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Abstract

Today, the attractiveness of coastal areas has resulted in coastal communities continuing to grow, giving rise to new settlements, public facilities, port facilities, and tourism development. More than 40% of the world's population lives in coastal areas and more than 570 low-lying coastal cities will face a sea level rise of at least 0.5 m by 2050, public facilities, and residential areas due to extreme ocean wave activity will be lost, and become vulnerable to disaster threats, especially geological hazards of earthquakes accompanied by tsunamis. The growing potential of coastal areas will increase the vulnerability of several communities and supporting facilities to tsunami wave damage, resulting in considerable land destruction and loss of life. Indonesia is ranked second in the world as the country most frequently hit by tsunamis because geographically, the Indonesian archipelago is located in the border zone of three major Plates, namely the Eurasian Plate, the Indo-Australian Plate, and the Pacific Plate with high seismic activity that has the potential to generate earthquakes as the main effect of seismic activity and tsunamis as a secondary effect. Tsunamis occurring in the last 10 years are relatively rare because they occur unexpectedly, suddenly, unusually, and the biggest killer of people living in coastal areas against tsunamis. Although tsunami disasters cannot be avoided, their impact can be wisely mitigated through robust tsunami mitigation measures, as has been successfully demonstrated by several countries that have survived tsunami disasters. This is the background for conducting a tsunami disaster mitigation study with structural countermeasures (coastal protection and coastal forests) as a step towards building disaster-ready coastal communities in the near future.

[*] Masterminded EasyChair and created the first stable version of this document
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1 Introduction

Indonesia, which is geographically located on the Pacific Ring of Fire, namely the meeting of three world tectonic plates such as the Indo-Australian Plate, Eurasian Plate and Pacific Plate, is very vulnerable to natural disasters such as earthquakes, volcanic eruptions, and tsunamis (Ayuningtyas et al., 2021). In recent years, Indonesia has experienced a significant increase in both the frequency and severity of these events. The series of catastrophic events has enormous consequences for local communities, both from physical, socio-economic and psychological aspects. Recently, public concerns related to natural disasters have increased with the issue of megathrust as reported in the news; "BMKG Says Indonesia's Megathrust Earthquake is Just Waiting for Time, Could Reach M 8.9 (Yefta, 2024). With such great disaster potential, proper mitigation is needed because we realize that the coastal areas in Indonesia have an attraction in national development. The attractiveness of coastal areas results in coastal communities continuing to develop, giving rise to new settlements, port facilities, and tourism development. More than 40% of the world's population lives in coastal areas and more than 570 low-lying coastal cities will face sea level rise of at least 0.5 m by 2050, public facilities and residential areas due to extreme ocean wave activity will be lost and become areas vulnerable to disaster threats, especially geological hazards of earthquakes accompanied by tsunamis. (Dika Rojikin, 2020).

A tsunami is a series of ocean waves caused by a sudden and powerful disturbance, such as an earthquake, volcanic eruption or undersea landslide. Tsunami events generate very powerful waves in the deep ocean that can travel long distances at very high speeds, and when a large tsunami reaches the coast, some of the tsunami waves are reflected offshore, but most of the tsunami waves will rise inland with increasing height depending on the topography and bathymetry of the affected and surrounding areas, which makes it difficult for coastal residents to detect and even almost impossible to avoid, causing flooding, resulting in loss of life, widespread infrastructure damage, and long-term economic and environmental consequences. Understanding the characteristics and behavior of tsunamis is critical to mitigating their impacts and protecting vulnerable coastal communities. Major tsunami events in world history such as the Indian Ocean Tsunami in 2004, Aceh Tsunami in 2004, Mentawai Island tsunami in 2010, Tohoku Tsunami in 2011, Palu Tsunami in 2018 and Sunda Strait tsunami in 2018, demonstrate the importance of implementing effective disaster management to reduce and protect lives and property (Takabatake et al., 2022). However, not all tsunamis are triggered by earthquakes. In some cases, undersea landslides or volcanic eruptions can also generate tsunami waves, making it difficult to predict and prepare for these events.

Despite the devastating impact of tsunamis, ongoing research and advances in technology continue to improve our understanding of these events and our ability to mitigate their effects. Proper evacuation planning is a key component of tsunami disaster mitigation, as it helps ensure the safe and efficient movement of individuals and communities to higher ground or predefined safety zones in the event of a tsunami. Structural measures for tsunami disaster mitigation play an important role in increasing the resilience of coastal areas and help coastal areas to withstand the destructive force of tsunamis, communities can better prepare for and respond to tsunami events. Researchers have also emphasized the importance of community involvement and awareness in improving the effectiveness of tsunami disaster mitigation efforts. By involving local stakeholders in the planning and implementation of mitigation strategies, communities can develop a greater sense of ownership and commitment to the process, which will ultimately improve the overall resilience of affected areas.

2 Research Method

This research will use a mixed methods approach, combining a review of relevant literature with a case study analysis of tsunami mitigation efforts in Indonesia. The literature review will draw on a variety of sources, including academic journals, government reports and industry publications, to examine the current state of knowledge on the role of structural engineering in tsunami disaster mitigation and then relate it to our research.

3 Results and Discussion

Indonesia's vulnerability to natural disasters is well documented. Indonesia's location along major tectonic fault lines and the presence of a number of active volcanoes contribute to its high risk profile. Existing research highlights the need for a comprehensive disaster management approach that focuses not only on response and recovery, but also on proactive mitigation strategies. One such strategy is the implementation of robust structural design and construction practices to ensure the resilience of buildings, infrastructure and other critical facilities in the face of tsunami events.

Research has shown that the design and construction of tsunami evacuation buildings, or "vertical evacuation" structures, can be an effective way to protect communities in areas vulnerable to this disaster. These buildings are designed to withstand the force of a tsunami and provide a safe haven for residents and visitors, allowing them to evacuate until the tsunami threat has passed. In addition to vertical evacuation structures, the feasibility of tsunami evacuation routes and the identification of suitable evacuation sites are also important considerations in disaster mitigation planning. (Mutiawati et al., 2022). These solutions involve the design and construction of barriers, buildings and infrastructure, the following are some of the key aspects of these solutions: Seawalls and Barriers, Tsunami-Resistant Buildings, Natural and Hybrid Solutions, Hydraulic Structures, Hybrid Approaches, Community Planning and Evacuation Structures, Education and Awareness.

3.1 Structural Tsunami Disaster mitigation

Structural mitigation of tsunami disasters in various countries that are successful in mitigating tsunami disasters where there are several areas that survived the tsunami due to structural mitigation forms can provide valuable perspectives in the development of mitigation strategies in Indonesia. For example in Fudai Village, Japan, which survived the tsunami in 2011 by building a tsunami gate at the mouth of the river as high as 15.5 meters, it was able to save the area from a 17-meter tsunami that only flowed about a few hundred meters from the tsunami gate (Suppasri et al., 2013). Japan has implemented a vertical evacuation system by building a tsunami evacuation building that can accommodate thousands of people (Chang Seng, 2013). Sameera et al., (2017) emphasized the need to analyze the role of existing coastal structures in mitigating tsunami impacts, particularly in areas such as Sri Lanka that are highly vulnerable to tsunami events, modeling the impact of potential tsunamis on revetments and coastal railway embankments, obtained a fairly good level of tsunami protection, but may require upgrading to withstand larger events. Although current economic analysis does not justify upgrading these structures (assuming a functioning early warning system), the authors highlight the potential long-term financial benefits of small investments in mitigating damage from small-scale tsunamis. In France, investments in coastal infrastructure such as breakwaters and mangrove re-establishment have helped reduce tsunami damage.

3.2 Structural Tsunami Disaster mitigation in Indonesia

Structural forms of mitigation in Indonesia are an important component to reduce the impact of future tsunami events. Appropriate building codes, evacuation infrastructure and community-based preparedness programs are essential to protect vulnerable coastal areas. Structural mitigation consists of natural structural mitigation, such as implementing greenbelt and artificial structural mitigation such as building seawalls, breakwaters and establishing evacuation points and routes. In addressing the risk of tsunami disaster in Indonesia, various structural mitigation efforts have been implemented in several coastal areas, for example, areas that survived the tsunami disaster were Flores Island in 1933 and Sinjai Regency because they had mangroves that were able to protect the area, then in 2004 in Singkil City which was also saved because of the presence of mangroves with a thickness of 500 meters (Karminarsih, 2007).

As each region has unique geographic and spatial characteristics, the best structural mitigation strategies will vary. Here are some examples based on research in various regions in Indonesia:

1. Carita Sub-district, Pandeglang Regency**:** Low vulnerability areas are recommended to build *seawalls*, *breakwaters*, and mangrove forests (Hidayat & Hendrakusumah, 2021).
2. Pangandaran: Spatial analysis recommends mangrove planting, evacuation routes, temporary evacuation sites, breakwaters, and early warning systems (Lestari et al., 2023)
3. Sanana District, Sula Islands Regency, North Maluku: Recommendations include coastal reclamation as a buffer zone, breakwater, temporary evacuation buildings, evacuation routes, and other tsunami mitigation supporting infrastructure (Purwanto et al., 2017).
4. Watu Pecak, Lumajang district: Based on interpretation of area conditions, surveys, interviews, and secondary data, mangrove planting, breakwater construction, building relocation, and early warning systems are recommended (Noviantoro et al., 2022).
5. Molibagu Coastline: Natural structural mitigation by creation of green areas, evacuation routes, and decentralized area development (Ointu et al., 2015).
6. Pariaman City, West Sumatra: Use of functional spaces divided into protection zones, limited use zones, and development zones. In high-risk areas, mangrove planting is recommended (Ihsan & Pramukanto, 2017).
7. Banda Aceh City: The multi-layer system approach to tsunami vulnerability results in mitigation recommendations based on the level of vulnerability. For example, in areas with high vulnerability (layer 1), it is necessary to strengthen and maintain the existing breakwater and seawall. In layer 2, freeing up 100 meters of coastal border land and establishing mangrove paths. In layer 3, implement a silvofisheries system, and in layer 4, build an overpass (Agussaini et al., 2022).

Indonesian regulations, such as Law No. 1/2014 on the Management of Coastal Areas and Small Islands, mandate a minimum coastal buffer of 100 meters. Here are some examples of structural mitigation recommendations based on research in several regions:

1. The Mentawai Islands tsunami disaster mitigation is differentiated based on Zone (Putra, 2011) namely: Conservation zone (directly adjacent to the sea): Fisheries, mangrove forests 200-300 meters wide, and avoiding bay-like coastal forms that can exacerbate tsunami currents. Buffer zone: Breakwater, seawall, and beach nourishment. Free zone: Can be utilized for various activities.

2. Palu City (Sarapang et al., 2019), conducted a spatial analysis showing the need for mangrove planting and protection of natural forests and protected forests. Then Jabbar (2024) in his research recommended the construction of a tsunami gate or sluice gate at the mouth of the river that can block the entry of tsunami water through the river to settlements at 8 locations spread across all sub-districts, imposing a buffer zone, in this case it can be done by making a greenbelt / green belt, namely mangroves with a planting thickness of 300-500 m from the coastline are considered capable of reducing tsunamis, building seawalls that can block the impact of tsunami disasters and combined with breakwater to reduce the propagation rate of tsunami waves, imposing a 100 meter coastal boundary rule. Especially in areas with concave morphology that can reduce the turbulence of tsunami energy to land so as to minimize tsunami water reaching settlements.

3. Pangandaran Regency, West Java, the local government has undertaken several structural mitigation efforts, such as: Development of temporary evacuation facilities and infrastructure that are designed to be safer and integrated with early warning systems to facilitate the evacuation process during a tsunami disaster. In addition, the structuring and strengthening of public buildings, such as schools and hospitals, to make them more resilient to tsunami impacts. Aceh, studies show that structural mitigation efforts such as the construction of coastal protection structures such as groins, jetties and revetments can help reduce tsunami disasters (Pancasilawan, 2020). In addition, the development of vertical evacuationstructures in Banda Aceh is also a focus, although they need to be improved to protect the community.

4. Pacitan, Indonesia, efforts have been made to build structural components, develop coastal forests and install marine radar on land to mitigate tsunamis (Syamsidik et al., 2020).

From several studies and applications of structural tsunami disaster mitigation that have been conducted by previous researchers as previously described, we realize the importance of those structural mitigation models that have been successful including, coastal protection (seawall), seawall, mangrove etc. From these findings, one of the research ideas to answer the need for structural tsunami disaster mitigation in coastal areas by considering the existing bathymetry and topography in Indonesia is to conduct research related to hybrid mitigation between artificial structures with permeable seawalls and coastal vegetation that can grow in coastal areas and can live in the tropics.

4 Conclusions

1. It is important to note that the combination of these structural and engineering solutions, together with effective land use planning and early warning systems, contribute to a comprehensive tsunami mitigation strategy. The integration of traditional and nature-based approaches can improve the overall resilience of coastal areas and reduce tsunami impacts on people and infrastructure.
2. The importance of community involvement and awareness in improving the effectiveness of tsunami disaster mitigation efforts. By involving local stakeholders in the planning and implementation of mitigation strategies, communities can develop a greater sense of ownership and commitment to the process, which will ultimately increase the overall resilience of the affected area.

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