

# Toward the Improvement of Port Construction in African Bays: A Literature Review of Scientific Advances on the Seismic Stability of Rubble Mound Breakwaters



A. Morabit<sup>1\*</sup>, A. El Ghoulbזורي



Laboratory of Applied Sciences, National School of Applied Sciences AL Hoceima, Abdelmalek Essaadi University, Tetouan, Morocco.

**ABSTRACT:** The progressive integration of African port infrastructures into global maritime networks underscores the strategic importance of ensuring the seismic stability of coastal engineering structures that support resource exports and economic development. This review synthesizes current knowledge on rubble-mound breakwaters, emphasizing their behavior and stability under seismic loading. It examines documented damages to ports and breakwaters during major earthquakes and analyzes empirical data and case studies illustrating the impact of seismic loads on these structures. The paper also reviews experimental, numerical, and analytical approaches used to assess breakwater stability and explores reinforcement strategies aimed at improving seismic resilience. Overall, this study provides a comprehensive overview of the damages and advances in enhancing the performance of rubble-mound breakwaters under seismic conditions, offering valuable insights for engineers and researchers in structural engineering.

**KEYWORDS:** Rubble mound breakwater, Seismic vulnerability, Stability, Reinforcement, Coastal infrastructure.

[Received Aug. 24, 2025; Revised Oct.21, 2025; Accepted Dec.21, 2025]

Print ISSN: 0189-9546 | Online ISSN: 2437-2110

## I. INTRODUCTION

Ports play a vital role in Africa's economic growth, but many coastal structures such as rubble-mound breakwaters are exposed to seismic risks. Limited studies have focused on their performance and stability during earthquakes, especially in African contexts. This lack of comprehensive understanding makes it difficult to ensure the safety and resilience of these key infrastructures. The objective of this review is to bring together existing research on the seismic behavior of rubble-mound breakwaters, summarize observed damages and **scientific findings** from past earthquakes, and highlight current methods and strategies used to improve their seismic performance.

### A. Generalities

The seismic stability of rubble mound breakwaters represents a critical challenge in coastal engineering worldwide, with heightened significance for African coastal regions. Numerous African ports are situated within seismically active zones, exposing their maritime infrastructure to increasing risks of earthquake induced damage. Considering Africa's expanding role in global trade and its heavy dependence on coastal ports for the export of natural resources, it is imperative to advance the seismic resilience of these vital structures to safeguard economic growth and ensure uninterrupted maritime operations.

Ports are essential infrastructures that not only provide direct and indirect economic advantages but also contribute to broader economic development, although assessing these wider effects can be difficult. Ports function as "funnels" for economic growth, acting as catalysts that trigger three main types of impacts, as described by Notteboom et al. (2022).

- Direct Benefits to the Port.
- Indirect Benefits to Port Users.
- Induced Benefits to the Economy.

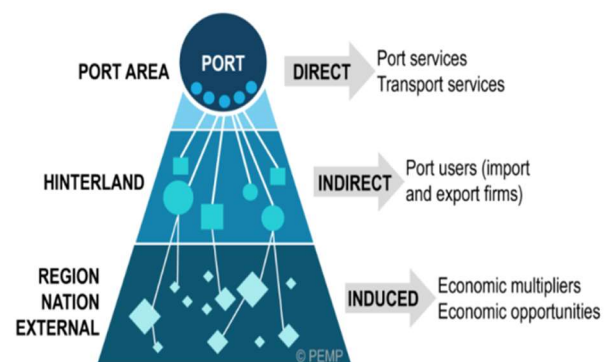


Figure 1 The Port as a Funnel to Economic Development (Notteboom, et al.,2022)

\*Corresponding author: abdelmajid.morabit@etu.uae.ac.ma

Different types of ports are designed to handle specific functions in international logistics: Cargo Ports, Cruise Ports, Fishing Ports, Inland Ports, Marinas, Military Ports etc.

Tsinker (1997) provides detailed insights into the design, operational considerations, and challenges associated with each type of port structure. He elucidates on a variety of port structures, including Quay Walls and Wharves, Jetties and Piers, Breakwaters, Docks, Bulkheads, Mooring Buoys, Slipways, Terminal Facilities, Navigation Aids, Tidal Barriers, Ro-Ro Facilities, Shipyards and Repair Yards, Floating Docks.

### B. Importance of Breakwaters in coastal engineering and protection

The integration of breakwaters into coastal defense schemes highlights the importance of engineered solutions in combating the challenges posed by sea-level rise and increased storm intensity due to climate change. As coastal populations continue to grow, the reliance on such structures underscores the need for innovative and sustainable approaches to coastal protection.

### C. Definition and purpose of rubble mound breakwaters.

Rubble mound breakwaters are comprised of layers of large rocks or concrete elements that absorb, reflect, and dissipate the energy of incoming waves, thereby reducing wave action on the shore and preventing coastal erosion and damage to coastal infrastructure (Akrash et al.,2023; Sajan et al.,2024; Leone et al.,2025). According to the Rock Manual (2007) a rubble mound breakwater is an engineered structure comprising layered materials, primarily rocks and sometimes concrete elements, strategically placed to form a mound that provides shoreline protection against wave action and erosion while facilitating safe harbor conditions. The rubble mound breakwater typically consists of several layers, including a core, filter layers, and armor layers:

– Core: The innermost part of the breakwater, usually made of quarry-run stones or smaller rocks. The core provides the main mass of the structure and is designed to support the layers above.

– Filter Layers: Positioned between the core and the armor layers, filter layers consist of graded materials designed to prevent the migration of finer materials from the core while allowing water to drain freely. This prevents hydraulic pressures from building up within the structure.

– Armor Layer: The outermost layer, exposed to wave action, made of larger rocks or specially designed concrete units. This layer protects the breakwater from wave and current erosion. Armor units are often shaped to interlock and dissipate wave energy effectively.

The Rock Manual, (2007) describes six types of rubble mound breakwaters, each providing a suite of solutions tailored to diverse environmental conditions, operational needs, and material availabilities.

– Conventional Rubble Mound: This is the most commonly used form, featuring a simple trapezoidal cross-section. The armour layer may cover the crest and part of the lee slope as well as the front face. Its primary function is to provide shelter to other structures, such as jetties or berths.

– Conventional Rubble Mound with Crown Wall: These structures are mainly used for port protection. The crown wall or crest element, which often incorporates a roadway, allows access along the breakwater. This is essential where the lee side of the breakwater is

used for port operations, such as ship mooring (quay) or storage (platform).

– Berm Breakwater: This design features armourstone placed in a berm on the seaward slope. There are three types of berm breakwaters, depending on the stability level of the armourstone:

– Non-reshaping statically stable breakwater, where few stones are allowed to move.

– Reshaped statically stable berm breakwater, where during extreme storm conditions the armourstone is redistributed by the waves to form a naturally stable profile within which the individual stones are stable.

– Dynamically stable reshaping berm breakwater, where during extreme storm conditions the armourstone is redistributed by the waves to form a naturally stable S-profile with the individual stones still moving up and down the slope.

– Low-Crested Breakwaters: These structures are used where wave conditions need to be modified but overtopping is acceptable, or where horizontal visibility is a requirement, for example, for aesthetic purposes. They generally allow significant wave overtopping and may be partially emergent above the water surface or fully submerged, depending on the tidal state.

– Caisson-Type or Vertically Composite Breakwater: This combines a rubble mound with a caisson, where the caisson is placed on top of the mound. The rubble mound may serve only as a low-level foundation for the caisson or occupy a significant proportion of the depth. Depending on the depth of the mound relative to the water level and waves, the mound may or may not need protection.

– Horizontally Composite Breakwater: Another combination of a rubble mound with a caisson, where the caisson is placed behind a rubble mound-type seaward protection made of armourstone or artificial units that are of sufficient size to be hydraulically stable. The caisson may be placed on top of a foundation of smaller armour stones.

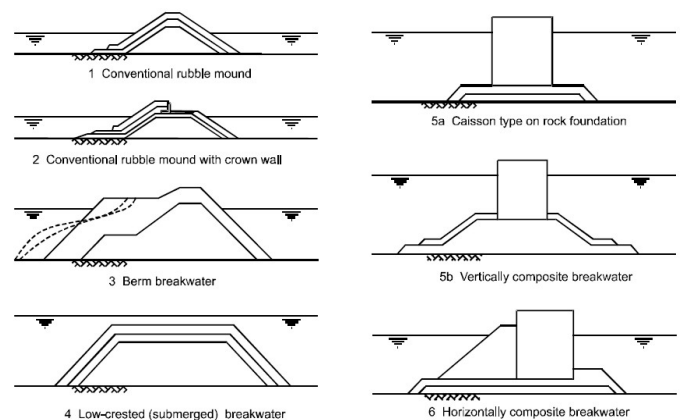


Figure 2: Typical cross-sections of various types of rubble mound breakwater  
The Rock Manual (2007)

The development of rubble mound breakwater design and construction techniques has been significantly shaped by the need to address vulnerabilities to earthquakes and other destabilizing factors. Earthquakes, in particular, pose a critical challenge due to the seismic forces they can exert on the structure of breakwaters, potentially leading to settlement or displacement of the constituent materials. This concern has led engineers to

integrate seismic considerations into the design process, emphasizing the selection of materials and construction methods that can absorb and dissipate these forces effectively (Morabit and El Ghoulboursi, 2024; Akarsh et al., 2024; Sugianto et al., 2025; Givheki et al., 2025).

## II. SEISMIC VULNERABILITY OF COASTAL STRUCTURES

### A. Vulnerability and Damage Mitigation in Coastal Structures

Coastal regions are susceptible to a range of natural hazards, including seismic events, which pose significant risks to infrastructure critical for economic, social, and environmental sustainability. The convergence of seismic activity with other coastal hazards amplifies the vulnerability of these areas, necessitating a comprehensive understanding and strategic approach to risk mitigation (Verschuur et al. 2023), (Charuka et al. 2023).

Recent studies highlighted that the majority of global port infrastructure is exposed to multiple natural hazards, with seismic risks often intersecting with other extreme events like flooding and sea-level rise. This multi hazard exposure requires a nuanced approach to infrastructure design, emphasizing resilience and adaptability (Verschuur et al. 2023), (Ayyub et al. 2012).

A focus on seismic risk assessment for interdependent infrastructure systems underscores the importance of addressing both aleatory and epistemic uncertainties. Innovative frameworks and tools are being developed to quantify and manage these risks, leveraging simulation based approaches and sensitivity analyses (Cavaliere et al. 2020)

The need for retrofitting and upgrading existing infrastructure to withstand seismic events is paramount. Recent research advocates for a probabilistic methodology for seismic risk mitigation, emphasizing the role of critical infrastructure resilience in minimizing economic losses and enhancing recovery post-disaster (Urlainis et Shohet, 2022).

The integration of green and grey infrastructure emerges as a contemporary global practice in coastal management, aiming to enhance resilience against seismic and other related hazards. This shift represents a move towards more sustainable and adaptive coastal management strategies, acknowledging the limitations of traditional, reactive approaches (Charuka et al. 2023).

Examining specific case studies, such as coastal management strategies in Ghana, illustrates the challenges and opportunities in implementing adaptive and integrated approaches to seismic risk mitigation. These examples highlight the global nature of the challenge and the diverse strategies employed to address it (Charuka et al. 2023).

Understanding and mitigating the seismic risks to coastal infrastructure demand a multidisciplinary approach, integrating insights from engineering, environmental science, and urban planning. The ongoing shift towards sustainable and resilient coastal management practices offers hope for mitigating the impacts of seismic events on vulnerable coastal regions.

Yoshimi, (1970) conducted a critical investigation into the seismic behaviors affecting coastal infrastructure, offering invaluable insights into soil dynamics and structural vulnerabilities under earthquake forces. His comprehensive analysis explored the phenomenon of soil liquefaction and its significant impact on the

stability and safety of harbor and port facilities. Through meticulous field studies and theoretical models, Yoshimi's work not only laid the groundwork for future advancements in earthquake resistant design but also emphasized the crucial need for integrating seismic risk assessments into the development and reinforcement of coastal infrastructures. His findings have become a cornerstone for engineers and urban planners striving to enhance the resilience of coastal areas against seismic threats, marking a significant contribution to the field of earthquake engineering and disaster mitigation.

Building upon Yoshimi's research, Hayashi and Katayama,(1970) provided a detailed examination of the 1968 Tokachioki earthquake's impact on harbor structures. Their study, titled 'Damage to Harbour Structures by the Tokachioki Earthquake,' not only documented the extensive damages sustained by various harbor facilities but also evaluated the efficacy of existing design standards in mitigating seismic risks. Their findings revealed that the prevalent design methodologies, although seemingly conservative, played a crucial role in minimizing damage. This research emphasized the importance of robust seismic design principles in the planning and construction of coastal infrastructure and served as a pivotal reference for enhancing the earthquake resilience of port and harbor facilities, highlighting the ongoing need for refinement of design standards to safeguard critical coastal infrastructure against future seismic events.

Advancing the discussion, Susumu and Tomohiro (1993) examined the seismic damages to coastal infrastructure through the application of Finite Element Method (FEM) analyses, presenting a comprehensive study on the vulnerability and response of such structures to seismic events. Their investigation provided deep insights into the mechanisms of damage and potential failure modes faced by coastal infrastructure when subjected to earthquake forces. By leveraging advanced FEM simulations, their study not only elucidated the complex interactions between seismic forces and coastal structures but also proposed improved design and assessment strategies aimed at enhancing the resilience of these critical assets. The findings from this research significantly contributed to the field of earthquake engineering by offering a detailed quantitative assessment of seismic risks, which is essential for the development of more robust and earthquake-resistant coastal infrastructure.

The 1995 Kobe earthquake provided a significant case study for understanding the seismic risks to coastal infrastructure, particularly through the lens of soil liquefaction effects on port facilities. Soga's paper (Soga, 1998), meticulously documented the widespread soil liquefaction in Port Kobe and its consequent impacts, including ground settlements of 20-50 cm and severe damage to port and harbor structures. By analyzing the performance of ground improvement techniques, such as vibro-compaction and sand compaction piles, Soga's research underscored the critical importance of anticipatory measures and engineering interventions in mitigating the seismic vulnerability of coastal infrastructure. This study not only enhanced our understanding of the interaction between seismic forces and liquefiable soils but also served as a vital guide for designing more resilient coastal infrastructure to withstand earthquake-induced challenges.

In a pivotal extension of the discussion on seismic impact, Chang (2000) explored the aftermath of the 1995 Great Hanshin

Earthquake and its profound effects on the Port of Kobe. This case study elucidated the extensive and prolonged economic repercussions that seismic events can have on port operations, which far exceeded the immediate physical damages. Chang's comprehensive analysis revealed how the Kobe earthquake disrupted port facilities and triggered a fundamental realignment in shipping patterns and port competitiveness on a global scale. The study underscored the necessity for coastal infrastructure to integrate seismic risk assessments and resilience strategies into their planning and development processes, highlighting the importance of preparedness and adaptability in facing natural disasters.

Responding to the need for improved seismic resilience, the 'Seismic Design Guidelines for Port Structures' by PIANC (2001) introduced a groundbreaking framework for mitigating seismic risks to coastal infrastructure, shifting from traditional force-based design to a performance-based methodology. This paradigm shift emphasized the assessment of acceptable structural and operational damage levels in the face of seismic events, categorizing earthquake motions into two distinct levels to accommodate both common and extreme scenarios. By delineating performance grades from S to C, the guidelines set clear expectations for the seismic resilience of port structures, effectively balancing safety, functionality, and cost considerations. Integral to this approach was the recognition of soil structure interaction as a critical factor in seismic design, promoting a holistic view that integrates both geotechnical and structural dynamics. Through its comprehensive and flexible design philosophy, the PIANC guidelines significantly advanced the field of coastal engineering, providing a robust framework for enhancing the earthquake preparedness of marine infrastructure globally.

Following the advancements in seismic design guidelines, Yüksel et al. (2002) conducted an in-depth study on the effects of the Eastern Marmara Earthquake on marine structures and coastal areas, providing a detailed analysis of the seismic risks facing coastal infrastructure. Through meticulous fieldwork and stability analysis following the devastating earthquake on August 17, 1999, in north-west Turkey, their research illuminated the substantial impact of seismic forces on various types of marine structures along the coast of Izmit Bay. The investigation showcased how the active faults, including the primary and secondary faults associated with the earthquake, led to severe damage to most marine structures in the region, causing notable settling and sliding of coastal areas. This work not only added valuable empirical data to the field of seismic engineering but also highlighted the paramount importance of considering geotechnical properties and soil-structure interaction problems in the seismic design of marine and coastal structures. Their findings underscored the need for comprehensive seismic assessments and the implementation of effective design strategies to mitigate the risks posed by earthquakes to coastal infrastructure, providing essential insights for enhancing the resilience of marine structures in seismically active regions.

Complementing the technical and empirical studies, Cinna Lomnitz's historical survey of major earthquakes in Chile from 1535 to 1960 serves as a foundational piece in understanding the seismic risks to coastal infrastructure within one of the most seismically active regions of the world (Lomnitz, 2004). By

meticulously documenting the frequency, magnitude, and impacts of these seismic events, Lomnitz highlighted the vulnerability of coastal regions to both earthquakes and associated tsunamis, exemplified by the devastating 1960 event (Mw 9.5), the largest recorded earthquake globally. This work emphasized the critical need for resilient coastal infrastructure in seismically active zones, underpinning the importance of historical seismic data in informing engineering practices and disaster preparedness strategies. Lomnitz's comprehensive catalog and analysis offered invaluable insights into the patterns of seismic activity along the Chilean coast, providing a crucial reference for the development of mitigation measures aimed at reducing the seismic risk to coastal infrastructure.

Further exploring the tools for seismic risk management, Nathan and Wood (2004) utilized Geographic Information System (GIS) technology to assess the seismic and tsunami vulnerability of port and harbor communities in the Pacific Northwest. Their study, titled 'Vulnerability of Port and Harbor Communities to Earthquake and Tsunami Hazards: The Use of GIS in Community Hazard Planning,' outlined a methodology for assessing the holistic vulnerability of these critical coastal infrastructures. By integrating natural, socioeconomic, and hazard data, they highlighted the potential for significant loss of life and property damage in these areas, emphasizing the crucial role of GIS in identifying vulnerabilities and prioritizing mitigation efforts. Their research underscored the importance of enhancing seismic design codes and preparedness strategies to improve the resilience of coastal infrastructure against the backdrop of increasing seismic and tsunami risks.

Echoing the critical need for robust engineering responses, the 1999 Kocaeli earthquake, studied by Sumer et al. (2007) further exemplified the seismic risks to coastal infrastructure. The earthquake's impact on Izmit Bay in Turkey highlighted the critical seismic risks to marine structures, particularly their susceptibility to soil liquefaction triggered by seismic activity. With a magnitude of Mw 7.4, the earthquake precipitated extensive liquefaction-induced damages, including settlements, seaward displacements, and structural tilting, severely compromising port operations. The detailed findings emphasized the paramount importance of comprehensive geotechnical evaluations and the implementation of robust liquefaction mitigation strategies in the engineering of coastal infrastructures. The documented damages elucidated the necessity of incorporating soil-structure interaction considerations and potential liquefaction effects in seismic risk evaluations for coastal areas, advocating for the integration of sophisticated engineering methodologies to bolster the seismic resilience of marine structures against such catastrophic events.

Continuing the discussion on the need for advanced engineering methodologies, Na et al. (2008) conducted a probabilistic assessment for the seismic performance of port structures, specifically focusing on caisson-type quay walls during seismic events. Utilizing a 2D numerical model, their study replicated the seismic behavior observed in the PC1 berth at Port Island, Kobe, during the 1995 earthquake. The research highlighted the pivotal role of uncertainties in soil properties—particularly the friction angle and shear modulus of reclaimed soil in influencing the seismic response of port structures. Through detailed analyses, including tornado diagram and first-order second-moment (FOSM) analyses, the study underscored the significant variability

in the residual horizontal displacement (RHD) of quay walls. This emphasized the necessity for probabilistic approaches in evaluating and enhancing the seismic resilience of coastal infrastructure, contributing to a deeper understanding of the complex interplay between seismic forces and port infrastructure. The findings provided essential insights for the development of more robust design and assessment strategies to mitigate seismic risks in coastal areas.

Further emphasizing the need for integrated soil-structure interaction considerations, the study by Dash et al. (2009) on the seismic damage to the Kandla Port and Customs Office tower during the 2001 Bhuj earthquake provided critical insights into the seismic risks for coastal infrastructure. The analysis focused on the combined effects of soil liquefaction, lateral spreading, and the axial-load-induced settlement on the piled foundations, which led to the significant tilting of the tower. This incident highlighted the vulnerability of coastal structures to seismic forces and underscored the importance of integrating soil-structure interaction effects into the design and assessment processes to enhance resilience. The findings from this case study emphasized the necessity for rigorous geotechnical investigations and the development of engineering solutions tailored to address the unique challenges posed by seismic activities in coastal areas, thereby contributing to the safer design and construction of coastal infrastructure against future seismic threats.

In a profound examination of vulnerabilities and rapid response measures, Werner et al. (2011) studied the seismic performance of Port-au-Prince during the 2010 Haiti earthquake. This research outlined the extensive damage due to soil liquefaction, inadequate performance of structural components, and pre-existing conditions of the port facilities. It further illustrated the effectiveness of emergency repair efforts led by a U.S. military task force in swiftly restoring essential cargo throughput, crucial for the nation's recovery and emergency response. Werner et al.'s findings emphasize the significant role of engineering, maintenance, and disaster preparedness in enhancing the seismic resilience of coastal infrastructures, providing essential lessons for the global engineering community on mitigating risks and ensuring rapid recovery in the aftermath of seismic events.

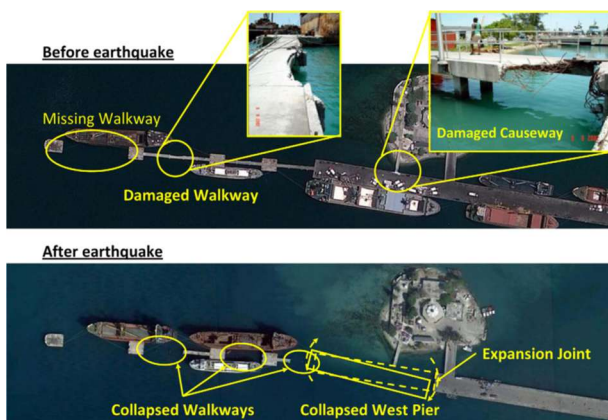


Figure 3 The South Pier of Port-au-Prince before and after the earthquake (Werner et al., 2011)

Delving into the extensive damage inflicted upon Japan's northeastern coastal infrastructure, Imamura and Suppasri(2011)

conducted a pivotal analysis of the 2011 Tohoku earthquake and tsunami. Highlighting critical vulnerabilities and lessons for future seismic risk mitigation, their study revealed the limitations of existing coastal defenses and emergency response strategies. The comprehensive evaluation of the event's impact emphasized the need for an integrated approach to seismic risk management, incorporating robust coastal defense mechanisms, advanced early warning systems, and community-centered evacuation and urban planning strategies. This study stands as an essential reference for enhancing the resilience of coastal infrastructure against the multifaceted threats posed by earthquakes and tsunamis, advocating for a paradigm shift in disaster preparedness and response strategies to safeguard vulnerable coastal communities. In a detailed investigation into the seismic failures experienced at the Port-au-Prince seaport during the devastating 2010 earthquake, Green et al. (2011) presented an exhaustive analysis of the effects of ground failures, specifically focusing on liquefaction, lateral spreading, and the resultant collapse of infrastructure within the seaport. Through a combination of geotechnical field investigations, laboratory analyses, and data interpretation, the study shed light on the vulnerabilities of coastal infrastructure to seismic events, particularly highlighting the behavior of calcareous sands under seismic loading. The insights gained from this research are invaluable for enhancing our understanding of seismic risks associated with coastal infrastructure, demonstrating the critical role of geotechnical assessments in the design and management of seismically resilient port facilities. The findings underscored the necessity of incorporating comprehensive geotechnical evaluations in the planning and retrofitting of coastal structures to mitigate future seismic threats, making it a pivotal reference for policymakers, urban planners, and engineers involved in the development and maintenance of coastal infrastructure in earthquake-prone regions.

Providing an extensive analysis of the severe damage sustained by Japan's coastal infrastructure, Kazama and Noda (2012) offered vital insights into the seismic challenges faced during one of the most catastrophic natural disasters in modern times. Their study detailed the repercussions on human lives, housing, and critical infrastructure components such as roads, railways, ports, and utility systems. Emphasizing the urgent need for improved earthquake resilience in coastal zones, the research highlighted the necessity for innovative engineering approaches and robust design methods to protect coastal infrastructure from the powerful impacts of earthquakes and tsunamis. This significant contribution to the fields of seismic risk management and disaster readiness made a profound impact on the understanding and mitigation of seismic risks in coastal areas.

In the comprehensive study by Brunet et al. (2012) the seismic vulnerability of port facilities in southern Chile during the devastating 27 February 2010 Maule earthquake was meticulously examined, revealing the extensive damages that underscore the critical seismic risks associated with coastal infrastructure. With direct damage costs for the affected ports estimated at nearly US\$300 million, the study highlighted soil related failures such as liquefaction, lateral spreading, and pile failures as predominant contributors to the observed damages. Contrasting these findings, the paper also presented the South Coronel Pier as a paradigm of resilience, where the

implementation of seismic isolation techniques prior to the earthquake significantly mitigated damage, ensuring operational continuity. This case underscored the effectiveness of seismic isolation in safeguarding coastal infrastructure against seismic threats, providing a valuable framework for enhancing resilience through informed design and retrofitting strategies. Brunet et al.'s work serves as a pivotal reference for addressing seismic risks in coastal infrastructure, emphasizing the importance of advanced engineering solutions in mitigating the impact of earthquakes.

Highlighting the seismic vulnerability of coastal infrastructure, particularly gravity-type quay walls, the Great East Japan Earthquake on March 11, 2011, was detailed in an investigation conducted by Takahashi et al. (2011). The Port of Hitachinaka in Ibaraki Prefecture, a vital freight transport hub for the northern Kanto region, suffered notable damages. Despite being constructed on a stiff sandy stratum and backfilled with coarse-grained rock waste to prevent liquefaction, the quay walls experienced significant seaward displacement and backfill subsidence due to the earthquake's strong motion. This incident underscores the critical need for reassessment and enhancement of seismic resilience in the design and construction of coastal infrastructures to mitigate the impacts of future seismic events. The study not only documents the extent of the damage but also serves as a pivotal reference for understanding the behavior of gravity-type quay walls under seismic duress, providing valuable insights for improving resilience against seismic risks in coastal infrastructure.

In their comprehensive examination of the 2011 Tohoku earthquake tsunami's impact on Tokyo Bay, Sasaki et al. (2012) unveiled critical findings regarding the tsunami's behavior and its consequent damage to coastal infrastructure within the bay. Utilizing field surveys, analysis of observed tsunami wave profiles, and sophisticated numerical hind casting with FVCOM and Delft 3D Flow, the study documented significant tsunami-induced inundations in various ports across Chiba Prefecture, achieving notable run-up heights. It was observed that the tsunami propagated through Tokyo Bay with a height of approximately 0.9 m for the second wave, maintaining almost uniform height across the bay's major axis. The research further indicated that in certain ports, tsunami wave heights were locally amplified due to wave reflection, the geometrical configuration of the ports, and potential harbor resonance effects. This detailed analysis not only sheds light on the tsunami's dynamics within Tokyo Bay but also underscores the necessity of incorporating these insights into the enhancement of coastal infrastructure's resilience to seismic risks, offering a vital resource for future tsunami risk management and infrastructure planning in similar coastal settings.

The comprehensive analysis by Percher et al. (2013) on the seismic and tsunami resilience of port and harbor structures following the 2011 Great Tohoku Earthquake offers critical insights into the seismic risks associated with coastal infrastructure. Their investigation, which examined over 14 major port facilities along the Tohoku coastline, found that despite facing one of the largest tsunamis recorded, the majority of port structures, notably pile-supported and gravity wall structures, sustained minimal catastrophic damage. This resilience underscores the efficacy of pre-existing seismic design codes in Japan, which included considerations for liquefaction

mitigation based on ground motions with a 75-year return period. The findings of this study are pivotal, highlighting the importance of robust seismic design and construction practices for coastal infrastructure, and offer valuable lessons for enhancing resilience against future seismic and tsunami events globally.

The comprehensive study by Yasuda et al. (2013) offers critical insights into the seismic risks faced by coastal infrastructure. Through detailed analysis of the widespread soil liquefaction and its devastating effects on structures in the Tohoku and Kanto regions, the paper highlights the vulnerability of urban and coastal areas to seismic events. Particularly, it emphasizes the severe damage inflicted on Urayasu City and various infrastructures, including roads, river dikes, and sewage systems, underscoring the need for seismic design considerations that address liquefaction risks. This work not only contributes to the understanding of the 2011 earthquake's impact but also serves as a crucial reference for enhancing the resilience of coastal infrastructure against future seismic threats, making it an essential resource for researchers, engineers, and policymakers involved in earthquake preparedness and urban planning.

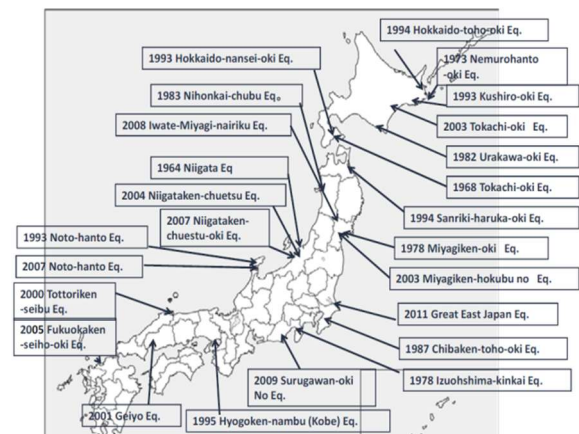


Figure 4 Sites of soil liquefaction in Japan caused by earthquakes from 1964 to 2011 (Yasuda et al., 2013)

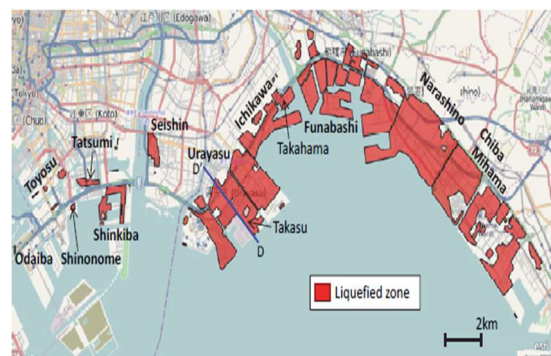


Figure 5 Liquefied areas from Odaiba in Tokyo to Chiba (Yasuda et al., 2013)

The research conducted by Mori et al. (2013) provided an insightful analysis of the seismic risks to coastal infrastructure, focusing on the devastating impact of the 2011 Tohoku earthquake tsunami along the Sanriku Coast. By evaluating various coastal protection measures, including natural barriers and engineered structures such as offshore breakwaters, the study emphasized the critical importance of preparedness and

resilience against seismic-induced tsunamis. The findings highlighted the differential effectiveness of coastal defenses in mitigating tsunami damage, particularly the significant role of offshore breakwaters in reducing the force and extent of tsunami impacts on coastal communities. Mori et al.'s comprehensive approach, which combined field surveys, numerical simulations, and detailed damage assessments, offered valuable insights for enhancing the resilience of coastal infrastructure to future seismic events. This research became a seminal reference for researchers, policymakers, and engineers involved in the design and implementation of seismic risk management strategies for coastal areas.

In their comprehensive analysis of the 2011 Tohoku earthquake and subsequent tsunami impacts, Sugano et al. (2014) delved into the seismic and tsunami-induced damages to coastal structures across the Tohoku region of Japan. Through meticulous field investigations covering around 600 km of coastline and subsequent analytical studies, the research conducted by the Port and Airport Research Institute elucidated the relative resilience of coastal infrastructure to seismic ground motion, attributed to its long duration and high-frequency components. This work significantly advanced our understanding of the interplay between seismic forces and tsunami inundation on coastal facilities, highlighting the necessity of integrating both seismic and tsunami risk considerations in the design and retrofitting of coastal infrastructure. Sugano et al.'s findings underscored the imperative for a holistic approach to enhancing the seismic resilience of coastal structures, providing invaluable insights for the engineering and planning of future coastal defenses against the dual threats of earthquakes and tsunamis.



Figure 6 Damage to a Steel Sheet Pile Quay Wall at Soma Port During the 2011 Tohoku Earthquake Off the Pacific Coast (Sugano et al., 2014)

In their insightful review on tsunami-induced currents and their impact on ports, Borrero et al. (2015) elucidated the multifaceted risks tsunamis pose to coastal infrastructure beyond the immediate destruction from inundation. By synthesizing historical accounts and cutting-edge research, they illustrated the underappreciated yet substantial threat of tsunami generated currents to maritime operations and port facilities. Drawing from significant tsunamis in the early 21st century, including the devastating 2004 Indian Ocean and 2011 Tohoku events, the authors advocated for a comprehensive approach to tsunami hazard assessment that incorporates the dynamics of tsunami currents. This work significantly contributed to our understanding of seismic risks for coastal infrastructure, highlighting the importance of integrating current related impacts

into the design and retrofitting of ports and coastal defenses to mitigate future seismic threats effectively.

The study by Athanasopoulos et al. (2020) in Soil Dynamics and Earthquake Engineering provided critical insights into seismic risks for coastal infrastructure, focusing on the 2014 Cephalonia earthquake's impact on the ports of Lixouri and Argostoli, Greece. This comprehensive investigation into lateral spreading and soil liquefaction revealed significantly lower seismic-induced lateral movements behind quay walls than empirical predictions suggested, highlighting the essential role of such infrastructure in mitigating seismic risks. Their findings illuminated the intricate relationship between seismic activities, coastal infrastructure resilience, and geotechnical conditions, offering valuable lessons for enhancing coastal infrastructure's preparedness and design in earthquake-prone areas.

In 2024, field observations following the Noto Peninsula earthquake revealed significant damage to the eastern breakwater at Iida Port, including an uncommon seaward tilting failure mode associated with strong ground motion and excess pore water pressure generation (Otsubo et al., 2025). The study demonstrated that cyclic seismic loading led to a substantial reduction in soil stiffness and strength, thereby weakening the foundation response and amplifying damage during subsequent tsunami action. These findings highlight the critical role of soil degradation and soil structure interaction in governing the seismic vulnerability of coastal structures.

#### *B. Review of Seismic Vulnerability and Damage Mitigation in Rubble Mound Breakwaters*

In their seminal work, Wang et al. (1978) delved into the seismic responses of rubble-mound breakwaters, a study prompted by the evolving need to safeguard coastal and offshore infrastructure against earthquakes. Prior to this research, the design of rubble-mound breakwaters primarily focused on wave loading, with minimal consideration for seismic forces due to the inherent robustness of such structures. Through a series of laboratory experiments, the team explored the stability of armor units under seismic loading, identifying crest settlement as the dominant failure mode rather than catastrophic structural failure. This investigation revealed that rubble-mound breakwaters exhibit significant resilience to seismic activities, with structural damage mainly manifesting as changes in crest elevation. Their findings underscore the importance of incorporating seismic considerations in the design and assessment of breakwaters, particularly in regions prone to earthquakes. This research significantly contributes to the field by highlighting the need for seismic resilience in coastal protection structures, ensuring they can withstand not just the forces of the ocean, but the shaking ground beneath them.

Expanding on the exploration of seismic effects on coastal structures, Memos and Protonotarios (1993) conducted a comprehensive study on the failure of the Patras breakwater extension due to seismic events. They delved into the complex interplay between hydrodynamic forces and geotechnical conditions under seismic loading. Their investigation revealed that the seismic activity significantly amplified the loading on the breakwater's mound, which was founded on soft, compressible clay, thus exceeding its low safety margins and leading to failure. The study underscored the critical importance of considering

seismic effects in the design and construction of coastal structures, particularly in seismically active regions. Through a combination of analytical expressions and empirical data, the research provided insights into the dynamic response of rubble mound breakwaters under seismic loading, laying a foundation for more resilient coastal engineering practices. This case study not only highlighted the necessity of thorough geotechnical assessments and seismic analyses in breakwater design but also proposed improvements to design practices that could mitigate similar failures in the future.

Furthering the understanding of seismic resilience in coastal defense. Memos' research on the seismic response of rubble-mound breakwaters offered critical insights into the resilience of these coastal defenses against earthquakes (Memos 2000).

Through experimental analysis of models placed on both rigid and soft foundations, the study revealed that while breakwaters on rigid beds display considerable seismic resistance, the presence of soft foundation soil can significantly undermine structural integrity, leading to large settlements or even failures. The investigation highlighted the importance of hydrodynamic forces, which, although minor compared to inertia effects, can alter the fundamental oscillation period of the mound and should not be overlooked in seismic analyses. Memos emphasized the critical need for thorough design considerations in seismically active regions with soft soil foundations to ensure the stability and effectiveness of rubble-mound breakwaters, marking a significant contribution to coastal engineering and earthquake preparedness strategies.

PIANC (2001) represented a pioneering effort to incorporate a performance-based design philosophy into the seismic assessment of port structures, including rubble mound breakwaters. Recognizing the unique challenges posed by seismic forces to such coastal defenses, the guidelines emphasized a nuanced approach that went beyond traditional force-balance methods, advocating for a comprehensive understanding of soil-structure interaction and the dynamic responses of these structures under seismic loading. Specifically, the guidelines outlined a methodology for evaluating the seismic performance of rubble mound breakwaters by defining acceptable levels of structural and operational damage, establishing performance grades based on desired outcomes post-earthquake, and prioritizing the analysis of failure mechanisms that these structures might face during seismic events. This progressive approach underscored the importance of integrating geotechnical and structural considerations in the design and assessment of rubble mound breakwaters to ensure their resilience in seismically active regions, thereby contributing significantly to the advancement of coastal engineering practices in the face of seismic threats.

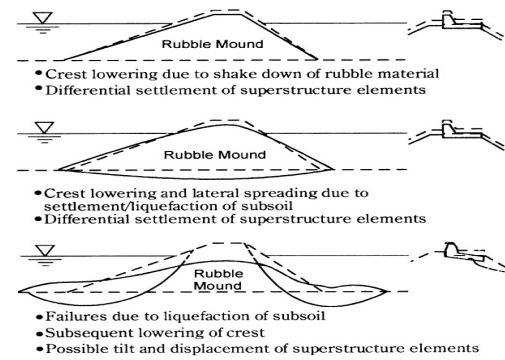


Figure 7 Deformation/failure modes of rubble mound breakwater (PIANC, 2001)

Advancing the understanding of breakwater behavior under seismic loading, Memos et al. (2001) explored the seismic resilience of rubble-mound breakwaters, highlighting the impact of foundation soil quality and seismic forces on these coastal structures. Published in the proceedings of Coastal Engineering 2000, this research provided invaluable insights into the behavior of rubble-mound breakwaters under seismic loading through a blend of physical and mathematical modeling. The findings underscored the substantial influence of foundation conditions on breakwater stability, demonstrating that soft foundation soils significantly exacerbate seismic-induced damages. This study presented a critical examination of breakwater performance in seismically active regions, offering essential guidelines for enhancing structural resilience through careful consideration of foundation soil characteristics and seismic action in the design phase. The thorough investigation into both rigid and yielding foundation scenarios presented a clear narrative on the essential considerations for designing rubble-mound breakwaters capable of withstanding seismic disturbances, making a significant contribution to the field of coastal engineering and seismic resilience planning.

Integrating hydrodynamic loading and seismic shaking dynamics, Memos et al. (2003) delved into the seismic behavior of rubble-mound breakwaters with a focus on the interaction between hydrodynamic loading and the seismic shaking of the structure. Through the development of a boundary element code paired with a geotechnical code, the study presented a nuanced methodology for predicting hydrodynamic pressures and structural accelerations, validated through shaking-table experiments. This integrated approach signified a leap forward from traditional methods, such as Westergaard's relation, by accounting for the water-structure interaction and the excitation frequency's impact on breakwater behavior. The findings emphasized the critical influence of foundation soil quality on the pressures and induced accelerations, highlighting that weak foundations can lead to significant deformations of the structure, especially in tall structures under resonance conditions. Moreover, the research underscored that Westergaard's expression tends to overestimate pressures, except in scenarios involving a rigid base and low-acceleration, high-frequency shakings. By offering a comprehensive analysis that combines experimental validation with theoretical modeling, this study provided invaluable insights into the design and assessment of rubble-mound breakwaters in seismically active regions, marking



a substantial contribution to the field of seismic and maritime engineering.

In a comprehensive field analysis, the research conducted by Yüksel et al. (2004) investigated the seismic response of the Ereğli Fishery Port's rubble mound breakwater during the 1999 Kocaeli (Izmit) earthquake in Turkey, a seismic event of magnitude Mw 7.4. This study comprehensively analyzed the earthquake-induced deformations, incorporating field investigations, standard penetration tests (SPTs), and a variety of analytical methods to examine deformation mechanisms. A significant aspect of their analysis focused on the potential contribution of soil liquefaction to the observed deformations. The geological setting of the Izmit Bay, coupled with the earthquake's ground motions, provided a context for understanding the extensive damage and deformation mechanisms experienced by the breakwater. Through the application of limit equilibrium and finite-element methods, the study concluded that liquefaction of the silty sand layer beneath the breakwater likely contributed to its observed instabilities. This research emphasized the critical need for considering soil liquefaction effects in the seismic analysis of marine structures, offering valuable insights for the design and assessment of infrastructure in seismically active coastal regions.

Providing an extensive review on earthquake-induced liquefaction around marine structures, Sumer et al. (2007) provided a comprehensive analysis of the mechanisms and implications of soil liquefaction for coastal engineering, with a particular emphasis on its effects on rubble mound breakwaters. Their research offered an in-depth exploration of the state-of-the-art understanding of seismic-induced liquefaction, elucidating the conditions under which this phenomenon occurs and its potential to cause significant damage to marine infrastructure. The authors discussed various case studies and lessons learned from historical seismic events that have impacted marine structures, highlighting the critical role of geotechnical investigations and the implementation of appropriate design and construction practices to mitigate the risks associated with liquefaction. Through a detailed examination of existing codes and guidelines regarding seismic-induced liquefaction and its implications for marine structures, Sumer et al., contributed valuable insights into the development of more resilient coastal defenses in the face of seismic threats, underscoring the importance of integrating seismic considerations into the planning, design, and maintenance of marine structures. This work not only serves as an essential resource for coastal engineers and researchers but also advances the collective knowledge on safeguarding coastal infrastructure against the destructive forces of earthquakes.

Conducting a comprehensive investigation, Cihan and Yüksel (2011) provided a comprehensive investigation into the failure mechanisms and behaviors of conventional rubble-mound breakwaters subjected to seismic loads. Their research was particularly relevant in the context of understanding how seismic events affect the stability and integrity of coastal protective structures. Through both experimental and numerical analyses, the study explored the effects of cyclic loads with varying frequencies and amplitudes on two types of model breakwaters—one with toes and the other without. Their findings indicated that toes increase the seismic resistance of these structures by

preventing lateral spread of the core and armor materials under seismic loading. Additionally, their research highlighted that settlement and deformation are prominent failure modes under seismic conditions, especially for structures built on rigid foundations. Their work underscored the importance of considering seismic loading in the design of coastal structures to mitigate the risk of failure due to earthquakes. Such insights are crucial for enhancing the resilience and safety of coastal infrastructure in seismically active regions.

In their pivotal research on the behavior of homogeneous rubble mound breakwaters under cyclic loads, Cihan et al. (2012) embarked on an extensive experimental and numerical investigation to elucidate the dynamic responses of breakwater materials to seismic activities. His study delved into the effects of seismic loading on both the armor and core materials constituting rubble mound breakwaters. Through meticulously designed shaking tank experiments, the researchers explored the seismic behaviors of these structures under various dynamic loadings with variable frequencies and amplitudes, both in dry and submerged conditions. The findings revealed that settlements of the examined materials escalated with increasing base acceleration, highlighting a significant susceptibility to seismic influences. Moreover, his research underscored the importance of considering seismic forces in the design of coastal defense structures, particularly in regions prone to seismic activities. By comparing the responses of breakwaters composed solely of armor or core materials, the study offered critical insights into the failure mechanisms induced by seismic events, paving the way for the development of more resilient coastal infrastructure capable of withstanding the forces of nature.

Presenting an exhaustive analysis, Kubilay et al. (2013) an exhaustive analysis of the seismic responses of rubble mound breakwaters armored with concrete units such as tetrapods and cubes was presented. Their work delved into the dynamic behavior of these structures under seismic loadings through both experimental and numerical methodologies. A notable contribution of this study was its focus on the impact of different placement methods of tetrapods and the use of cube blocks on the seismic resilience of breakwaters. The experimental setup included a one-dimensional shaking tank to simulate seismic loads, enabling detailed observation of the deformation patterns and failure mechanisms under such conditions. Numerically, the study employed finite element method (FEM) simulations to complement and validate the experimental results, offering insights into the material behavior and structural integrity of breakwaters faced with seismic forces. Their research highlighted the critical need for incorporating seismic considerations in the design and construction of coastal protection structures, especially in seismically active regions. The findings from Kubilay et al.'s work provide valuable guidelines for engineers and designers in enhancing the durability and effectiveness of breakwater systems against the threats posed by earthquakes.

In their detailed exploration of the dynamic behavior of rubble-mound breakwaters under seismic loading, Yang and Jin (2016) illuminated the significant influences of seawater–structure–foundation interaction. Employing the Arbitrary Lagrangian–Eulerian (ALE) approach alongside dynamic finite element methods, their study simulated the earthquake-induced responses

of these structures with an eye toward understanding the complex interplay between the breakwater, its foundation, and surrounding seawater. This comprehensive analysis, conducted using the LS-DYNA finite element program, revealed that interactions between these components significantly affected the breakwater's residual displacements. Notably, the research underscored that such interactions do not merely mitigate displacement risks but can exacerbate them, particularly highlighting the enhanced impact of seawater-breakwater interaction on horizontal versus vertical displacement. Additionally, the study delved into the crucial role of seismic wave frequency content and the vertical component's impact on hydrodynamic pressure against the breakwater face. Yang and Jin's findings advocated for a nuanced inclusion of these dynamic interactions in seismic safety evaluations of rubble-mound breakwaters, providing pivotal insights for the engineering field focused on coastal protection against earthquake-induced forces. Seismic events pose significant dangers to coastal structures and rubble mound breakwaters, as evidenced by past studies and case analyses. The vulnerability of these infrastructures underscores the urgent need for continued research efforts to mitigate damages and enhance resilience. Building upon previous investigations, researchers must persist in their quest to refine methodologies, identify vulnerabilities, and develop innovative solutions. Advancing our understanding and improving upon previous findings can lead to minimizing the impacts of seismic events on coastal structures and breakwaters, ultimately safeguarding coastal communities and infrastructure against future disasters.

### III. METHODS USED FOR THE CALCULATION OF STABILITY OF RUBBLE MOUND BREAKWATERS

#### A. Numerical Simulations and Computational Methods

The advancement in numerical simulations and computational methods has significantly transformed the field of coastal engineering, particularly in the study of rubble mound breakwaters. From the finite element method (FEM) utilizing software like PLAXIS to the application of computational fluid dynamics (CFD) and multi-material Arbitrary Lagrangian Eulerian (ALE) methods, researchers have leveraged these sophisticated tools to unravel the complex dynamics governing the behavior of breakwaters under various loading conditions.

Memos et al. (2001) conducted a study on the seismic stability of rubble mound breakwaters, employing the Finite Element Method (FEM). Their study involved mathematical modeling to simulate the seismic response of granular materials in breakwaters and their interaction with seismic waves, aiming to enhance understanding of these structures' behavior under earthquake conditions.

In addition, Memos et al. (2003) introduced a numerical model that integrates the structural response of rubble mound breakwaters with the hydrodynamic behavior of water during seismic events. This methodology likely utilized a coupled Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) approach, allowing for accurate simulations of the interactions between the breakwater structures and the surrounding water under seismic stress. This integrated modeling approach is crucial for understanding and enhancing the seismic

resilience of coastal defenses by considering both structural and fluid dynamics.

Employing the Finite Element Method (FEM) using PLAXIS 2D, Cihan and Yuksel (2011) analyzed the deformation mechanisms of breakwaters under cyclic loading. Their research reiterated the use of PLAXIS for FEM analysis, focusing on a detailed material model that simulates the physical properties and behaviors of breakwater components under dynamic conditions. This approach provides critical insights into how breakwaters respond to repetitive stress, which is essential for predicting their long-term durability and functionality in coastal defense systems.

Similarly, Cihan et al. (2012) utilized the Finite Element Method (FEM) using PLAXIS 2D to examine material behavior under cyclic loads within breakwater structures. Their research focused on detailed stress-strain analysis, which is essential for understanding how breakwaters respond to repetitive forces. The study also considered the materials' behavior in both saturated and unsaturated conditions, providing a comprehensive view of how different environmental conditions affect the structural integrity and performance of breakwaters.

Cihan and Yuksel (2013) also utilized the Finite Element Method (FEM) with PLAXIS software to simulate the dynamic response of rubble mound breakwaters under cyclic loading. The study harnessed the capabilities of PLAXIS, to focus on nonlinear soil behavior. It employed a hardening soil model which is crucial for accurately representing the material properties of breakwaters under seismic loads. This approach allowed for a detailed understanding of how breakwaters respond structurally and materially to repeated stress, enhancing predictions about their performance and resilience during seismic events.

Besides, Ye et al. (2013) advanced seismic response analysis by developing a 3D Finite Element Method (FEM) program, based on Biot's dynamic poro-elastic theory. Building on the 2D FEM program DIANA SWANDYNE-II, this study focused on the behavior of a rubble mound breakwater situated on a 3D poro-elastic seabed under strong earthquake conditions. The model meticulously accounted for the accelerations of soil particles and employed Biot's theory as the governing equation, providing a detailed and dynamic perspective on how breakwaters respond to seismic forces.

Lou et al. (2015) employed the Multi-material Arbitrary Lagrangian Eulerian (ALE) method, a numerical approach particularly effective for analyzing problems that involve large deformations, fluid-structure interactions, and material interfaces. This method was utilized to simulate the wave impacts on breakwater structures, capturing the resulting stresses and deformations with high fidelity. The ALE method's capability to handle the dynamic interactions between different materials and the fluid dynamics of waves provides detailed insights into the breakwater's responses to external forces and potential failure mechanisms under extreme conditions.

Furthermore, Yang and Jin (2016) employed a combination of the Arbitrary Lagrangian-Eulerian (ALE) approach and Dynamic Finite Element Method (FEM) using LS-DYNA to explore the seismic responses of breakwaters during earthquakes. This sophisticated numerical methodology was specifically selected for its ability to manage complex interactions between seawater, the breakwater foundation, and structural displacements. The ALE approach was particularly adept at accurately tracing free

surfaces and moving boundaries, crucial for modeling dynamic interactions in a seismic context while maintaining the integrity of the computational mesh.

In their study, Sasikumar et al. (2017) employed Computational Fluid Dynamics (CFD) using the open-source CFD model REEF3D to analyze wave kinematics within berm breakwaters featuring different berm geometries. The method involved solving the Volume averaged Reynolds Averaged Navier-Stokes (VRANS) equations to model the porous flows. This approach was validated against experimental data, demonstrating its effectiveness in accurately simulating flow through porous media.

Moreover, in the study by Celli et al. (2018) a numerical model was utilized to evaluate the effects of submerged berms on the stability of conventional rubble mound breakwaters. This research aimed to extend the design criteria for such breakwaters by incorporating the effects of submerged berms with small thickness relative to water depth. The numerical simulations were used to validate the modified design criteria against experimental data, establishing a new parametric correction factor for the incident significant wave height at the toe of the structure.

In the study conducted by Zhao et al. (2020), a frequency-domain finite element model was employed as the numerical method. This comprehensive approach was designed to simulate the complex interactions among breakwater structures, seawater, seabed, and bedrock during seismic events. The model likely incorporated intricate boundary conditions and detailed representations of material behavior under dynamic loading conditions. This methodology was crucial for accurately analyzing the multifaceted impacts of seismic activities on coastal engineering structures, providing valuable insights into how these structures respond to such extreme conditions.

In their research, Zhang et al. (2020) utilized the Optimal Probabilistic Method for cost optimization in designing rubble mound breakwaters, with a focus on minimizing the overall costs. This includes the costs associated with construction and potential repairs stemming from specific failure modes like overtopping, armor instability, and crown wall sliding. To capture the impact of these failure modes on the structure's performance and maintenance costs, the study employed auxiliary coefficients. These coefficients quantitatively described how significantly each failure mode could affect the breakwater. Moreover, the methodology incorporated reliability analysis to account for the interdependencies among the various failure modes. This analytical approach enabled a thorough optimization of the breakwater design by balancing cost-effectiveness with structural reliability and safety under diverse conditions.

Additionally, in the study by Zhao et al. (2020), an Integrated Numerical Model was developed to explore foundation issues in submerged rubble mound breakwaters situated on liquefiable sites. This model, incorporating Fluid-Seabed-Structure Interactions (FSSI), was specifically designed to simulate the dynamic behaviors of loose sand deposits and the initiation of liquefaction triggered by interactions between the fluid, seabed, and structure. By focusing on these interactions, the model could accurately predict the vulnerability of the breakwater's foundation under seismic or other dynamic loads. To ensure the model's accuracy and reliability, its predictions were validated against experimental results, demonstrating its effectiveness in

capturing the complex phenomena associated with seabed liquefaction near submerged breakwaters. This research offers significant insights into the design and assessment of breakwaters on susceptible seabeds, enhancing their resilience and performance.

The diverse array of numerical simulations and computational methods applied across studies has significantly enriched our understanding of rubble mound breakwaters. Through the use of FEM, CFD, ALE, and other dynamic simulation techniques, researchers have been able to accurately model the complex interactions of wave forces, soil behavior, and structural integrity under various environmental loads. The insights derived from these studies not only contribute to the optimization of breakwater design, considering both economic and structural reliability aspects but also enhance our understanding of failure modes and their interactions. These computational approaches have facilitated a deeper exploration into the nuanced behaviors of breakwater systems, guiding the development of innovative solutions to improve their performance and resilience. As we move forward, the continued evolution of numerical methods and computational technologies promises to further advance the field of coastal engineering, enabling the design of more durable, efficient, and environmentally sustainable coastal protection structures.

### *B. Experimental Methods in Rubble Mound Breakwater*

The study and advancement of coastal engineering practices, particularly in the design and optimization of rubble mound breakwaters, have been significantly propelled by the utilization of experimental methods and physical models. The study conducted by Sumer and Fredsøe (2000) offered an in-depth exploration into the interactions between wave dynamics and rubble mound breakwaters through experimental analysis, shedding light on the wave-induced forces that affect breakwater structures. By conducting detailed wave flume tests, the research evaluated the response of various breakwater configurations and materials to different wave conditions, focusing on phenomena such as wave overtopping, scouring effects, and armor unit movement. This comprehensive examination revealed critical insights into the performance impacts of armor layer choices, berm utilizations, and core material selections under wave action. Sumer et al.'s findings not only augmented the current understanding of rubble mound breakwater dynamics but also served as a practical guide for their design and reinforcement to combat erosive and destabilizing wave forces. The methodical approach, from experimental setup to data analysis, bridged theoretical models with empirical evidence, contributing significantly to both the scholarly and applied realms of coastal engineering. This ensured the development of more effective and enduring coastal protection measures

Transitioning to seismic considerations, Memos et al. (2001) were dedicated to unveiling the seismic behavior of rubble mound breakwaters, employing a combination of shaking table experiments and mathematical modeling to simulate the effects of seismic loading on such structures. By focusing on breakwaters placed on both rigid and yielding bases, Memos et al. offered a nuanced view of how foundation soils influenced the seismic response of breakwaters. Their methodological rigor and depth of analysis shed light on the complex dynamics at play,

underscoring the necessity for careful consideration of foundation conditions in the design of seismic-resilient coastal structures.

Moreover, Memos et al.'s intricate study examined the seismic behavior of rubble-mound breakwaters by accounting for the coupling between hydrodynamic loading and structural shaking (Memos et al. (2003)). Through the development and application of boundary element and geotechnical codes, complemented by shaking table experiments, Memos et al. simulated the pressures and accelerations experienced by these structures during seismic events. Their innovative methodology introduced a new way to incorporate water-mound interaction in seismic analyses, offering a valuable tool for designing breakwaters capable of withstanding seismic forces while maintaining their structural integrity and functionality.

In an innovative exploration of rubble mound breakwaters' resilience to seismic forces, Yüksel et al. (2006) meticulously examined how such structures reacted under varied seismic frequencies and amplitudes. The investigation was anchored in a series of experiments utilizing a specially constructed shaking tank, which simulated the seismic conditions these breakwaters might encounter. Through this rigorous experimental setup, Yüksel et al. measured the deformation of homogeneous breakwater models, capturing their dynamic responses to seismic loading. The findings crucially underscored the dominance of seismic frequency over amplitude in dictating the extent of deformation, with a notable observation that the most significant deformation unfolded within the initial seconds of seismic exposure. Yüksel et al.'s study significantly advanced our understanding of designing rubble mound breakwaters capable of withstanding the rigors of seismic activities.

Furthermore, Park et al. (2007) investigated the role of submerged structures in enhancing the stability of rubble mound breakwaters. Using a detailed experimental approach in a wave flume to simulate interactions between waves and submerged structures, they analyzed the influence of these structures on wave run-up and reflection coefficients. Park et al.'s experimental findings revealed that submerged structures significantly reduced wave run-up on breakwaters, pointing to a promising design strategy to bolster breakwater stability in response to the challenges posed by rising sea levels and increased wave activity due to global warming.

In their 2011 study, Cihan and Yüksel (2001) employed a rigorous experimental methodology to investigate the stability of rubble mound breakwaters under seismic conditions. Their approach involved the use of a shaking tank to simulate the effects of cyclic loading on two types of breakwater models—one with toes and one without. The tank was equipped with a single-degree-of-freedom shaking mechanism that could replicate various frequencies and amplitudes of seismic waves. To accurately control and measure the response of the breakwaters to these dynamic loads, the researchers utilized automatic cranes to ensure consistent placement and compaction of the core materials. The experimental setup also included advanced data acquisition systems and image processing techniques to document the deformation and failure patterns of the breakwaters. This comprehensive setup allowed

them to systematically analyze the influence of toes on the structural integrity and performance of rubble mound breakwaters, providing valuable insights into their behavior under earthquake-like conditions.

In the same way, the experimental methodology employed to assess the stability of rubble mound breakwaters under seismic conditions involved the use of a specially designed shaking tank (Cihan et al., 2012). This shaking tank facilitated controlled seismic simulations by allowing one degree of freedom in movement, thereby closely mimicking earthquake effects. Within this setup, both armor and core materials of the breakwaters were tested separately to evaluate their respective responses to various cyclic load conditions. These conditions varied in both frequency and amplitude, enabling a detailed observation of the breakwater's dynamic responses. The testing environment included wave absorbers at both ends of the tank to minimize reflective wave interferences, ensuring the integrity of the seismic simulation.

Similarly, Cihan et al. (2013) centered their study on understanding the behavior of breakwaters outfitted with artificial armoring units under cyclic loading. They interwove experimental shaking table tests with numerical Finite Element Method (FEM) simulations to investigate the deformation and damage mechanisms that such structures endured under cyclic loading conditions. Cihan et al.'s findings highlighted the crucial role of the type and arrangement of armoring units in the overall resilience of breakwater structures. Their study not only advanced our theoretical knowledge of breakwater dynamics but also provided practical guidance for designing more durable and effective coastal defense mechanisms.

Van Gent et al. (2013) conducted a comprehensive study focused on the stability of rubble mound breakwaters with a horizontal berm. The experimental tests, performed in a wave flume at Deltares, Delft, explored the influence of berm width, berm level, and wave steepness on the stability of the rock slopes above the berm. A series of configurations with varying berm dimensions and positions relative to the still water level (SWL) were tested against increasing wave heights to measure the erosion profile and eroded area. The findings led to the development of a prediction formula for determining the required rock size in the upper slope, highlighting the potential for significant material size reduction and cost savings in breakwater construction. This study filled a critical knowledge gap regarding the stability impact of berms on steeper slopes and above the berm section, providing valuable insights for coastal engineering design and optimization.

In the study conducted by Van Gent et al. (2013) on the stability of rubble mound breakwaters with a berm, an experimental methodology was applied to assess how berms affect the structural integrity of such coastal defenses. The investigation involved a series of physical model tests, which meticulously analyzed the influence of berms on rock stability under various hydraulic conditions. These tests were crucial for deriving empirical formulas that predict the necessary rock size for different sections of the breakwater. The findings from van Gent's study have provided significant insights into the optimization of rubble mound breakwaters, ensuring enhanced

stability and reduced overtopping risks through strategic berm placement.

Additionally, Lou et al. (2015) ventured into the interactions between solitary waves and elastic seawalls on rubble mound breakwaters through a blend of two-dimensional numerical models and physical model tests. Utilizing the multi-material Arbitrary Lagrangian Eulerian (ALE) method, the study aimed to capture the highly nonlinear interactions, including the effects of structural dynamic responses and the seawall's design parameters on wave pressures. The physical experiments were conducted in a wave flume, generating solitary waves to impact a modeled breakwater while measuring wave pressures and water-on-deck phenomena. The experimental data served to validate the computational models, which demonstrated good agreement with physical observations. This research underscored the significance of considering elasticity and structural dynamics in breakwater design, especially under extreme wave conditions, offering a methodological advancement in the simulation of fluid-structure interactions.

Aniel-Quiroga et al. (2018) provided a comprehensive analysis of how rubble mound breakwaters withstand the first wave impact and subsequent overflow conditions of tsunamis. Utilizing scaled model laboratory experiments, they simulated solitary wave tests and overflow scenarios to assess damage mechanisms and thresholds for tsunami wave damage. This methodological approach facilitated a deep understanding of tsunami wave interactions with breakwater structures, offering valuable insights into damage mechanisms. The empirical evidence gathered by Aniel-Quiroga et al. laid the groundwork for proposing a threshold for tsunami wave damage, instrumental in guiding the design and enhancement of coastal structures to mitigate the devastating effects of tsunamis.

In addition, Celli et al. (2018) had ambitiously extended the design criteria for conventional rubble mound breakwaters, focusing on those incorporating submerged berms. Through a synergistic approach that blended numerical simulations with experimental investigations, they had meticulously evaluated the impact of low berms on wave action and armor stability. The culmination of Celli et al.'s efforts was the proposition of a novel stability formula, which enhanced the reliability and efficacy of design criteria for rubble mound breakwaters. This advancement represented a significant leap forward in understanding breakwater behavior in the presence of berms and equipped engineers with a more robust framework for designing structures resilient against natural forces.

Chen et al. (2019) conducted a comprehensive investigation into how a berm and surface roughness influence wave overtopping discharge at dikes. Through physical model tests, the study examined the effects of these variables on overtopping rates. It involved deriving new empirical formulae from the experimental data to provide more accurate estimations of how berms and roughness reduce overtopping discharge. The study introduced a novel formula that estimates the reductive influence of varying roughness along the waterside slopes that include a berm. These findings significantly advance our understanding of wave-dike interaction dynamics and contribute to enhanced dike safety by improving predictions of overtopping discharges,

ultimately helping to mitigate risks associated with coastal flooding.

In the study by Ghalandarzadeh et al. (2021) an innovative approach was utilized to analyze the seismic performance of rockfill breakwaters using shaking table model tests. These experiments were conducted to simulate the conditions that breakwaters face during seismic events. The models, based on the breakwaters of South Pars Petrochemical Port, were subjected to controlled seismic loads to assess deformation and settlement behaviors. The experimental setup included precise scaling of the model dimensions and material granulometry to reflect real-world conditions accurately. This method enabled a detailed examination of how breakwaters, especially those composed of rockfill, respond under seismic stress, emphasizing the importance of shear deformation and volumetric strain in the overall stability of these structures.

The diverse array of studies presented, encompassing the impacts of berms, the resilience of rubble mound breakwaters to seismic forces, and the stability of these structures under tsunami impacts, underscores the pivotal role of experimental methods and physical modeling in advancing coastal engineering practices. By meticulously simulating the multifaceted conditions that breakwaters are exposed to, researchers have not only deepened our scientific understanding of wave-dike and wave-structure interactions but have also significantly contributed to the evolution of engineering designs aimed at mitigating the risks associated with coastal flooding and seismic events. The insights derived from these experimental investigations offer a robust foundation for the development of more effective, durable, and cost-efficient coastal defense mechanisms. As we move forward, the continued integration of empirical research findings into the design and optimization of rubble mound breakwaters will be essential in enhancing the safety and sustainability of coastal infrastructures, thereby safeguarding communities and ecosystems against the unpredictable forces of nature.

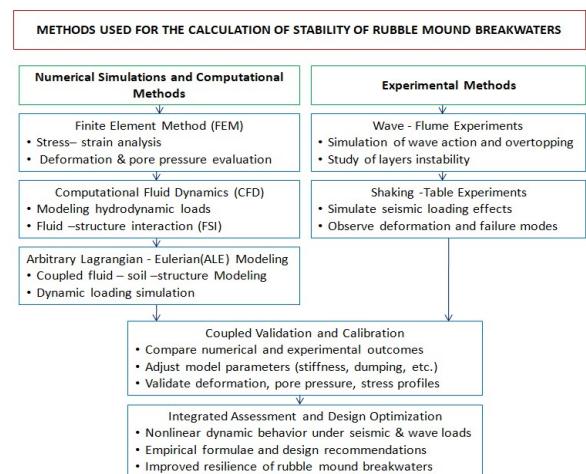


Figure 8 Flowchart of methods used for the calculation of stability of rubble mound breakwaters

Figure 8 illustrates the integrated framework combining numerical and computational methods (FEM, CFD, ALE) with experimental approaches (wave flume and shaking table tests)

for analyzing, validating, and optimizing the stability of rubble mound breakwaters under hydrodynamic and seismic actions. Numerical and computational methods have been extensively employed in previous studies to analyze the stability of rubble mound breakwaters under complex hydrodynamic and seismic conditions. Approaches based on the Finite Element Method (FEM), Computational Fluid Dynamics (CFD), and Arbitrary Lagrangian–Eulerian (ALE) techniques have enabled detailed modeling of fluid–structure and soil–structure interactions. These methods, often implemented through advanced software such as PLAXIS or LS-DYNA, allow researchers to simulate deformation, pore pressure, and stress distribution under dynamic loading. The use of coupled numerical models integrating structural and hydrodynamic responses has been particularly effective in capturing the nonlinear behavior of breakwaters during seismic and wave actions, as demonstrated by numerous earlier investigations.

Complementary to computational modeling, experimental methods—including wave-flume tests and shaking-table experiments—have been widely applied to validate and refine theoretical and numerical findings. Previous research has utilized these physical models to examine wave overtopping, armor instability, and deformation mechanisms under cyclic or seismic loading. The empirical data obtained from such experiments have played a crucial role in calibrating numerical models and developing empirical design formulas for stability assessment.

Collectively, these prior studies highlight the synergistic role of computational and experimental approaches in improving the accuracy, reliability, and resilience of rubble mound breakwater design under both hydrodynamic and seismic influences.

#### **IV. ENHANCING STABILITY OF RUBBLE MOUND BREAKWATERS THROUGH DESIGN MODIFICATIONS AND REINFORCEMENT STRATEGIES**

##### *A. Structural Reinforcement Strategies for Rubble Mound Breakwaters*

Previous studies have extensively investigated structural reinforcement strategies for rubble mound breakwaters, aiming to enhance their resilience against seismic forces and other environmental hazards. These studies have delved into various approaches, including the use of innovative materials, geometries, and placement methods, to strengthen breakwater structures and minimize damage during extreme events.

Sumer and Fredsøe (2000) conducted a comprehensive experimental study on 2D scour and its protection at rubble-mound breakwaters, revealing critical insights into reinforcement methods and design effects. Their methodology centered on experimental flume tests with two different slopes of breakwater models, examining the impacts of both regular and irregular wave conditions on scour patterns. The study delineated the scour-deposition patterns in front of rubble-mound breakwaters, emphasizing that these patterns resemble those observed in front of vertical-wall breakwaters, with alternating scour and deposition zones parallel to the structure.

Importantly, they found that the maximum scour depth at rubble-mound breakwaters is notably smaller than that at vertical-wall breakwaters. The researchers also explored toe protection strategies, including the use of stone aprons, assessing their effectiveness in mitigating scour at the breakwater toe. Through a series of methodical tests, they derived empirical formulas and guidelines for designing toe protection measures that significantly enhance breakwater stability. This study provided a pivotal reference for coastal engineers focusing on optimizing the design and reinforcement of rubble mound breakwaters to mitigate scour-induced damage effectively.

Expanding on these insights, Park et al. (2007) investigated the impacts of submerged structures on the stability of rubble mound breakwaters through experimental methods. The methodology explored the influence of different dimensions of submerged structures (width, height) and their distances from the breakwater on wave reflection and run-up, utilizing a variety of wave steepness and incident wave conditions. The experimental setup involved a horizontal flume where the breakwater and submerged structures were tested under generated irregular waves based on the Bretschneider-Mitsuyasu spectrum. The findings revealed that submerged structures significantly enhance the stability of rubble mound breakwaters by reducing wave run-up and reflection coefficients. The dissipation of wave energy by the submerged structures, through wave breaking and reflection, proved pivotal in stabilizing the breakwater. The research identified optimal design parameters for submerged structures, suggesting that their inclusion in breakwater design can mitigate the effects of rising sea levels and increased wave heights due to global warming.

In a related study, Marcel R.A. van Gent et al. (2013) conducted physical model tests to investigate the impact of a horizontal berm on the stability of rubble mound breakwaters' upper slopes. By varying berm widths and levels relative to the sea-water level and considering different wave steepness conditions, they derived a prediction formula for the armor layers' stability on the upper slope. These tests, conducted in a wave flume, simulated controlled wave conditions based on the Jonswap spectrum. The findings indicated that the presence of a berm significantly influenced the stability of the rock in the armor layer, enabling the use of smaller rocks on the upper slope compared to designs without a berm. Their study offered empirical formulas for predicting damage and determining the required stone size for the upper slope above the berm, showcasing how berms could reduce wave overtopping and enhance slope stability, thus potentially leading to cost savings in breakwater construction.

Expanding on this research, Marcel R.A. van Gent (2013) focused on the rock stability of rubble mound breakwaters with a berm and provided a comprehensive investigation into enhancing the resilience of such structures through strategic design modifications. Through a series of physical model tests, the study offered valuable insights into the significant role that a berm can play in reducing wave overtopping and in minimizing the required rock size for the construction of more efficient breakwater designs. The experiments examined the influence of various parameters including the slope angle,

berm width, berm level, and wave steepness on the stability of the rock slopes above and below the berm. The findings underscored the effectiveness of berms not only in mitigating wave overtopping but also in increasing the stability of the armor layer, particularly for the slope above the berm where significant reductions in rock size could be achieved without compromising stability. This research contributed to the body of knowledge on coastal engineering by providing empirically derived prediction formulas that can guide the design of rubble mound breakwaters, emphasizing the nuanced effects of berms on overall structural integrity and performance. The implications of these findings are crucial for optimizing the design and reinforcement of breakwaters, offering practical solutions to the challenges posed by sea-level rise and increasing wave heights due to climate change.

Complementing previous studies, the research conducted by Sasikumar et al. (2017) on the numerical investigation of wave kinematics inside berm breakwaters using the REEF3D computational fluid dynamics (CFD) model provided a pioneering approach to enhancing the design and stability of berm breakwaters. Their study focused on varying berm geometry's influence on wave interaction and breakwater performance, specifically examining the effects of berm height, width, and slope on the internal wave kinematics, including pore pressure and velocities. Utilizing the Volume-averaged Reynolds Averaged Navier–Stokes (VRANS) equations for porous flows, the research validated the VRANS approach within REEF3D through comparisons with experimental data, highlighting the model's effectiveness in accurately simulating complex hydrodynamic processes. By conducting detailed simulations under a variety of berm geometries, the study shed light on optimal berm configurations that minimize overtopping and internal pressures, contributing significantly to the field of coastal engineering. This methodical numerical analysis extended the empirical database, providing valuable insights into the design considerations for berm breakwaters, with the potential to improve their resilience against wave action through informed design adjustments. The incorporation of numerical modeling as a complementary tool alongside physical experimentation marked a significant advancement in the design process for these critical coastal defense structures.

Expanding on these insights, in the comprehensive study by Celli et al. (2018) the authors embarked on a pioneering exploration to refine the design criteria for conventional breakwaters enhanced with submerged berms. Recognizing the multifaceted roles that berms play—from mitigating breakwater settlements on soft soils, reducing wave overtopping, to bolstering armor layer stability—the research aimed to supply an advanced design criterion specifically for armor layers in the presence of submerged berms with relatively small thickness compared to the water depth. Leveraging a combination of numerical models validated against experimental data, the study meticulously evaluated the interaction between incident waves and submerged berms. The focal point of their methodology was the development of a parametric correction factor, which modified the incident significant wave height at the toe of the structure, thereby integrating seamlessly into well-established design formulas.

This novel approach was validated through experimental comparisons, underscoring the critical importance of applying design criteria within their appropriate validity ranges to prevent unsafe armor sizing. The outcomes of this research significantly enhanced the toolkit available to coastal engineers, providing a robust and practical framework for the design and optimization of rubble mound breakwaters in the face of challenging environmental conditions.

In a complementary investigation, the study by Chen et al. (2019) presented a comprehensive investigation into the effects of berms and surface roughness on wave overtopping at dikes, employing an extensive series of physical model tests to understand the interaction dynamics between wave forces and dike structures. This research was significant in advancing coastal engineering practices by developing new empirical formulas that accurately predicted wave overtopping discharges. These formulas accounted for various parameters, including the presence of berms (both impermeable and permeable) and the level of surface roughness, offering insights into their combined and individual impacts on reducing wave overtopping. Notably, the study introduced location-weighting coefficients for assessing the influence of roughness elements placed along different parts of the dike slope, a novel approach that improved the precision of overtopping discharge predictions. The findings from this research provided valuable guidance for the design and optimization of dike structures, ensuring enhanced safety and resilience of coastal defenses against the challenges posed by sea-level rise and storm surges.

In their pivotal research, Bayesteh and Mansouriboroujeni (2019) meticulously explored the reinforcement mechanisms of rubble mound breakwaters constructed on soft soil within tidal flats, focusing on the profound effects of design modifications. Their study meticulously utilized geosynthetics for reinforcement, presenting a critical solution to the substantial settlement issues encountered during breakwater construction on such challenging terrains. Through an innovative combination of numerical simulations via the discrete element method (DEM) and a full-scale case study, the research evaluated the impact of geogrid configurations—encompassing pattern, size, and the number of layers—on the performance and stability of breakwaters. The findings revealed that the primary mechanism behind the settlement of unreinforced breakwaters was the submersion of individual rockfill particles into the soft seabed. The introduction of reinforced geogrids not only acted as an effective separator, minimizing horizontal deformation and preventing the individual movement of rockfill particles, but also substantially reduced material loss, enhancing the overall structural integrity of the breakwater. This study offered invaluable insights into the design and optimization of rubble mound breakwaters, emphasizing the critical role of geosynthetic reinforcement in mitigating settlement issues associated with soft seabed foundations, thereby advancing the field of coastal engineering towards more resilient coastal defense systems.

Similarly, in their study on the effects of basal reinforcement on the sinking and deformation of rubble mounds on a soft seabed, Ghazi et al. (2020) utilized physical model tests to

quantitatively compare the mechanisms of basal reinforcement and gravity replacement methods in reinforcing rubble mound breakwaters. This research was particularly relevant in the context of constructing breakwaters on soft seabeds, a scenario presenting significant engineering challenges, including material loss due to sinking into the soft seabed and major deformations during and after construction, which could lead to instability. The study's findings revealed that the use of geotextiles as a form of basal reinforcement not only reduced horizontal deformation by up to 42% but also had minimal impact on settlement, highlighting the geotextile's effectiveness in providing both reinforcement and separation. This dual role significantly reduced material loss by up to 44%, offering a substantial improvement over traditional methods. Their approach, employing both experimental model tests and detailed analyses, offered valuable insights into the design and optimization of rubble mound breakwaters for enhanced stability and efficiency in coastal engineering applications.

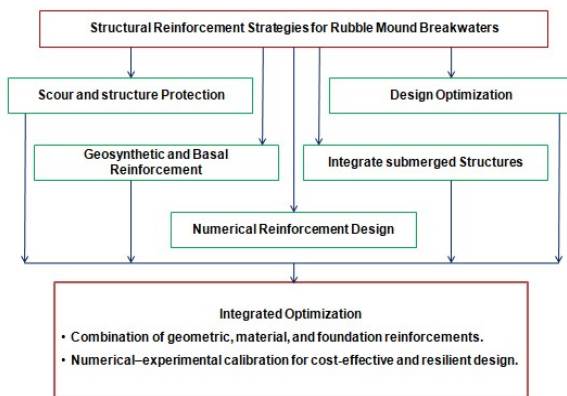


Figure 9 Flowchart of structural reinforcement strategies for Rubble Mound Breakwaters

Figure 9 synthesizes previous research on structural reinforcement strategies for rubble-mound breakwaters, focusing on improving their stability and durability under different loading conditions. The figure highlights the main reinforcement approaches identified in the literature, including scour and structural protection, geosynthetic and basal reinforcement, design optimization, and the integration of submerged structures. These strategies are consolidated within a unified framework of numerical reinforcement design and integrated optimization, combining geometric, material, and foundation enhancements. This comprehensive approach, validated through experimental and numerical studies, contributes to achieving cost-effective, resilient, and sustainable coastal protection systems.

### B. Seismic Reinforcement Techniques for Rubble Mound Breakwaters

The seismic reinforcement of rubble mound breakwaters is a critical aspect of coastal engineering, given

the susceptibility of these structures to seismic events. Various techniques have been developed and studied to enhance the resilience of rubble mound breakwaters against seismic forces. These techniques include the use of innovative construction materials, such as artificial units like tetrapods and cubes, as well as strategic placement methods to optimize the structure's response to seismic loading. Additionally, advanced numerical modeling and simulation techniques have been employed to assess the seismic performance of breakwaters and inform design decisions.

The study by Memos et al. (2001) investigated the seismic resilience of rubble mound breakwaters, focusing on the effects of seismic loading on structures with different foundation conditions. Conducted against the backdrop of global areas prone to seismic activity, this research underscored the critical interplay between foundation type and seismic response. The experiments utilized two model breakwaters: one on a rigid base and another on loose sand, subjected to increasing seismic accelerations. The findings revealed that while breakwaters on rigid foundations exhibited remarkable resistance to seismic forces, those on softer soils displayed significant deformations, emphasizing the foundation's role in the seismic behavior of these structures. The use of waterproof acceleration transducers and miniature soil pressure transducers enabled detailed measurements during seismic simulations. Moreover, the study integrated mathematical modeling, employing finite element codes and boundary element methods, to simulate soil behavior and hydrodynamic pressures accurately. This comprehensive approach highlighted the necessity of considering foundation conditions and seismic effects in the design and construction of rubble mound breakwaters, especially in seismically active regions. Memos, Bouckovalas, and Tsiachris' work significantly contributed to our understanding of coastal structure resilience, offering a foundation for future research aimed at enhancing the stability of rubble mound breakwaters under seismic loading.

In a complementary study, Cihan and Yuksel (2011) exhaustively examined the deformation behaviors of rubble mound breakwaters subjected to cyclic seismic loads, particularly focusing on structures built on rigid foundations. Through a meticulously designed experimental setup involving a shaking tank, the research delved into the responses of conventional breakwater configurations with and without toe structures under various dynamic loading conditions characterized by different frequencies and amplitudes. This approach not only aided in understanding the failure mechanisms precipitated by seismic activities but also evaluated the stabilizing effects of toe additions on these coastal defenses. Their findings, substantiated by both experimental observations and corroborated through numerical analyses using the finite element method (FEM), underscored the significant impact of toes in enhancing the seismic resilience of rubble mound breakwaters. The study's innovative use of a single degree of freedom shaking tank and an automated raining crane system for replicating consistent core material densities represented a significant methodological advancement in simulating seismic effects on coastal structures. Furthermore, the numerical simulations,



conducted with PLAXIS software and employing a hardening soil model, provided valuable insights into the deformation patterns and stability under seismic loads. By detailing the cyclic responses of breakwaters with meticulous comparisons between experimental and numerical results, Cihan and Yuksel's research profoundly contributed to the coastal engineering field, offering a solid foundation for designing rubble mound breakwaters that are more robust against seismic disturbances.

Expanding further, Cihan and Yuksel (2013) focused on the dynamic response of rubble mound breakwaters armored with artificial units, specifically tetrapods and cubes, under cyclic loading, addressing both experimental and numerical perspectives. The experimental component involved the development of a shaking tank to simulate seismic loadings on breakwater models situated on a rigid bed, at a 1:50 scale, with slopes of 1:2. These models were subjected to various cyclic loadings to observe deformation patterns, employing two distinct placement methods for tetrapods and a random placement for cubes in the armor layer. The core material's packing density and porosity were standardized using a specialized laying system, with deformation and damage assessed through profiler measurements and image processing techniques. The numerical simulation utilized finite element method (FEM) software, aiming to identify the material properties of tetrapods and cubes under seismic conditions, contrasting with natural rock. The research illuminated the critical role of placement method and material type on the seismic resilience of breakwaters, contributing essential insights for the design of coastal structures against dynamic loading. Cihan and Yuksel's study signifies a substantial step forward in understanding the seismic behavior of breakwaters armored with artificial units, offering valuable guidelines for their design and construction in seismically active regions.

Ghalandarzadeh et al. (2021) explored reinforcement methods for rubble mound breakwaters under seismic loading. The research focused on assessing the effectiveness of various reinforcement strategies using scaled shaking table model tests of the South Pars Petrochemical Port's breakwaters in Iran. The findings emphasize that while the densification of the upper layers of breakwaters could not consistently control settlement when the core was composed of fine-grained materials, the inclusion of a pile support system provided significant resistance against seismic-induced deformations. This method ensured minimal settlement of critical infrastructure, such as pipelines laid across the crest of the breakwaters, highlighting its potential as a viable reinforcement strategy in earthquake-prone areas.

Expanding on these findings, Akarsh et al. (2023) delved into the critical analysis of rubble mound breakwaters under seismic forces, emphasizing the significance of innovative design techniques and advanced numerical models to bolster the structures' seismic resilience. Their findings highlighted the crucial role of specific design adaptations, such as strategically placing geosynthetics and armor units, in enhancing the breakwaters' capacity to withstand seismic loads efficiently. This research yielded substantial insights into the dynamic interplay between seismic events and rubble mound breakwaters, offering valuable knowledge to advance

the development of more resilient coastal defense mechanisms against earthquakes.

In a related context, Sajan et al. (2023) conducted a comprehensive evaluation of geosynthetic-reinforced rubble mound breakwaters (RMBs) to mitigate tsunami-induced damage, recognizing the historical challenges faced by traditional RMB designs during severe tsunami events, including foundation failures and inadequate wave energy dissipation. Their research delved into innovative approaches, such as integrating geosynthetics and implementing novel design configurations, to enhance RMB resilience against seismic and tsunami forces. By analyzing failure mechanisms like seepage forces and scouring effects exacerbated by tsunami waves, the study proposed a suite of countermeasures, including geobags, geogrids, crown walls with shear keys, and reinforced foundation soils. These modifications aimed to significantly reduce breakwater vulnerability, ensuring better structural integrity and functional performance during tsunami events, thereby providing effective coastal protection.

Similarly, Sajan et al. (2024) delineated the crucial engineering strategies needed to fortify the seismic resilience of rubble mound breakwaters. Their study extensively examined the susceptibility of these structures to earthquakes, scrutinizing conventional and modern design and reinforcement approaches under seismic conditions. The findings underscored the importance of integrating specialized designs like stone columns with advanced numerical modeling techniques to assess and improve breakwaters' seismic performance. By centering on the dynamic interplay between breakwater structures and seismic forces, the research yielded invaluable insights for enhancing the resilience of coastal defenses, vital for reducing the potential for catastrophic damage during seismic events.

Furthermore, Akarsh et al. (2024) conducted a study which provided crucial insights into the seismic resilience of rubble mound breakwaters. The research investigated the structural responses of these breakwaters to seismic forces through shake table tests coupled with numerical analyses, with a focus on evaluating the effects of design elements that could enhance stability under seismic loading conditions. Their findings revealed that specific design strategies, including the incorporation of certain geometries and materials, significantly influenced the breakwater's ability to withstand seismic forces. By integrating experimental data with numerical models, the study offered a comprehensive understanding of how seismic actions impact rubble mound breakwaters, thereby providing valuable guidelines for the design of more robust coastal defense structures capable of withstanding seismic events.

Building upon prior research, Morabit and ElGhoulbזורi (2024) systematically evaluated multiple design variants to assess their influence on the seismic stability of rubble mound breakwaters, utilizing empirical data from a port project in northwest Morocco. Their study quantified the stabilizing effects of various foundation soil types including rockfill, sand, sand reinforced with ballast columns, and vibrocompacted fill on structural performance under seismic loading. Furthermore, the investigation encompassed the impact of berm geometry, specifically its height and length, as

well as variations in the rear slope inclination of the breakwater. Dynamic analyses were performed by applying harmonic wave excitations across a range of frequencies and amplitudes, employing the finite element method within the PLAXIS 2D software environment. These findings underscore the critical importance of geotechnical and geometrical factors in the seismic design and optimization of breakwater structures.

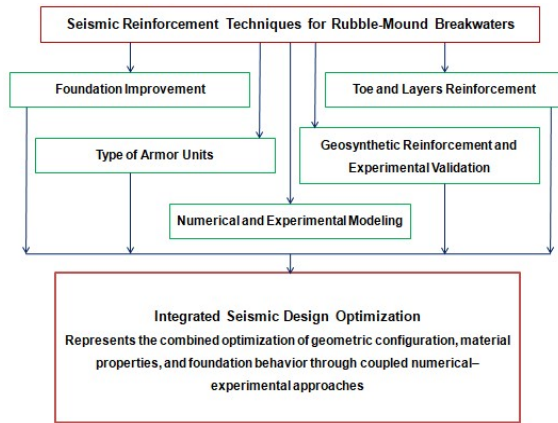


Figure 10 Flowchart of seismic reinforcement techniques for Rubble-Mound Breakwaters

Figure 10 presents the main seismic reinforcement techniques identified in previous research on rubble-mound breakwaters. Foundation improvement, through soil densification or pile-supported bases, effectively mitigates settlement and lateral spreading. Complementarily, toe and layer reinforcement enhances overall stability by strengthening the toe zone and layers to control deformations. The adoption of interlocking armor units such as tetrapods or cubes further increases energy dissipation and resistance to displacement. Meanwhile, geosynthetic reinforcement using geogrids or geotextiles improves shear strength and limits seismic deformation. Supported by numerical and experimental modeling notably Finite Element Method simulations and shaking-table tests these approaches converge within an integrated seismic design framework that optimizes structural performance and resilience under dynamic loading.

## V. CONCLUSION

The present review has synthesized current knowledge on the seismic behavior and stability of rubble-mound breakwaters, emphasizing their critical role in coastal protection. It examined the vulnerability of Rubble mound breakwaters to seismic loading, the methods used to assess their stability, the reinforcement strategies aimed at improving their performance. By integrating theoretical, numerical, and experimental findings, this study highlights the progresses achieved in understanding damage mechanisms and in developing resilient design solutions. The insights presented are particularly relevant for the growing African port infrastructure, where seismic resilience is vital for ensuring safe and sustainable maritime operations. Ultimately, this review contributes to advancing safer, more durable coastal

engineering practices that protect both economic activities and coastal communities.

## AUTHOR CONTRIBUTIONS

**A. Morabit:** Conceptualization, Methodology, Investigation, Resources, Data Curation, Writing Original Draft Preparation, Writing Review and Editing.

**A. El Ghoulbzouri:** Validation, Investigation, Resources, Writing Original Draft Preparation, Writing Review and Editing.

## REFERENCES

- Akarsh, P. K.; B. Chaudhary; M. K. Sajan; and S. Kumar** (2023). Seismic Responses of Rubble Mound Breakwater: Numerical Analyses. Paper presented at the International Symposium on Construction Resources for Environmentally Sustainable Technologies, Singapore, 237–246, Singapore: Springer Nature Singapore. doi:10.1007/978-981-99-9219-5\_22.
- Akarsh, P. K.; B. Chaudhary; M. K. Sajan; S. Kumar; and B. Sah** (2024). Seismic stability evaluation of rubble mound breakwater: Shake table tests and numerical analyses. *Soil Dynamics and Earthquake Engineering*, 178: 108466. doi:10.1016/j.soildyn.2024.108466.
- Aniel-Quiroga, Í.; C. Vidal; J. L. Lara; M. González; and Á. Sainz** (2018). Stability of rubble-mound breakwaters under tsunami first impact and overflow based on laboratory experiments. *Coastal Engineering*, 135: 39–54. doi:10.1016/j.coastaleng.2018.01.004.
- Athanasopoulos, G. A.; G. C. Kechagias; D. Zekkos; A. Batilas; X. Karatzia; F. Lyrantzaki; and A. Platis** (2020). Lateral spreading of ports in the 2014 Cephalonia, Greece, earthquakes. *Soil Dynamics and Earthquake Engineering*, 128: 105874. doi:10.1016/j.soildyn.2019.105874.
- Ayyub, B., and M. Kearney** (2012). *Sea Level Rise and Coastal Infrastructure: Prediction, Risks, and Solution*. American Society of Civil Engineers, USA. doi:10.1061/9780784412008.
- Bayesteh, H., and R. Mansouriboroujeni** (2019). Mechanisms of settlement of a rubble mound breakwater on a soft soil in tidal flats. *Marine Georesources & Geotechnology*, 38(10): 1163–1176. doi:10.1080/1064119X.2019.1656312.
- Borrero, J. C.; P. J. Lynett; and N. Kalligeris** (2015). Tsunami currents in ports. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 373(2053): 20140372. doi:10.1098/rsta.2014.0372.
- Brunet, S.; J. C. de la Llera; A. Jacobsen; E. Miranda; and C. Meza** (2012). Performance of port facilities in Southern Chile during the 27 February 2010 Maule earthquake. *Earthquake Spectra*, 28: 553–579. doi:10.1193/1.4000022.
- Cavaliere, F., and P. Franchin** (2020). Seismic Risk of Infrastructure Systems with Treatment of and Sensitivity to Epistemic Uncertainty. *Infrastructures*, 5(11): 103. doi:10.3390/infrastructures5110103.

- Celli, D.; D. Pasquali; P. De Girolamo; and M. Di Risio** (2018). Effects of submerged berms on the stability of conventional rubble mound breakwaters. *Coastal Engineering*, 136: 16–25. doi:10.1016/j.coastaleng.2018.01.011.
- Chang, S. E.** (2000). Disasters and transport systems: loss, recovery, and competition at the Port of Kobe after the 1995 earthquake. *Journal of Transport Geography*, 8: 53–65. doi:10.1016/S0966-6923(99)00023-X.
- Charuka, B.; D. B. Angnuureng; and S. K. M. Agblorti** (2023). Contemporary Global Coastal Management Strategies and Coastal Infrastructure and Their Application in Ghana: A Systematic Literature Review. *Sustainability*, 15: 12784. doi:10.3390/su151712784.
- Chen, W.; M. R. A. Van Gent; J. J. Warmink; and S. J. M. H. Hulscher** (2019). The influence of a berm and roughness on the wave overtopping at dikes. *Coastal Engineering*, 156: 103613. doi:10.1016/j.coastaleng.2019.103613.
- Ghalandarzadeh, A.; S. Ghalandarzadeh; and F. Abdi** (2021). Experimental study on the seismic deformations of rockfill breakwaters. *Soil Dynamics and Earthquake Engineering*, 147: 106760. doi:10.1016/j.soildyn.2021.106760.
- Ghazi, H.; H. Shahir; and A. Ghalandarzadeh** (2020). Effect of basal reinforcement on sinking and deformation of rubble mounds on a soft seabed. *International Journal of Geotechnical Engineering*, 14(7): 1–10. doi:10.1080/19386362.2020.1822570.
- Givehki, M.; J. Melby; F. G. Moreno; K. Hodgins; and A. Farhadzadeh** (2025). Effects of design parameters and sea level rise on lifecycle performance of rubble-mound breakwaters: A computational-statistical framework. *Coastal Engineering*, 204: 104897. doi.org/10.1016/j.coastaleng.2025.104897
- Green, R. A.; S. M. Olson; B. R. Cox; G. J. Rix; E. Rathje; J. Bachhuber; and N. Martin** (2011). Geotechnical aspects of failures at Port-au-Prince seaport during the 12 January 2010 Haiti earthquake. *Earthquake Spectra*, 27: 43–65. doi:10.1193/1.3636440.
- Hayashi, S., and T. Katayama** (1970). Damage to harbour structures by the Tokachioki earthquake. *Soils and Foundations*, 10(2): 84–102.
- Iai, S., and T. Kameoka** (1993). Finite element analysis of earthquake induced damage to anchored sheet pile quay walls. *Soils and Foundations*, 33(1): 71–91.
- Imamura, F., and S. Anawat** (2011). Damage due to the 2011 Tohoku earthquake tsunami and its lessons for future mitigation. *Proceedings of the International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake*, Tokyo, Japan, 1–4.
- Kazama, M., and T. Noda** (2012). Damage statistics (Summary of the 2011 off the Pacific Coast of Tohoku Earthquake damage). *Soils and Foundations*, 52(5): 780–792. doi:10.1016/j.sandf.2012.11.003.
- Leone, E.; A. Francone; A. Paglialunga; F. Ciardulli; J. Long; A. Aloisi; and G. R. Tomasicchio** (2025). Overtopping assessment of a rubble mound breakwater with rubble-mound breakwaters under cyclic loads. *Coastal Engineering*, 58(6): 528–539. doi:10.1016/j.coastaleng.2011.02.002.
- Cihan, K., and Y. Yuksel** (2013). Deformation of breakwater armoured artificial units under cyclic loading. *Applied Ocean Research*, 42: 79–86. doi:10.1016/j.apor.2013.05.002.
- CIRIA; CUR; and CETMEF** (2007). *The Rock Manual: The Use of Rock in Hydraulic Engineering* (2nd Edition). C683, CIRIA, London, UK.
- Dash, S. R.; L. Govindaraju; and S. Bhattacharya** (2009). A case study of damages of the Kandla Port and Customs Office tower supported on a mat-pile foundation in liquefied soils under the 2001 Bhuj earthquake. *Soil Dynamics and Earthquake Engineering*, 29(2): 333–346. doi:10.1016/j.soildyn.2008.03.004
- innovative armor units: A physical and numerical study. *Journal of Coastal Research*, 113(SI): 804–808.
- Lomnitz, C.** (2004). Major earthquakes of Chile: A historical survey, 1535–1960. *Seismological Research Letters*, 75(3): 368–377.
- Lopa, R. T.; R. Karamma; and C. Paotonan** (2025). Development of oscillating water column breakwater model. *Civil Engineering Journal*, 11(4): 1268–1292. doi:10.28991/CEJ-2025-011-04-02.
- Lou, Y. F.; C. Luo; and X. L. Jin** (2015). Numerical simulations of interactions between solitary waves and elastic seawalls on rubble mound breakwaters. *Structural Engineering and Mechanics*, 53(3): 393–410. doi:10.12989/sem.2015.53.3.393.
- Memos, C. D.** (2000). Experimental investigation of the seismic response of rubble-mound breakwaters. *Maritime Engineering and Ports II, WIT Transactions on The Built Environment*, 51: 320–330.
- Memos, C. D., and J. N. Protonotarios** (1993). Patras breakwater failure due to seismic loading. *Coastal Engineering*, 3343–3356.
- Memos, C. D.; A. Kiara; and E. Pavlidis** (2003). Coupled seismic response analysis of rubble-mound breakwaters. *Proceedings of the Institution of Civil Engineers – Water and Maritime Engineering*, 156(1): 23–31. doi:10.1680/wame.2003.156.1.23.
- Memos, C.; G. Bouckovalas; and A. Tsiachris** (2001). Stability of rubble-mound breakwaters under seismic action. In *Coastal Engineering 2000*, 1585–1598.
- Morabit, A., and A. El Ghoulbzouri** (2024). Effects of berms on rubble mound breakwater stability under seismic loading. *International Journal of Engineering*, 37(10): 1957–1969. doi.org/10.5829/ije.2024.37.10a.08.
- Morabit, A., and A. El Ghoulbzouri** (2024). Effects of soil foundation and mesh size on rubble mound breakwater stability under seismic loading. *Civil Engineering and Architecture*, 12(3): 1708–1725. doi.org/10.13189/cea.2024.120333.
- Morabit, A., and A. El Ghoulbzouri** (2024). Impact of rear slope variation on rubble mound breakwater stability

under seismic loading. *Civil Engineering Journal*, 10: 115–135. doi.org/10.28991/CEJ-SP2024-010-08.

**Mori, N.; D. T. Cox; T. Yasuda; and H. Mase** (2013). Overview of the 2011 Tohoku earthquake tsunami damage and its relation to coastal protection along the Sanriku Coast. *Earthquake Spectra*, 29: 127–143. doi:10.1193/1.4000118.

**Na, U. J.; S. R. Chaudhuri; and M. Shinozuka** (2008). Probabilistic assessment for seismic performance of port structures. *Soil Dynamics and Earthquake Engineering*, 28(2): 147–158. doi:10.1016/j.soildyn.2007.05.003.

**Nathan, J. W., and J. W. Good** (2004). Vulnerability of port and harbor communities to earthquake and tsunami hazards: The use of GIS in community hazard planning. *Coastal Management*, 32(3): 243–269. doi:10.1080/08920750490448622.

**Notteboom, T.; A. Pallis; and J. P. Rodrigue** (2022). *Port Economics, Management and Policy*. Routledge, New York, USA. doi:10.4324/9780429318184.

**Otsubo, M.; H. Takahashi; O. Kurihara; I. Sato; T. Matsuda; N. Naito; and M. Shiga** (2025). Failure mechanisms of the eastern breakwater at Iida Port triggered by the 2024 Noto Peninsula Earthquake and tsunamis. *Coastal Engineering Journal*, 67(4): 595–608. doi:10.1080/21664250.2025.2569216

**Park, S. H.; S. O. Lee; T. H. Jung; and Y. S. Cho** (2007). Effects of submerged structure on rubble-mound breakwater: Experimental study. *KSCE Journal of Civil Engineering*, 11: 277–284.

**Percher, M.; W. Bruin; S. Dickenson; M. Eskijian; Y. Oritatsu; and R. W. Rudolph** (2013). Performance of port and harbor structures impacted by the March 11, 2011 Great Tohoku Earthquake and Tsunami. In *Ports 2013: Success Through Diversification*, 610–619.

**PIANC** (2001). *Seismic Design Guidelines for Port Structures*. Balkema, Rotterdam, The Netherlands, 474 p.

**Sajan, M. K.; B. Chaudhary; A. P. Kotrabasappa; S. Kumar; and B. Sah** (2024). Novel Techniques for Reinforcing Rubble-Mound Breakwater against Tsunamis. *Journal of Geotechnical and Geoenvironmental Engineering*, 150(3): 04024002. doi:10.1061/JGGEFK.GTENG-11773.

**Sajan, M. K.; B. Chaudhary; P. K. Akarsh; and S. Kumar** (2023). Geosynthetic reinforced rubble mound breakwater for mitigation of tsunami-induced damage. *Geotextiles and Geomembranes*, 52(1): 72–94. doi:10.1016/j.geotextmem.2023.09.003.

**Sasaki, J.; K. Ito; T. Suzuki; R. U. A. Wiyono; Y. Oda; Y. Takayama; and H. Takagi** (2012). Behavior of the 2011 Tohoku earthquake tsunami and resultant damage in Tokyo Bay. *Coastal Engineering Journal*, 54(01): 1250012. doi:10.1142/S057856341250012X.

**Sasikumar, A.; H. Bihs; A. Kamath; O. Musch; and Ø. A. Arntsen** (2017). Numerical Investigation of Wave Kinematics Inside Berm Breakwaters With Varying Berm Geometry Using REEF3D. Paper presented at the International Conference on Offshore Mechanics and Arctic Engineering, Trondheim, Norway, Vol. 57731, V07AT06A035. American Society of Mechanical Engineers.

**Soga, K.** (1998). Soil liquefaction effects observed in the Kobe earthquake of 1995. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering*, 131(1): 34–51. doi:10.1680/geng.1998.131.1.34.

**Sugano, T.; A. Nozu; E. Kohama; K. I. Shimosako; and Y. Kikuchi** (2014). Damage to coastal structures. *Soils and Foundations*, 54(4): 883–901. doi:10.1016/j.sandf.2014.06.018.

**Sumer, B. M., and J. Fredsøe** (2000). Experimental study of 2D scour and its protection at a rubble-mound breakwater. *Coastal Engineering*, 40(1): 59–87. doi:10.1016/S0378-3839(00)00006-5.

**Sumer, B. M.; A. Ansal; K. O. Cetin; J. Damgaard; A. R. Gunbak; N. E. O. Hansen; A. Sawicki; C. E. Synolakis; A. C. Yalciner; Y. Yuksel; and K. Zen** (2007). Earthquake-induced liquefaction around marine structures. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 133(1): 55–82. doi:10.1061/(ASCE)0733-950X(2007)133:1(55).

**Takahashi, H.; T. Oohashi; and H. Endoh** (2011). Earthquake damage investigation of gravity-type quay walls in Ibaraki Port. *Proceedings of the International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake*, Tokyo, Japan, 1–4.

**Tsinker, G. P.** (1997). *Port Engineering: Planning, Construction, Maintenance, and Security*. John Wiley & Sons, New York, USA.

**Uralinis, A., and I. M. Shohet** (2022). Seismic Risk Mitigation and Management for Critical Infrastructures Using an RMIR Indicator. *Buildings*, 12(10): 1748. doi:10.3390/buildings12101748.

**Van Gent, M. R.** (2013). Rock stability of rubble mound breakwaters with a berm. *Coastal Engineering*, 78: 35–45. doi:10.1016/j.coastaleng.2013.03.003.

**Van Gent, M. R.; G. M. Smith; and I. M. van der Werf** (2013). Stability of rubble mound breakwaters with a berm: the upper slope. In *Coastal Structures 2011*, 423–434.

**Verschuur, J.; E. E. Koks; and S. Li** (2023). Multi-hazard risk to global port infrastructure and resulting trade and logistics losses. *Communications Earth & Environment*, 4: 5. doi:10.1038/s43247-022-00656-7.

**Wang, H.; C. Y. Yang; C. Lamison; and S. S. Chen** (1978). Loadings on rubble-mound breakwaters due to earthquakes. In *Coastal Engineering 1978*, 2244–2262.

**Werner, S.; N. McCullough; W. Bruin; A. Augustine; G. Rix; B. Crowder; and J. Tomblin** (2011). Seismic performance of Port de Port-au-Prince during the Haiti earthquake and post-earthquake restoration of cargo throughput. *Earthquake Spectra*, 27: 387–410. doi:10.1193/1.3638711.

**Yang, X., and X. Jin** (2016). Dynamic analysis of a rubble-mound breakwater subject to earthquake including seawater–structure–foundation interaction. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 230(2): 310–326. doi:10.1177/1475090215569820.

**Yasuda, S.; I. Towhata; I. Ishii; S. Sato; and T. Uchimura** (2013). Liquefaction-induced damage to structures

during the 2011 Great East Japan Earthquake. *Journal of JSCE*, 1(1): 181–193.

**Ye, J. H., and D. S. Jeng** (2013). Three-dimensional dynamic transient response of a poro-elastic unsaturated seabed and a rubble mound breakwater due to seismic loading. *Soil Dynamics and Earthquake Engineering*, 44: 14–26. doi:10.1016/j.soildyn.2012.08.011.

**Yoshimi, Y.** (1970). An outline of damage during the Tokachioki earthquake. *Soils and Foundations*, 10(2): 1–14.

**Yuksel, Y.; B. Alpar; A. C. Yalciner; E. Cevik; O. Ozguven; and Y. Celikoglu** (2002). Effects of the Eastern Marmara Earthquake on marine structures and coastal areas. *Water and Maritime Engineering*, 156(2): 147–163. doi:10.1680/wame.2002.156.2.147.

**Yüksel, Y.; K. Ö. Çetin; O. Özguven; N. S. Isik; E. Cevik; and B. M. Sümer** (2004). Seismic response of a rubble mound breakwater in Turkey. *Proceedings of the Institution of Civil Engineers – Maritime Engineering*, 157(4): 151–161. Thomas Telford Ltd.

**Yuksel, Y.; M. Berilgen; K. Cihan; E. O. Cevik; U. Dizman; and A. C. Yalciner** (2006). The seismic 16/j.oceaneng.2019.106843.

responses of a rubble mound breakwater. *Proceedings of the ISOPE International Ocean and Polar Engineering Conference*, San Francisco, USA, ISOPE. doi:10.1142/9789814282024\_0008.

**Zhang, Y.; Z. Liu; Y. Wang; and C. Wang** (2020). Analysis and verification of an optimal design solution for rubble mound breakwaters considering interactions of failure modes. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 146(2): 04020001. doi:10.1061/(ASCE)WW.1943-5460.0000544.

**Zhao, H. Y.; J. F. Zhu; X. L. Liu; D. S. Jeng; J. H. Zheng; and J. S. Zhang** (2020). Numerical investigation of dynamic soil response around a submerged rubble mound breakwater: II. Loose sandy seabed. *Ocean Engineering*, 215: 107891. doi:10.1016/j.oceaneng.2020.107891.

**Zhao, M.; G. Zhang; P. Wang; X. Du; and X. Zhang** (2020). An accurate frequency-domain model for seismic responses of breakwater-seawater-seabed-bedrock system. *Ocean Engineering*, 197: 106843. doi:10.10