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REVIEW

General Review of the Worldwide Tsunami Research

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Abstract

With the advancement of the global economy, the coastal region has become heavily developed and densely populated and suffers significant damage potential considering various natural disasters, including tsunamis, as indicated by several catastrophic tsunami disasters in the 21st century. This study reviews the up-to-date tsunami research from two different viewpoints: tsunamis caused by different generation mechanisms and tsunami research applying different research approaches. For the first issue, earthquake-induced, landslide-induced, volcano eruption-induced, and meteorological tsunamis are individually reviewed, and the characteristics of each tsunami research are specified. Regarding the second issue, tsunami research using post-tsunami field surveys, numerical simulations, and laboratory experiments are discussed individually. Research outcomes from each approach are then summarized. With the extending and deepening of the understanding of tsunamis and their inherent physical insights, highly effective and precise tsunami early warning systems and countermeasures are expected for the relevant disaster protection and mitigation efforts in the coastal region.

Keywords Earthquake induced tsunami; Landslide induced tsunami; Volcano eruption induced tsunami; Meteorological tsunami; Post-tsunami field survey; Numerical modeling; Laboratory experiment

1 Introduction

With the increase in economic activities and population in the coastal region worldwide, the demand for the prevention and mitigation of tsunamis has dramatically increased, especially considering the relatively high frequent occurrence of global tsunamis in the last two decades. With the development of various research approaches, researchers are always on the way to a superior understanding of the generation, propagation, and inundation processes of tsunamis.

Article Highlights

- Characteristics of the tsunamis induced by four different mechanisms are individually specified.
- Tsunami research from three different approaches is comprehensively reviewed and summarized.
- From the direct post-tsunami field survey to the complicated numerical and physical models, understanding of tsunami's sophisticated mechanism is gradually extended.
- Great research efforts with interdisciplinary cooperation is appealed for the tsunamis simultaneously triggered by multiple sources.

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Developed from the traditional single intuitive analysis, the acknowledgment of the causes and characteristics of tsunamis has currently turned into an interdisciplinary study with composite mechanisms. This phenomenon is ascribed to the emergence of multi-research approaches and relevant supporting technologies. Tsunamis were often previously studied as secondary disasters after earthquakes or volcanic eruptions. Assumptions indicate that the tectonic movement of the earth's crust is the direct source of tsunamis (e.g., earthquakes and volcano eruptions). The achievement of information relies on the field survey and survivor interviews, which turns out to be the text description and rough data-based characteristic records of tsunamis. With the recent gradual maturity of post-disaster survey techniques, computer-based numerical simulation models, and the completeness of the worldwide stereoscopic measure station network, the complete tsunami wave sequence and the corresponding information can be extensively recorded. Therefore, the effective information embedded in various data can be fully mined through field surveys (Liu et al. 2005; Mori et al. 2011), numerical simulations (Titov et al. 2005; Shimozono et al. 2012), laboratory experiments

(Yeh et al. 1994; Liu et al. 2014), statistical analysis (Zhang and Niu 2020; Gao et al. 2022), and theoretical analysis (Deng et al. 2016; Cheng and Liu 2020; Cheng and Liu 2023; Zeng and Liu 2022). These tsunami studies gradually extend our understanding of the physical insights of tsunamis, which helps establish effective countermeasures against this natural disaster.

A general review of the existing tsunami studies is created in this paper from a twofold viewpoint: tsunami with different generation mechanisms and tsunami research using different research approaches. The paper is organized as follows. Section 2 reviews the tsunamis induced by earthquakes, landslides, volcano eruptions, and meteorological events. Among these events, earthquake or meteorological event-induced tsunamis can lead to transoceanic damages, while landslide or volcano eruption-induced tsunamis generally result in local disasters. Section 3 further discusses various tsunami research approaches, including post-tsunami field surveys, numerical simulations, and laboratory experiments. Section 4 finally provides a brief conclusion.

2 Tsunamis with different generation mechanisms

2.1 Earthquake-induced tsunami

An offshore earthquake with sea floor displacement is regarded as the most common cause of enormous transoceanic tsunamis (Figure 1), which generally lead to catastrophic damages and loss of human lives. Such destructive tsunamis can be dated back to the Jougan/Keicho earthquake and tsunami in 869/1611 in Japan (Minoura et al. 2001) and the Lisbon earthquake tsunami in 1755 (the largest tsunami directly encountered in Europe (Zitellini et al. 2001)). These events provide an example for researchers to understand the tsunami phenomenon preliminarily. In the modern period, the 1960 Chilean tsunami, induced by a great Mw 9.5 earthquake off the Chilean coast (the largest earthquake ever instrumentally recorded), even hit the Pacific coast of Japan approximately 22 h after the earthquake, causing unexpected far-field damages. The 2004 Sumatra tsunami resulted in considerable fatalities around the Indian Ocean coast. The 2011 Tohoku tsunami led to serious infrastructure damage and impacted coastal communities despite the leading role of Japan in implementing tsunami mitigation measures, which even caused iceberg calving in Antarctica (Brunt et al. 2011). The rupture fault (coseismic tsunami source area) of the subduction zone tsunami is generally remarkably large on the order of several hundred kilometers (Kato et al. 2012), which can even reach 1600 km for the 2004 Sumatra earthquake/tsunami (the longest rupture fault till now (Nalbant et al. 2005)). As indicated in Figure 1, the significant movement of the seabed rupture fault (generally occurring within several minutes), especially in the vertical direction, could trigger the displacement of the quiescent water body above the seabed, thus initiating the outward propagation of the tsunami movement.

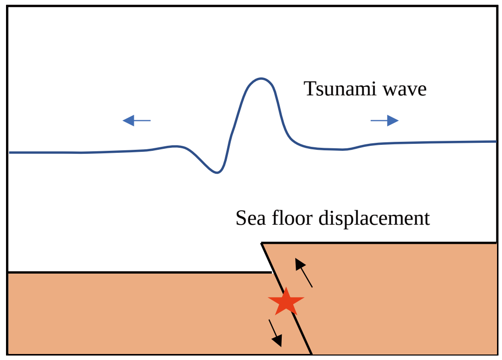


Figure 1 Sketch of the earthquake-induced tsunami

In the nearshore area, the early warning signal of the incoming tsunami could come from the ground shaking, the abnormal ebb tide (the coastline rapidly recedes, exposing a wide area of the seafloor), and unusual noises (Gregg et al. 2006). When this type of tsunami approaches the coastal region, the tsunami wave height could rapidly and significantly increase due to the wave shoaling from the gradually shallow bathymetry and the negligible offshore wave steepness, forming a high water wall with a fast propagation velocity (around 10 m/s (Fritz et al. 2012)) and resulting in a tremendous momentum if impacting on the coastal structures. Catastrophic damages to coastal infrastructures and human societies occur after the inundation of the land. Earthquake-induced tsunamis occur right after the earthquake, under which coastal infrastructures have generally become fragile after the high-frequency ground shaking by the earthquake, thus weakening the protecting function of structures. Simultaneously, other concomitant disasters, such as land subsidence (Meilianda et al. 2010), liquefaction (Yulianto et al. 2020), and fire (Onozato et al. 2016), could also further deteriorate the aftermaths of the earthquake and tsunami.

The study of the earthquake-induced tsunami gradually accelerated since the 1960s and became increasingly popular after the 1990s with the abrupt surge in the relevant literature (Cheng et al. 2020). Studies on past tsunami events generally rely on sporadic written records (Lau et al. 2010) as well as on the analysis of tsunami deposits from the geological viewpoint (Ishimura and Miyauchi 2015). With the development of the network for seismological observation (on the land (GEONET) (Ozawa et al. 2011), and even in the sea (SGOS) (Sato et al. 2011)), various first-hand earthquake information could be accurately recorded, which facilitates the deep understanding of the subsequent tsunami generation and propagation. With the global deployment of a large number of offshore DART buoys and the installation of nearshore tidal gauge stations updated after the 2004 Sumatra tsunami, real-time offshore and nearshore tsunami wave characteristics could be recorded; these characteristics are valuable for the prevention and mitigation efforts in the coastal region.

The study of the earthquake-induced tsunami generally focuses on the following three main themes: tsunami generation, propagation, and inundation. For tsunami generation, the waveforms recorded in buoys and tide gauges contain information concerning the spatial and temporal distributions of the fault slip (Satake et al. 2013), which could be used to inverse the tsunami source parameters (Fujii et al. 2011). The initial gradual rise in the water level is associated with large slips at the deep plate interface. Meanwhile, the delayed huge slip with dynamic overshoot is responsible for the generation of the enormous impulsive wave in the 2011 Tohoku tsunami, causing unexpected disasters in the coastal region (Ide et al. 2011). In addition, the inelastic deformation of unconsolidated sediments and a coseismic slip on splay faults (Hossen et al. 2015) and the effects of the horizontal displacement of the seafloor (Gusman et al. 2012), the trench slope (MacInnes et al. 2013), and the strike-slip earthquake (sloshing effect) (Elbanna et al. 2021; Han et al. 2021) could be possible candidates for tsunami generation.

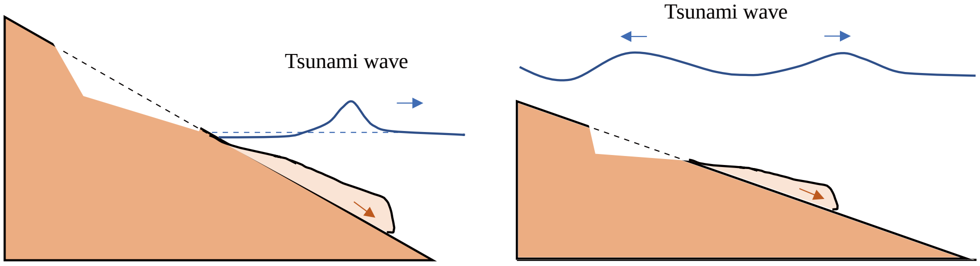
Regarding tsunami propagation, various factors could affect the tsunami wave properties, such as ocean ridges, which may guide the tsunami propagation (Wang et al. 2021). Furthermore, Kowalik and Murty (1989) indicated that the Coriolis force has minimal influence on small period waves, whereas the tsunami wave along the shelf with a long period is likely to be modified by the Coriolis force. Nevertheless, the Coriolis force mainly influences the wave height and not the traveling time (Shuto 1991). In addition, astronomic tides may affect tsunami dynamics, leading to the amplification of tsunami height due to the nonlinear interaction between tide and tsunami in the coastal region (Myers and Baptista 2001).

Considering the tsunami inundation over the land region, one of the fundamental subjects of tsunami research is disaster prevention and mitigation, in which a tsunami hazard map is generally required for the tsunami risk assessment (Horspool et al. 2014). Such a tsunami hazard map not only depends on the incoming tsunami characteristics (e.g., water depth and flow velocity) but also on the detailed local topography feature and building configuration, as well as many human-related factors (local population density, accessibility to the evaluation route, and age distribution of the society) and community-related factors (industry layout, city planning). Protection of the landward buildings provided by the seaward front buildings was confirmed in different places during the 2011 Tohoku tsunami field survey (Liu et al. 2013; Yeh et al. 2013). Probabilistic hazard assessments are a fundamental tool for assessing the threats posed by hazards to societies and are important for underpinning evidence-based decision making regarding risk mitigation activities. Efficient rescue operations and reasonable evaluation planning could be achieved by applying the pre-assessed tsunami hazard map.

2.2 Landslide-induced tsunami

A landslide tsunami is defined as a tsunami caused by subaerial or submarine mass failure, as shown in Figures 2(a) and 2(b), respectively. Landslide-induced tsunamis are rare considering the statistical results of tsunami database (Cheng et al. 2020) and are also thought to be markedly localized and of lower energy than earthquake-induced tsunamis; however, recent studies reveal that such tsunamis could also produce destructive tsunami waves (McMurthy et al. 2004). The coseismic source area is considerably larger than those caused by landslides; however, landslides may generate substantially high local tsunamis. For instance, the 1958 Lituya Bay megatsunami caused a tsunami runup height of more than 524 m, which is the highest record height ever (Fritz et al. 2009b). Even in the inland area, landslides may lead to damage to the opposite side of the reservoirs or rivers. For instance, a significant landslide occurred in Daning River, Chongqing, China, in 2015, which induced a 6 m high bore and caused casualties and overturning of many ships.

Quantifying the size and return period of various landslides is still challenging (Geist and Lynett 2014). In many cases, landslides are regarded as the additional tsunami



(a) Subaerial failure (b) Submarine failure

Figure 2 Sketch of the landslide-induced tsunamis source to the primary source of vertical displacement of the seafloor induced by an earthquake (further intensification of the nearshore tsunami height); thus, landslide-induced tsunamis have currently gradually attracted the attention of researchers. Tappin et al. (2014) indicated that if the Tohoku tsunami is entirely ascribed to slipping on an earthquake fault, some discrepancies still exist between the published model and recorded data (e.g., the observed run-up heights of up to 40 m measured along the Sanriku coast, the timing and high-frequency content of tsunami recorded at nearshore buoys, and the biases of rupture centroids). Accordingly, they argued that submarine landslides should also be considered. During the 2018 Sulawesi tsunami, a destructive tsunami reached Pula city within a few minutes after the collapse of landslides close to the coastal areas (Nagai et al. 2021). Takagi et al. (2019) argued that any modern early warning system is unlikely to work effectively against such short-warning time tsunamis. Thus, considering a way to help quickly increase the awareness of local residents of the potential disaster and evacuate them from the landslides is necessary for disaster risk managers. Considering the South China Sea region, giant submarine landslides on the continental shelves (e.g., Brunei and Baiyun submarine slides) are also deemed as hitherto fundamentally unquantified tsunami threats (Terry et al. 2017; Li et al. 2022), on which various studies have been conducted (Ren et al. 2019).

2.3 Volcano eruption-induced tsunami

During the eruption of underwater or coastal volcanos, part of the released energy could be directly or indirectly transmitted to the sea, leading to the generation of tsunamis. Volcanic tsunamis are popular around the Pacific rim of the volcanic zone, especially in Southeast Asia (Indonesia, Philippines, and Papua New Guinea), representing around 5% of all tsunamis listed for the last four centuries (Latter 1981). The direct disasters caused by the submarine volcanic eruption are often small, ascribed to its location in the deep ocean and the rare surrounding residents. However, the consequences of these disasters could be significant once it triggers a tsunami. The 1883 Krakatoa tsunami, which is the largest historical tsunami due to volcanic activities, was caused by the eruption of Krakatoa, a submarine volcano located in Indonesia. The pyroclastic flows from this eruption reached the sea, and the triggered tsunami wave ran up to 41 m, leading to 36000 fatalities (Simkin and Fiske 1983). Ward and Day (2001) argued that with the eruption of the Cumbre Vieja volcano, a huge amount of rock could drop into the sea, triggering tsunamis transiting the entire Atlantic Basin and then arriving at the US coasts with 10–25 m in height.

Various mechanisms are implied in the generation of volcanic tsunamis, as demonstrated in Figure 3. Except for Figure 3(b), other subfigures of Figure 3, though with different scenarios, are consistent with the tsunami formation of water displacement. The most destructive are those generated by the impacts of pyroclastic flow deposits into the sea (Figure 3(c)) as well as volcanic-triggered landslides (similar to the mechanisms shown in Figure 2). Therefore, volcano eruption-induced tsunamis are frequently associated with landslide-induced tsunamis (which could also be triggered by the earthquake). On the contrary to caldera collapse (Figure 3(d)), caldera uplift associated with volcanic

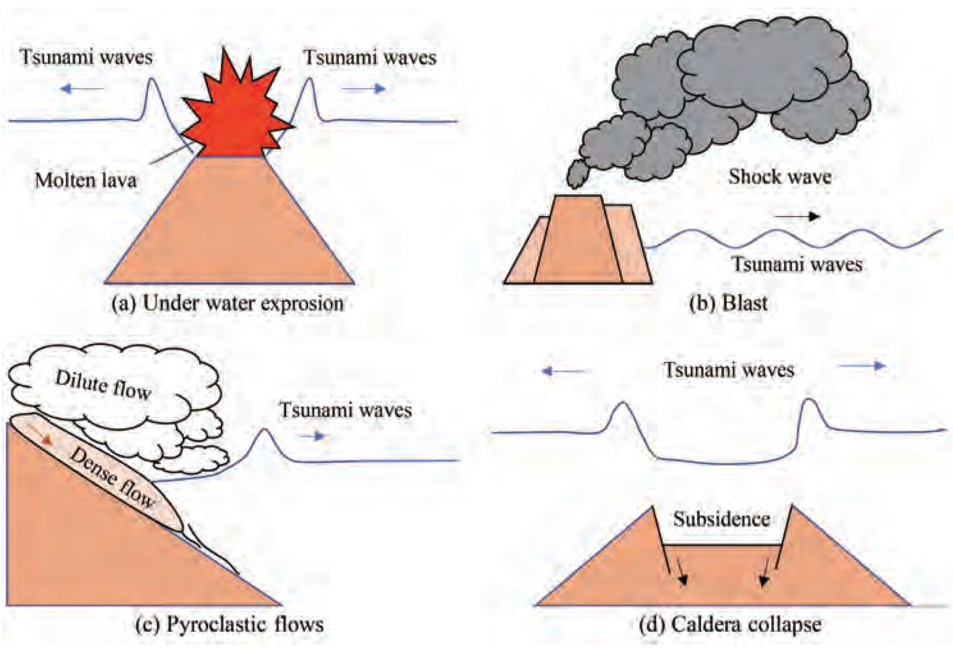


Figure 3 Typical causes of the volcano eruption-induced tsunamis (similar to Paris et al. (2014))

activities can be regarded as another generation mechanism for volcanic tsunamis, as evidenced during the 2015 Torishima volcanic tsunami, Japan (Sandanbata et al. 2018).

The precise nature and dynamics of the interactions and processes that generate waves during volcano eruptions are slightly understood. Nevertheless, with the recent re-eruption of the Anak Krakatau volcano and accompanying tsunamis from flank collapse in 2018, volcano eruption-induced tsunamis attracted significant attention among researchers. The 2018 Anak Krakatau volcano flank collapse involved a relatively small slide volume (<0.2 km^3) but produced a deadly tsunami affecting local coastlines due to the lack of warning (Ye et al. 2020). The post-event field survey confirmed that the maximum tsunami run-up height is 13.5 m and the maximum inundation distance is 330 m with a short tsunami period nature of 6.6–7.4 min (Muhari et al. 2019).

2.4 Meteorological tsunami

The meteorological tsunami, also known as "meteotsunamis," is caused by a sharp change in the atmospheric pressure, that is, the atmospheric pressure disturbance, which is related to various meteorological events (e.g., tropical cyclones (Niu and Zhou 2015; Zhang and Liu 2021)). For a static case, the pressure drop of 1 hPa leads to an elevated water surface of approximately 1 cm, while a moving low-pressure system could cause a substantially large water level rise and a considerably complex wave pattern (Niu and Chen 2020; Zhang and Liu 2022). Previously, the meteotsunami was an underrated hazard (Pattiaratchi and Wijeratne 2015). By contrast, Vilibić et al. (2021) confirmed that the occurrence rate of meteotsunamis has strongly increased in recent years. The eruption of the 2022 Hunga-Tonga volcano significantly raised the interest of researchers in the meteorological tsunami, which is a typical example of the volcanic meteorological source of the tsunami, as shown in Figure 3(b).

On Jan. 15, 2022, the eruption of the Hunga-Tonga volcano generated a violent underwater explosion, created atmospheric pressure disturbances spreading out in the form of Lamb waves detected in in-situ observations all over the globe (Amores et al. 2022), which could even be tracked for more than a week while they propagated five times around the earth (Otsuka 2022). Fast-moving atmospheric Lamb waves are confirmed to drive the uniformly small leading tsunami waves (Kataoka et al. 2022; Yamada et al. 2022), which arrived earlier than theoretically expected for a tsunami wave freely propagating away from the volcano (Carvajal et al. 2022). Kubota et al. (2022) confirmed that the scattering of the leading waves related to bathymetric variations in the Pacific Ocean produced subsequent long-lasting tsunamis, and various waves generated from moving and static sources increase the complexity and lengthen the duration of tsunamis compared with ordinary earthquake-induced tsunamis.

Section 2 reviews global tsunamis considering their genetic sources. The complexity of the tsunami research lies in the accompanying superposition of multiple generation mechanisms in different temporal and spatial sequences during the occurrence of a tsunami event. For instance, the generation of the 2022 Tonga tsunamis comes from the superposition of volcano eruption, landslide, and meteorological Lamb waves. The sources of some tsunami events are still under debate despite extensive studies. For example, Choi et al. (2003) claimed that the 1883 Krakatau tsunamis were volcanic meteorological tsunamis, while Maeno and Imamura (2011) argued that they were induced by a large volume of pyroclastic flow with a certain discharge rate. Therefore, the tsunami research still needs further investigation.

3 Tsunami research approaches

3.1 Post-tsunami field survey

Post-tsunami field survey is a fundamental tsunami research approach used to obtain crucial and first-hand scientific data on the relevant tsunami event. In the past, the tsunami information relied on the interviews of survivors recorded in some historical documents (e.g., drawings and paintings) to restore the previous scenarios. Since the late 1800s, post-tsunami surveys started to collect relevant data by immediately locating the impacted areas after the disaster, and these surveys are characterized by the systematic measurement and reporting of wave heights (Bourgeois 2009). For example, detailed tsunami height records are available for the 1896 Meiji earthquake and tsunami along the Sanriku region, Japan, a tsunami-prone region (Liu et al. 2013).

The establishment of the International Tsunami Survey Team after the 1992 Nicaragua tsunami promotes the standardization of post-tsunami field survey methodology with international and interdisciplinary collaboration (Satake et al. 1993). Tsunami traces, such as watermarks on buildings and windows, debris lines on the beach or roof, and changes in vegetation color, could only be retained within a limited period after the tsunami event; therefore, a post-event field survey must first be conducted after tsunamis and other similar disasters, such as storm surges (Fritz et al. 2009a). In such a survey, the inundation and run-up heights are generally measured by laser, GPS, and other instruments with tidal correction. Figure 4 shows typical definitions of different tsunami hydrodynamic terminologies, including the tsunami height, flow depth (inundation depth), inundation height, run-up height, and inundation distance.

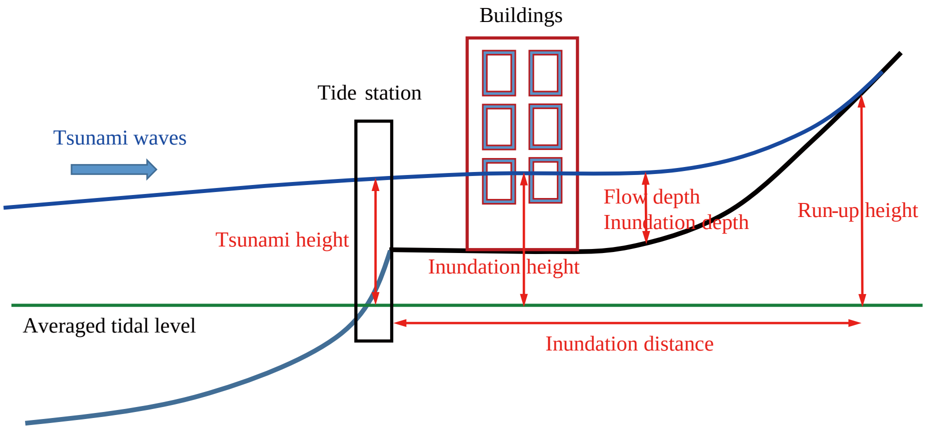


Figure 4 Definition of different tsunami hydrodynamic data terminologies (similar to IOC-UNESCO (1998))

After the 2004 Indian Ocean tsunami, different survey teams conducted post-tsunami data collections all around the Indian Ocean coasts, including Sumatra and Banda Aceh (the most damaged areas near the epicenter (Borrero 2005)), Thailand (Siripong 2006), India (Yeh et al. 2006), Sri Lanka (Liu et al. 2005), and even in Oman (Okal et al. 2006) and Somalia (Fritz and Borrero 2006). Regarding the 2011 Tohoku tsunami, approximately 300 researchers from throughout Japan participated in the post-tsunami survey, and the joint research groups conducted a tsunami survey along a 2000 km stretch of the Japanese coast (Mori et al. 2012). More than 5200 locations have been surveyed, even within the 30 km restricted zone of the Fukushima nuclear power plant, generating the largest tsunami survey dataset in the world (publicly available athttps://coastal.jp/tsunami2011/). This survey revealed that maximum run-up heights larger than 10 m are distributed along 500 km of the Japanese coast in direct distance.

3.2 Numerical modeling

Today, numerical simulation has become a powerful approach for tsunami research, playing significant roles in real-time forecasting and warnings as well as hazard assessment. The depth-integrated linear shallow water equation (LSWE) is generally used as the governing equation, and the finite difference method is used for the numerical scheme to simulate the transoceanic propagation of tsunami waves timely for tsunami early warning. Nevertheless, the application of the nonlinear shallow water equation (NLSWE) is necessary to simulate the local tsunami propagation in the nearshore area as well as its inundation over the land accurately. Table 1 lists four globally used tsunami numerical models. The characteristics and applications of these models are also specified. Sugawara (2021) established a detailed review of the numerical modeling of tsunamis. Two different approaches are introduced to solve the frequency dispersion in the numerical simulation. The first approach is based on the LSWE/NLSWE but utilizes the numerical errors (i.e., numerical dispersion) by carefully selecting the spatial and temporal grid sizes (e.g., Burwell et al. 2007; Wang 2009). The second approach aims to implement the Boussinesq equation with iterative calculations of the large matrix to solve its dispersive term (Sato 1996; Fuhrman and Madsen 2009; Grilli et al. 2019). In addition, the Green–Naghdi equations are applied to earthquake-induced and underwater landslide-induced tsunamis (Zhao et al. 2011; Duan and Zhao 2013). Using the Navier–Stokes equations, Ai et al. (2021) established a three-dimensional non-hydrostatic model for submarine landslide-induced tsunami wave simulation. Simulation of the tsunami propagation and inundation process has generally reached a satisfactory stage, while further improvement of the numerical modeling is limited by the relatively unsatisfactory estimation of the tsunami source parameters, which determine the initial conditions of the numerical simulation. Different from the aforementioned deterministic numerical simulations, probabilistic tsunami hazard assessment (PTHA) is a fundamental tool for assessing the threats posed by hazards to communities. PTHA, which introduces the methods of probability and statistics and considers the uncertainty of related parameters (e.g., possible tsunami-genic sources, uncertainties of model inputs, and parameters in systematic ways of formulations) as much as possible to describe the return period of tsunami events, is an important method for underpinning evidence-based decision making considering risk mitigation activities (Horspool et al. 2014). For example, Geist and Parsons (2006) developed the relationship between tsunami size and exceedance probabilities for a given location and period. With 1380000 potential earthquake scenarios, Gao et al. (2022) conducted the PTHA for the coast around the Pearl River estuary and assessed the tsunami hazards posed by the earthquakes along the Manila Trench. Accordingly, PTHA could be a powerful approach to tsunami risk management and disaster mitigation.

Table 1 Four typical tsunami numerical models

Models	Reference	Characteristics	Main Applications	Additions
TSUNAMI	Goto et al. (1997)	SWE solved in leapfrog schemes	Tsunami simulation; real-time forecasting and warning	Versions: N2/N3/F1/F2
MOST	Titov and Gonzalez. (1997)	SWE in the spherical coordinate system to consider the earth curvature and Coriolis force	Simulation of the tsunami generation, propagation, and inundation process	Standard tsunami model for NCTR in the USA
COMCOT	Liu et al. (1998)	SWE in the spherical and Cartesian coordinate solved with the multinested grid system	Tsunami simulations in deep-water, nearshore coastal regions, and inundation	Latest version: 1.7
GEOCLAW	LeVeque and George (2008)	Application of Clawpack model in tsunami with the adaptive mesh encryption system	Simulation of the detailed wave fission due to the allowance of the discontinuities	High numerical efficiency

3.3 Laboratory experiment

Several experimental studies have been conducted on tsunamis. In these studies, different wave shapes have been applied to represent the tsunami hydrodynamics, such as solitary wave (breaking or nonbreaking (Synolakis 1987; Li and Raichlen 2001)), trough-led N-wave (Goseberg et al. 2013; Schimmels et al. 2016), and dam–break wave (Lauber and Hager 1998; Wuthrich et al. 2018). Such experimental studies help reveal the tsunami hydrodynamic characteristics in their different propagation stages, including detailed flow features (water depth, flow velocity (Liu and Liu 2017)), tsunami wave/bore run-up process along the slope (Lu et al. 2018; Wu and Liu 2022), as well as beach response and groundwater movement under tsunami actions (Exton and Yeh 2022; Yang et al. 2022).

Various damages on the coastal structures could easily be observed in the disaster area during the post-tsunami field survey. Accordingly, tsunami interaction on coastal structures and their failure mechanisms become an important research theme in laboratory experiments considering the safe design of coastal structures in the future. A 2D flume is generally used to investigate the bore/surge impact on the vertical wall, mainly focusing on the impact pressure measurement (Ramsden 1996; Lobovsky et al. 2014; Kihara et al. 2015). The bore/surge impact on a wall leads to complicated pressure signals, which are fairly sensitive spatially and temporally. Shen et al. (2020) classified the entire surge impact process into three stages and vertically divided it into two impact zones. Results confirmed that such bore/surge impact process and pressure are nondeterministic (Xie and Shimozono 2022) due to the air entrapment effect in the intensive turbulent impact process. In addition, Shen and Liu (2022) confirmed that not only the hydrodynamic features but also the structure parameters are crucial considering the structural dynamic response of a coastal structure, and resonance becomes nonnegligible for structures with small damping and short natural period. 3D physical experiments are recently conducted to simulate the tsunami inundation and wave pressures regarding the actual field situations (Kihara et al. 2021; Krautwald et al. 2022), which further extend the understanding of the tsunami–structure interaction process.

For the above tsunami – structure studies, structures are generally fixed; as moving structures, tsunami boulders could also be frequently observed during the post-tsunami field survey (Sato et al. 2012; Liu et al. 2013). Investigations on such a boulder movement provide valuable information to help identify and interpret paleo-tsunami imprints on the coastal landscapes, which is useful for evaluating the risk of future tsunami disasters and aiding in future disaster mitigation efforts. Liu et al. (2014) conducted a series of tsunami boulder experiments in a dam – break flume and confirmed that boulder dislodgement is not triggered immediately by the arrival of the tsunami bore, and the total boulder displacement is rather sensitive to the initial incoming flow conditions. Subsequently, many experimental studies related to tsunami boulder transport are available, as comprehensively reviewed by Oetjen et al. (2020). They suggested that rather than exact values, parameter ranges should be used in the model analysis considering the complex physics and limited current knowledge.

4 Conclusion

This study creates a general review of the global tsunami research from two different aspects, namely, tsunamis caused by different generation mechanisms and tsunami research using different research approaches. Considering the generation source, tsunamis induced by earthquakes, landslides, volcano eruptions, and meteorological factors are reviewed in sequence. Meanwhile, three different research approaches applied in the tsunami study are also discussed with the integration of the up-to-date outcomes from each individual approach. With time passing by, the understanding of tsunamis gradually extends from the most common one caused by earthquakes to the sophisticated meteorological tsunamis and from the direct post-tsunami field survey to the complicated numerical and physical models. These phenomena significantly improve the ability to set up an effective tsunami early warning system and protect and mitigate tsunami-induced disasters. Nevertheless, tsunamis simultaneously triggered by multiple sources, such as the recent 2022 Hunga-Tonga volcano eruption-induced transoceanic tsunamis, still need further comprehensive research efforts with interdisciplinary co-operation.

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