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Tsunami Risks to Countries Surrounding the Caribbean Sea - A Literature Review

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Abstract: *The Caribbean Sea is an active tectonic region where earthquakes and volcanoes are common,and which may generate tsunamis. Tsunamis in the Caribbean Sea are much rarer than hurricanes, but these are comparable to hurricanes with respect to loss of life and damage to properties, ecosystems and marine structures and facilities.Tsunami risk assessments are required for infrastructure development, emergency planning and decision-making to estimate potential loss of life, damage to properties and marine facilities and to develop rescue and mitigation measures and plan clean-up operations. This paper presents the summary of a literature review carried out on tsunami risks to the countries surrounding the Caribbean Sea. A list of major tsunamis in the Caribbean Sea has been provided. Earthquake and landslide parameters required for generating initial tsunami levels are also provided in this paper. Initial tsunami levels can be generated using these parameters in order to drive a numerical model to predict rise in sea surface due to a tsunami.Steps in a tsunami study are illustrated in this paper. Structural design considerations and tsunami risk reduction measures are also discussed.The methodology described in this paper for tsunami risk assessment in the Caribbean Sea could also be applied to other sites around the world.*

Keywords: *Tsunami, Natural Hazards, Caribbean Sea, Numerical Modelling, Port Development, Caribbean Sea*

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I. Introduction

1.1 Formation of tsunamis

“Tsunami” is a Japanese word written with two Chinese characters. “Tsu” means “harbour/port” and “nami” means “wave” and, therefore, “tsunami” means “harbour/port wave” in Japanese. The naming comes from the fact that tsunamis seem to appear suddenly and become very violent in shallow areas, attacking low-lying areas that are actively used and densely populated, such as port areas [1].

A tsunami (also known as a seismic sea wave) is a series of water waves (similar to shallow water waves) in a water body caused by the abrupt displacement of a large volume of water initially resembling a rapidly rising tide. A tsunami can be generated by underwater earthquakes, landslides, fault breaks (ruptures), volcanic eruptions and other underwater explosions (such as the detonation of nuclear devices), glacier calving, impact of objects from outer space (such as meteorites, asteroids, comets) and other disturbances in water. Ninety (90) percent or more of historical tsunamis in the world have been generated by earthquakes in the sea and coastal regions. Generally larger and shallower hypocentre earthquakes cause larger tsunamis [1].

1.2 Propagation of tsunamis

Tsunami wave periods range from minutes to hours (typically 5 to 60 minutes) and having a wavelength much longer than sea waves and can travel long distances across the oceans. Their behaviour is similar to shallow water waves (because their wavelength is >> water depth) which means that the speed (v) is calculated as the square root of the product of the water depth (h) and the acceleration due to gravity (g) i.e. $v = \sqrt{(gh)}$. Consequently, tsunamis travel very fast in deep oceans. For example, if the water depth is 5000m, the speed will be more than 200m/s or about 800km/hour.

A tsunami wave is normally not very high in deep water but when it approaches the coastline, the wave will begin to steepen due to shoaling effects and, depending on the size of the incoming wave, can reach a height of more than 10m.

1.3 Damages from tsunamis

Tsunamis can cause significant damage to coastal facilities such as seaports, oil terminals and jetties during their construction and operation.Significant loss of life and damage to properties, ecosystems and marine facilities can occur due to tsunamis. Typical examples of such coastal and marine structures and facilities are flood and coast protection structures, revetments, seawalls, quay walls, dikes, retaining structures, piers, breakwaters, port and dry dock buildings and facilities, ferry terminals, wharf, dolphin, barges, gates, warehouses, boats, small ships and larger vessels including cargos, oil tankers, bulk carriers and passenger carriers. Damage due to collision among boats, small ships or larger vessels is common during a tsunami.

Furthermore, such natural hazards put lives and properties in coastal areas at great risks through flooding and submergence of low-lying areas. Very high tides during a tsunami may damage installations, dwellings, transportation and communication systems, trees etc. and cause fires resulting in considerable loss of life, damage to properties and ecosystems. Destruction of transportation or communication infrastructures hampers clean-up and rescue efforts. High tides during a tsunami may cause floods and submergence of low-lying areas and can lead to mudslides and landslides in mountainous areas causing loss of life and property. The resulting floods, standing water and coastal inundation pollute drinking water sources and spread diseases leading to outbreak of epidemics. Tsunamis also cause secondary damage from floating debris, drifting trees and vessels, sediment erosion and deposition and spreading of fire.

As reported in [2], the 1960 Valdivia earthquake (M_w 9.5), 1964 Alaska earthquake (M_w 9.2), 2004 Indian Ocean earthquake (M_w 9.2) and 2011 Tōhoku earthquake (M_w 9.0) are recent examples of powerful megathrust earthquakes that generated tsunamis (known as tele-tsunamis or distant tsunamis) that can cross entire oceans. The 2004 Indian Ocean tsunami was among the deadliest natural disaster in human history with at least 230,000 people killed or missing in 14 countries bordering the Indian Ocean. The 2011 tsunami in Japan resulted to 15,894 deaths, 6,152 injured and 2,562 people missing. The 2011 tsunami damaged many buildings, dams, bridges, nuclear power stations and severalother infrastructures. The World Bank's estimated economic cost due to the 2011 tsunami was US$235 billion, making it the costliest natural disaster in world history. As reported in [3], deaths from the 1945 earthquake in the Makran Subduction Zone that generated tsunamis along the coastlines of Iran and Pakistan were reported to be as many as 4,000 people. Furthermore, the tsunami caused catastrophic damage to properties and other coastal facilities.

1.4 Types of faults and properties of tsunamigenic earthquakes

Dip-slip faults are the faults which move along the direction of the dip plane and are described as either normal or reverse or thrust faults, depending on their motion. Strike-slip faults are the faults which move horizontally and are classified as either right-lateral or left-lateral.

An earthquake induced tsunami is generated by a seafloor deformation associated with submarine and near-coast earthquakes with shallow depth (<50 km), large magnitude (M > 6.5) and dip–slip mechanism [4]. Strike–slip fault motion produces a small vertical deformation of the sea floor, and consequently the induced tsunamis are usually of smaller height [4].

1.5 The present study

This paper presents the summary of a literature review carried out on tsunami risks to the countries surrounding the Caribbean Sea. A list of major tsunamis in the Caribbean Sea has been provided. Earthquake and landslide parameters required for generating initial tsunami levels are also provided in this paper. Initial tsunami levels can be generated using these parameters to drive a numerical model to predict rise in sea surface due to a tsunami. Steps in a tsunami study are illustrated in this paper. Structural design considerations and tsunami risk reduction measures are also discussed. The methodology described in this paper for tsunami risk assessment in the Caribbean Sea could also be applied to other sites around the world.

1.6 Definitions of tsunami water level and wave height

Definitions of tsunami water level and wave height generally used are illustrated in Figure 1 [5]. A tsunami wave height refers to the vertical distance from trough to peak of a tsunami wave. A tsunami level (also called a tsunami height) is referred to the height of the water column above a datum, usually the Mean Sea Level (MSL). Any tsunami level (or tsunami height) in this paper refers to a level above the MSL.

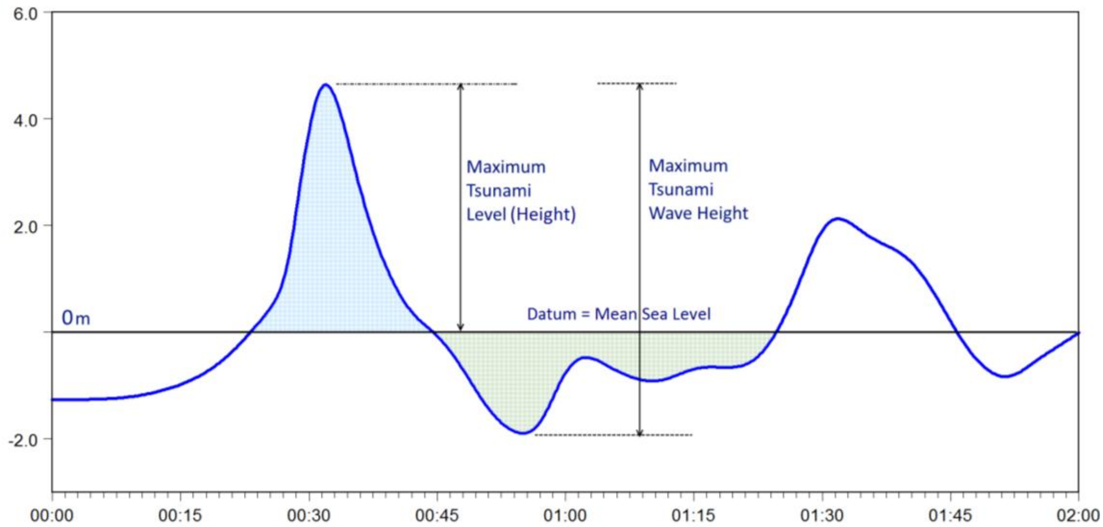

Figure 1: Definitions of tsunami water level and wave height[5]

II. Steps in a Tsunami Study

Steps and software generally used in a complete tsunami study are illustrated in Figure 2 [revised from (5)].

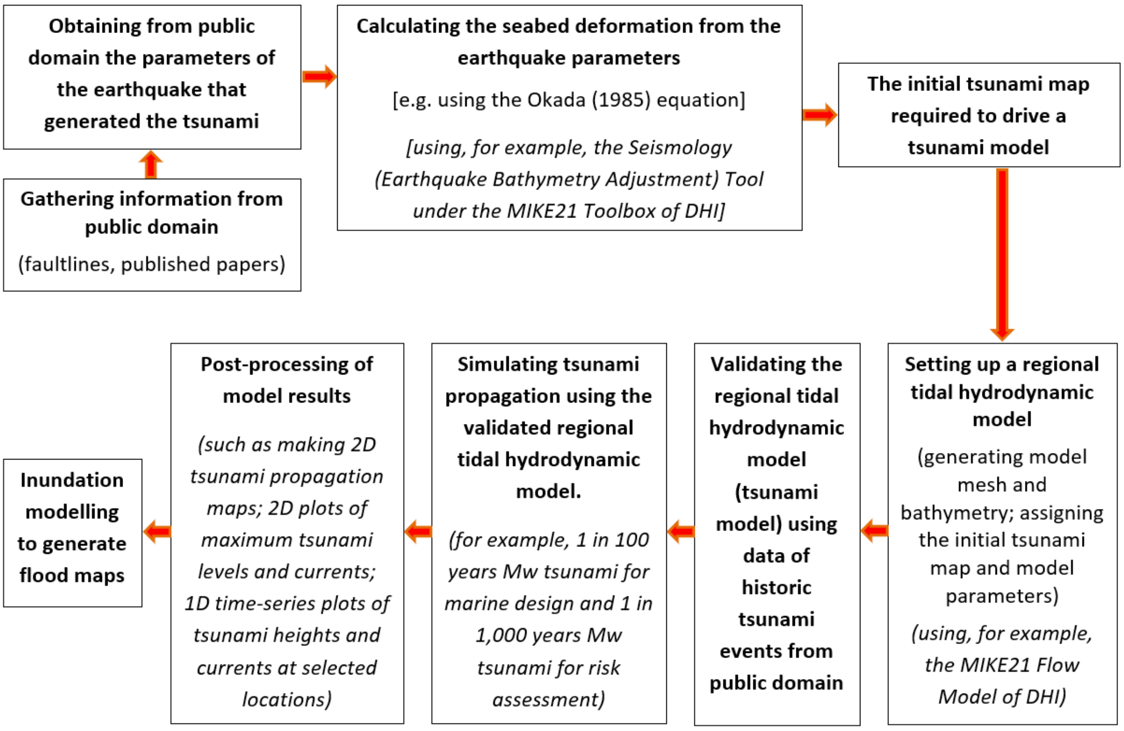

Figure 2: Steps and software generally used in a tsunami study [revised from (5)]

III. Plate Tectonics and Seismicity in the Caribbean Sea

The Caribbean Sea is an active tectonic region where earthquakes and volcanoes are common and which may generate tsunamis. The faultlines around the Caribbean Sea are shown in Figure 3[6] (by the red line).There were many earthquakes in the Caribbean Sea region in the past [7].

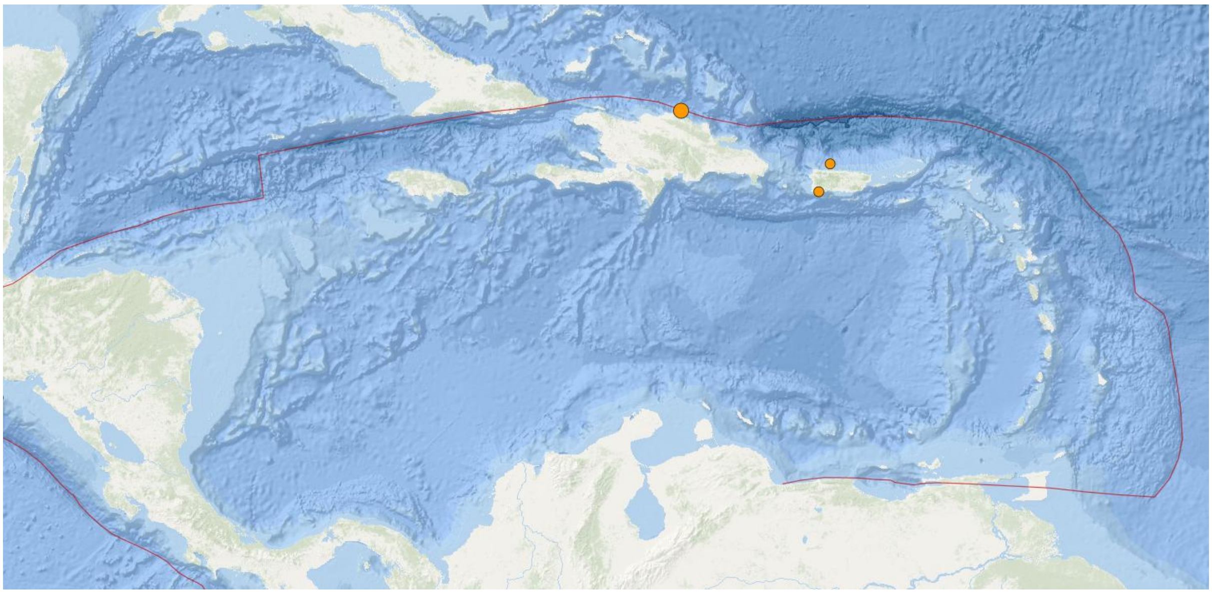

Figure 3: Plate tectonicsofthe Caribbean Sea[6]

IV.Major Tsunamis in the Caribbean Sea Region

Tsunamis in the Caribbean Sea are much rarer than hurricanes, but these are comparable to hurricanes with respect to loss of life and damage to properties, ecosystems and marine structures and facilities. Tsunamis in the Caribbean Sea may occur from undersea earthquakes (local and distant), volcanic eruptions and landslides. The recurrence rate for tsunamis in the Caribbean is approximately one destructive tsunami per century for local earthquakes and one destructive tsunami per 200 years for distant earthquakes [8]. These recurrence rates are small but not negligible. Tsunami risk assessments are required for infrastructure development, emergency planning and decision-making to estimate potential loss of life, damage to properties and marine facilities and to develop rescue and mitigation measures and plan clean-up operations.

There have been ten confirmed earthquake-generated tsunamis in the Caribbean Basin in the past 500 years with four causing fatalities and an estimated 350 people in the Caribbean were killed by these events [8]. The most likely tsunamis to affect the Eastern Caribbean are those which can be triggered by shallow earthquakes (less than 50km depth) and magnitude greater than 6.5. There are two groups of earthquakes which may generate tsunamis in the Caribbean, namely a) earthquakes occurring within the region and b) distant earthquakes occurring outside of the region (tele-tsunamis). There have been approximately 50 local earthquakes in the past 500 years with the potential to cause a tsunami but only 10-20% of these earthquakes actually generated tsunamis. The tele-tsunamis pose a somewhat lower threat than tsunamis caused from local earthquakes. The primary tele-tsunami sources are the Azores-Gibraltar fracture zone that produced the well documented 1755 Lisbon Earthquake and Tsunaminear Portugal and the LaPalma Volcano in the Canary Islands [8].

It was thought that an earthquake of Mw 8.0 was about right for the largest one might expect inthe Caribbeanbased on the history of earthquakes there and the length and motion of the faults. But after the 2004 event at the Sunda Trench in Indonesia, some think that several faults in the Caribbean region could be capable of producing earthquakes of magnitude 8.6, and the catastrophic planning by the emergency management community is considering 8.5 and 9.0 earthquakes [9].

According to NCEI (NOAA National Centers for Environmental Information), over 65 confirmed tsunamis have been observed and approximately 4,500 people have lost their lives to tsunamis in the Caribbean and adjacent regions in the past 500 years [10]. Therefore, to minimise the risks, the CARIBE WAVE annual tsunami exercise is being conducted to assist tsunami preparedness efforts throughout the Caribbean and adjacent regions [10].

Table 1 [11] provides a list of the major tsunamis in the Caribbean Sea.

Table 1 – List of major tsunamis in the Caribbean Sea [11]

Date	Region	Magnitude	Deaths	Comments
28/01/2020	Jamaica, Cuba, Cayman Islands	7.7 Mw	-	0.3–1 meter tsunami
12/01/2010	Haiti	7.0 Mw	100,000–316,000	Extreme damage and minor damaging tsunami
21/11/2004	Guadeloupe, Dominica	6.3 Mw	1	Non-destructive tsunami

24/06/1984	Dominican Republic	6.7 Mw	5	Limited damage / tsunami
04/08/1946	Dominican Republic	7.8 Mw	2,550	Destructive tsunami
11/10/1918	Puerto Rico	7.1 Mw	76–116	Destructive tsunami
14/01/1907	Jamaica	6.2 Mw	800–1,000	Tsunami
18/11/1867	Virgin Islands	7.2 Mw	24	Destructive tsunami
07/05/1842	Haiti	8.1 Ms	5,300	Severe damage and destructive tsunami
02/05/1787	Puerto Rico	6.9, 8.0–8.25	-	Tsunami
07/06/1692	Jamaica	7.5 Mw	~5,000	Tsunami
16/04/1690	Antigua, Saint Kitts and Nevis	8.0 Ms	Some	Destructive tsunami

The historical tsunami distribution in the Caribbean Sea (numbers – tsunami intensity) was shown in [7]. Table 2 [7] provides a list of tsunamis with intensity 2-3 in the Caribbean Sea. Ms is the surface magnitude; I is the tsunami intensity and H_{max} is the maximum wave height. Zaibo et al. (2003) [7] showed the epicentres of historical tsunamis used in their numerical simulation.

Table 2 – List of tsunamis with intensity 2-3 in the Caribbean Sea obtained from Zaibo et al. (2003) [7]

Date	Latitude (°)	Longitude (°)	Ms	I	H_{max}(m)	Source
01.09.1530	10.7	-64.1	7	2	7.3	PeninsuladeParia,Cuba
01.09.1543	10.6	-64.1	7	2		Cumana,Venezuela
01.03.1688	17.6	-76.7		2		PortRoyal,Jamaica
16.04.1690	17.5	-61.5	8	2		CharlotteAmalie,USVirginIs.
07.06.1692	17.8	-76.7	7	3	10	PortRoyal,Liganee,Jamaica
18.10.1751	18.5	-70.7	7	2		AzuadeCompostela,Haiti
21.11.1751	18.5	-73.5	7	2	7	StMartin, Antigua, Martinique
11.06.1766	20	-75.5	7	2		Jamaica
03.10.1780	18.1	-78.1	7	2	3.2	SavannalaMar, Jamaica
28.03.1787	19	-66	8	2.5	4	S. Mexico
05.05.1802	10	-60		2		RioOrinoko,Cumana,Venezuela
26.03.1812	10.3	-64.1		2		LaGuaira, Venezuela
11.11.1812	18	-76.5		2		Annotto Bay, Jamaica
30.11.1823	14.2	-61.1		2		StPierre, Martinique
30.11.1824	14.5	-61		2		StPierre, Martinique
07.05.1842	18.5	-72.5	7.7	3	8.3	Hispaniola, Haiti
17.07.1852	19.5	-75.5		2		SantiagodeCuba, Cuba
09.08.1856	15.8	-84.3		2	5	RioPatuca, Honduras
18.11.1867	18.4	-64.3	7.5	3	10	StThomas,VirginIs.
29.10.1900	10.3	-65.9		3	10	Puerto Tay, Venezuela
14.01.1907	18.2	-76.7	7	2	9.1	Annotto Bay, Jamaica
11.10.1918	18.5	-67.5	7.5	2.5	6	Aguadilla, Puerto Rico
04.08.1946	19.25	-69	8	2	4.7	Hispaniola,Dominican Republic
02.12.1951	13.5	-60		2		Puerto Rico and Barbados
17.08.1952	18.4	-68.4		2		PuertoRico,DominicanRep,
18.01.1955	11.3	-69.4	5.5	2		LaVela, Venezuela
03.09.1979	11.5	-69.3		2		PuertoCumaredo, Venezuela

V.Previous Numerical Modelling Studies

a. Tsunamis from earthquakes

Work by Mercado and McCann (1998) on the 1918 tsunami [12]

A magnitude Mw 7.3 earthquake occurred at 10:14 in the morning of 11 October 1918 at about 15 km off the northwest coast of Puerto Rico. The earthquake generated a large tsunami which was one of the deadliest events in the region damaging along the western and northern coasts of the island. The maximum tsunami runup was 6m and about 40 people died. Mercado and McCann (1998) carried out a numerical simulation of the 1918 Puerto Rico tsunami. The tectonic and tsunamigenic environment around Puerto Rico was reviewed, the fault parameters for the 1918 event were estimated, and a numerical simulation was performed by them using a tsunami propagation and runup model obtained through the Tsunami Inundation Modelling for Exchange (TIME) program. Model results were compared with the observed runup values all along the west coast of Puerto Rico.

Mercado and McCann (1998) stated that the Mona Canyon Fault was the most probable source of the 1918 earthquake. They also stated that there are at least seven other faults in the Mona Canyon region capable of generating tsunamis, although some of those appear to be shorter and, therefore, less capable than the Mona Canyon Fault System. According to Mercado and McCann (1998), tsunami events larger than that of the 1918 event seem improbable given existing data.

Mercado and McCann (1998) provided the fault segments and their parameters for the Mona Canyon Fault(such as location, length, width, focal depth, strike angle, dip angle, slip angle and displacement). They also provided the parameters for other significant faults in the Mona Canyon Region.

Work by Xu et al. (2022)on the 2020 tsunami [13]

An earthquake at 19:10 on 28 January 2020 (UTC) with Mw 7.7 struck the Caribbean Sea region (19.421°N, 78.763°W) between Jamaica, the Cayman Islands and Cuba. The earthquake parameters were quickly provided by various earthquake agencies. The focal depth of the earthquake was 4.8 km. Strong shakes of the earthquake were felt across many Caribbean countries, especially in south of Cuba, northwest of Jamaica and the Cayman Islands, and felt as far away as the United State (State of Florida) and parts of Mexico.A small tsunami was generated by the earthquake. The maximum vertical seafloor displacement associated with the strike-slip earthquake was about 1.5m. The COMCOT model was used by Xu et al. (2022) to simulate the tsunami. The simulation results were compared to tide gauge records. They found that the small-scale tsunami was not generated solely by co-seismic seafloor deformation from the strike-slip event, but that earthquake-triggered submarine landslide was the primary cause. Hence, the combined effect of the two sources leads to the small-scale tsunami.

Work by Zaibo et al. (2003) on potential tsunamis [7]

Zaibo et al. (2003) [7] carried out estimation of far-field tsunami potential for the Caribbean coast based on numerical simulation. They discussed the tsunami problem for the coast of the Caribbean basin and presented the historical data of tsunami in the Caribbean Sea. They estimated the far-field tsunami potential for the Caribbean Sea by creating the synthetic catalogue of possible tsunami generating in the open sea. In absence of sufficient information available on the source parameters of the earthquake they chose length of the fault 120 km, width 30 km, dip angle 70°, slip angle 90°, displacement 8m and focal depth from the HTDB/ATL catalogue or 3,000m if there is no such information. These parameters they used to simulate the 1867 Virgin tsunami which was one of the most destructive tsunamis in the Caribbean basin. They carried out numerical simulation of potential tsunamis in the Caribbean Sea in the framework of the nonlinear-shallow theory to compute the tsunami wave height distribution along the Caribbean Coast. The distribution of maximum crest amplitude in the Caribbean Sea (1867 event) is presented. Zones with low tsunami risk in the Caribbean Sea are also identified. These results can be used to estimate the far-field tsunami potential of various coastal locations in the Caribbean Sea.

Work by Yalciner et al. (2010) on potential tsunami [14]

Yalciner et al. (2010) carried out numerical modelling to understandthe possible effects of near-field and far-field tsunamis on Lesser Antilles.The Lesser Antilles is a group of islands in the Caribbean Sea, forming part of the West Indies in Caribbean region of the Americas. The selected rupturecharacteristics considering a thrust fault of a possible tsunami are provided (such as epicentre, length, width, focal depth, strike angle, dip angle, slip angle and displacement). The numerical modelling was carried out using TUNAMI N3 and NAMI DANCE models and provided model results of potential tsunamis generated in the centre of the Caribbean Sea. They found that the maximum amplitude of the water elevation in Lesser Antilles could reach up to 3–4m. The travel time of tsunami is 1.5 hours to the northern islands of Lesser Antilles and 2 hours to the southern islands of Lesser Antilles. They stated that the southern coast of Caribbean Seawould be much more effected comparing to the Lesser Antilles when a tsunami is generated in the centre of the Caribbean Sea.

Work by Grilli et al. (2010) on potential tsunami [15]

Grilli et al. (2010) carried out numerical simulations of the coastal impact of large co-seismic tsunamis initiated in the Puerto Rican trench. Both far-field areas along the upper US East coast (and other Caribbean islands), and in more detail in the near-field areas along the Puerto Rico North Shore (PRNS) were investigated. An extreme co-seismic source of Mw 9.1 as well as a smaller Mw 8.7 source were considered. Parameters for these selected earthquake magnitudes were provided. A fullynonlinear and dispersive long wave tsunami model (FUNWAVE) was used.Coastal runup and inundation were then simulated fortwo selected areas.

b. Tsunamis from volcanic eruptions and landslides

Approximately 5% of known tsunami events were generated by volcanoes, producing some of the most destructive tsunamis on record [16]. There are mainly two potential sources of tsunamis triggered by volcanic eruption namely, Kick'em Jenny volcano and Canary Islands [17]. Kick'em Jenny is a prime source for tsunamigenic events on a potentially hazardous scale, possibly affecting the whole of the eastern Caribbean region.

6.2.1 Tsunamis from the Kick'em Jenny volcano

Kick'em Jenny (Kick-'em-Jenny or Mt. Kick-'Em-Jenny) is an active submarine volcano (or seamount) on the Caribbean Sea floor, located 8 km north of the island of Grenada and about 8 km west of Ronde Island in the Grenadines. Kick-'em-Jenny rises 1,300 m above the seafloor on the steep inner western slope of the Lesser Antilles ridge. The Global Volcanism Program reports the summit to be 185 m below the sea surface. The volcano was unknown before 1939. The first record of the volcano was in 1939 although it must have erupted many times before that date. On 23–24 July 1939 an eruption broke the sea surface, sending a cloud of steam and debris 275 m into the air and generating a series of tsunamis around 2m high when they reached the coastlines of northern Grenada and the southern Grenadines. A small tsunami also reached the west coast of nearby Barbados, where "a sea-wave" suddenly washed over a coastal road, most likely at Paynes Bay. The volcano has erupted on at least twelve occasions between 1939 and 2017 (the last being on 29 April 2017), although no subsequent eruption has been as large as the 1939 one. The above information was obtained from [18].

According to UWI [2025], not all volcanic eruptions at Kick-'em-Jenny will generate tsunamis and not all these tsunamis will be large. Studies show that the worst eruption at Kick-'em-Jenny is capable of generating a wave with an amplitude of 10 m in open waters at a distance of 10 km from the vent. Waves of this amplitude could be generated only if the volcano began to erupt in water depths of less than about 130 m but currently the water depth to the vent is 268 m. The above information was obtained from [19].

Dondin et al. (2012) modelled a sector collapse event of a prototype Kick'em Jenny volcano using VolcFlow, a finite difference code based on depth-integrated mass and momentum equations. They estimated the volume and the leading-edge runout of the landslide to be 4.4 km^3 and 14 km, respectively. The reconstruction of the proto-Kick'em Jenny was based on two main assumptions, namely (1) the external flanks of the horseshoe-shaped structure belonged to the base of former edifice and (2) the reconstructed slopes of the upper proto-edifice did not exceed 40° as observed on most volcanoes worldwide. The above information was obtained from [20].

Gisler et al. (2006) performed two-dimensional simulations of an event in a geometry resembling that of Kick-em Jenny with their SAGE adaptive mesh Eulerian multifluid compressible hydrocode. They used realistic equations of state for air, water, and basalt, and follow the event from the initial explosive eruption, through the generation of a transient water cavity and the propagation of waves away from the site. They found that even for extremely catastrophic explosive eruptions, tsunamis from Kick-em Jenny are unlikely to pose significant danger to nearby islands. The above information was obtained from [21].

The eruption process of each volcano is unique and, therefore, attempts to generalise tsunamigenic mechanisms are extremely tentative. However, the theory of underwater explosion generated water waves is applicable to submarine volcanoes to simulate explosive eruptions. Using this theory, initial maximum ocean surface displacements were calculated by Smith and Shepherd (1993) for Kick'em Jenny hydro-eruptions, corresponding to various event magnitudes (up to a 'worst-case' scenario eruption on the scale of Krakatau, 1883 in Indonesia). Wave propagation theories are then applied by them to the resulting tsunami wave dispersion, before beach shoaling equations are used to estimate the maximum tsunami run-up at adjacent coastal areas. They prepared maps of the region showing the paths of the wavefronts (raytracing), travel times and maximum wave run-up amplitudes along coastlines. Finally, they assessed how great a hazard the volcano represents, by considering the probability of each magnitude event occurring. The above information was obtained from [22].

An estimate of the potential height of tsunami waves generated following slope failure on the flanks of Kick'em Jenny was carried out by Smith and Shepherd (1996) using the basic solitary wave theory combined with equations of energy conservation. Generally, landslide-generated tsunamis possess little energy and, unless they are confined in a bay or a channel are only hazardous close to the source. However, the results by Smith and Shepherd (1996) show that with the low-lying Grenadine Islands situated a few kilometres to the east, even a relatively small landslide event at Kick'em Jenny has the potential to produce waves that would prove hazardous to both coastal populations and ships. The above information was obtained from [16].

6.2.2 Tsunamis from the Canary Islands volcano

The Canary Islands are an archipelago in the Atlantic Ocean and the southernmost Autonomous Community of Spain. They are located in the north-west of Africa with the closest point to the continent being 100 km away. The seven main islands from largest to smallest in area are Tenerife, Fuerteventura, Gran Canaria, Lanzarote, La Palma, La Gomera, and El Hierro. The above information was obtained from [23].

The Canary Islands are well-known for their volcanic origins and ongoing volcanic activities. The islands are built from submarine volcanoes that grew over time with eruptions building up layers of lava flows that eventually emerged as islands. Several islands such as La Palma, Tenerife and Lanzarote have experienced recent eruptions and feature prominent volcanic structures. La Palma's Cumbre Vieja volcano has been particularly active in recent times with a significant eruption in 2021.

There have been more than 17 eruptions in the Canary Islands since the 1400s but none resulting in a “megatsunami” across the Atlantic [24].

The Cumbre Vieja Volcano lies on the Island of La Palma in the Canary Islands. The institution that oversees the monitoring (INVOLCAN) does not recognise the volcano-edifice stability as a potential tsunami risk. Pyroclastic density currents that can cause tsunamis are unlikely to occur at these volcanoes. Even though they can occur, evidence shows that tsunamis produced, as a result of instability of the volcano-edifice are generally localised. Trans-oceanic tsunami generated by eruptions are unlikely. The above information was obtained from [25].

The Canary Islands are a group of seven volcanic islands that lie 100 km off the coast of Africa.The coastlines of the Canaries are characterized by massive, steep cliffs.Cumbre Vieja is the main volcano on the island of La Palma and has erupted recently causing large cracks to growinvolving the significant motion of the western volcano flank. This has caused speculation that this flank could collapse.The flank has a volume of 1.5 trillion metric tons and models suggest that if it were to collapse it would generate a tsunami of 1000 m high that would be 50 m when it arrived in Europe and along the eastern coast of the US. Because this scenario would be devastating to major cities including those in the USA, it has been rigorously investigated by scientists. The hypothesis that Canary Island collapse generates megatsunami is not universally accepted. This scepticism arises from the fact that island collapse may not have been catastrophic, instead occurring slowly in numerous discrete small events rather than a single giant collapse. Such a slow collapse would not generate a large tsunami. In summary, it does not appear that a devastating megatsunami generated in the Canary Islands is imminent. There is potential for collapse of the volcanic flanks on the islands, but these events will likely be less dramatic than once feared and with waves only devastating on a local scale. The above information was obtained from [26].

Abadie et al. (2011) [27] carried out numerical simulations of wave generation by the potential flank collapse of the Cumbre Vieja Volcano (CVV; La Palma, Canary Islands, Spain). They considered several slide scenarios of different volumes (20, 40, 80, 450 km^3). Simulations of tsunami sources were performed using the 3D incompressible multifluid Navier-Stokes model THETIS. Both 2D and 3D simulations (the latter using a cylindrical mesh) were performed, which investigate near-field wave generation. Their results show that a slide of 60-70 km^3 would have very significant consequences, at least for La Palma and other surrounding islands. Far-field waves (tsunamis) were simulated in the 2D horizontal, fully nonlinear and dispersive, Boussinesq model FUNWAVE, which was initialised with the 3D Navier-Stokes solution. The above information was obtained from [27].

Abadie et al. (2012) [28] carried out numerical modelling of tsunami waves generated by the flank collapse of the Cumbre Vieja Volcano (CVV) [La Palma, Canary Islands] considering tsunami source and near-field effects. They carried out the numerical simulations in two stages (i) the initial slide motion and resulting freesurface elevation are first calculated using a 3D Navier-Stokes model and (ii) generatedwaves are then input into a 2D (horizontal) Boussinesq model to further simulate propagation to the nearby islands. They considered several slide scenarios featuring different volumes (20, 40, 80, 450 km^3) based on partly result from a geotechnical slope stability analysis. They found that wave trains for each scenario share common features in terms of wave directivity,frequency, and time evolution, but maximum elevations near CVV significantly differ, ranging from 600 to 1200 m (for increasing slide volume). Their computations show that significant energy transfer from slide to waves only lasts for a short duration (order of 200 s). The above information was obtained from [28].

Abadie et al. (2019) [29] carried out computation of the tsunami source with a calibrated multi-fluid Navier-Stokes model, hazard assessment, and model intercomparison for La Palma landslide. They presented new results on the potential La Palma collapse event, previously described and studied in
Abadie et al. (2012). Three scenarios of slide volumes (i.e. 20, 40 and 80 km^3) were considered. Modelling of the initiation of the slide to the water wave generation was carried out using THETIS, a 3D Navier-Stokes model. The slide was considered as a Newtonian fluid whose viscosity was adjusted to approximate a granular behaviour. After 5 minutes of propagation with THETIS, the generated water wave was transferred into FUNWAVE-TVD, for 15 minutes of Boussinesq model simulation, to build a wave source suitable for propagation models. The wave impact was found to be very significant for the maximum slide volume considered on surrounding islands and coasts, as well as on remote most exposed coasts such as Guadeloupe. The wave impact in Europe was significant (for specific areas in Spain and Portugal) to moderate (Atlantic French coast). The above information was obtained from [29].

Harris et al. (2012) [30] carried out numerical modelling of tsunamis generated by four scenarios of slide volumes (i.e. 20, 40, 80 and 450 km^3). Near-field tsunami impact and far-field tsunami propagation and coastal impact at distant locations (such as North America, Western Europe and West Africa) were investigated.

Løvholt et al. (2008) [31] carried out numerical simulations of a tsunami that might result from the extreme case of a flank collapse of the Cumbre Vieja volcano at the La Palma Island by combining a multilateral model for the wave generation with Boussinesq models for the far-field propagation. A slide volume of 375 $km^3$was consideredin their 3D computations. The cylindricalsymmetric and 3D results were used as input to Boussinesq simulationsfor the continued propagation. The slide applied forthe cylindrically symmetric simulations had avolume of 473 km^3.They found that the slide speed is close to critical, effectively generating an initial wave of several hundred meters height. They also found that the commonly used hydrostatic models fail to describe the far-field propagation. They found that consequences of the La Palma scenario would be largest at the Canary Islands and also the whole central Atlantic would face grave consequences. The above information was obtained from [31].

VI.Tsunami Risk Assessment Methodology

The probability of occurrence of a tsunami is very low but if it occurs it can be devastating. Therefore, an adequate level of tsunami risk assessment is essential for any major coastal project. The first step in assessing the tsunami hazard is to carry out a statistical analysis of the historical tsunami events in a certain region. This is not an easy task because large tsunamis are rare which makes a robust statistical analysis almost impossible.

Initially a seismic risk assessment should be carried out to a) identify the major fault lines in the region b) assess the risks to the site from tsunamis and c) determine the most critical tsunamigenic earthquake affecting the site. Published literature and papers can be obtained from the public domain to identify historic tsunamis to assess the risks and to obtain earthquake parameters required for tsunami modelling.

VII.Source Parameters of Tsunamis in the Caribbean Sea

a. Tsunamis from earthquakes

Potential tsunami sources in the Caribbean Sea from [17] are listed below:

1) Western Muertos Trough (WMT)
2) Small Muertos Trough (SMT) 1
3) Small Muertos Trough (SMT) 2
4) Muertos Trough Mega-splay (MS)
5) Northern Panamá Deformed Belt (NPDB)
6) West branch of the South Caribbean Deformed Belt (WSCDB)
7) East branch of the South Caribbean Deformed Belt (ESCDB)
8) Full Southern Caribbean Deformed Belt (FSCDB)
9) Puerto Rico Trench (PRT)
10) Mona Extension Fault (MEF)

The potential tsunami sources in the Caribbean Sea listed above are shown in Figure 4obtained from [17]. Tsunami source parameters for the above sub-areas are provided in Table 3obtained from [17].

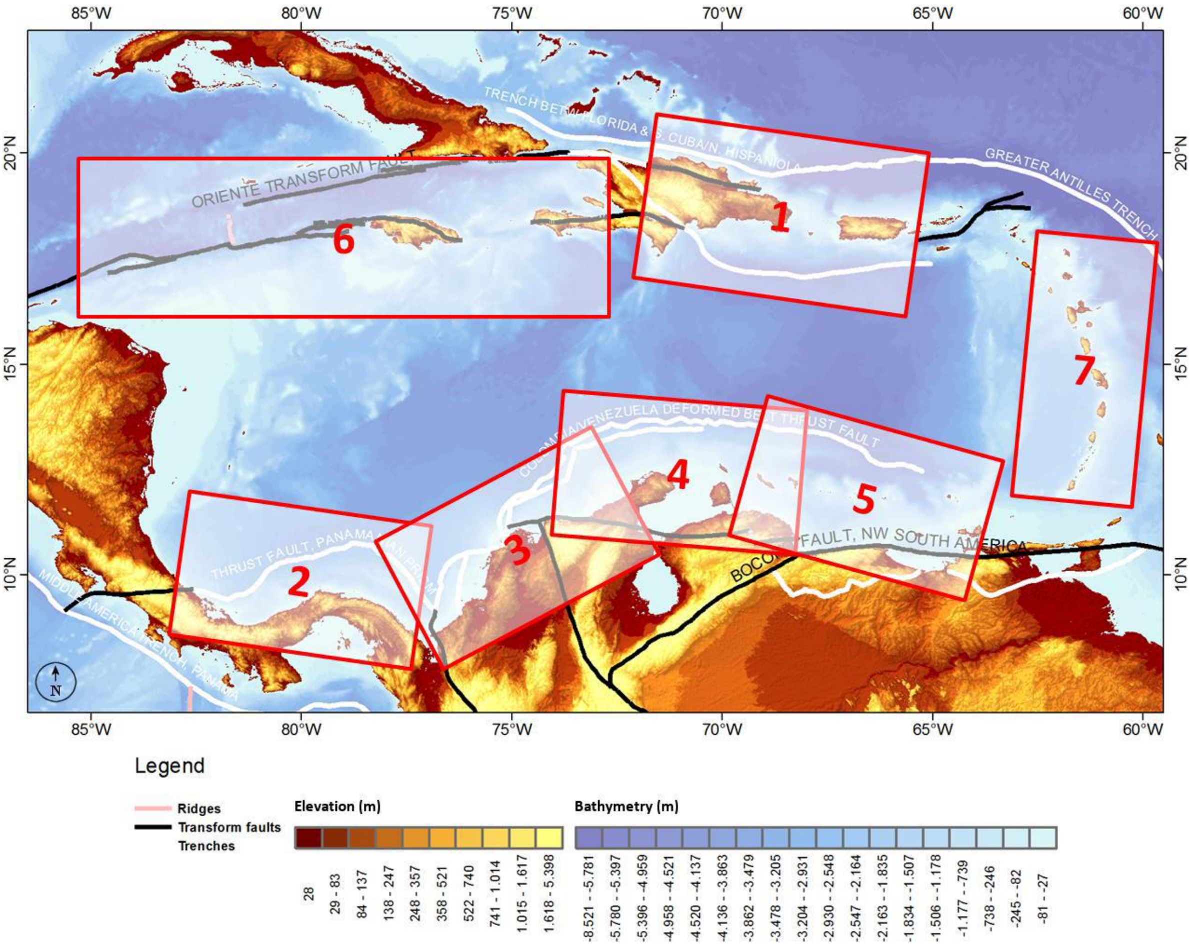

Figure 4: General overview of main tectonic structures obtained from [17] (http://ig.utexas.edu/marine-and-tectonics/plates-project/; background elevation from GEBCO08)

Table 3 – Source parameters of tsunamis in the Caribbean Sea [obtained from (17)]

Sources	Lat (°)	Long (°)	Depth (km)	Strike (°)	Dip (°)	Rake (°)	Slip (m)	Length (km)	Width (km)	Mw
1 (WMT)	17.6	-69.5	2.5	280	9	90	4	290	30	8.0
2 (SMT1)	17.6	-70.0	2.5	285	11	90	3	140	25	7.6
3 (SMT2)	17.4	-68.7	2.5	275	10	90	3	150	25	7.6
4 (MS)	17.7	-69.8	3.5	279	14	90	3	190	20	7.7
5 (NPDB)	9.8	-77.8	25	142	40	90	10	243	80	8.5
6 (WSCDB)	12.3	-73.7	25	53	17	90	7.4	500	90	8.6
7 (ESCDB)	13.1	-69.3	20	96	20	90	8.03	500	90	8.7
8 (FSCDB)	Composite sources (WSCDB + ESCDB)									
9 (PRT)	19.3	-66.5	20	86	20	23	8.0	500	110	8.7
10 (MEF)	18.3	-67.8	10	110	70	270	6.0	80	20	7.6

b. Tsunamis from seabed landslides

The location and orientation of the Complutense Slump(CS)was shown in [17]. The volume of the slump was 224km^3 as shown in Table 4 [in (17) from (32)]. Volume estimation was obtained from multichannel seismic profiles in which an average height of 0.7 km of material was removed during the occurrence of the landslide. The tsunami simulation will require bringing the bathymetry of the region to the pre-landslide state.

Table 4 – Source parameters of the Complutense Slump[obtained from (32)as reported in (17)]

Source	Lat (°)	Long (°)	Depth (km)	Volume (km3)
CS	17.6	-69.6	3.4	320 km^2 x 0.7 km = 224 km^3

c. Tsunamis from volcanic eruptions

Kick'em Jenny volcano

Dondin et al. (2012) [20] modelled a sector collapse event of a prototype Kick'em Jenny volcano using VolcFlow, a finite difference code based on depth-integrated mass and momentum equations. They estimated the volume and the leading-edge runout of the landslide to be 4.4 km^3 and 14 km, respectively.

Initial maximum ocean surface displacements were calculated by Smith and Shepherd (1993) [22] for Kick'em Jenny hydro-eruptions, corresponding to various event magnitudes (up to a ‘worst-case’ scenario eruption on the scale of Krakatau, 1883 in Indonesia).

Canary Islands volcano

Abadie et al. (2011 [27], Abadie et al. (2012) [28] and Abadie et al. (2019) [29] carried out numerical simulations of wave generation by the potential flank collapse of the Cumbre Vieja Volcano (CVV; La Palma, Canary Islands, Spain). They considered several slide scenarios of different volumes (20, 40, 80, 450 km^3). Their results show that a slide of 60-70 km^3 would have very significant consequences, at least for La Palma and other surrounding islands.

Harris et al. (2012) [30] carried out numerical modelling of tsunamis generated by four scenarios of slide volumes (i.e. 20, 40, 80 and 450 km^3).

Løvholt et al. (2008) [31] carried out numerical simulations of a tsunami that might result from the extreme case of a flank collapse of the Cumbre Vieja volcano at the La Palma Island by combining a multilateral model for the wave generation with Boussinesq models for the far-field propagation. A slide volume of 375 $km^3$was consideredin their 3D computations. The cylindricalsymmetric and 3D results were used as input to Boussinesq simulationsfor the continued propagation. The slide applied forthe cylindrically symmetric simulations had avolume of 473 km^3.

VIII.Earthquake Return Periods for the Caribbean Sea

Earthquake magnitudes (Mw) for various return periods were obtained from Rong et al. (2015) [33] and are provided in Table 5andshown in Figure 5.

Table 5 – Return period values for earthquake magnitudes in the Caribbean Loop [33]

Return periods	Mw	Sources
1	*4.50*	*Extrapolated*
10	*6.85*	*Extrapolated*
20	*7.40*	*Extrapolated*
50	7.95	[33]
100	8.22	[33]
200	*8.45*	*Interpolated*
250	8.51	[33]
500	8.67	[33]
1,000	*8.80*	[33]

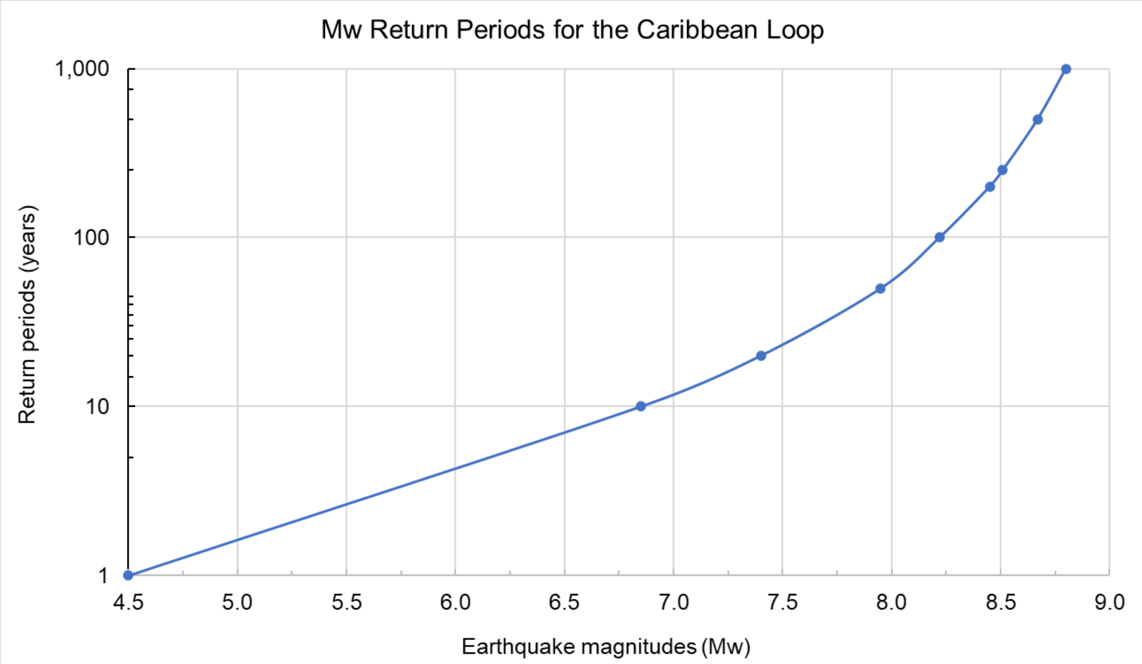

Figure 5 – Return period values for earthquake magnitudes in the Caribbean Loop plotted using data from Table 5[33]

IX. Recommended Design Considerations

The potential impact of a tsunami event on the design of coastal and marine facilities may be summarised as follows:

1) Shoaling results in an increase in water levels and stronger currents inshore and the measures will be required to protect structures from scouring of the foreshore and seabed and limit damage to the crest if heavy overtopping occurs;
2) The foreshore will be subjected to flooding as the tsunami waves and surge approach; and
3) Facilities located on the landward slope are at risk from tsunami wave run-up and surge.

X. Tsunami Risk Reduction Measures

Damage due to a tsunami depends on the strength and proximity of the tsunami as well as local bathymetry and topography and location of people, structures and facilities.

It is almost impossible to fully protect people and settlements from major tsunami events. However, various soft and hard measures (independently or in combination) could be adopted to reduce fatalities and damage to key infrastructure.

Some potential measures to reduce the risk of damage from major tsunami events are highlighted below:

1) Detection, early warning systems and real-time observation systems are of great importance to save lives and reduce damage by timely evacuation and emergency response;
2) Appropriate awareness and understanding among the general public will reduce death toll;
3) Mitigation plans and evacuation and rescue preparedness by responsible authorities will reduce damage and death toll;
4) Tsunami risk assessment, flood risk and inundation hazard maps;
5) Tsunami shelters (elevated building) are of great use for people to flee to avoid inundation;
6) Evacuation towers and/or platforms for quick access to safety above tsunami wave;
7) Developing artificial forest and vegetation such as coastal mangroves and casuarinas of appropriate width behind the shoreline will reduce tsunami wave energy by acting as natural buffers;
8) Maintaining natural sand dunes;
9) Regulations for development in the coastal zone;
10) Saline embankments to prevent salt-water entering the fertile lands;
11) Raising ground levels of important structures and facilities such as warehouses, terminals and quays will reduce risk to these being flooded;

12) Planning for resilient infrastructure to ensure roads, buildings, bridges, and utility facilities withstand tsunami impact; and
13) Constructing tsunami defence structures such seawalls, dikes, gates, nearshore breakwaters and offshore barriers will reduce risk and damage by absorbing and deflecting wave energy. However, these structures are huge and are very expensive.

For major coastal infrastructure, the adoption of appropriate design parameters, a proper assessment of structural loads, forces and stability in combination with a detailed understanding of tsunami processes will reduce the level of damage resulting from these events. Furthermore, physical modelling of major coastal and marine structures and mooring systems to investigate their stability under severe conditions will be helpful to reduce damage due to tsunamis.

Risks Reduction from Mudslides and Landslides

Landslides and mudslides are downhill earth movements that can move slowly and cause damage gradually. These can also move rapidly destroying property and taking lives suddenly and unexpectedly. They typically carry heavy debris like trees and boulders which can cause severe damage along with injury or death. Faster movement of mudslides makes these deadly.High tides during a tsunami may cause floods and submergence of low-lying areas and can lead to mudslides and landslides in mountainous areas causing loss of life and property.

There is nothing one can do to prevent a mudslide or a landslide. However, one can always be prepared and take necessary steps to lessen the impact of a mudslide or prevent one altogether. Some guidelines are briefly mentioned below:

1) Conducting risk assessment;
2) Creating public awareness and practicing an evacuation plan;
3) Staying up to date on storm, rainfall and tsunami warnings during times of increased risk;
4) Watching for any visible signs such as cracks on land, debris flows or trees tilting or boulders knocking;
5) Staying alert and awake;
6) Moving out of the path of the landslide or debris flow; and
7) Some erosion control measures might be helpful (such as installing barrier walls, improving drainage systems and planting trees with deep and extensive root systems).

Risks Reduction from Flash Floods

Flash floods are rapid flooding of low-lying areas such as washes, rivers, dry lakes and depressions due to heavy rain associated with a severe thunderstorm, hurricane, or tropical storm, or by meltwater from ice and snow. A flash flood may also occur after the collapse of a natural ice or debris dam, or a human structure such as a man-made dam. A flash flood is differentiated from a regular flood by having a timescale of fewer than within six hours (often within 3 hours) of the heavy rainfall (or other cause). The sign of an approaching flash flood is sudden rushing water in a stream that is normally dry or nearly dry.

Flash floods can be catastrophic ranging from damages in buildings and infrastructure to impacts on vegetation, soil erosion, human lives and livestock.

Flash flood is a natural calamity which is difficult to control but risks can be reduced by taking various measures such as those listed below:

1) Develop a real-time forecasting system
2) Assess flooding risk and prepare emergency evacuation plan
3) Educate residents about flash flood risks and practice evacuation routes, shelter plans, and flash flood response
4) Keep up to date of any signs of heavy rain and flood risk information
5) Move to higher ground if rapidly rising water is seen or heard
6) Improve drainage by, for example, installing rain gardens, permeable surfaces (like pavers or gravel instead of concrete), and plant trees to increase water absorption
7) Regulations for development on floodplains and wetlands, and implement of flood-resilient building codes
8) Construction of protection structures like flood barriers, non-return valves, and flood doors

XI. Summary

This paper presents the summary of a literature review carried out on tsunami risks to the countries surrounding the Caribbean Sea. A list of major tsunamis in the Caribbean Sea has been provided. Earthquake and landslide parameters required for generating initial tsunami levels are also provided in this paper. Initial tsunami levels can be generated using these parameters to drive a numerical model to predict rise in sea surface due to a tsunami. Steps in a tsunami study are illustrated in this paper. Structural design considerations and tsunami risk reduction measures are also discussed. The methodology described in this paper for tsunami risk assessment in the Caribbean Sea could also be applied to other sites around the world.

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The main purpose of this paper was to assist the local and the regional scientists, practitioners and authorities in carrying out tsunami risk assessments for the countries surrounding the Caribbean Sea. Such risk assessments are required for infrastructure development, emergency planning and decision-making to estimate potential loss of life, damage to properties, ecosystems and marine structures and facilities and to develop rescue and mitigation measures and plan clean-up operations.

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