphasize the importance of improving disaster preparedness and mitigation strategies in Indonesia, which is a highly vulnerable region to megathrust earthquakes due to its position on the Pacific Ring of Fire. The research highlights the need for seismic hazard assessments to understand the likelihood and potential impacts of such seismic events, as well as encouraging increased public awareness and the implementation of effective early warning systems. By learning from Japan's successful disaster management practices, Indonesia can strengthen its resilience to future seismic threats, thereby reducing the risks associated with large earthquakes and their accompanying tsunamis.

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