

Review

Effectiveness of Engineered Tsunami Mitigation Measures: A Review of Current Approaches and Research Needs, Part I: Field Surveys

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Abstract

Tsunamis, though infrequent, pose catastrophic threats to coastal communities and infrastructure, underscoring the urgent need for effective mitigation strategies. This review provides a comprehensive evaluation of current engineered countermeasures, specifically seawalls, breakwaters, and water-filled canals, by synthesizing findings from post-tsunami field surveys. Evidence from major events, such as the 2011 Tohoku Tsunami, indicates that well-designed structural measures can substantially reduce tsunami wave energy and delay inland inundation, thereby improving the resilience of coastal infrastructure. However, their effectiveness depends heavily on proper geometric configuration, construction quality, regular maintenance, and integration with non-structural measures such as evacuation planning. Recent experimental and numerical investigations have also highlighted the potential of innovative countermeasures, in attenuating bore forces and protecting critical infrastructure. Despite advancements, significant knowledge gaps remain, particularly concerning the long-term reliability, cost-effectiveness, and adaptability of these systems under diverse tsunami conditions. This critical review aims to identify these gaps and outline key priorities for future research and development. The findings contribute to a deeper understanding of structural tsunami mitigation and support the advancement of integrated, resilient strategies for reducing disaster risk in tsunami-prone regions worldwide.

Keywords: tsunami; mitigation solutions; structural countermeasures; field surveys

1. Introduction

Since the earliest stages of human civilization, coastal and inland regions have experienced differing levels of development. Today, approximately 90% of the world's largest cities are located in coastal areas [1]. The United Nations reports that nearly 60% of these coastal cities are at risk of tsunamis, emphasizing the urgent need for risk-informed urban development and resilient coastal strategies [2]. Coastal regions face growing threats from tsunamis, as tragically demonstrated by the 2004 Indian Ocean Tsunami (IOT) and the 2011 Great East Japan Tsunami (GEJT) [3].

These catastrophic events revealed the shortcomings of depending exclusively on structural defenses which, in some cases, failed or created a false sense of security. As a result, strategies have increasingly shifted toward integrated risk management frameworks that blend engineered defenses with non-structural measures such as land-use planning, early warning systems, evacuation protocols, and ecological buffers and multilayer approaches [4,5]. Structural countermeasures (such as seawalls and breakwaters) aim to



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reduce wave energy, while non-structural strategies, including early warning systems and land-use planning, focus on preparedness and risk reduction [6]. However, the effectiveness of these measures varies depending on tsunami characteristics, coastal topography, and the robustness of their design. This review critically examines the performance of structural mitigation techniques by synthesizing evidence from post-tsunami field surveys, laboratory experiments, and computational modeling. It seeks to highlight best practices and identify unresolved challenges in safeguarding coastal infrastructure and communities against tsunami hazards.

Although this review primarily evaluates the effectiveness of engineered tsunami mitigation measures, it is important to recognize that additional hazards may influence their performance in certain regions. For example, field observations following the 2011 Great Tohoku tsunami on the Kuril Islands demonstrated that tsunami-driven ice significantly increased the destructive forces acting on coastal infrastructure [7]. While this phenomenon is limited to cold-region coastlines, it highlights the need for future studies to consider the influence of ice on the performance and design of tsunami mitigation measures in ice-prone environments.

1.1. Tsunamis

Tsunamis (a term of Japanese origin meaning “harbor wave”) are long-wavelength, high-energy sea waves primarily generated by large-scale disturbances in or near ocean basins [8]. These rare but devastating phenomena can travel vast distances across oceans with minimal energy loss and, upon reaching shallow coastal regions, can transform into towering walls of water capable of causing widespread destruction [9]. Unlike regular wind-generated waves, tsunamis involve the movement of the entire water column, making them uniquely powerful and destructive when they strike land.

Over the past few decades, awareness of tsunami hazards has increased significantly due to catastrophic events such as the 2004 Indian Ocean Tsunami and the 2011 Great East Japan Earthquake and Tsunami which led to the deaths of nearly 300,000 individuals and inflicted extensive economic and infrastructural damage amounting to billions of dollars [10,11]. As illustrated in Figure 1, the 2011 Tohoku Tsunami caused extensive destruction along the northeastern coast of Japan. The comparison of Google Earth satellite images before and after the tsunami clearly demonstrates the scale of structural damage to coastal infrastructure.



Figure 1. Google Earth satellite images of the District of Yuriago (a) before and (b) after the 2011 Tohoku Tsunami.

These disasters highlighted the vulnerability of both human settlements and critical infrastructure along coastlines, prompting a global response focused on improved hazard assessment, risk mitigation, and public preparedness [12]. Today, research into tsunami behavior, early warning systems, and resilient infrastructure design continues to evolve, emphasizing the need for international collaboration and informed policy development to reduce future risks [13]. The number of academic publications related to tsunamis increased significantly after the 2004 Indian Ocean Tsunami. As shown in Figure 2, the number of related studies with the keyword of “tsunami” rose sharply, reflecting a growing global research interest in understanding tsunami hazards, enhancing early warning systems, and advancing effective mitigation strategies.

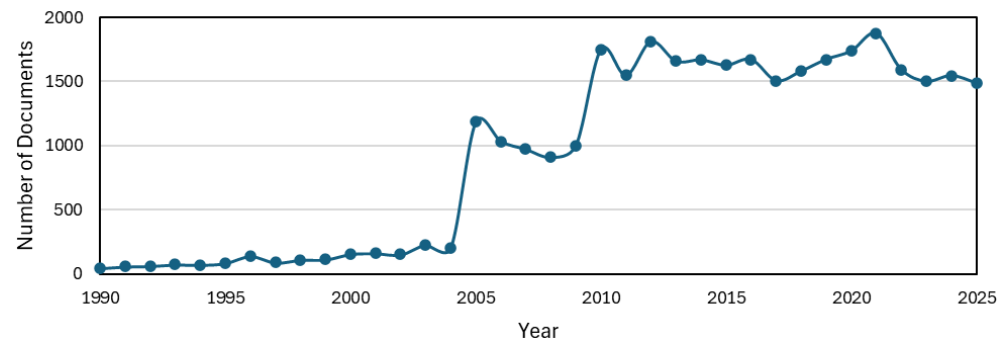


Figure 2. Annual number of publications indexed in Scopus retrieved using TITLE-ABS-KEY (“tsunami”), indicating a marked increase in research output after the 2004 Indian Ocean Tsunami.

1.2. Importance of Mitigation Measures

Tsunamis have caused significant damage to infrastructure and human life worldwide in recent decades [14]. The 2004 Indian Ocean Tsunami and the 2011 Great East Japan Tsunami were much stronger than what existing disaster protection systems could handle. They caused catastrophic damage to coastal communities and infrastructure, resulting in enormous economic losses, environmental degradation, and loss of life. Following the Indian Ocean Tsunami, researchers focused on developing early warning systems and evacuation plans to reduce the impact of future events. Since then, various methods have been proposed and implemented to protect coastal infrastructure. These include non-structural measures like planting coastal vegetation, building sand dunes, and maintaining lagoons and coral reefs, and structural measures like seawalls, large barriers, floodgates, and specially built evacuation buildings [6,15].

The selection of engineered tsunami mitigation measures should consider not only hydraulic performance but also construction costs, maintenance requirements, local tsunami hazard frequency, and long-term economic feasibility. In regions where tsunami occurrence is infrequent, site-specific cost–benefit analyses are essential to identify practical and sustainable mitigation strategies.

1.3. Tsunami Design Guidelines and Standards

While the design of structures in flood-prone areas has been widely studied, few existing codes specifically address the design of onshore civil structures in tsunami-prone regions [16]. The increasing awareness of tsunami hazards has led to the development of various national and international guidelines aimed at improving coastal resilience through proper design and mitigation strategies. These guidelines incorporate the latest scientific research and engineering practices to provide comprehensive frameworks for assessing tsunami risks, determining appropriate design loads, and implementing effective structural and non-structural measures [17].

Japan's long history of repeated tsunami events has resulted in the development of comprehensive guidelines, standards, and building codes, as well as a substantial body of academic and industry literature focused on tsunami risk and mitigation since the 1950s. In 2000, the Building Technology Research Institute in Japan introduced engineering guidelines for the structural design of tsunami refuge buildings, proposing a method based on experimental studies. The method was updated in 2005 and published as the Structural Design Method of Buildings for Tsunami Resistance (SMBTR) [18], which was validated using buildings affected by the 2004 Indian Ocean Tsunami. The SMBTR provides detailed formulations for tsunami wave pressure and force calculations, considers buoyancy effects, and acknowledges the influence of surrounding obstacles in reducing tsunami loads on structures [19].

In the United States, initial provisions addressing tsunami-induced loading were introduced in the 1980s through Hawaii's Building Code. The City and County of Honolulu Building Code (CCH) incorporates specific regulations and design criteria to enhance the resilience of structures against tsunami hazards [20]. Recognizing Honolulu's vulnerability to tsunamis, the code mandates rigorous standards for foundation design, structural integrity, and materials to resist hydrodynamic forces and debris impacts. The CCH emphasizes the integration of both structural and non-structural mitigation measures, including elevation requirements and site planning, to reduce the risk to life and property.

In 2011, the Federal Emergency Management Agency (FEMA) released the fourth edition of the Coastal Construction Manual [21]. This document provides guidance for the design and construction of structures in coastal areas vulnerable to damage from natural hazards. FEMA also has issued comprehensive publications such as FEMA P-646, Guidelines for Design of Structures for Vertical Evacuation from Tsunamis [22], which provides detailed recommendations for designing evacuation structures that can withstand the extreme forces generated by tsunamis while ensuring the safety and accessibility of occupants. It outlines planning, siting, and structural design criteria to ensure these facilities can withstand tsunami forces, including hydrostatic, hydrodynamic, and debris impact loads.

American Society of Civil Engineers (ASCE) Standard 7-22 [23] is one of the most widely recognized standards that provides minimum design loads for buildings and other structures, including tsunami-induced forces. ASCE 7-22 outlines detailed methodologies to estimate hydrodynamic pressures, debris impact forces, and erosion effects caused by tsunami inundation, emphasizing the importance of incorporating these forces into structural design to enhance the resilience and survivability of coastal infrastructure. The Tsunami Loads and Effects Subcommittee of the ASCE/SEI 7 Main Committee has prepared a dedicated chapter on tsunami loads and effects, which was introduced in the ASCE/SEI 7-16 standard [24].

In addition to the design guidelines developed in Japan and the United States, tsunami-resistant design provisions have also been established in other tsunami-prone countries. For example, the Russian Federation has developed the Set of Rules for buildings and structures located in tsunami-hazard areas. A comprehensive overview of the Russian approach to tsunami resilience and coastal protection is provided by Klyachko et al. (2023) [25].

Despite these advancements, challenges remain in standardizing tsunami design criteria globally due to regional variations in tsunami characteristics, coastal geomorphology, and socio-economic factors. Continued research and refinement of guidelines are essential to address gaps in knowledge and enhance the effectiveness of engineered mitigation measures worldwide.

1.4. Objectives and Scope of the Review

Although the effects of tsunami-induced loads on onshore structures have been widely investigated in numerous studies [16,26–29], relatively few studies have focused on tsunami mitigation countermeasures, highlighting that further research is needed to develop a deeper understanding of their effectiveness in reducing tsunami-induced forces on coastal infrastructure. The objective of this review is to provide a comprehensive evaluation of engineered tsunami mitigation measures, specifically seawalls, breakwaters, and canals, and their effectiveness in reducing tsunami impacts on coastal infrastructure. By reviewing and analyzing findings from field observations, laboratory experiments, and numerical simulations at two different parts, this critical study primarily aims to provide a thorough review of the current literature on engineered structural tsunami mitigation strategies. This review primarily aims to identify existing gaps in knowledge and to highlight the essential future directions and research priorities within this field. Ultimately, the goal is to support the development of more resilient and sustainable coastal infrastructure capable of withstanding future tsunami events.

The scope of this review encompasses structural tsunami mitigation measures (seawalls, breakwaters, and canals) with a particular emphasis on coastal protection strategies that directly interact with tsunami waves. These strategies are designed to attenuate wave energy, delay inland inundation, and minimize damage to coastal infrastructure. In addition to evaluating existing structural countermeasures, the review explores emerging research directions aimed at enhancing the resilience of coastal infrastructure. It also addresses innovative approaches to reducing the risk of structural failure under tsunami loading, thereby contributing to more effective and sustainable coastal defense solutions.

2. Tsunami Hazards and Impacts on Coastal Infrastructure

2.1. Generation and Propagation of Tsunamis

Tsunami waves are triggered for various reasons, of which the most common cause is earthquakes, exemplified by the 2004 Indian Ocean Tsunami and the 2011 Japan Tsunami [30]. Tsunamis may also result from non-seismic causes such as underwater landslides (e.g., the 1998 Papua New Guinea event [31]), volcanic eruptions (e.g., the 2022 Hunga Tonga eruptions [32]), asteroid or comet impacts [33], and glacial calving (e.g., the 1958 Lituya Bay mega tsunami [34]). With climate change accelerating glacial retreat, the potential for tsunamis from non-seismic sources is receiving increased attention [35].

As shown in Figure 3, once tsunamis are generated, these waves propagate across the ocean at high speeds, often hundreds of kilometers per hour, with long wavelengths and low wave heights in deep water. As they approach shallow coastal areas, the waves slow down and increase in height due to the decreasing water depth, eventually breaking near the shore. This breaking can form a tsunami bore, a turbulent, fast-moving wall of water resembling a tidal bore, or a tsunami surge, which is a rapid, continuous flow of water flooding inland. The inundation that follows causes widespread flooding, damaging infrastructure along the coast [36–38]. Continuous tsunami inundation may last from a few minutes to several hours [39,40].

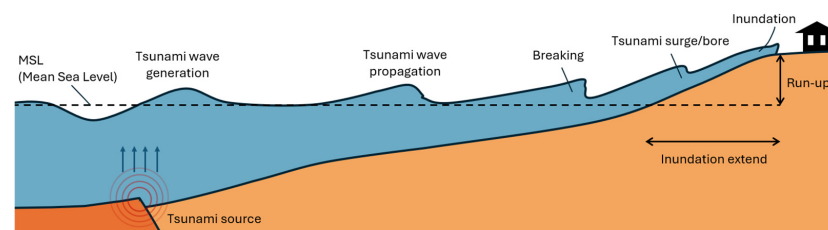


Figure 3. Tsunami generation and propagation toward coastline and its impact on coastal infrastructure.

Following the 2011 Great East Japan Tsunami, tsunamis in Japan were classified into two categories: Level 1 (L1) and Level 2 (L2). L1 tsunamis, with return periods ranging from several decades to around 100 years, are used for disaster prevention and typically cause inundation depths under 7–10 m. L2 tsunamis, with return periods of a few hundred to a few thousand years, are considered for disaster mitigation and can produce much greater inundation depths, often over 10 m and reaching up to 20–30 m. The 2004 Indian Ocean and 2011 Great East Japan tsunamis fall into this category [41,42].

2.2. Interaction of Tsunamis with Coastal Infrastructure

The interaction between tsunami inundation and coastal infrastructure is complex and highly destructive due to the immense energy and momentum carried by tsunami bores. As tsunamis reach the coast, the waves exert various hydrodynamic and impact forces on structures, including hydrostatic pressure, hydrodynamic drag, uplift, debris impact, and scour at foundations. These forces can lead to partial or complete structural failure, particularly when infrastructure is not designed to withstand such extreme loading conditions [22,23]. Structures located near shorelines are vulnerable during tsunami events. Studies of the 2004 IOT and the 2011 GEJT have shown that inadequately designed or maintained infrastructure suffered extensive damage [3,43,44]. For example, during the GEJT, many reinforced concrete buildings were toppled or displaced due to strong hydrodynamic forces and foundation scour, while bridges were washed away by buoyant uplift and debris impacts [45–47].

As shown in Figure 4, the time history of tsunami-induced force on structures typically exhibits multiple phases [48]. Understanding the different phases of tsunami-induced force time history is crucial, as mitigation countermeasures may influence each phase differently and with varying effectiveness [49]. The interaction of bore fronts with structure generates an impulsive force, followed by a quasi-steady force during the continuous inundation [50,51]. The impulsive force phase is characterized by a short-duration, high-magnitude pressure spike, often attributed to air entrainment and strong turbulence at the bore front. During the quasi-steady phase, the hydrodynamic force is governed by the steady interaction of bore height and flow velocity, and the pressure distribution tends to resemble a hydrostatic profile. The transition between these two loading phases is referred to as the transition phase [16,19,52,53]. Depending on the characteristics of the incoming bore and the geometry of the structure, the maximum force may occur either in the impulsive or quasi-static phase [50,54–56].

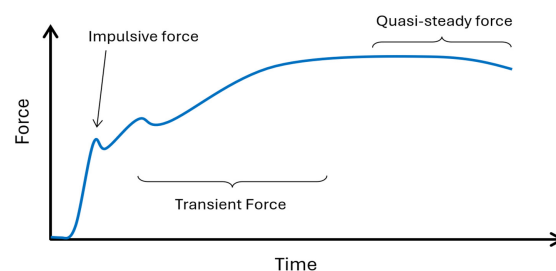


Figure 4. Schematic of the time history of force exerted on structures by tsunami-induced bores.

2.3. Types of Tsunami Forces and Coastal Infrastructure Failure Mechanisms

Tsunamis exert a wide range of destructive forces onto coastal infrastructure, which vary in magnitude depending on the tsunami characteristics, coastal geometry, and structural design. Because of the significant impact of tsunami-induced forces on structures which is one of the primary causes of failure in coastal infrastructure, many researchers have investigated the interaction between tsunami bores and infrastructure located on affected coastal zones [51,57,58]. One of the earliest studies in this field was conducted by

Cumberbatch (1960), who analytically examined the forces exerted by tsunami waves on a vertical wall [59].

ASCE 7-22 categorizes tsunami-induced forces on structures into two main types: hydrostatic and hydrodynamic loads [23]. Hydrostatic loads include buoyancy forces, unbalanced lateral hydrostatic force, residual water surcharge load on floors and walls, and hydrostatic surcharge pressures on foundation. Hydrostatic forces result from water pressure acting on submerged or partially submerged structures. These are relatively straightforward to calculate but can be substantial in the case of deep inundation. Hydrodynamic drag, caused by the horizontal motion of the wave, applies large forces along the flow direction. Buoyant forces, including uplift, occur when the water level rises around or under structures, potentially dislodging poorly anchored elements such as slabs or lightweight buildings. In addition to the incoming flow, the receding phase of a tsunami can generate significant return-flow velocities, which may impose additional hydrodynamic loading on structures and contribute to severe local scour around foundations and coastal infrastructure. Therefore, both the inundation and drawdown phases should be considered when evaluating tsunami-induced impacts.

Tsunami-induced structural damage to coastal infrastructure arises from multiple factors, including hydrostatic and hydrodynamic forces, impacts from floating debris, the fire spread through floating debris and flammable liquids, as well as soil erosion leading to slope instability or foundation failure [22]. Hydrostatic and hydrodynamic loads can directly damage infrastructure by exerting forces on buildings, potentially causing them to slide, overturn, or collapse entirely [46]. Another critical failure mechanism arises from debris impact loads, which can be highly impulsive and difficult to predict. Large floating objects like cars, shipping containers, or even small boats can strike buildings with devastating force. These impacts were widely observed in Japan during the GEJT [45]. Scour and erosion at the base of structures further compromise their stability by removing supporting soil. Breakage or overturning due to loss of bearing capacity is often the result. According to Nakamura et al. (2021), unanticipated scour depths during tsunami run-up were responsible for the collapse of several bridge superstructures in coastal Japan [60]. Figure 5 illustrates various examples of infrastructure failures that occurred during past tsunami events.



Figure 5. Various examples of infrastructure failure that occurred during past tsunami events: (a) Overturning of reinforced concrete apartment building, Onagawa, Japan, 2011, (b) shoreline protection structure failure, Tanohata, Japan, 2011, (c) Debris impact, Banda Aceh, Indonesia, 2004, (d) movement and breakage of Tetrapod armor units, Japan, 2011.

3. Classification of Mitigation Countermeasures

Tsunami defense strategies can be classified into structural, non-structural, and hybrid approaches. Structural measures focus on physical deflection or dissipation of wave energy, non-structural strategies emphasize preparedness and planning, and hybrid solutions integrate both types to achieve more resilient, adaptable outcomes for coastal communities. Figure 6 presents an overview of existing tsunami countermeasure options.

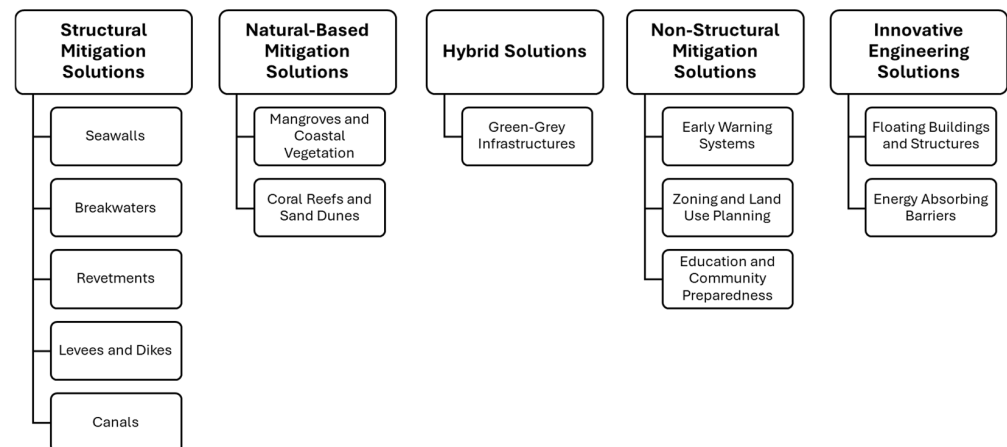


Figure 6. Tsunami countermeasures—an outline of existing options.

3.1. Structural Measures

Structural countermeasures are engineered systems designed to attenuate tsunami-induced loads exerted on structures located near affected coastlines (Figure 7). These countermeasures are typically constructed along coastlines or in strategic inland areas to protect human life, infrastructure, and economic assets. Among the most common structural elements are seawalls, breakwaters, and canals, each with distinct hydrodynamic behaviors and performance limitations.

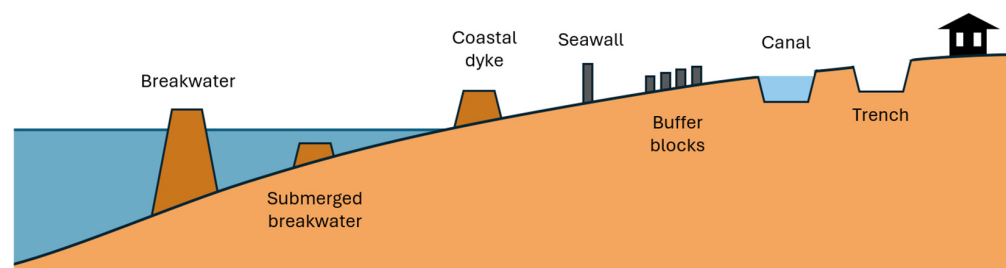


Figure 7. Typical structural coastal protection used to mitigate tsunami effects.

3.1.1. Seawalls

Constructing seawalls in tsunami-prone coastal regions is a widely implemented strategy for reducing inundation risk. Seawalls are vertical or sloped barriers constructed along coastlines to prevent inland flooding and reduce tsunami inundation. Their primary function is to reflect or dissipate wave energy before it reaches critical infrastructure [61]. While high seawalls offer effective protection against tsunamis, they can be relatively expensive to build [29]. Their performance, however, is highly dependent on whether overtopping occurs. In cases where overtopping is possible, seawalls may not only fail to prevent damage but also can increase destruction during extreme wave events [62]. Additionally, their presence can potentially reduce evacuation readiness.

3.1.2. Breakwaters

Among the primary structural mitigation strategies, the construction of continuous or detached breakwaters, either submerged or emerged, is widely implemented [6]. Breakwaters are offshore structures, either floating or fixed, that act as the first line of defense by reducing incoming wave energy. In tsunami events, submerged or detached breakwaters can mitigate wave energy before they reach the shoreline. They are particularly useful in harbors and bays where port infrastructure is vulnerable. Studies have demonstrated that breakwater shape, porosity, and arrangement significantly influence tsunami dissipation. The location of the breakwater is also a critical parameter influencing its effectiveness in resisting tsunami forces [63].

3.1.3. Canals

Water-filled canals, channels, or dug pools located inland or near coastal infrastructure have been introduced as innovative tsunami mitigation strategies. These features function as energy sinks by absorbing part of the tsunami bore, thereby reducing the forces exerted on structures situated behind them [64,65]. Although seawalls and breakwaters are generally more effective at dissipating tsunami energy and allowing additional time for evacuation, they are often associated with significantly higher construction costs. Moreover, failure or overtopping of these structures may lead to more destructive tsunami impacts [66]. Post-tsunami field investigations have demonstrated that a water-filled canal parallel to the coastline can effectively dissipate the energy of incoming tsunami bores [46,47].

3.2. Non-Structural Measures

Non-structural approaches aim to reduce tsunami risk without relying on physical barriers or infrastructure. These strategies include early warning systems, hazard zoning, tsunami evacuation maps, public education, and awareness campaigns [67]. Among them, urban planning plays a crucial role in restricting the development of critical infrastructure within high-risk coastal zones. Although such measures do not prevent the physical impact of tsunami waves, they are highly effective in minimizing casualties and economic losses when properly implemented [12]. Countries like Japan exemplify comprehensive non-structural frameworks by integrating real-time alert systems, frequent evacuation drills, and robust public risk communication initiatives.

3.3. Hybrid Approaches

Hybrid mitigation strategies integrate both structural and non-structural elements to create multi-layered defense systems. For example, a coastal area may use seawalls in combination with elevated evacuation structures, real-time warning systems, and green infrastructure like mangroves or dunes. Some recent studies also explore combining engineered measures to balance flow reduction and overtopping control. Oshiro et al. (2015) investigated the effectiveness of canals and coastal forest barriers in reducing tsunami flow velocity and delaying wave arrival time [68]. Rif'atin et al. (2025) examined the combined effects of sea dikes and trenches as a mitigation strategy [69]. These approaches seek to address the limitations of individual methods by leveraging the strengths of multiple systems. Future research should focus on optimizing these synergies under budgetary and spatial constraints, especially in rapidly urbanizing coastal regions.

4. Field Evaluation of Engineered Tsunami Mitigation Measures

Coastal communities face increasing risks from tsunamis, which can result in catastrophic loss of life and severe damage to infrastructure [70]. In response, various engineered mitigation strategies have been implemented or proposed globally to reduce tsunami im-

pacts [45,71,72]. While a wide range of structural and non-structural approaches exist, this study focuses exclusively on the structural countermeasures of seawalls, breakwaters, and water-filled canals due to their direct hydraulic interaction with tsunami bores and their prominence in both practical applications and academic research. Seawalls function as vertical or sloped barriers that reflect and block incoming waves [61], breakwaters dissipate wave energy offshore before it reaches vulnerable shorelines [73], and water-filled canals or trenches aim to attenuate bore momentum through flow diversion and energy absorption [49,74]. Evaluating the performance of these systems is critical for enhancing coastal resilience and informing the development of future design guidelines. To this end, this section provides an in-depth assessment of their effectiveness based on post-tsunami field survey studies.

Comprehensive forensic engineering field surveys were conducted by expert teams following major tsunami events offering critical post-disaster data and valuable insights into tsunami impacts, structural performance, and coastal vulnerability [46,47,75–79]. These surveys yield invaluable empirical data, highlighting both successes and failures, which in turn guide future design improvements and policy decisions. After each significant tsunami, researchers, engineers, and disaster experts promptly deploy to the affected coastal areas to carry out thorough field assessments. Such on-site investigations are essential because they provide direct, real-world observations of the tsunami's impact on the landscape, infrastructure, and communities [80].

Nistor and Palermo (2015) [81] carried out detailed tsunami damage surveys shortly after three major tsunami events: the 2004 Indian Ocean Tsunami (in Indonesia and Thailand), the 2010 Chile Tsunami, and the 2011 Tohoku Tsunami in Japan. The main goal of these surveys was to study how different structures responded to the extreme forces caused by the inland flooding from the tsunamis. Based on their field survey following the January 2024 Tsunami, Heidarzadeh et al. (2024) [76] found three primary failure mechanisms were identified for coastal structures: overturning due to tsunami backwash, structural damage from inundation currents and wave pressure, and impacts caused by floating debris.

4.1. Post-Tsunami Damage Assessment of Seawalls

Seawalls are among the most common structural mitigation measures designed to act as physical barriers against incoming tsunami waves (Figure 8). Following the 2011 Great East Japan Earthquake and Tsunami, extensive field surveys conducted by the Japan Meteorological Agency and research institutions documented the performance of seawalls along the northeastern coast of Honshu Island. In areas where seawalls were constructed according to updated design standards, with heights ranging from 8 to 15 m, significant reduction in wave overtopping and inland inundation was observed [71]. These seawalls effectively shielded urban zones, preserving critical infrastructure such as power plants and transportation routes. However, some seawalls were overtopped when tsunami heights exceeded design levels, leading to catastrophic flooding. Additionally, certain seawalls suffered structural damage due to scouring and undermining at their base, indicating the need for enhanced foundation designs and scour protection [3].

During a post-tsunami reconnaissance following the 2004 Sumatra event, Dalrymple and Kriebel (2005) observed increased levels of infrastructure damage directly behind openings in coastal seawalls in Phuket, Thailand [77]. The effectiveness of seawalls is also linked to maintenance and integration with natural buffers such as coastal forests and dunes.

Following their field survey after Noto Tsunami, Heidarzadeh et al. (2024) [78] identified several locations along the Sea of Japan coast where the concrete seawall effectively prevented tsunami overtopping. This protective function was clearly evidenced by the

clean and undisturbed condition of the area behind the seawall, indicating that the tsunami had not overtopped the structure. They also observed cases where seawalls were overtopped by tsunami waves, showing no signs of structural damage. Despite tsunami heights reaching 3.7–3.9 m in the area, the seawall sustained no visible damage, which is attributed to the high-quality construction and robust design of the structure. Their study highlights a failure case in which concrete seawall blocks were overturned over a 25 m stretch due to tsunami backwash, a mechanism also observed during the 2011 Tohoku Tsunami [82]. Notably, the failure occurred in an unprotected section of the seawall, whereas adjacent segments equipped with rock armor or a rockfill shoulder remained stable. This underscores the importance of reinforcing the seaward face of vertical seawalls with armor layers extending to the seawall's full height.

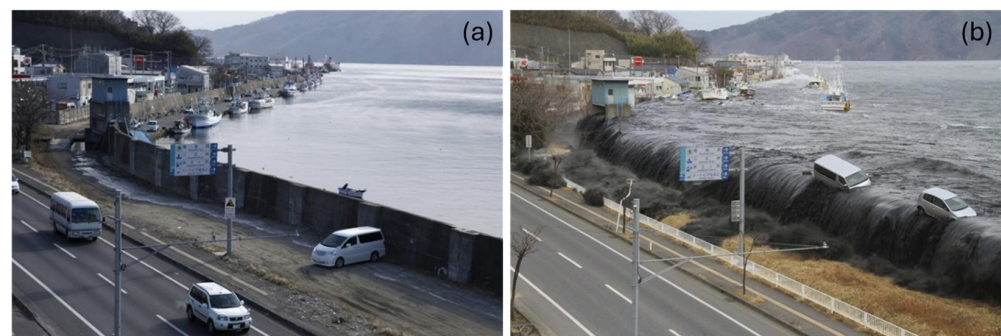


Figure 8. (a) Seawall and (b) tsunami overtopping during the 2011 event in Miyako, Japan (source: Reuters).

Based on their field survey following the 2011 Great East Japan Tsunami, Suppasri et al. (2013) [72] identified three primary causes of seawall damage. First, the two seawalls crossed in an X shape, which caused the tsunami waves to accumulate and increase in size at the center where they intersected. Second, the foundations of the seawalls were weakened, as the soil properties near the river likely disrupted the stability of the foundations. Lastly, the seawalls were not properly maintained and were inadequately connected to each other. This allowed the tsunami to flow over the seawalls and form a high-speed water jet, with the strong current causing scouring around the foundations and further weakening the structures.

4.2. Breakwater Performance in Tsunami Events

Breakwaters, including rubble mound and submerged types, serve to reduce incoming wave energy before it reaches the shoreline. Following the 2004 Indian Ocean Tsunami, field surveys in Aceh, Indonesia, found that coastal areas protected by breakwaters experienced substantially reduced wave heights and run-up levels compared to unprotected locations [15]. Rubble mound breakwaters with high porosity allowed partial infiltration of tsunami waves, dissipating energy via turbulence and friction. However, in some cases, insufficient structural robustness led to breakwater displacement or partial failure under extreme loads (Figure 9), emphasizing the need for optimized design against hydrodynamic forces and debris impact [72].

Submerged breakwaters, being less visually obtrusive, have proven effective in dissipating wave energy by inducing wave breaking [83]. Surveys of tsunami-affected sites with submerged reefs or artificial breakwaters indicate reductions in run-up heights by up to 30% [3]. Field investigations of Nistor and Palermo (2015) [81] following the 2011 Tohoku Tsunami revealed that many breakwaters along Japan's Tohoku coast, primarily designed for storm protection, suffered severe damage or complete failure under tsunami loading. Composite breakwaters with concrete armor units showed greater resilience compared to

caisson-type breakwaters, largely due to their porosity, which helped dissipate wave energy, although some armor units were also damaged. The performance of these units varied with size and weight, and current design methods for tsunamis remain underdeveloped and unverified.



Figure 9. Breakwater damage during tsunami event.

The Kamaishi breakwater in Japan, completed in 2009 at a cost of approximately ¥120 billion (around \$1.5 billion), was recognized as the world's deepest breakwater. Although it was ultimately destroyed by the 2011 Great East Japan Earthquake Tsunami, it significantly reduced the tsunami's force and height by approximately 40% and delayed its inland arrival by about six minutes and provided critical additional time to evacuate to higher ground [84]. Following their field survey of the 2024 Noto Peninsula Earthquake and Tsunami, Inagaki et al. (2025) emphasized the critical role of coastal protection structures in damage mitigation [79]. They observed that areas behind breakwaters experienced minimal impact, whereas unprotected zones and structural weaknesses in hydraulic defenses were associated with significantly greater damage. They found several locations, which tsunami flooding occurred where coastal defenses were absent or had crest elevations lower than the tsunami height, emphasizing the need to address structural weak points in coastal protection systems. Tsunami waves penetrated further inland through weak points in coastal defenses, particularly in areas lacking offshore structures like detached or port breakwaters.

Heidarzadeh et al. (2024) surveyed three locations around Toyama where no tsunami damage was observed [78]. The area is protected by a three-layer coastal protection system consisting of a detached rubble mound breakwater about 100 m offshore, a concrete stepped revetment at the shoreline, and an earth-fill dike behind it, collectively standing approximately 2.5 m above sea level. They also reported on the Shika nuclear power plant, which sustained no damage and is protected by multiple coastal layers, including an offshore caisson breakwater, coastal vegetation, a coastal road, and a solid concrete wall, along with significant elevation above sea level.

4.3. Observations of Engineered and Natural Canals

Canals, whether natural or engineered, and whether water-filled or empty, can influence tsunami wave propagation by modifying flow patterns and velocities (Figure 10). Although less extensively studied than seawalls or breakwaters, field evidence from coastal Japan suggests that wide canals and channels can act as hydraulic buffers by diverting and attenuating tsunami wave fronts [85].



Figure 10. Image of tsunami propagating over a canal during the 2011 Japan Tsunami event (source: Reuters).

The Buckingham Canal, located near Chennai in southeast India, is a long channel about 30 m wide and 10 m deep that runs parallel to the coast at a distance of 1 to 2 km. During the 2004 Indian Ocean Tsunami, the canal helped protect some higher ground areas from damage because the tsunami first filled the canal, which acted like a buffer zone. The canal also helped return the water back to the sea within 10 to 15 min [86]. Tokida and Tanimoto (2012) demonstrated that a water-filled depression formed by tsunami flooding referred to as a “dug pool” can effectively reduce tsunami flow velocity [87]. The Buckingham Canal played a significant role in reducing casualties, particularly among fishermen in coastal regions of Andhra Pradesh and around Chennai, India [88]. These findings highlight the potential of canals as effective tsunami countermeasures for protecting both coastal infrastructure and human lives.

In some cases, canals combined with vegetation or shallow embankments have slowed tsunami propagation, reducing peak forces exerted on downstream infrastructure (Figure 10). However, the effectiveness of such features depends heavily on canal geometry. During the 2011 Japan Tsunami, the tsunami waves swept away coastal forests, overflowed the Kita-Teizan Canal, and caused destruction far inland in Miyagi Prefecture. However, post-disaster field surveys suggest that, despite the severe conditions, the combination of vegetation and the canal may have helped to some extent in reducing the tsunami’s force [89]. Historically, the design of the Kita-Teizan Canal reflected a common approach in which a coastal forest served as a windbreak, with the canal positioned behind it. This layered arrangement was likely intended to enhance natural protection along the coast [68].

5. Discussion and Conclusions

This review provides a comprehensive resource for researchers in the field observations, who are investigating the role of structural measures in mitigating tsunami energy and protecting coastal infrastructure, by highlighting the limitations and gaps in current research. This study has investigated the effectiveness of three key structural tsunami mitigation measures of seawalls, breakwaters, and water-filled canals, by considering findings from post-tsunami field observations. Unlike many available studies that focus on the forces exerted on these types of mitigation structures or the coastal infrastructure, this review has specifically studied the effects of these mitigation countermeasures on

tsunami mitigation and downstream infrastructure. As such, only a carefully selected set of studies were included, prioritizing those that explored impact mitigation rather than structural resistance.

Seawalls and breakwaters have long been recognized as protection structures; when properly designed and maintained, they can reduce tsunami wave energy, delay inland flooding, and protect critical assets. However, their effectiveness highly depends on factors such as geometry, construction quality, local topography, and tsunami characteristics. While generally reliable for more frequent, moderate events (Level 1 tsunamis), studies show that these structures may fail due to scouring and overtopping, particularly during rare but extreme events (Level 2 tsunamis).

Canals, especially when water-filled and strategically integrated into coastal layouts, are a relatively recent and less explored alternative. Recent research suggests they can dissipate tsunami energy, reduce bore front velocity, and lower forces on downstream structures, particularly when combined with natural buffers like coastal vegetation. However, their broader adoption remains constrained by the lack of standardized design protocols, limited field validation, and minimal large-scale implementation data.

Future research should adopt multi-disciplinary, site-specific, and system-level approaches that combine high-resolution simulations with robust field measurements. Particular attention should be given to cost-effective, scalable solutions like canals and hybrid strategies, especially in low-resource settings where traditional infrastructure may be financially or spatially unfeasible. In addition, the potential for multifunctional coastal infrastructure should be further investigated, where existing or planned structures can provide protection against tsunamis while simultaneously addressing other coastal hazards, such as storm surges, erosion, or flooding. Such dual-purpose approaches can improve the economic feasibility, public acceptance, and long-term sustainability of tsunami mitigation strategies, particularly in regions with infrequent tsunami occurrences.

In addition, future research should investigate the potential of multifunctional coastal infrastructure, where existing or planned structures can provide tsunami mitigation benefits while also addressing other coastal hazards, such as storm surges, erosion, or flooding. Such dual-purpose approaches can improve the economic feasibility, public acceptance, and long-term sustainability of tsunami mitigation strategies, particularly in regions with infrequent tsunami occurrences.

Finally, it is evident that no single countermeasure can fully protect coastal communities from tsunami threats. Integrated, multi-layered defense systems, such as combining seawalls with elevated evacuation routes, or pairing canals with vegetated buffers, offer more resilient and adaptable solutions. Bridging the identified gaps will not only enhance physical safety but also support the creation of adaptive, sustainable, and locally appropriate coastal defense strategies.

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