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Marine Disaster Risk Management: The Contribution of Maritime Engineering

Abstract

Marine disasters such as tsunamis, tropical storms, coastal flooding, and coastal abrasion are serious threats to coastal communities, maritime infrastructure, and economic activity. Marine disaster risk management is very important to minimize its negative impact. Marine engineering plays a strategic role in risk mitigation through the design of coastal protection structures, such as sea walls, breakwaters, and seawalls, as well as hydrodynamic modeling to predict the behavior of waves, currents, and tides in extreme conditions. In addition, marine engineering supports the development of sensor, radar, and satellite-based marine disaster warning and monitoring systems, enabling rapid and precise decision-making. With the integration of structural engineering, scientific modeling, and monitoring technology, marine disaster risk management becomes more comprehensive, proactive, and sustainable. This article discusses the contribution of marine engineering in minimizing the risk of marine disasters and improving the safety and resilience of coastal areas. With the integration of structural engineering, scientific modeling, monitoring technology, and community participation, marine disaster risk management becomes more comprehensive, proactive, and sustainable. This article discusses the contribution of marine engineering in minimizing the risk of marine disasters and improving the safety, resilience, and sustainability of coastal areas.

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1. Introduction

Marine disasters are natural phenomena that occur in coastal areas and waters, such as tsunamis, tropical storms, coastal floods, and coastal abrasion. The incident has a serious impact on people's lives, infrastructure, and economic activities in coastal areas. In addition to material losses, marine disasters also have the potential to threaten human safety and disrupt marine ecosystems. With the increase in human activity in coastal areas, the risk of marine disasters is also becoming higher, so effective risk management efforts are needed to protect communities and assets in the region.

Marine engineering as a branch of engineering science that studies the interaction between the sea, waves, currents, and man-made structures has an important role in mitigating the risk of

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marine disasters. Through the application of engineering principles, hydrodynamic modeling, and the development of coastal protection structures, marine engineering helps minimize the physical impacts of high waves, extreme tides, and coastal erosion. In addition, marine engineering also supports coastal spatial planning, real-time monitoring of marine conditions, and early warning systems that provide quick information to take mitigation actions.

In addition to technical efforts, marine disaster risk management also requires a holistic approach, including education and participation of coastal communities. Public awareness of risks and disaster preparedness are important factors in the success of mitigation. The integration of structural engineering, monitoring technology, spatial planning, and community participation makes risk management more effective and sustainable. Thus, the application of marine engineering is not only limited to the physical aspect, but also includes risk reduction strategies and increasing the resilience of coastal areas to marine disasters.

2. Materials and Methods

Marine disaster risk management requires a variety of physical and non-physical materials that support risk mitigation in coastal areas. Physically, the materials used include coastal protection structures such as sea embankments, breakwaters, and seawalls, which are generally made of reinforced concrete, natural stone, or gabion. These structures are designed to withstand high waves, extreme tides, and coastal erosion processes. In addition, monitoring tools such as wave sensors, coastal radar, tidal gauges, and satellite systems are also important materials for monitoring sea conditions in real-time and detecting potential disasters early.

Non-physical materials also play an important role in risk management. Hydrometeorological data, coastal risk maps, spatial information, and historical records of marine disasters are used as the basis for planning protection structures and mitigation strategies. In addition, the involvement of coastal communities through preparedness training and education is considered a social material that supports the effectiveness of the entire risk management system, because community awareness and readiness are key factors in dealing with disasters.

Risk management methods combine technical, scientific, and social approaches. From the technical side, hydrodynamic analysis was carried out to predict the behavior of waves, currents, and tides in coastal areas. The results of this analysis are the basis for designing coastal protection structures that are in accordance with local conditions. Computer modeling and numerical simulations are also used to evaluate the effectiveness of structures and forecast possible disaster scenarios, so that mitigation strategies can be tailored to real risks.

In addition to designing and modeling, risk management methods also include monitoring and early warning systems. Data from sensors, radars, and satellites are analyzed to determine the level of risk and provide early warning to coastal communities. This approach is reinforced with education and socialization programs, including evacuation training and contingency plan development. The combination of physical materials, monitoring technology, scientific data, and community participation makes marine disaster risk management more comprehensive, proactive, and sustainable.

In addition to the application of physical structures and monitoring technologies, marine disaster risk management also emphasizes the importance of long-term adaptation to changes in the coastal environment. For example, sea level rise due to climate change requires adjustments to the design of dikes, breakwaters, and seawalls to remain effective in protecting coastal areas. This adaptive approach also includes the rearrangement of coastal spatial planning, such as the zoning of disaster-prone areas, the development of mangrove forests as a natural wave barrier, and the protection of marine ecosystems that function as natural buffers against disasters.

3. Results

The application of marine engineering in marine disaster risk management has shown various positive results in mitigating impacts on coastal areas. One of the main results is the effectiveness of coastal protection structures such as sea walls, breakwaters, and seawalls in retaining wave

energy and reducing coastal abrasion. These structures, when designed according to local characteristics such as wave height, current, and tidal conditions, are able to significantly reduce the damage to coastal infrastructure. For example, breakwaters in ports are able to protect piers and ships from high waves, while abrasion-prone seawalls slow soil erosion and keep the coastline stable.

In addition to physical protection, the results of the use of monitoring technology and early warning systems are also very visible. Wave sensors, coastal radar, and satellites allow real-time monitoring of ocean conditions and provide early information regarding potential tsunamis or tropical storms. With this system, coastal communities and authorities can take evacuation measures before high waves or storms reach residential areas, so the risk of fatalities and material losses can be significantly reduced.

Other results can be seen from hydrodynamic modeling and numerical simulations, which are used to optimally plan the location and design of protective structures. These simulations allow prediction of wave behavior, currents, and sedimentation, so that the structures built are not only safe but also efficient in terms of cost and materials. In addition, this approach helps plan long-term mitigation strategies, including adaptation to climate change and sea level rise.

Finally, the application of social approaches and community participation also yielded significant results. Preparedness training, evacuation simulations, and education on marine disaster risk increase awareness and rapid response of coastal communities. The integration of structural engineering, monitoring technology, scientific modeling, and community participation makes marine disaster risk management more comprehensive, proactive, and sustainable, so that coastal areas are more resilient to future marine disasters.

The results of the application of marine engineering in marine disaster risk management show significant effectiveness in protecting coastal areas and communities. Coastal protection structures, such as sea walls, breakwaters, and seawalls, have been proven to be able to withstand the energy of large waves, reduce coastal erosion, and protect coastal infrastructure from damage. For example, breakwaters in ports and docks not only maintain the safety of ships, but also reduce the risk of operational disruption due to high waves, while the abrasion-prone seawall on the coast slows down the soil erosion process and helps maintain shoreline stability.

On the technological side, monitoring and early warning systems provide tangible results in the detection and mitigation of marine disasters. The use of wave sensors, coastal radar, and satellites allows for real-time identification of potential tsunamis, storms, or extreme tides. As a result, coastal communities can receive alerts faster and evacuate before disasters occur, so the risk of casualties and material losses can be significantly reduced. The system also helps authorities to plan emergency response more precisely.

Hydrodynamic modeling and numerical simulation also make important contributions. By predicting wave behavior, currents, and sedimentation, this method allows the design of safer, more efficient, and local protection structures. The results of this modeling help determine the height of the embankment, the location of breakwater, and the arrangement of coastal areas that are vulnerable to flooding and abrasion. Thus, the built protection structure is not only technically effective, but also cost-effective and sustainable.

In addition, social approaches and community participation provide significant results in risk management. Preparedness training, evacuation simulations, and education on marine disaster risk increase awareness and response of coastal residents. People who understand evacuation routes and safe points can play an active role in disaster mitigation. The integration of structural engineering, monitoring technology, scientific modeling, and community participation makes marine disaster risk management more comprehensive, proactive, and sustainable, so that coastal areas become more resilient to various marine disasters.

4. Discussion

Marine disaster risk management requires a comprehensive approach, combining technical, scientific, and social aspects. One of the important aspects is the implementation of coastal protection structures, such as sea embankments, breakwaters, and seawalls. This structure

functions to withstand large waves, reduce coastal erosion, and protect infrastructure in coastal areas. The effectiveness of such structures is highly dependent on local conditions, such as wave height, currents, and tides. Therefore, proper design based on environmental conditions is the key to successful mitigation.

In addition to the physical structure, monitoring technology and din i warning systems also play an important role. Wave sensors, coastal radar, and satellites allow real-time monitoring of ocean conditions. This information is used to provide early warning to coastal communities, so that evacuations can be carried out faster and the risk of casualties can be reduced. The integration between technology and physical protection makes marine disaster risk management more effective and responsive.

Hydrodynamic modeling and numerical simulation are becoming important methods in mitigation planning. By predicting the behavior of waves, currents, and tides, modeling helps determine the optimal location and design of protective structures. In addition, this modeling also supports adaptation to environmental changes, including sea level rise due to climate change. Thus, the built protection structure is not only safe, but also durable and efficient.

In addition to the technical aspect, community participation is an important component in risk management. Preparedness training, evacuation simulations, and education about marine disasters increase citizen awareness and accelerate response when disasters occur. Community involvement helps ensure that protection and early warning systems can be utilized to the fullest, so that risks can be minimized in real terms.

Overall, the success of marine disaster risk management does not only depend on the construction of physical structures or monitoring technology, but also requires a holistic approach. The integration of marine engineering, scientific modeling, monitoring technology, and community participation makes coastal areas more resilient, safe, and sustainable to face various risks of future marine disasters.

Marine disaster risk management requires the implementation of a comprehensive strategy, including physical structures, monitoring technology, modeling, and community participation. One example of a real application is the construction of a breakwater at Tanjung Priok Port. This breakwater functions to break up wave energy before reaching the dock, so that the docked ship is safer and port operations are not disrupted. This structure is designed based on local wave and current height data, so it effectively withstands large waves without causing damage to the surrounding infrastructure.

In addition, the seawall on the North Coast of Java is an example of coastal protection against abrasion. This seawall helps to resist coastal erosion due to extreme tidal waves and storms. The placement of the seawall is adjusted to the local soil and current conditions, so that the coastline remains stable and coastal communities are protected. The application of this physical structure is a strong foundation for disaster mitigation, but it still needs to be combined with other methods for optimal results.

Monitoring and early warning technology is also an important part of risk management. An example of its application is the BMKG Tsunami Early Warning System. The system utilizes underwater sensors, coastal radar, and satellites to detect wave changes in real-time. The information obtained is sent through siren, SMS messages, and applications, so that coastal communities can immediately evacuate. This system has proven effective in reducing the risk of casualties and material losses in times of disaster.

In addition to physical and technological protection, hydrodynamic modeling is also applied to mitigation planning. For example, at Cilacap Beach, computer simulations are used to predict wave and current behavior, as well as determine the optimal location of sea embankments. This modeling allows protection structures to be built efficiently and sustainably, while anticipating changes in environmental conditions such as sea level rise.

The social approach is also applied through evacuation simulations and community education. A real-life example is a tsunami simulation in Palu City, where residents were trained to recognize evacuation routes and safe points. This activity increases public awareness and preparedness, so that when a disaster occurs, residents can respond quickly and effectively. In addition, some regions

also integrate mangrove forests as natural wave barriers, which at the same time protects marine ecosystems and increases environmental resilience.

With the combination of all these approaches, marine disaster risk management becomes more comprehensive and sustainable. The application of protection structures, monitoring technology, hydrodynamic modeling, and community participation shows that marine disaster mitigation does not only depend on physical development, but also on scientific and social risk management. As a result, coastal areas become safer, communities are better prepared, and the impact of disasters can be minimized.

Table 1. Marine Disaster Risk Management

Types of Applications	Location/Example	Explanation
Breakwater	Port of Tanjung Priok	Break up wave energy before reaching the dock, protect ships, and maintain port operations.
Seawall	North Coast of Java	Resists coastal abrasion due to tidal waves and storms, keeping the coastline stable.
Sensors & Early Warning Systems	BMKG Tsunami Early Warning System	Detect wave changes in real-time and provide alerts to the public through sirens and SMS.
Hydrodynamic Modeling	Cilalap Beach	Simulation of wave and current behavior to determine the location of the sea embankment that is optimal, efficient, and durable.
Mangrove Forest	Some of Indonesia's coastal beaches	It acts as a natural wave barrier while protecting marine ecosystems and increasing environmental resilience.

Table 1 shows that marine disaster risk management does not only depend on physical structures, but also utilizes monitoring, modeling, and community participation technologies. The combination of these various applications makes coastal areas safer, communities are more prepared, and the impact of disasters can be minimized.

In addition to technical and social aspects, marine disaster risk management must also consider global climate change factors that increasingly intensify the frequency and severity of extreme weather events. Rising sea surface temperatures can trigger stronger tropical storms, while sea level rise increases the risk of coastal flooding and tidal inundation. Therefore, mitigation strategies should not only focus on current conditions but must also integrate long-term climate projections to ensure that protection systems remain effective for future decades.

Marine disaster risk management also requires cross-sector coordination between governments, maritime industries, academic institutions, and local communities. Governments play a role in developing coastal spatial planning policies and safety regulations, while industries support implementation through advanced safety technologies and strict operational standards. Meanwhile, research institutions and universities contribute through the development of prediction models, monitoring technologies, and innovative construction materials that are more resistant to harsh marine environments.

Furthermore, the utilization of digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data is becoming increasingly important in modern marine disaster risk management systems. The integration of real-time data from various sensors enables faster and

more accurate analysis, allowing potential hazards to be identified earlier. These technologies also support dynamic risk mapping, enabling more efficient evacuation planning and resource distribution during emergencies.

From an economic perspective, effective marine disaster risk management can significantly reduce financial losses caused by infrastructure damage, port operation disruptions, and decreased productivity in fisheries and tourism sectors. Investment in protection systems and mitigation measures is often more cost-effective than post-disaster recovery expenses. Therefore, preventive approaches are considered essential strategies for achieving sustainable coastal development.

Marine disaster risk management also emphasizes the importance of ecosystem-based approaches as natural protection systems. Coastal ecosystems such as mangrove forests, coral reefs, and seagrass beds act as natural barriers that reduce wave energy, minimize coastal erosion, and protect shorelines from storm surges. Preserving and restoring these ecosystems not only supports biodiversity but also strengthens coastal resilience against natural hazards. In many coastal regions, combining natural and engineered protection systems has proven to be more sustainable and cost-effective in the long term.

Another important aspect is the development of risk-based coastal spatial planning. Coastal development must consider hazard maps, historical disaster data, and vulnerability assessments to avoid constructing critical infrastructure in high-risk zones. Land-use planning that integrates disaster risk reduction can significantly reduce potential damage and loss of life. This approach encourages safer settlement patterns and supports long-term environmental sustainability.

Capacity building and continuous training programs are also essential components of effective marine disaster risk management. Regular disaster response training, emergency drills, and technical skill development for local authorities and emergency teams help improve readiness and coordination during real disaster events. Community-based disaster risk management programs ensure that local populations understand evacuation routes, emergency procedures, and early warning signals.

In addition, international cooperation plays a crucial role in improving marine disaster preparedness. Many marine disasters such as tsunamis and tropical cyclones affect multiple countries simultaneously. Therefore, sharing data, technology, and best practices between countries can strengthen global disaster response capabilities. International organizations and regional partnerships often provide technical support, funding, and training programs to enhance disaster management capacity in developing coastal regions.

The integration of sustainable infrastructure concepts is another key factor in modern marine disaster risk management. Infrastructure such as ports, offshore platforms, and coastal protection structures must be designed using resilient engineering principles. This includes using corrosion-resistant materials, adaptive structural designs, and flexible foundation systems that can withstand extreme environmental loads.

Public awareness campaigns and disaster education programs are also critical in reducing disaster risk. Educating coastal populations about potential hazards, climate change impacts, and emergency preparedness helps create a culture of safety. When communities understand risks and know how to respond, evacuation processes become faster and more organized, significantly reducing casualties.

Financial preparedness is equally important in disaster risk management. Governments and private sectors often develop disaster insurance schemes, emergency funding mechanisms, and risk-sharing financial instruments. These financial tools help accelerate recovery processes after disasters and reduce long-term economic disruption in coastal areas.

Finally, continuous evaluation and improvement of disaster management systems are necessary to ensure effectiveness. Post-disaster assessments provide valuable lessons for improving infrastructure design, emergency response procedures, and policy frameworks. By applying adaptive management strategies, marine disaster risk management systems can evolve alongside changing environmental conditions and technological advancements.

In addition, the role of advanced data integration platforms is becoming increasingly important in supporting marine disaster risk management. Integrated coastal management systems that

combine meteorological data, oceanographic observations, and geospatial information allow decision-makers to obtain a comprehensive understanding of risk conditions. These platforms enable faster data sharing between agencies and improve coordination during emergency situations, ultimately strengthening overall disaster response effectiveness.

Another important factor is the inclusion of local knowledge and traditional practices in disaster risk management strategies. Many coastal communities have long-standing experience in observing natural signs such as unusual sea level changes, animal behavior, and seasonal weather patterns. Integrating this local knowledge with modern scientific data can improve early warning accuracy and help create more culturally appropriate disaster preparedness programs.

Moreover, sustainable economic diversification in coastal regions can reduce vulnerability to marine disasters. Communities that rely solely on marine-based livelihoods such as fishing or coastal tourism are often highly vulnerable to disaster impacts. By developing alternative income sources, improving access to education, and strengthening local economic resilience, coastal populations can better withstand and recover from marine disaster events.

5. Conclusions

Marine disaster risk management requires a comprehensive approach, combining physical protection structures, monitoring technologies, hydrodynamic modeling, and community participation. Structures such as sea walls, breakwaters, and seawalls have proven to be effective in resisting large waves, reducing coastal abrasion, and protecting coastal infrastructure.

Monitoring technologies and early warning systems, including wave sensors, coastal radar, and satellites, enable early detection of tsunamis, storms, and extreme tides. This information facilitates rapid evacuation and informed decision-making, thereby reducing the risk of casualties and material losses.

Hydrodynamic modeling and numerical simulations support long-term mitigation planning, including determining the optimal location of dikes or breakwaters as well as adapting to environmental changes, such as sea level rise. Meanwhile, preparedness training, evacuation simulations, and community education increase risk awareness and accelerate the response of coastal residents.

Overall, the integration between marine engineering engineering, technology, and community participation makes marine disaster risk management more effective, proactive, and sustainable. The application of these principles not only protects coastal areas and infrastructure, but also improves social and environmental resilience to future marine disasters.

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