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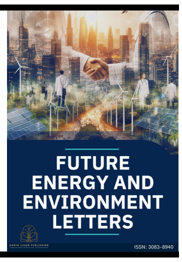

A Global Review on Extreme Wave Events: Impacts and Mechanisms

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ABSTRACT

Extreme wave events such as tsunamis, storm surges, and rogue waves have increasingly threatened coastal communities worldwide. However, the lack of consolidated documentation of recent events hinders effective risk assessment and mitigation. This study aims to provide a global overview of extreme wave events and evaluate their physical and socio-economic impacts, with emphasis on Southeast Asia and Malaysia. A comprehensive review was conducted using data from the NOAA Center for Tsunami Research and international disaster databases. The study examined the major tsunamis from 2018 to 2024, including events in Japan, Taiwan, Indonesia, and Mexico, along with their respective magnitudes, casualties, and infrastructural damages. Special attention was given to Malaysian coastal regions such as Terengganu and Penang, where wave-induced flooding and infrastructure destruction are recurrent during monsoon seasons. Key findings reveal that northern Malaysia remains highly vulnerable to extreme waves, often resulting in population displacement and property loss. The study also reviewed engineering advancements such as the use of carbon nanotube-reinforced concrete to enhance the resilience of coastal infrastructure. In conclusion, the research underscores the urgent need for integrated coastal risk management strategies combining hazard forecasting, sustainable structural materials, and long-term adaptation planning to reduce future vulnerabilities.

1. Introduction

The wave can be explained as the observable oscillations or the disturbances of water surface on water basins as suggested by Toffoli and Bitner-Gregersen [35]. While the term extreme waves often refer to the condition where the wave height achieves or exceeds a certain threshold, normally a percentile (such as 95th or 99th) of the entire wave height record as suggested by Jamous and Marsooli [13]. Liu *et al.,* [16] also suggested that the extreme waves may even threaten human life, besides property security, infrastructure, and marine engineering. According to Hansom *et al.,* [10], the cases of extreme waves would generally occur in the event of tsunami, meteotsunami events or major

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storms at the sea by means of constructive interference of wave trains or by the interaction of non-linear wave. They also suggested that the extreme waves could be further categorized into storm waves, giant waves (or "rogue" waves), tsunami and meteotsunami. In simpler language, the tsunami can be explained as destructive waves consist of a series of long period waves [19].

Since the detailed wave patterns and behavior records of unreported wave events are unavailable, this study focuses only on the publicly reported and recorded extreme wave events on media and academic resources, primarily tsunami across the world. To ease the study, the term extreme wave in this study refers to a wave event exceeding its usual behavior recorded and reported, causing destruction or damage to the local community. This study aims to provide a consolidated view of recent global and regional extreme wave events. It serves as a valuable resource for policymakers, researchers, and engineers involved in coastal zone management. The objective includes are to review and synthesize the current global knowledge on extreme wave events, as well as to identify and highlight the recent occurrences of extreme wave events with significant impacts, particularly in Southeast Asia and Malaysia.

To date, there is a lack of review on extreme wave event globally dated 2024 onwards, while the available research was mainly covering the other topics such as modelling approach in describing such event according to Belmont [3], changes in extreme wave at ocean of certain region, analysis and estimation of wave conditions in coastal area according to Gramcianinov *et al.,* [9], trends of extreme wave event in certain region according to Osinowo [28] and other technical studies. While an updated global review on extreme wave event discussing the extreme wave event, impacts and mechanism is lacking, the study here hence aims to bridge the mentioned gap, to raise the awareness on the extreme wave event for policy maker's reference, for a more effective mitigation.

1.1 Extreme Wave Events in Malaysia

One of a notable and most impactful wave extreme event in Malaysia was the first ever tsunami resulted from the 2004 Indian Ocean Tsunami according to Moon *et al.* [22], which impacted several coastal cities in northern part of Malaysia, including Pulau Langkawi, Penang Island, Kedah, Perak and Selangor, with a maximum wave runup from 3.8 m to 8 m in different cities, causing the destruction of 1535 residential buildings.

Besides the first ever tsunami recorded in Malaysia, some other recent high amplitude wave events were also reported in newspapers. For example, as reported by National Water Research Institute of Malaysia (NAHRIM) [24], the huge wave event in Terengganu from 11 January of 2025 causes a total of 299 victims from 78 families to relocate in the temporary shelter of Pusat Pemindahan Sementara (PPS) in malay. The Stars [34] also reported the huge wave event in January 2025 destroyed the shelter of 23 families in Kuala Terengganu, which involved 80 victims (66 from Kemaman and 14 in Dungun), and the wave heights reached 3.8 m to 4 m at Pantai Geliga and Pantai paka with speeds of 60 km/h. In addition, The New Straight Times [29] also reported that a wave height up to 5.8 m was expected in the September 2024, in northern states of Malaysia including Pulau Pangkor, Kedah and Perak. In December of year 2023, The New Straits Time [25] reported that the Kuala Terengganu also experienced 3 waves of floods due to the high wave events, causing a total victims of less than 10000 recorded by Jabatan Pengurusan Bencana Negeri Terengganu (JPBNT), or the Department of Disaster Management of Terengganu State.

This information directly demonstrates that the coastal zones in Malaysia, particularly the northern regions such as Terengganu, Penang, Langkawi and Kedah are highly vulnerable to the extreme wave event, especially during the monsoon season with higher tide events, where the proper mitigation should be taken.

1.2 Impacts of Extreme Wave Events and Potential Improvement

To study the possible impacts of extreme wave events, particularly the tsunami on the residential buildings in northern regions of Malaysia, Moon *et al.,* [20] conducted a numerical and physical simulation on the impact of tsunami on the roof of residential building, and concluded that under the simulation, an impulsive pressure up to 2.2 times of hydrostatic pressure measured at Pascal exerted on the roof eave of gabled roof, a common roof found in the residential building in northern regions of Malaysia caused by the simulated wave. Their other studies [21] also proven that the maximum impulsive pressures of 10 cm and 35 cm measured in pressure head were recorded under the nominal wave height of 40 mm and 100 mm using the prediction model. This implies a huge destruction force and impacts on the coastal residential buildings from huge waves from technical perspectives. Chua *et al.* [4], on the other hand, simulates the tsunami at Manilla Trench with TUNAMI-12 model to assess the potential damage of tsunami towards the global port network, and concluded that the tsunami may destroys the 11 ports with a wave height from 3.31 m to 11.12 m, with closures up to 200 days and losses exceeding 2 million TEU at key ports. This implies that the port is also vulnerable to extreme wave events, with higher economical loss than the direct economic loss from other infrastructure and residential buildings destruction.

While the impacts of extreme wave events on coastal communities and infrastructure are increasing, recent attention has also turned toward engineering adaptation strategies to mitigate such risks. Structural reinforcement using resilient and environmentally sustainable materials may be an effective approach, particularly for low-lying coastal zones with limited evacuation capacity. From a materials engineering perspective, innovative concrete formulations incorporating nanomaterials have shown potential for improving structural resilience under hydrodynamic forces. For example, Jing *et al.* [15] demonstrated that the addition of multiwalled carbon nanotubes (MWCNTs) into rice husk ash (RHA)-based concrete significantly improved its mechanical properties, reduced porosity, and enhanced chloride ion resistance. Using such enhanced concrete for coastal protection infrastructure such as seawall and revetments might be a promising approach to minimize the impacts from extreme wave events, which prevent the structure from destroyed by the wave due to high loading and forces, while minimizing the permeability.

2. Methodology

A comprehensive review was conducted on the recent tsunami events dated 2018 onwards, which caused notable and significant impacts globally. The primary source of reference comes from the National Oceanic and Atmospheric Administration (NOAA) Center for Tsunami Research, a research institute under the government of United States, and then aided with other official documents released NGOs available online, such as the Asian Disaster Reduction Bodies, World Bank Group and International Federation of Red Cross (IFRC) for the detail impacts. Out of all, 4 most recent and major tsunamis were discussed.

3. Results

In this chapter, the paper would summarize and discuss the findings from different researchers on the types of waves, the mechanisms of extreme waves and summary of extreme wave events.

3.1 Types of Waves

Ocean waves are primarily formed by the wind blowing across the surface of the sea. This wind energy originates from the sun, which heats the Earth's surface unevenly, creating pressure differences that drive air movement. As the wind transfers its energy to the water, it generates waves that are generally irregular and unpredictable. Because of this randomness, ocean waves are often described using statistical methods, such as a wave spectrum that represents the distribution of wave energy across different frequencies and directions, while assuming random phases [30].

Under certain conditions, much larger and more energetic wave often referred to as extreme or freak wave can form. These rare waves typically result from the random combination or focusing of different wave frequencies and directions, creating a temporary concentration of energy. This is more likely to happen during a rough sea state, when overall wave energy is high. As waves move into shallower coastal waters, the decreasing depth causes wave crests to steepen and eventually break due to increased velocity, which can further enhance the formation of extreme waves near the shore [30].

In addition to wind-generated waves, extreme waves can also be caused by geological or atmospheric disturbances. Tectonic activity, underwater volcanic eruptions, coastal landslides, or even impacts from space objects can displace large volumes of water and trigger tsunamis. Although once referred to as tidal waves or seismic sea waves, tsunamis are not caused by tides. Another type of extreme wave, known as a meteotsunami, is generated by sudden changes in atmospheric pressure, such as those caused by fast-moving storm systems. These pressure shifts create large oscillations in the water, similar to seiches, and can produce waves up to 6 meters high. Meteotsunamis can occur in many parts of the world and, despite being localized, have the potential to cause serious coastal damage.

As illustrated in the figure 1 below, the impacts of extreme waves can range from minor beach and dune erosion or overwash to the complete devastation of coastal villages due to widespread erosion and flooding. The remains of a fishing village near Tacloban, Phillipines after a 5 m typhoon-produced storm surge in November 2013 killed more than 6,000 people and destroyed more than 100,000 dwellings. Much of the damage at the coast was done by extreme waves and the storm surge [10].

Fig. 1. The impacts of extreme waves illustrated near Tacloban, Phillipines [10]

3.1.1 Mechanism of extreme waves

Modulational instability is a nonlinear process where energy in a uniform wave train spontaneously concentrates into one or more large waves due to small perturbations, often described by the nonlinear Schrödinger equation. These instabilities amplify wave heights exponentially, especially in deep water, forming rogue waves without external interference [14]. This occurs because the interaction of wave components leads to energy transfer from surrounding waves into a single dominant wave. The best-documented example is the Draupner wave, recorded on January 1, 1995, off the coast of Norway in the North Sea. This event was the first to be confirmed by instruments and matched predictions from nonlinear theory. Regions with deep waters and long, persistent swell patterns like the North Atlantic, Norwegian Sea, and Gulf of Alaska are prone to such phenomena.

Constructive interference occurs when wave systems from different sources converge and align in phase, causing their amplitudes to add up momentarily and form a much larger wave. This linear process can occur even in relatively calm seas and is governed by the principles of superposition [36]. It happens because multiple wave trains traveling in different directions can unpredictably reinforce each other when their crests coincide. The Ekofisk platform in the North Sea recorded a rogue wave in 2007 believed to be caused by this mechanism. Although less predictable than nonlinear focusing, constructive interference can produce waves just as dangerous. Regions such as the Bay of Biscay, South China Sea, and coastal Chile are common zones due to frequent interaction of overlapping swell systems.

When ocean waves encounter strong opposing currents, their wavelengths shorten and heights increase due to compression of wave energy. This can create very steep and unstable waves capable of reaching rogue wave status [38]. The opposing current slows down the front of the wave, forcing it to steepen and rise vertically, increasing the likelihood of wave breaking. A prominent example is the rogue wave encountered by the Esso Languedoc supertanker in 1980, which occurred in the Agulhas Current off South Africa. This region remains one of the most notorious hotspots for rogue wave formation due to its persistent and fast northward-flowing currents opposing Southern Ocean swells. Other high-risk zones include the Kuroshio Current (Japan) and the Brazil Current.

Figure 2 below was taken by first mate Philippe Lijour aboard the supertanker Esso Languedoc, during a storm off Durban in South Africa in 1980. The wave approached the ship from behind before breaking over the deck, but in this case caused only minor damage. The mast seen starboard in the photo stands 25 metres above mean sea level. The mean wave height at the time was between 5-10 meters [37].

Fig. 2. supertanker Esso Languedoc [37]

Bathymetric focusing occurs when underwater terrain such as seamounts, ridges, or continental shelves refract and concentrate wave energy into a smaller area, significantly amplifying wave heights. This mechanism is similar to how a lens focuses light. The refraction caused by abrupt changes in seafloor depth bends wave fronts inward, allowing them to converge and stack in height [17]. One well-known incident involves the Queen Mary 2, which was struck by a 29-meter wave in the North Atlantic—likely intensified by nearby underwater topographic features. Similar bathymetric conditions exist off New Zealand's Kaikōura Canyon, Monterey Bay (USA), and Indonesia's Lombok Strait, all of which are prone to focusing wave energy through seabed-induced convergence.

Wave shoaling is a coastal phenomenon where waves slow down and increase in height as they move from deeper to shallower water, often leading to wave steepening and breaking. While typically associated with tsunamis, storm-driven wave shoaling can also cause rogue waves close to shore. The energy of the wave is compressed into a smaller vertical space as the bottom rises, causing it to grow in height and sometimes break violently [5]. The 2004 Indian Ocean tsunami highlighted how shoaling can amplify wave energy dramatically near coastal areas. Shoaling-related rogue waves are more likely along coasts with sharp bathymetric gradients such as Valparaíso (Chile), Izu Peninsula (Japan), and Liguria (Italy).

Atmospheric forcing occurs when abrupt meteorological phenomena such as squalls, storms, or pressure drop generate additional energy on the sea surface, creating high waves. This can lead to "meteotsunamis" or rogue waves in both offshore and coastal areas. Wind gusts or sudden drops in barometric pressure apply uneven forces on the sea surface, causing rapid displacement and abnormal wave growth [18]. A classic case is the Queen Elizabeth 2, which encountered a 29-meter rogue wave in the North Atlantic during Hurricane Luis in 1995. Storm-prone regions like the Bay of Bengal, Western Australia, and the Northwest Atlantic off Canada and the US are especially vulnerable to this mechanism.

Figure 3 below shows the formidable sea state associated with such events, illustrating the severe threat rogue waves pose to maritime safety. These extreme, unexpectedly large waves can arise even in the presence of well-forecasted weather systems, challenging conventional wave prediction models and emphasizing the need for continued research into their formation mechanisms and potential impacts on vessels and offshore infrastructure [27].

Fig. 3. Big waves in the North Atlantic [27]

Table 1 below summarizes the six primary mechanisms responsible for the formation of extreme or rogue waves. Each mechanism is associated with specific oceanographic or meteorological conditions that trigger the amplification of wave height beyond normal expectations. The table highlights the key conditions for each mechanism, such as modulational instability, wave–current interactions, or atmospheric pressure disturbances. Additionally, it identifies high-risk regions and countries where these mechanisms are most likely to occur based on historical events and scientific literature. This summary helps contextualize where and why extreme waves are more likely to develop, offering insights critical for maritime safety, coastal management, and further research.

Table 1
Summary of rogue wave generation mechanisms, key conditions, and high-risk regions

Mechanism	Key Conditions / Triggers	High-Risk Countries / Regions
Nonlinear Wave Interaction	Modulational instability due to narrow-banded, long-crested wave trains in deep water	Norway, North Atlantic Ocean, Norwegian Sea, Gulf of Alaska
Constructive Interference	Random superposition of waves or crossing sea states	North Sea, Bay of Biscay, South China Sea, coastal Chile
Wave–Current Interaction	Opposing strong ocean currents with incoming waves, causing steepening and energy focusing	South Africa (Agulhas Current), Japan (Kuroshio Current), Brazil (Brazil Current)
Bathymetric Focusing	Seafloor features like canyons or ridges that concentrate wave energy	New Zealand (Kaikōura Canyon), USA (Monterey Bay), Indonesia (Lombok Strait), North Atlantic (QM2)
Wave Shoaling	Rapid depth change causing wave height increase near shore	Indonesia, Japan (Izu Peninsula), Italy (Liguria), Chile (Valparaíso)
Atmospheric Forcing	Sudden pressure changes, squall lines, or atmospheric gravity waves (meteotsunamis)	North Atlantic (Hurricane Luis), Bay of Bengal, Western Australia, Mediterranean, US East Coast

3.2 Summary of Extreme Wave Events

Table 2 below summarizes the recent tsunamis from the year 2018 up to August 2024, with their respective triggered Moment Magnitude, recorded NOAA, Center for Tsunami Research. From table 1, the most recent tsunami event happened on the Hyuganada Sea (Japan) on 8th August of 2024 was induced by an earthquake with moment magnitude of Mw 7.1, caused total casualty of 16 people (3 persons seriously injured and 13 people slightly injured), with 79 total destroyed houses (1 totally destroyed, 2 half destroyed and 77 partially damaged houses) according to the Japan Cabinet Office (2024) written in Japanese, and English translation provided by Asian Disaster Reduction Center [2].The earthquake of 7.1 on the Richter scale at a depth of 31 kilometers also resulted in extensive disruption to transport and infrastructure networks. The operation of high-speed rail lines, including the Kyushu and Nishi Kyushu Shinkansen lines, was temporarily suspended, and ferry services from Kobe to Miyazaki were suspended [31].

On the other hand, the second most recent tsunami mentioned in the Table 2 occurred in Taiwan on 2nd April 2024 [26]. The tsunami generated by the Mw 7.4 earthquake off Hualien, generated visible but comparatively modest effects compared to the greater seismic event. Coastal tide gauges at the port of Hualien recorded waves of up to 72 cm at Hualien port, with the sea level falling approximately 1.3 m before the arrival of the peak wave 30 minutes following the quake. Economic analysis according to National Centers for Environmental Information [23] suggests tsunami-specific losses were insignificant relative to total earthquake losses. Most of the around US $2.5 million worth of agricultural losses—primarily to fisheries and livestock—resulted from ground shaking and not from flooding due to tsunamis.

Another notable tsunami event on the list, which is the tsunami occurred at the central Sulawesi of Indonesia on 28th September of 2018, which led to more than 4400 fatalities affected around 170000 people and economic loss of more than 1.3 US billion dollars according to the Global Facility for Disaster Reduction and Recovery [8]. The economic impact extended even to the physical damages. The National Disaster Mitigation Agency (BNPB) [1] estimated overall damages and losses at some Rp15.29 trillion (approximately US$1.07 billion), with the residential sector bearing the brunt.

The January 15, 2022, Hunga Tonga–Hunga Ha'apai volcano eruption and the subsequent tsunami had a major impact on Tonga, with the World Bank [39] placing the damage at approximately US$90.4 million, or roughly 18.5% of the nation's GDP. Infrastructure suffered estimated damages of US$20.9 million in the form of roads, causeways, power and water supply, ports, and the submarine cable for communication. The agricultural sector was considerably affected, with 85% of farming households experiencing some form of impact, leading to estimated damages of US$20.9 million due to crop damage and destruction of shallow reef fisheries. The devastation included approximately 600 buildings, with a minimum of 300 residential ones, incurring severe impact to the tourism industry with high damage to accommodation, wharves, and workers' houses [6]. Ashfall cleanup expenses were estimated at approximately US$5 million for buildings and paved road facilities. The event affected approximately 85,000 people across Tonga, highlighting the extensive human and economic toll of this disaster [33].

Table 2
Recent tsunami events from 2018 [27]

Date	Area	Moment Magnitude (Mw)
Aug. 8, 2024	Hyuganada Sea, Japan (Kyushu)	7.1
Apr. 2, 2024	Hualien, Taiwan	7.4
Sep. 19, 2022	Aquila, Mexico	7.6
Jan. 15, 2022	Hunga Tonga-Hunga Haʻapa (volcano)	-
Aug. 12, 2021	South Sandwich Islands	8.1
Jul. 29, 2021	Perryville, Alaska	8.2
Mar. 4, 2021	Kermadec Islands	8.1
Feb. 10, 2020	Loyalty Islands	7.7
Oct. 19, 2020	Sand Point, Alaska	7.6
Jul. 22, 2020	Alaska Peninsula	7.8
Jun. 23, 2020	Oaxaca, Mexico	7.4
Mar. 25, 2020	Kuril Islands	7.5
Jun. 15, 2019	Kermadec	7.2
Sep. 28, 2018	Sulawesi	7.5
Jan. 23, 2018	Kodiak, Alaska	7.9

Another tsunami occurred at Sunda Straits affecting Indonesia which is not on the list above, occurred on 22nd December 2018. From the emergency plan of action final report issued by International Federation of Red Cross (IFRC) in year 2021 [12], the report mentioned that more than 1600 houses were destroyed severely, more than 600 houses were medium to lightly damaged and more than 16000 people were displaced, with more than 400 people killed and 14000 people injured. The report also provided the table of affected population in the disaster, as in Table 3. It is reported by The Jakarta Post [32] mentioned that 882 houses, 73 villas and hotels, 60 restaurants, and 434 yachts were burnt or damaged. The tourism industry, a significant one in the affected regions, was badly affected.

Table 3
Affected population from the tsunami at Sunda Straits [12]

Province	Deaths	Injured	Missing
Banten	288	10051	8
Lampung	122	5729	6
Total	410	15780	14

Finally, Imamura *et al.,* [11] summarised that the tsunamis from 1998 to 2017 resulted in a total of 251,770 casualties and an economic loss of 280 billion USD, signifying the socioeconomical impacts of extreme wave events.

4. Conclusions

Extreme wave events pose significant threats to coastal regions worldwide, with Southeast Asia and Malaysia being notably vulnerable due to their extensive coastlines and exposure to climatic disturbances. This review has highlighted the nature and causes of extreme wave events, summarized recent global and regional occurrences, and examined their physical, social, and economic impacts. In particular, the northern coastal regions of Malaysia, such as Terengganu and Penang, have been repeatedly affected by high wave activity, necessitating urgent attention to coastal risk management. Beyond documenting historical impacts, this study also emphasizes the importance of adopting forward-looking engineering strategies to mitigate future risks. Advancements in materials science, such as the development of sustainable concrete offer promising directions for enhancing the resilience of coastal infrastructure. By integrating hazard forecasting, structural adaptation, and sustainable construction technologies, a holistic approach can be achieved to reduce vulnerability and strengthen preparedness against future extreme wave events.

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