Guidelines for Design of Structures for Vertical Evacuation from Tsunamis

FEMA P646 / June 2008

FEMA

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Guidelines for Design of Structures for Vertical Evacuation from Tsunamis

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Prepared for

FEDERAL EMERGENCY MANAGEMENT AGENCY
National Earthquake Hazard Reduction Program

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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Notice

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Foreword

This publication was equally funded by the National Oceanic and Atmospheric Administration (NOAA), which leads the National Tsunami Hazard Mitigation Program (NTHMP) and by the Federal Emergency Management Agency (FEMA), which is responsible for the implementation portion of the National Earthquake Hazard Reduction Program (NEHRP).

FEMA initiated this project in September 2004 with a contract to the Applied Technology Council. The project was undertaken to address the need for guidance on how to build a structure that would be capable of resisting the extreme forces of both a tsunami and an earthquake. This question was driven by the fact that there are many communities along our nation's west coast that are located on narrow spits of land and are vulnerable to a tsunami triggered by an earthquake on the Cascadia subduction zone, which could potentially generate a tsunami of 20 feet in elevation or more within 20 minutes. Given their location, it would be impossible to evacuate these communities in time, which could result in a significant loss of life. Many coastal communities subject to tsunami located in other parts of the country also have the same potential problem. In these cases, the only feasible alternative is vertical evacuation, using specially design, constructed and designated structures built to resist both tsunami and earthquake loads.

The significance of this issue came into sharp relief with the December 26, 2004 Sumatra earthquake and Indian Ocean tsunami. While this event resulted in a tremendous loss of life, this would have been even worse had not many people been able to take shelter in multi-story reinforced concrete buildings. Without realizing it, these survivors were among the first to demonstrate the concept of vertical evacuation from a tsunami.

This publication presents the following information:

- General information on the tsunami hazard and its history;
- Guidance on determining the tsunami hazard, including the need for tsunami depth and velocity on a site-specific basis;
- Different options for vertical evacuation from tsunamis;
- Determining tsunami and earthquake loads and structural design criteria necessary to address them; and,
- Structural design concepts and other considerations.

This publication is the first of two documents on this issue. The second, currently under development, will present information on how the use of this design guidance can be encouraged and adopted at the State and local levels.

FEMA is grateful to the Project Management Committee of Steve Baldridge, John Hooper, Ian Robertson, Tim Walsh, and Harry Yeh. We are also grateful to the Project Review Committee, the members of which are listed at the end of the document, and to the staff of the Applied Technology Council. Their hard work has provided this nation with a first document of its kind, a manual on how citizens may for the first time be able to survive a tsunami, one of the most terrifying natural hazards known.

– Federal Emergency Management Agency

Preface

In September 2004 the Applied Technology Council (ATC) was awarded a "Seismic and Multi-Hazard Technical Guidance Development and Support" contract (HSFEHQ-04-D-0641) by the Federal Emergency Management Agency (FEMA) to conduct a variety of tasks, including the development of design guidance for special facilities for vertical evacuation from tsunamis, which ATC designated the ATC-64 Project. The effort was co-funded by FEMA and the National Oceanic and Atmospheric Administration (NOAA).

The developmental process involved a variety of activities including review of relevant research and state-of-the-practice documentation and literature, preparation of technical guidance and approaches for tsunami-resistant design, identification of relevant tsunami loads and applicable design criteria, development of methods to calculate tsunami loading, and identification of desired architectural and structural system attributes for vertical evacuation facilities.

The resulting guidance for design of special facilities for vertical evacuation from tsunami, as presented herein, addresses a range of relevant issues. Chapter 1 defines the scope and limitations of the guidance. Chapter 2 provides background information on tsunami effects and their potential impacts on buildings in coastal communities. Chapters 3 through 7 provide design guidance on characterization of tsunami hazard, choosing between various options for vertical evacuation structures, locating and sizing vertical evacuation structures, estimation of tsunami load effects, structural design criteria, and design concepts and other considerations. The document concludes with a series of appendices that provide supplemental information, including examples of vertical evacuation structures from Japan, example tsunami load calculations, a community design example, development of impact load equations, and background on maximum flow velocity and momentum flux in the tsunami runup zone.

ATC is indebted to the members of the ATC-64 Project Team who participated in the development of this document. The Project Management Committee, consisting of Steven Baldridge (Project Technical Director), Frank Gonzalez (who participated in early portions of the project), John Hooper, Ian Robertson, Tim Walsh, and Harry Yeh, were responsible for the development of the technical criteria, design guidance, and related recommendations. Technical review and comment at critical developmental

stages were provided by the Project Review Panel, consisting of Christopher Jones (Chair and ATC Board Representative), John Aho, George Crawford, Richard Eisner, Lesley Ewing, Michael Hornick, Chris Jonientz-Trisler, Mark Levitan, George Priest, Charles Roeder, and Jay Wilson. Peter N. Mork and Bernadette Hadnagy provided ATC report production services. The affiliations of these individuals are provided in the list of Project Participants.

ATC also gratefully acknowledges the input and guidance provided by Michael Mahoney (FEMA Project Officer), Robert Hanson (FEMA Technical Monitor), and William Holmes (ATC Project Technical Monitor).

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Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Objectives and Scope

Tsunamis are rare events often accompanied by advance warning. As such, strategies for mitigating tsunami risk have generally involved evacuation to areas of naturally occurring high ground outside of the tsunami inundation zone. Most efforts to date have focused on the development of more effective warning systems, improved inundation maps, and greater tsunami awareness to improve evacuation efficiency.

A Vertical Evacuation Refuge from Tsunamis is a building or earthen mound that has sufficient height to elevate evacuees above the level of tsunami inundation, and is designed and constructed with the strength and resiliency needed to resist the effects of tsunami waves.

In some locations, high ground may not exist, or tsunamis triggered by local events may not allow sufficient warning time for communities to evacuate low-lying areas. Where horizontal evacuation out of the tsunami inundation zone is neither possible nor practical, a potential solution is vertical evacuation into the upper levels of structures designed and detailed to resist the effects of a tsunami.

The focus of this document is on structures intended to provide protection during a short-term high-risk tsunami event. Such facilities are generally termed refuges. A *vertical evacuation refuge from tsunamis* is a building or earthen mound that has sufficient height to elevate evacuees above the level of tsunami inundation, and is designed and constructed with the strength and resiliency needed to resist the effects of tsunami waves.

This document is a resource for engineers, architects, state and local government officials, building officials, community planners, and building owners who are considering the construction and operation of tsunami-resistant structures that are intended to be a safe haven for evacuees during a tsunami event. It provides guidance on the design and construction of structures that could be used as a refuge for vertical evacuation above rising waters associated with tsunami inundation, and includes specific recommendations on loading, configuration, location, operation, and maintenance of such facilities. It is intended for use in areas of the United States that are exposed to tsunami hazard, but that should not preclude the use of this guidance for facilities located in other areas exposed to similar hazards.

1.2 Deciding to Construct a Vertical Evacuation Structure

Many factors influence the decision to construct a vertical evacuation structure, including:

- the likelihood of a region being affected by a tsunami event,
- the potential consequences of a tsunami event (e.g., damage, injury, and loss of life),
- the elements of a local emergency response plan, including available evacuation alternatives,
- the planned and potential uses for a refuge facility, and
- the cost of constructing a tsunami-resistant structure.

1.2.1 Tsunami Hazard versus Risk

Tsunami Hazard is a measure of the potential for a tsunami to occur at a given site.

Tsunami Risk is a measure of the consequences given the occurrence of a tsunami, which can be characterized in terms of damage, loss of function, injury and loss of life.

Hazard is related to the potential for an event to occur, while risk is related to consequences, given the occurrence of an event. Tsunami hazard is a measure of the potential for a tsunami to occur at a given site. It is also a measure of the potential magnitude of site-specific tsunami effects, including extent of inundation, height of runup, and velocity of flow. Tsunami risk is a measure of the consequences given the occurrence of a tsunami, which can be characterized in terms of damage, loss of function, injury and loss of life. Risk depends on many factors including vulnerability and population density.

Similar to other hazards (e.g., earthquake and wind) structural design criteria for tsunami effects are based on relative tsunami hazard. The decision to build a vertical evacuation structure, however, may ultimately be based on real or perceived risk to a local population as a result of exposure to tsunami hazard.

1.2.2 Decision-Making and Design Process

A flowchart outlining the decision-making and design process for vertical evacuation structures is shown in Figure 1-1.

Given a known or perceived tsunami threat in a region, the first step is to determine the severity of the tsunami hazard. This involves identification of potential tsunami-genic sources and accumulation of recorded data on tsunami occurrence and runup. Chapter 3 provides guidance on the assessment of tsunami hazard, which can include a probabilistic assessment considering all possible tsunami sources, or a deterministic assessment considering the maximum tsunami that can reasonably be expected to affect a site. Once potential tsunami sources are identified, and the level of tsunami hazard is known, site-specific information on the extent of inundation, height of runup, and velocity of flow is needed. Some of this information can be obtained from available tsunami inundation maps, where they exist; otherwise site-specific tsunami inundation studies must be performed.

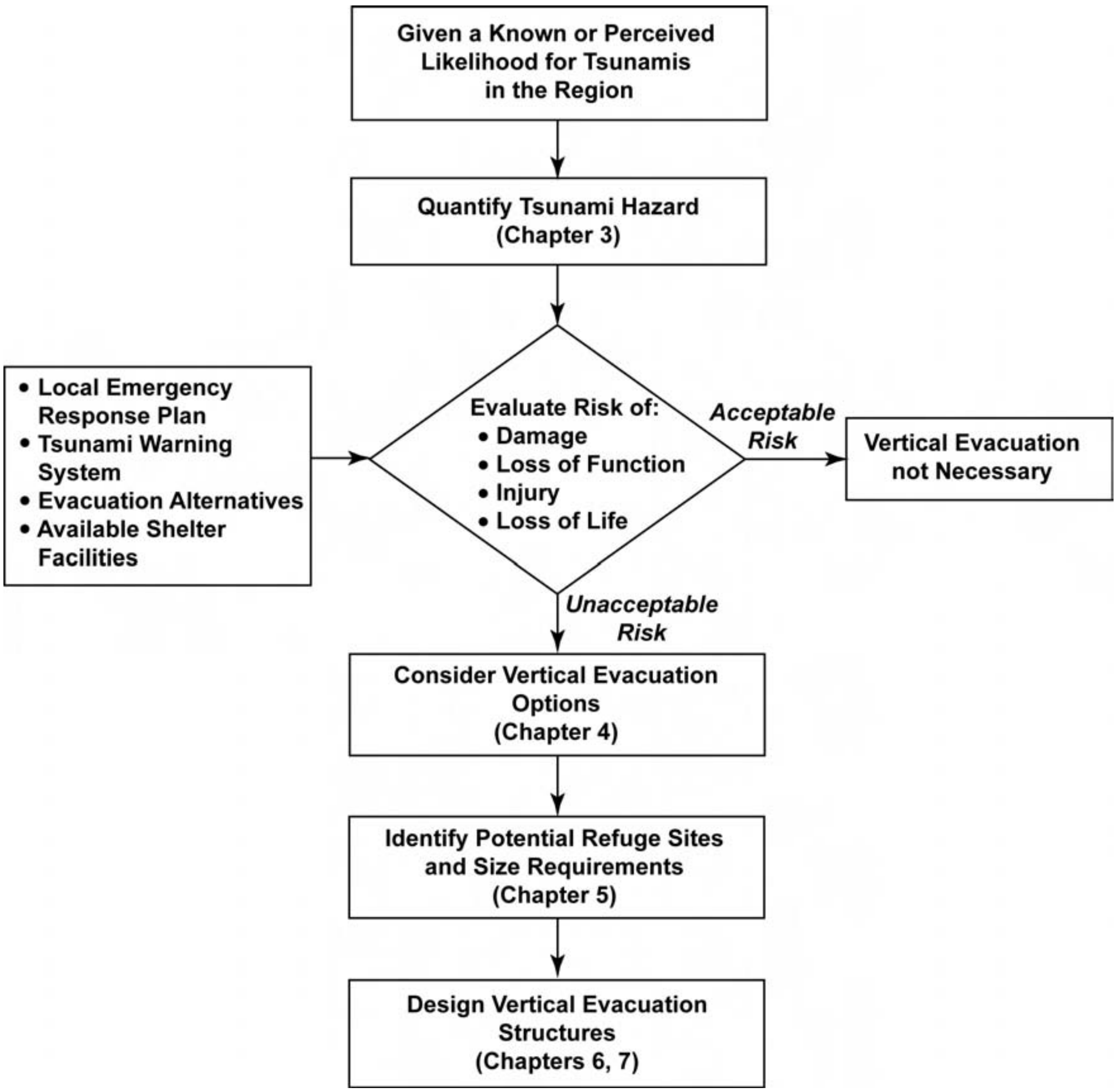


Figure 1-1 Decision-making and design process for vertical evacuation structures

Given the tsunami hazard and extent of inundation, the potential risk of damage, injury, and loss of life in the region must then be evaluated. Explicit evaluation of tsunami risk is beyond the scope of this document, and will depend on a number of different factors including the presence of a tsunami warning system, existence of a local emergency response plan, availability of various evacuation alternatives, vulnerability of the existing building stock, and locations of existing of short- and long-term shelter facilities. The feasibility of evacuation to existing areas of refuge, as well as the tsunami-resistance of these areas, must be considered. Vertical evacuation structures will likely be most useful when there is not enough time between the tsunami warning and tsunami inundation to allow a community to evacuate out of the inundation zone or to existing areas of high ground. In most cases this will be communities at risk for near-source-generated tsunamis.

Where the risk to a coastal community is deemed to be unacceptably high, vertical evacuation can be a possible solution for mitigating tsunami risk. Chapter 4 outlines a number of potentially viable options for design and construction of vertical evacuation structures.

Implementation of vertical evacuation requires a distribution of structures throughout the community that are suitable for providing refuge from the effects of tsunami inundation, and are appropriately sized for the population. Chapter 5 provides guidance on locating and sizing vertical evacuation structures.

Once the decision to utilize vertical evacuation is made, structures must be designed and constructed to be tsunami-resistant. Loading and other criteria for the design of vertical evacuation structures are provided in Chapters 6 and 7.

1.3 Limitations

This document is a compilation of the best information available at the time of publication. It provides guidance for design and construction of vertical evacuation structures that is currently not available in other design guides, building codes, or standards. It is not intended to supersede or replace current codes and standards, but rather to supplement them with guidance where none is otherwise provided. It is intended to provide specific recommendations and design criteria that are unique to tsunami loading conditions for vertical evacuation structures, once the decision has been made to build such a structure. It is not intended to mandate or imply that all structures in tsunami hazard areas should be made tsunami-resistant using these criteria. Such a decision would be cost-prohibitive, especially for light-frame residential structures.

Vertical evacuation structures designed in accordance with the guidance presented in this document would be expected to provide safe refuge under the assumed design conditions. For these structures, multiple design assumptions are required, including the intensity of a local earthquake that could threaten the structure prior to a tsunami, the flow depths and velocities of the design tsunami at the site, and the type of waterborne debris that may be characteristic at the site. Maximum loading must therefore be considered uncertain, and conservative assumptions should be made, particularly since these structures are expected to provide security and safety to the public.

Large damaging tsunamis are rare events, and existing knowledge is based on limited historic information. Coastal inundation patterns are based on complex combinations of many parameters, and are highly uncertain. Proportioning a structure for a design tsunami event does not necessarily mean the structure will be able to resist every possible tsunami event. Selection of the design tsunami is therefore based on the tsunami hazard in a region, the risk tolerance of a local community, and economic considerations.

1.4 Organization

This document provides guidance on siting concepts, performance objectives, design loads, design concepts, and emergency management issues that should be considered in locating, designing, and operating vertical evacuation structures as a refuge from tsunamis. Examples are presented that illustrate how the criteria are used. Information contained in this document is organized as follows:

Chapter 1 defines the scope and limitations for the guidance contained in this document. Chapter 2 provides background information on tsunami effects and their potential impacts on buildings in coastal communities. Chapters 3 through 7 provide design guidance on characterization of tsunami hazard, choosing between various options for vertical evacuation structures, locating and sizing vertical evacuation structures, estimation of tsunami load effects, structural design criteria, design concepts, and other considerations.

Appendices A through E provide supplemental information, including examples of vertical evacuation structures from Japan, example tsunami load calculations, a community design example, development of impact load equations, and background on maximum flow velocity and momentum flux in the tsunami runup zone.

A Glossary defining terms used throughout this document, and a list of References identifying resources for additional information, are also provided.

Chapter 2

Background

2.1 General

Tsunami is a Japanese word meaning “harbor” (tsu) and “wave” (nami). The term was created by fishermen who returned to port to find the area surrounding the harbor devastated. It is a naturally occurring series of waves that can result when there is a rapid, large-scale disturbance of a body of water. The most common triggering events are earthquakes below or near the ocean floor, but a tsunami can also be created by volcanic activity, landslides, undersea slumps, and impacts of extra-terrestrial objects. The waves created by this disturbance propagate away from the source. In deep water, the waves are gentle sea-surface slopes that can be unnoticeable. As the waves approach the shallower waters of the coast, however, the velocity decreases while the height increases. Upon reaching the shoreline the waves can have hazardous height and force, penetrating inland, damaging structures, and flooding normally dry areas.

A Tsunami is a naturally occurring series of ocean waves resulting from a rapid, large-scale disturbance in a body of water, caused by earthquakes, landslides, volcanic eruptions, and meteorite impacts.

In this document, tsunamis are categorized by the location of the triggering event and the time it takes the waves to reach a given site. A far-source-generated tsunami is one that originates from a source that is far away from the site of interest, and takes 2 hours or longer after the triggering event to arrive. A near-source-generated tsunami is one that originates from a source that is close to the site of interest, and can arrive within 30 minutes. Sites experiencing near-source-generated tsunamis will generally feel the effects of the triggering event (e.g., shaking caused by a near-source earthquake). A mid-source-generated tsunami is one in which the source is somewhat close to the site of interest, but not close enough for the effects of the triggering event to be felt at the site. Mid-source-generated tsunamis would be expected to arrive between 30 minutes and 2 hours after the triggering event.

A far-source-generated tsunami is one that originates from a source that is far away from the site of interest, and takes 2 hours or longer after the triggering event to arrive.

A near-source-generated tsunami is one that originates from a source that is close to the site of interest, and arrives within 30 minutes. The site of interest might also experience the effects of the triggering event.

A mid-source-generated tsunami is one in which the source is somewhat close to the site of interest, and would be expected to arrive between 30 minutes and 2 hours after the triggering event.

2.1.1 Historic Tsunami Activity

The combination of a great ocean seismic event with the right bathymetry can have devastating results, as was brought to the world’s attention by the Indian Ocean Tsunami of December 26, 2004. The tsunami created by the magnitude-9.3 underwater earthquake devastated coastal areas around the northern Indian Ocean. The tsunami took anywhere from 15 minutes to 7 hours to hit the various coastlines it affected. It is estimated that the tsunami took over 220,000 lives and displaced over 1.5 million people.

Wave propagation times from far-source-generated tsunamis can allow for advance warning to distant coastal communities. Near-source-generated tsunamis, however, can strike suddenly and with very little warning. The 1993 tsunami that hit Okushiri, Hokkaido, Japan, for example, reached the shoreline within 5 minutes after the earthquake, and resulted in 202 fatalities as victims were trapped by debris from the earthquake and unable to flee toward higher ground and more secure places.

Although considered rare events, tsunamis occur on a regular basis around the world. Each year, on average, there are 20 tsunami-genic earthquake events, with five of these large enough to generate tsunami waves capable of causing damage and loss of life. In the period between 1990 and 1999 there were 82 tsunamis reported, 10 of which resulted in more than 4,000 fatalities. With the trend toward increased habitation of coastal areas, more populations will be exposed to tsunami hazard.

Relative tsunami hazard can be characterized by the distribution and frequency of recorded runups. Table 2-1 provides a qualitative assessment of tsunami hazard for regions of the United States that are threatened by tsunamis, as it has been characterized by the National Oceanic & Atmospheric Administration (NOAA) using the last 200 years of data on recorded runups.

Table 2-1 Qualitative Tsunami Hazard Assessment for U.S. Locations (Dunbar, et. al., 2008)

Region	*Hazard Based on Recorded Runups*	*Hazard Based on Frequency of Runups*
Atlantic Coast	Very low to low	Very low
Gulf Coast	None to very low	None to very low
Caribbean	High	High
West Coast	High	High
Alaska	Very high or severe	Very high
Hawaii	Very high or severe	Very high
Western Pacific	Moderate	High

Alaska is considered to have the highest potential for tsunami generating events in the United States. Earthquakes along the Alaska-Aleutian subduction zone, particularly in the vicinity of the Alaskan Peninsula, the Aleutian Islands, and the Gulf of Alaska have the capability of generating tsunamis that affect both local and distant sites. The 1964 earthquake in Prince William Sound resulted in 122 fatalities, including 12 in California and 4 in Oregon. In 1994 a landslide-generated tsunami in Skagway Harbor resulted in one death and $21 million in property damage.

The Cascadia subduction zone along the Pacific Northwest coast poses a threat from northern California to British Columbia, Canada. An earthquake along the southern portion of the Cascadia subduction zone could create tsunami waves that would hit the coasts of Humboldt and Del Norte counties in California and Curry County in Oregon within a few minutes of the earthquake. Areas further north, along the Oregon and Washington coasts, could see tsunami waves within 20 to 40 minutes after a large earthquake.

Communities along the entire U.S. Pacific coastline are at risk for far-source-generated (trans-Pacific) tsunamis and locally triggered tsunamis. In southern California there is evidence that movement from local offshore strike-slip earthquakes and submarine landslides have generated tsunamis affecting areas extending from Santa Barbara to San Diego. The largest of these occurred in 1930, when a magnitude-5.2 earthquake reportedly generated a 20-foot-high wave in Santa Monica, California (California Geological Survey, 2006).

Hawaii, located in the middle of the Pacific Ocean, has experienced both far-source-generated tsunamis and locally triggered tsunamis (Pararas-Carayannis, 1968). The most recent damaging tsunami occurred in 1975, the result of a magnitude-7.2 earthquake off the southeast coast of the island of Hawaii. This earthquake resulted in tsunami wave heights more than 20 feet and, in one area, more than 40 feet. Two deaths and more than $1 million in property damage were attributed to this local Hawaiian tsunami (Pararas-Carayannis, 1976).

Although the Atlantic and Gulf Coast regions of the United States are perceived to be at less risk, there are examples of deadly tsunamis that have occurred in the Atlantic Ocean. Since 1600, more than 40 tsunamis and tsunami-like waves have been cataloged in the eastern United States. In 1929, a tsunami generated in the Grand Banks region of Canada hit Nova Scotia, killing 51 people (Lockridge et al., 2002).

Puerto Rico and the U.S. Virgin Islands are at risk from earthquakes and underwater landslides that could occur in the Puerto Rico Trench subduction zone. Since 1530, more than 50 tsunamis of varying intensity have occurred in the Caribbean. In 1918, an earthquake in this zone generated a tsunami that caused an estimated 40 deaths in Puerto Rico. In 1867, an earthquake-generated tsunami caused damage and 12 deaths on the islands of Saint Thomas and Saint Croix. In 1692 a tsunami generated by massive landslides in the Puerto Rican Trench reached the coast of Jamaica, causing an estimated 2,000 deaths (Lander, 1999).

2.1.2 Behaviors and Characteristics of Tsunamis

Tsunami wave periods can range from a few minutes to over 1 hour, resulting in an increased potential for reflection, amplification, or resonance within coastal features.

Information from historic tsunami events indicates that tsunami behaviors and characteristics are quite distinct from other coastal hazards, and cannot be inferred from common knowledge or intuition. The primary reason for this distinction is the unique timescale associated with tsunami phenomena. Unlike typical wind-generated water waves with periods between 5 and 20 sec, tsunamis can have wave periods ranging from a few minutes to over 1 hour (FEMA, 2005). This timescale is also important because of the potential for wave reflection, amplification, or resonance within coastal features. Table 2-2 compares various coastal hazard phenomena.

Table 2-2 Comparison of Relative Time and Loading Scales for Various Coastal Hazard Phenomena

Coastal Hazard Phenomenon	*Time scale (Duration of Loading)*	*Loading Scale (Height of Water)*	*Typical Warning Time*
Wind-generated waves	Tens of seconds	1 to 2 meters typical	Days
Tsunami runup	Tens of minutes to an hour	1 to 10 meters	Several minutes to hours
Hurricane storm surge	Several hours	1 to 10 meters	Several hours to a few days
Earthquake shaking	Seconds	N/A	Seconds to none

There is significant uncertainty in the prediction of hydrodynamic characteristics of tsunamis because they are highly influenced by the tsunami waveform and the surrounding topography and bathymetry. Although there are exceptions, previous research and field surveys indicate that tsunamis have the following general characteristics:

- The magnitude of the triggering event determines the period of the resulting waves, and generally (but not always) the tsunami magnitude and damage potential (FEMA, 2005).
- A tsunami can propagate more than several thousand kilometers without losing energy.
- Tsunami energy propagation has strong directivity. The majority of its energy will be emitted in a direction normal to the major axis of the tsunami source. The more elongated the tsunami source, the stronger the directivity (Okal, 2003; Carrier and Yeh, 2005). Direction of approach

can affect tsunami characteristics at the shoreline, because of the sheltering or amplification effects of other land masses and offshore bathymetry (FEMA, 2005). A numerical example for the 2004 Indian Ocean Tsunami is shown in Figure 2-1.

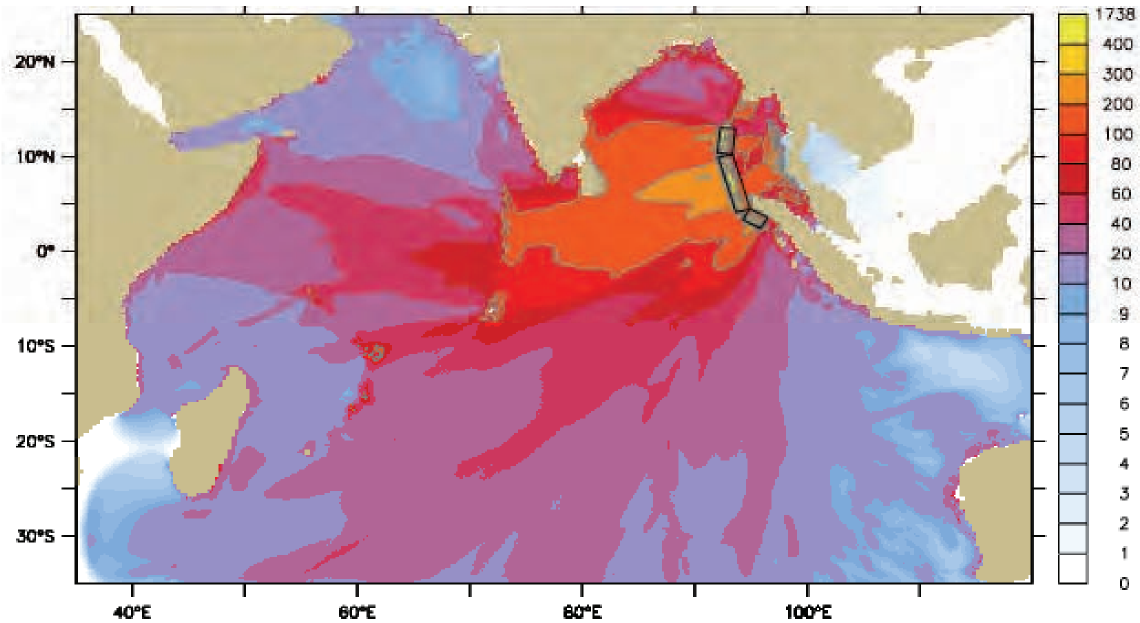
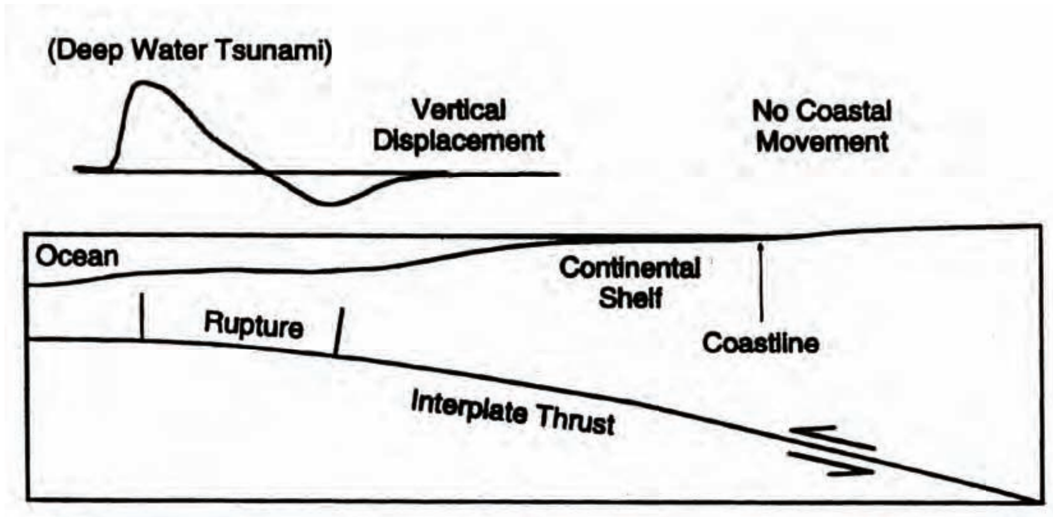


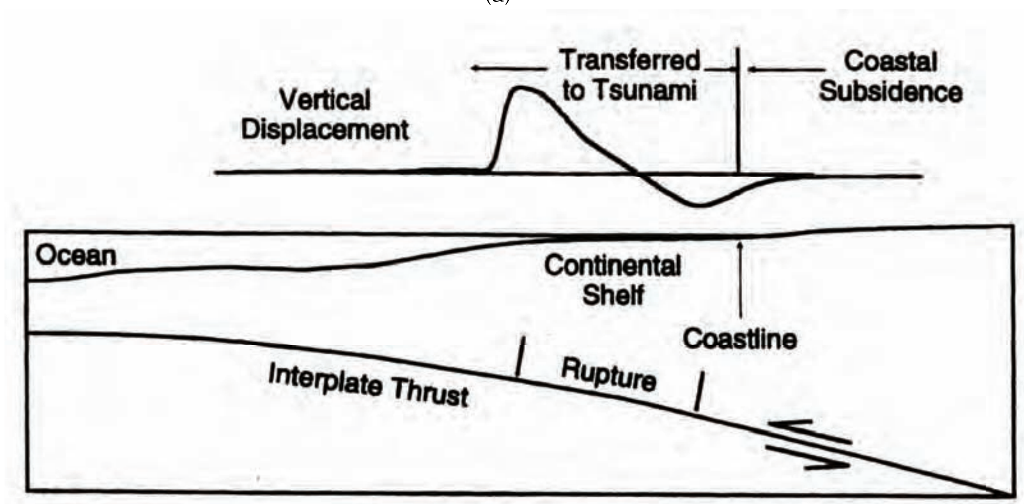
Figure 2-1 Maximum computed tsunami amplitudes (in centimeters) in the Indian Ocean (Titov, NOAA Center for Tsunami Research, http://nctr.pmel.noaa.gov/indo_1204.html)

- At the source, a tsunami waveform contains a wide range of wave components, from short to long wavelengths. Long wave components propagate faster than short wave components; therefore, a transoceanic tsunami is usually characterized by long-period waves (several to tens of minutes). Shorter wave components are left behind and attenuated by radiation and dispersion.

- For a locally generated tsunami, the first leading wave is often a receding water level followed by an advancing positive heave (an elevation wave). This may not be the case if the coastal ground subsides by co-seismic displacement. For far-source-generated tsunamis, the leading wave is often an elevation wave. This trend may be related to the pattern of sea floor displacement resulting from a subduction-type earthquake, shown schematically in Figure 2-2. Figure 2-3 shows a leading depression wave measured at a tide gage station in Thailand during the 2004 Indian Ocean Tsunami, in contrast with a leading elevation wave measured at the southern end of India.



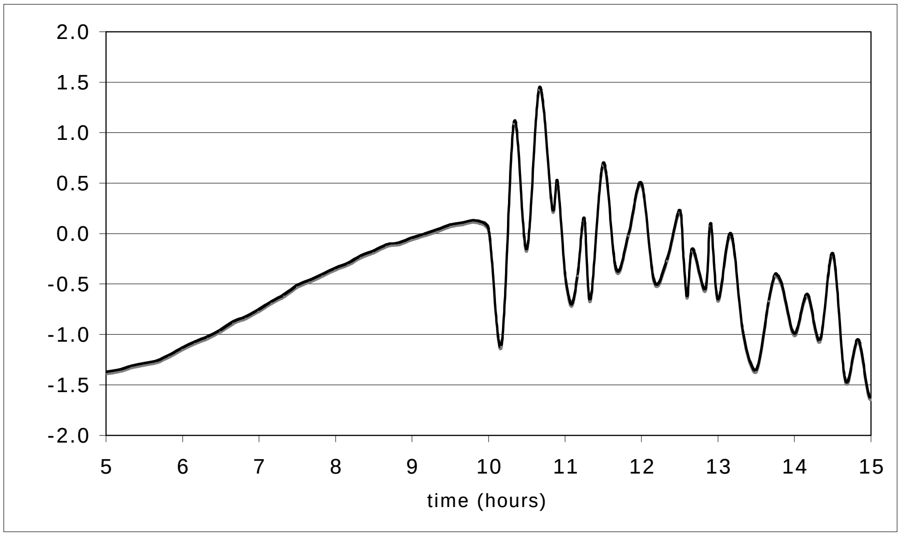
(a)



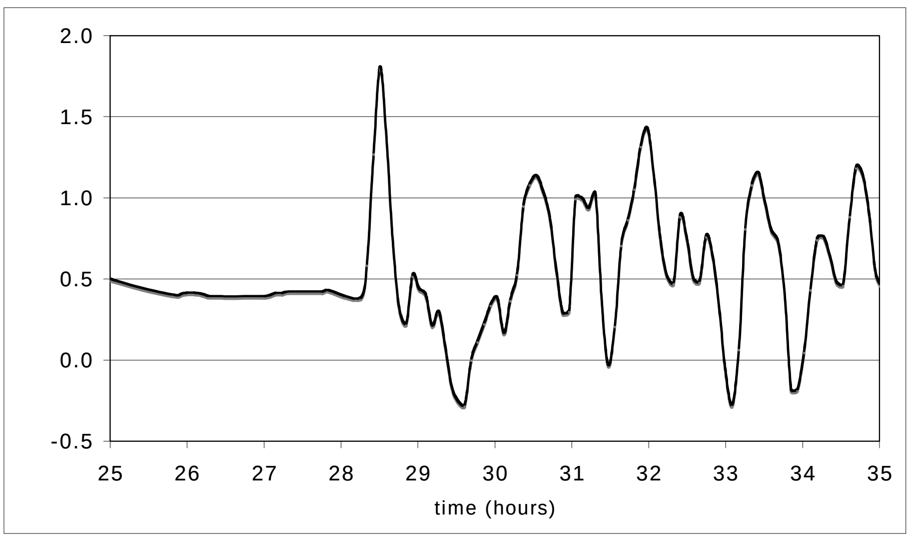
(b)

Figure 2-2 Schematic diagrams of the vertical displacement resulting from subduction-type fault dislocation: (a) rupture zone located far offshore; and (b) rupture zone adjacent to coastline with coastal subsidence (Geist, 1999).

- Tsunamis are highly reflective at the shore, and capable of sustaining their motion for several hours without dissipating energy. Typically several tsunami waves attack a coastal area, and the first wave is not necessarily the largest. Sensitive instrumentation can detect tsunami activity for several days.



(a)



(b)

Figure 2-3 Tide gage records (in meters) for the 2004 Indian Ocean tsunami at: (a) Ta Phao Noi, Thailand, showing the leading depression wave; and (b) Tuticorin, India, showing the leading elevation wave).

- Tsunami runup height varies significantly in neighboring areas. The configuration of the continental shelf and shoreline affect tsunami impacts at the shoreline through wave reflection, refraction, and shoaling. Variations in offshore bathymetry and shoreline irregularities can focus or disperse tsunami wave energy along certain shoreline reaches, increasing or decreasing tsunami impacts (FEMA, 2005).

Tsunami runup heights vary significantly in neighboring areas due to variations in offshore bathymetry that can increase or decrease local tsunami impacts.

Figure 2-4 shows significant variation in runup heights measured along the northwest coastline of Okushiri Island.

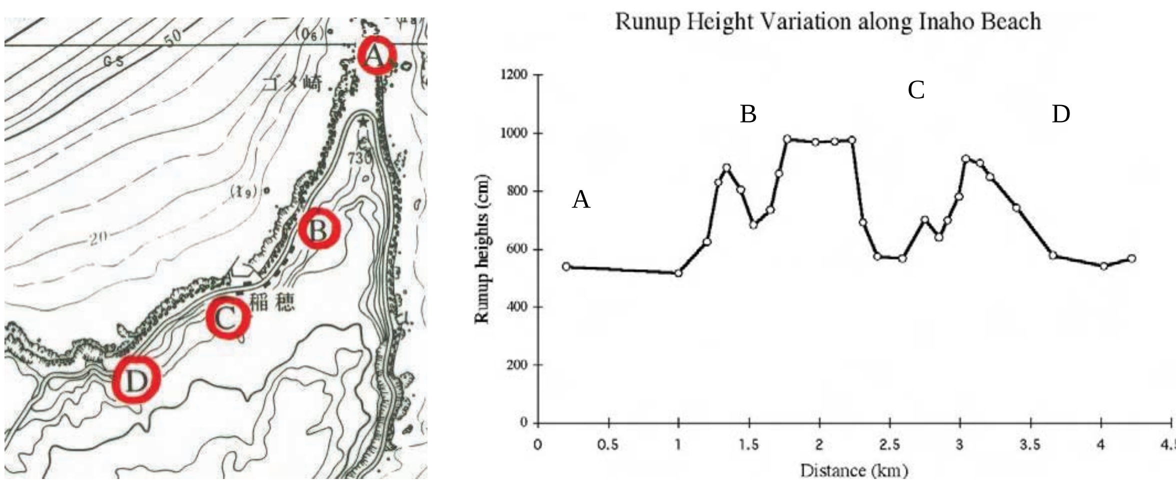


Figure 2-4 Measured runup heights of the 1993 Okushiri tsunami along Inaho Coast, demonstrating that runup height varies significantly between neighboring areas.

- The majority of eyewitness accounts and visual records (videos and photos) indicate that an incident tsunami will break offshore forming a bore or a series of bores as it approaches the shore. A turbulent bore is defined as a broken wave having a steep, violently foaming and turbulent wave front, propagating over still water of a finite depth, as shown in Figure 2-5. These broken waves (or bores) are considered relatively short waveforms (although still longer than wind-generated waves) riding on a much longer main heave of the tsunami. Such bore formations were often observed in video footage of the 2004 Indian Ocean tsunami.

Figure 2-5 Sketch of a bore and photo of the 1983 Nihonkai-Chubu Tsunami showing the formation of a bore offshore (Photo from Knill, 2004).

- After a bore reaches the shore, the tsunami rushes up on dry land in the formation of a surge, as shown in Figure 2-6. In some cases, especially when a long-wavelength, leading-elevation, and far-source-generated tsunami attacks land on a steep slope, the runup can be characterized as a gradual rise and fall of water (i.e., surge flooding) as shown in Figure 2-7. The impact of the 1960 Chilean tsunami at some Japanese localities and the 1964 Alaska tsunami at the town of Port Alberni, Canada are classic examples of surge flooding.

Figure 2-6 Sketch of a surge and photo of the 1983 Nihonkai-Chubu Tsunami showing the formation of a surge (Photo courtesy of N. Nara).

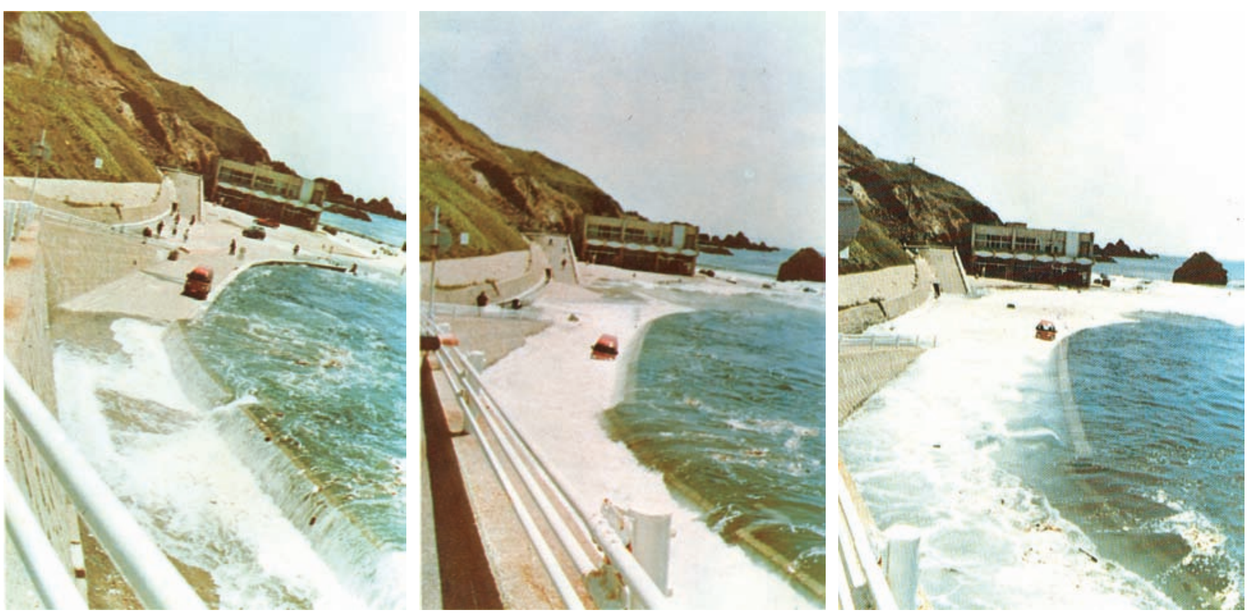


Figure 2-7 A sequence of photos of the 1983 Nihonkai-Chubu Tsunami showing surge flooding from tsunami runup (Photo courtesy of S. Sato).

2.2 Tsunami Effects on Buildings

Damage studies from historic tsunami events, the 2004 Indian Ocean Tsunami, and storm surge associated with Hurricane Katrina in 2005 have provided information on the response of the built environment to devastating tsunamis and coastal flooding. Although there is considerable damage to, and often total destruction of, residential and light-framed buildings during extreme coastal flooding, there are also numerous examples of mid- to high-rise engineered structures that survived tsunami inundation.

> There are numerous examples of mid- to high-rise engineered structures that have survived tsunami inundation.

Structural damage from tsunamis can be attributed to: (1) direct hydrostatic and hydrodynamic forces from water inundation; (2) impact forces from water-borne debris; (3) fire spread by floating debris and combustible liquids; (4) scour and slope/foundation failure; and (5) wind forces induced by wave motion.

2.2.1 Historic Data on Tsunami Effects

Studies of damage from historic tsunamis have shown that building survivability varies with construction type and tsunami runup height (Yeh et al., 2005). Figure 2-8 shows data on damage for various types of construction resulting from the 1993 Okushiri Tsunami and earlier tsunamis.

For a given tsunami height, wood frame construction experienced considerably more damage and was frequently destroyed, while reinforced concrete structures generally sustained only minor structural damage. Recent data, including those of the 2004 Indian Ocean Tsunami, support this conclusion.

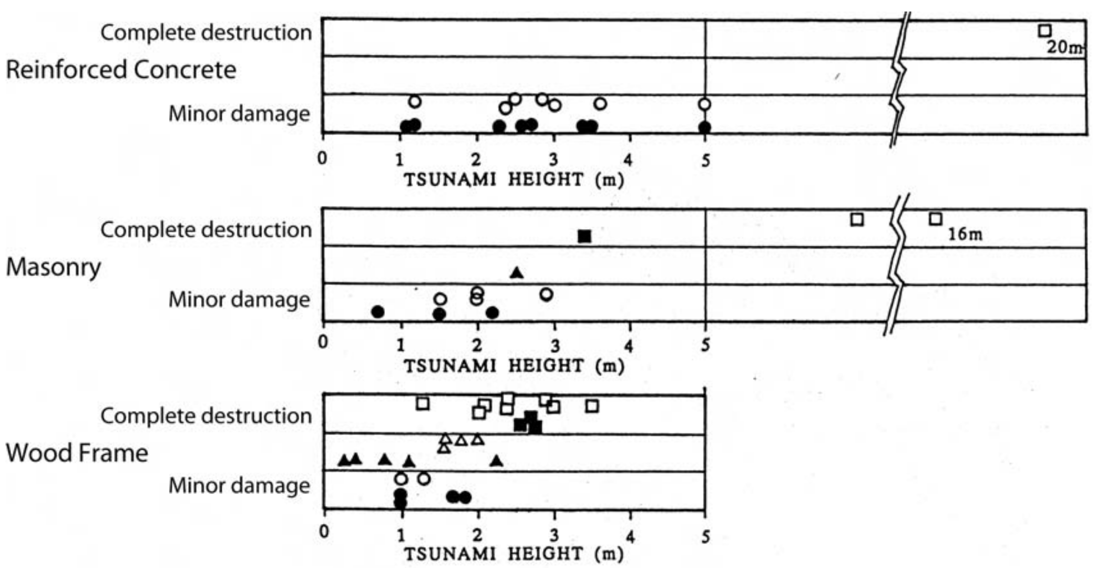


Figure 2-8 Degrees of building damage vs. tsunami runup height. Marks filled in black are data from the 1993 Okushiri tsunami; hollow marks are data from previous tsunami events (adapted from Shuto, 1994, Yeh, et al., 2005).

Note that the total destruction of one concrete structure is identified in Figure 2-8. This structure was the lighthouse at Scotch Cap, Unimak Island. The Scotch Cap lighthouse is shown in Fig. 2-9, before and after the 1946 Aleutian Tsunami. There is some question as to how well the lighthouse was constructed, but it is possible that its destruction was the result of a wave breaking directly onto the structure, which was located right at the shoreline. The breaking wave could have been equivalent to a "collapsing" breaker, one of the classifications of wave breakers used in coastal engineering (Weigel, 1964) that occurs at shorelines with steeply sloping beaches.

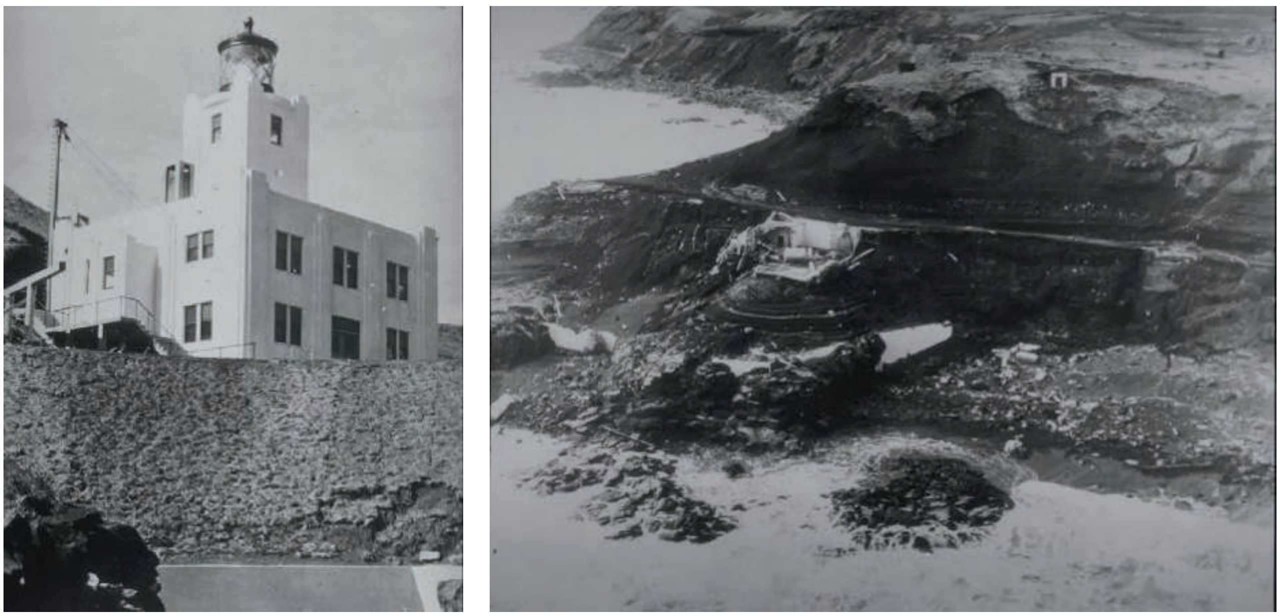


Figure 2-9 Scotch Cap Lighthouse destroyed by the 1946 Aleutian Tsunami

The 1993 Okushiri Tsunami completely destroyed the entire town of Aonae. Figure 2-10 shows bare concrete foundations typically observed as remnants of wood-frame residential construction after the tsunami.

The 1992 Nicaragua Tsunami event provided other examples of variations in the performance of different structures. Figure 2-11 shows severe scour and complete destruction of a grade-level wood-frame house (left), and survival of an elevated wood frame and a grade-level rigid masonry structure (right). All three houses were located on a beach berm in the same vicinity, less than 200 meters apart.

Building failures have been observed when waterborne debris traveling at significant speeds impacts buildings. An example of the destruction caused by the impact of water-borne debris from the 1993 Okushiri Tsunami is shown in Figure 2-12. The debris in this case was a fishing boat that had broken free from its moorings. Waterborne debris is also known to collect between structural supports creating a barrier that can significantly increase hydraulic forces on the building.

Figure 2-10 Total destruction of a group of wood-frame houses in Aonae Village, Okushiri, Island, Japan (1993 Okushiri Tsunami).

Figure 2-11 Beach houses with varying levels of damage in El Popoyo, Nicaragua (1992 Nicaragua Tsunami). All three houses are in the same vicinity.

Figure 2-12 Damage caused by impact from water-borne debris (fishing boat) in Aonae, Japan (1993 Okushiri Tsunami) (Photo courtesy J. Preuss).

In contrast to the many failures reported as a result of past tsunamis, many structures have been observed to survive tsunami inundation. Two structures that survived the 1993 Okishiri Tsunami are shown in Figure 2-13. Both are two-story reinforced concrete structures, and both were inundated by at least 3 meters of water.

Figure 2-13 Examples of reinforced concrete structures that survived the 1993 Okushiri Tsunami: vista house at Cape Inaho (left); and fish market in Aonae (right) (Photo courtesy N. Shuto).

2.2.2 Observations from the Indian Ocean Tsunami

Damage observed as a result of the 2004 Indian Ocean tsunami confirmed observations from historic data on tsunami effects, and provided new evidence on observed effects.

Figure 2-14 shows a damaged unreinforced masonry house in Devanaanpattinam, India. Foundations experienced severe scour, and the rear walls were forced out by hydraulic pressure due to flooding inside the house. This type of damage is commonly observed in masonry buildings.

Figure 2-14 Damaged masonry beach house in Devanaanpattinam, India (2004 Indian Ocean Tsunami).

As observed in past tsunamis, numerous engineered buildings survived the 2004 Indian Ocean Tsunami. In some instances, there was damage to structural elements at the lower levels, but seldom to an extent that led to total collapse of the structure. One example of a surviving structure is a mosque located at the waters edge in Uleele, Banda Aceh, shown in Figure 2-15. The inundation depth at the mosque was about 10 m (just under the roof line), and the surrounding town was destroyed. The mosque suffered significant damage but was still standing.

Dalrymple and Kriebel (2005) commented that the survival of many hotel buildings in Thailand was due in part to the relatively open nature of the first floor construction, so that “these buildings suffered little structural damage as the force of the tsunami broke through all of the doors and windows, thus reducing the force of the water on the building itself.”

The 2004 Indian Ocean Tsunami provided additional evidence of the effects of waterborne debris impact and scour on structural elements. Examples of waterborne debris included fishing boats and vehicles (Figure 2-16). Damage to structural elements of non-engineered reinforced concrete buildings was attributed to impact from such debris (Figure 2-17). Examples are also evident where debris damming resulted in damage to structural members (Figure 2-18). An example of observed scour below a shallow foundation is shown in Figure 2-19. From a review of available data taken by various survey teams, it appears that the maximum scour depth measured onshore was 3m in Khao Lak, Thailand.

Figure 2-15 Example of surviving reinforced concrete mosque in Uleele, Banda Aceh (Photo courtesy J. Borerro)

Figure 2-16 Examples of waterborne debris from the 2004 Indian Ocean Tsunami (Photos courtesy of M. Saatcioglu, A. Ghobarah and I. Nistor, CAEE, 2005).

A noteworthy structural failure encountered in the 2004 Indian Ocean Tsunami was uplift of precast concrete panels in buildings and docks (Figure 2-20). Uplift forces were sufficient to lift the concrete panels and break attachments between the panels and the supporting members. These failures cannot be explained by buoyancy effects alone, which reduce net downward gravity forces by the volume of water displaced. Net uplift forces sufficient to fail these elements have been attributed to additional buoyancy effects due to trapped air and vertical hydrodynamic forces caused by the rising water.

Figure 2-17 Damage to non-engineered concrete columns due to debris impact (Photos courtesy of M. Saatcioglu, A. Ghobarah and I. Nistor, CAEE, 2005).

Figure 2-18 Damage to corner column due to debris damming (Photo courtesy of M. Saatcioglu, A. Ghobarah and I. Nistor, CAEE, 2005).

Figure 2-19 Scour around shallow spread footing in Khao Lak area (Dalrymple and Kriebel, 2005).

Figure 2-20: Uplift damage to precast concrete floor panels and harbor piers (Photo courtesy of M. Saatcioglu, A. Ghobarah and I. Nistor, CAEE, 2005).

Also, lack of adequate seismic capacity led to a number of collapses of multistory reinforced concrete buildings in Banda Aceh and other areas near the epicenter of the magnitude-9.3 earthquake that triggered the tsunami (Figure 2-21). These collapses occurred prior to inundation by tsunami waves, and highlight the importance of providing adequate seismic resistance in addition to tsunami resistance in regions where both hazards exist.

2.2.3 Observations from Hurricane Katrina

The storm surge along the Mississippi Gulf coast was estimated to have been between 25 and 28 feet during Hurricane Katrina (FEMA 548, 2006). This resulted in extensive inundation of low-lying coastal regions from New Orleans, Louisiana to Mobile, Alabama.

(a) Beam-column connection failures

(b) Soft story failure

Figure 2-21. Examples of structural collapse due to strong ground shaking in Banda Aceh prior to tsunami inundation. (Photos courtesy of M. Saatcioglu, A. Ghobarah and I. Nistor, CAEE, 2005).

While hurricane storm surge and tsunami inundation both result in coastal flooding, the characteristic behavior of this flooding can be quite different. Hurricane storm surge typically inundates coastal areas for a longer duration (several hours) with repeated pounding from wave action and gusting winds. Tsunami inundation generally takes place over a shorter time period (tens of minutes) with rapidly changing water levels and sweeping currents. Because of these differences, extrapolation of conclusions from hurricane storm surge effects to tsunami inundation effects is necessarily limited. In spite of these differences, however, observations from Hurricane Katrina appear to support many of the effects documented with tsunami inundation and the conclusions drawn from historic tsunami data.

Observations from **Hurricane Katrina** appear to support many of the effects documented with tsunami inundation and the conclusions drawn from historic tsunami data.

The worst storm surge in Hurricane Katrina was experienced between Pass Christian and Biloxi along the Mississippi coast, and thousands of light-framed single- and multi-family residences were totally destroyed or badly damaged by this surge (FEMA 549, 2006). However, consistent with observations from past tsunamis, most multi-story engineered buildings along the coastline survived the surge with damage to nonstructural elements at the lower levels (Figures 2-22 to 2-24).

Figure 2-22 Gulf Tower Apartment building suffered substantial non-structural damage at the ground floor level, but remained structurally sound (Hurricane Katrina, 2005).

Figure 2-23 Pass Christian office building with cast-in-place concrete pan joist floor system that suffered non-structural damage at first two floors but no structural damage (Hurricane Katrina, 2005).

Figure 2-24 Condominium building in Gulfport, Mississippi, with wave and storm surge damage to non-structural elements at the ground floor, but no reported structural damage (FEMA 549, 2006).

Also consistent with past tsunami observations, Hurricane Katrina illustrated the effects of debris impact and damming. At the parking garage structure shown in Figure 2-25, impact from a barge-mounted casino failed a lower level column resulting in progressive collapse of the surrounding portions of the structure. In Figure 2-26, damming effects were significant enough to fail a series of prestressed concrete piles at a construction site when a shipping container lodged between the piles and blocked the surge flow.

Similar to uplift failures observed in the 2004 Indian Ocean Tsunami, uplift loading applied to the underside of floor systems is blamed for the collapse of elevated floor levels in numerous engineered structures. Parking garages constructed of precast prestressed concrete double-tee sections, like the one shown in Figure 2-27, were susceptible to upward loading caused by additional buoyancy forces from air trapped below the double-tee sections and upward hydrodynamic forces applied by the surge and wave action. Although most failures of this type did not result in collapse of the entire structure, loss of floor framing can lead to column damage, increased unbraced lengths, and progressive collapse of a disproportionate section of the building as shown in Figure 2-28. Cast-in-place concrete parking structures did not experience this type of failure.

Figure 2-25 Progressive collapse of upper floors of a parking garage due to damage in lower level columns from impact of an adjacent barge-mounted casino (Hurricane Katrina, 2005).

Figure 2-26 Failure of prestressed piles due to damming effect of shipping container (Hurricane Katrina, 2005).

2.2.4 Implications for Tsunami-Resistant Design

There is much evidence that appropriately designed structural systems can survive tsunami inundation.

This enables consideration of vertical evacuation as a viable alternative when horizontal evacuation out of the inundation zone is not feasible.

Building survivability varies with construction type and tsunami runup height. While observations from past tsunamis show that certain types of construction are largely destroyed by high-velocity water flow, there is much evidence that appropriately designed structural systems can survive tsunami inundation with little more than nonstructural damage in the lower levels, and can continue to support the levels of a building above the flood depth. This enables consideration of vertical evacuation as a viable alternative when horizontal evacuation out of the inundation zone is not feasible.

Observed effects from historic tsunami data, the 2004 Indian Ocean Tsunami, and supporting evidence from extreme storm surge flooding associated with Hurricane Katrina result in the following implications for tsunami-resistant design:

- Vertical evacuation structures should be well-engineered reinforced concrete or steel frame structures.
- In the case of near-source generated tsunami hazards, vertical evacuation structures must be designed for seismic loading in addition to tsunami load effects.

Figure 2-27 Negative bending failure of a prestressed double-tee floor system due to uplift forces (Hurricane Katrina, 2005).

- Vertical evacuation structures should be located away from the wave breaking zone.
- Impact forces and damming effects from water-borne debris are significant and must be considered.
- When elevated floor levels are subject to inundation, uplift forces from added buoyancy due to trapped air and vertical hydrodynamic forces on the floor slab must be considered.
- Scour around the foundations must be considered.
- Because of uncertainty in the nature of water-borne debris and the potential for very large forces due to impact, progressive collapse concepts should be employed in the design of vertical evacuation structures to minimize the possibility of disproportionate collapse of the structural system.

Figure 2-28 Concrete frame of three-story apartment building that partially collapsed due to failure of the post-tensioned flat slab in the bay closest to the Gulf of Mexico (Hurricane Katrina, 2005).

Chapter 3
Tsunami Hazard Assessment

Tsunami hazard in a particular region is a combination of the presence of a geophysical tsunami source, exposure to tsunamis generated by that source, and the extent of inundation that can be expected as a result of a tsunami reaching the site. The consequences of that hazard to the population of a coastal community are a function of the time it takes a tsunami to propagate from a source to the site, maximum flood depth, maximum current velocity, integrity of the built environment, and the ability to evacuate to areas of refuge.

Modeling of tsunami inundation is a key component of tsunami hazard assessment. Current efforts to characterize tsunami hazard include:

The NOAA Tsunami Program: Forecast Modeling and Mapping

The National Tsunami Hazard Mitigation Program: Credible Worst-Case Scenarios

The FEMA Map Modernization Program: Probabilistic Tsunami Hazard Assessments

Inundation is a complex process influenced by many factors. These include the source characteristics that determine the nature of the initially generated waves, the bathymetry that transforms the waves as they propagate to the shoreline, the topography traversed, the structures and other objects encountered, and the temporal variation in bathymetry, topography, structures and other objects caused by the impact of successive waves. In general, the physics of tsunami inundation is time-dependent, three-dimensional, and highly nonlinear.

Modeling of tsunami inundation is a key component of tsunami hazard assessment. Progress has been made in the development of modeling tools, but theory is still under development. This chapter provides an overview of currently available modeling tools and associated products available through nationally coordinated efforts such as the NOAA Tsunami Program and the U.S. National Tsunami Hazard Mitigation Program (NTHMP).

3.1 Current Tsunami Modeling and Inundation Mapping

Site-specific inundation models and model-derived products, including maps, are essential for reliable tsunami hazard assessment. The NOAA Tsunami Program and the NTHMP are engaged in closely related modeling efforts. The NOAA Tsunami Program is focused on the development of the NOAA Tsunami Forecast System (Titov and Synolakis, 2005). The NTHMP Hazard Assessment effort is working on the development of inundation maps for emergency management programs (González, et al., 2005a). Both efforts are fundamentally dependent on tsunami numerical modeling technology.

Tsunami modeling studies generally result in products that include a spatial mapping of the model output in either static or animated form. Primary tsunami wave parameters include the amplitude $\eta(x,y,t)$ and associated current velocity components $u(x,y,t)$ and $v(x,y,t)$. A Geographic Information System (GIS) database of these output parameters and associated input data (e.g., model computational grids and source parameters) can be used to derive parameters such as flood depth, velocity, acceleration, and momentum flux.

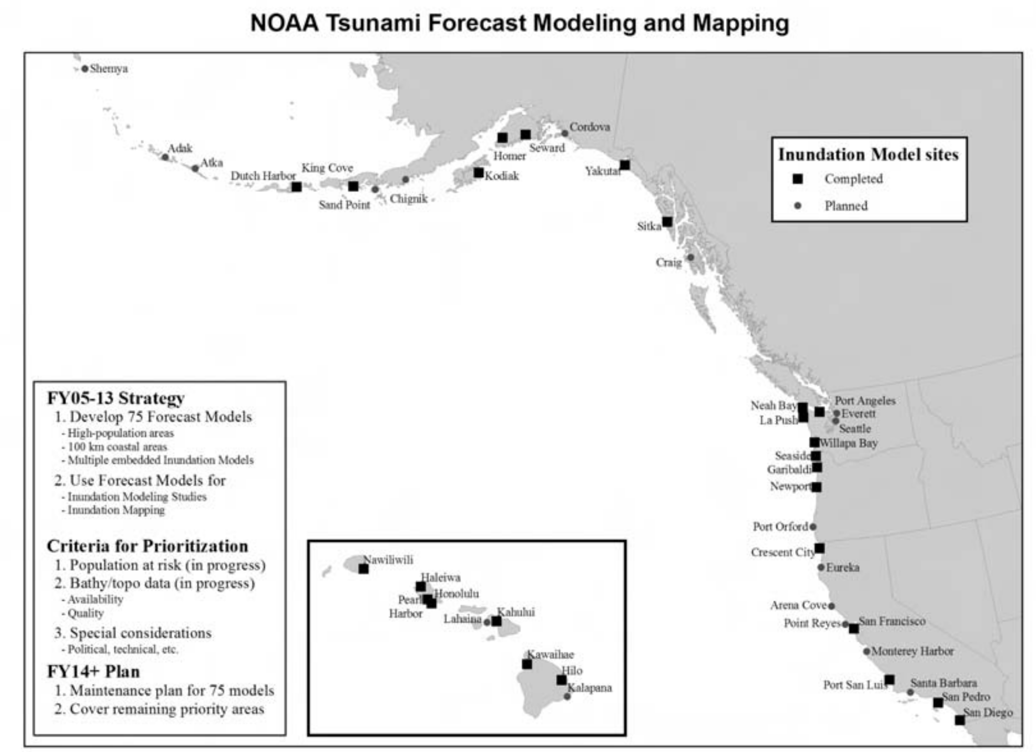
3.2 The NOAA Tsunami Program: Forecast Modeling and Mapping

As part of the Tsunami Forecasting System, NOAA is developing site-specific inundation models at 75 sites shown in Figure 3-1. The National Center for Tsunami Research (NCTR) at the Pacific Marine Environmental Laboratory (PMEL) in Seattle, Washington, has the primary responsibility for this forecast modeling and mapping effort. The first step at each site is the development of a Reference Model using a grid with the finest resolution available, followed by extensive testing against all available data to achieve the highest possible accuracy. The second step is development of the Standby Inundation Model (SIM), which is used as the forecast model. This is done through modification of the grid to optimize for speed, yet retain a level of accuracy that is appropriate for operational forecast and warning purposes.

The NCTR employs a suite of tsunami generation, propagation, and inundation codes developed by V.V. Titov (1997). On local spatial scales, nonlinear shallow water (NSW) equations are solved numerically. Propagation on regional and transoceanic spatial scales requires equations that are expressed in spherical coordinates. Propagation solutions are obtained by a numerical technique that involves a mathematical transformation known as splitting (Titov, 1997). Consequently, this suite of models has become known as the Method of Splitting Tsunamis (MOST) model.

Because life and property are at stake when tsunami warnings are issued, NOAA requires that models used in the Tsunami Forecasting System meet certain standards (Synolakis, 2006). Among the requirements are:

- *Peer-reviewed publication.* A peer-reviewed article must be published that documents the scientific and numerical essentials of the model and includes at least one model comparison study using data from an historical tsunami.



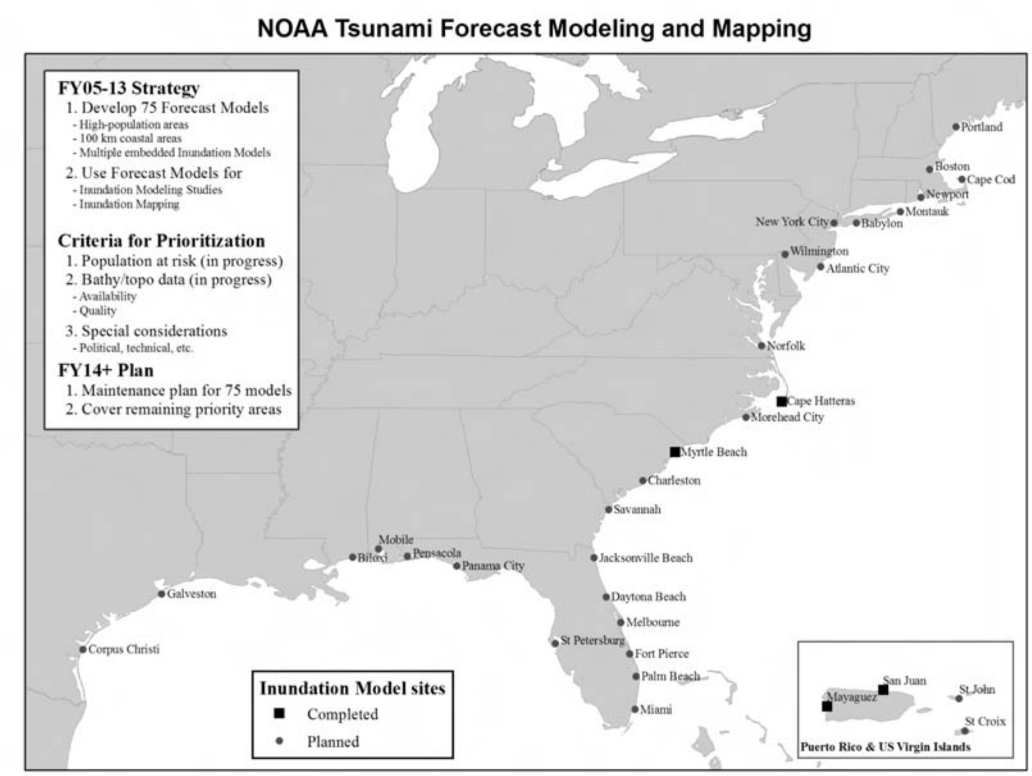


Figure 3-1 Coastal sites for site-specific tsunami inundation models for the Tsunami Forecasting System.

- *Benchmarking.* The model must be tested against other peer models in a benchmark workshop, and the results documented in a report. The National Science Foundation has supported two tsunami inundation modeling benchmark workshops (Yeh, et al., 1996; Liu, et al., 2006).
- *Operational assessment*. Important factors to be assessed include the model speed, accuracy, special operating environment needs, ease of use, and documentation.

Models meeting these requirements include the ADCIRC model (Luettich and Westerink, 1991, 1995a, and 1995b; Myers and Baptista, 1995), hydrodynamic models of Kowalik and Murty (1993a, 1993b) as applied and field-checked against observed inundation in Alaska by Suleimani and others (2002a; 2002b), and the MOST model (Titov and Synolakis, 1998).

The MOST model has been extensively tested against laboratory experimental data and deep-ocean and inundation field measurements, and by successful modeling of benchmarking problems through participation in NSF-sponsored tsunami inundation model benchmark workshops.

As of June 2008, reference inundation models and forecast models have been completed using the MOST model for seven sites in Alaska, four sites in Washington, three sites in Oregon, five sites in California, seven sites in Hawaii, one site in North Carolina, and one site in South Carolina. Planned and completed sites are shown in Figure 3-1.

The primary function of these models is to provide NOAA Tsunami Warning Centers with real-time forecasts of coastal community inundation before and during an actual tsunami event. However, these site-specific inundation models can be applied to inundation modeling studies and the creation of inundation parameter databases, digital products, and maps specifically tailored to the design process.

3.3 The National Tsunami Hazard Mitigation Program: Credible Worst-Case Scenarios

State mapping efforts performed as part of the National Tsunami Hazard Mitigation Program (NTHMP) are based on credible worst-case scenarios. Credible worst-case scenario maps are based on a geophysical tsunami source that can be scientifically defended as a worst-case scenario for a particular region or community, and a tsunami inundation model simulation for that scenario. The simulation output becomes the basis for maps that typically display maximum inundation depth and maximum current speed or velocity. Example worst-case scenario inundation model results for Seattle, Washington are shown in Figure 3-2. These products are provided to state geotechnical scientists, who then produce official state inundation maps such as the one for Seattle, Washington shown in Figure 3-3.

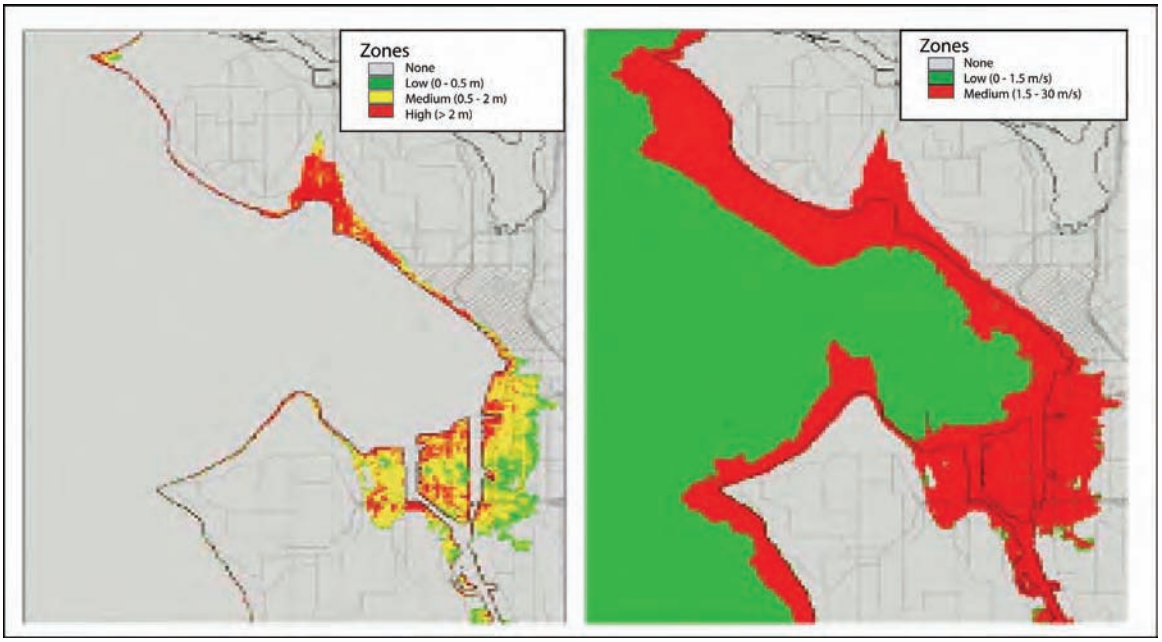


Figure 3-2 Tsunami inundation modeling products for Seattle, Washington. Left panel: zoned estimates of maximum inundation depth. Right panel: zoned estimates of maximum current (Titov, et al., 2003).

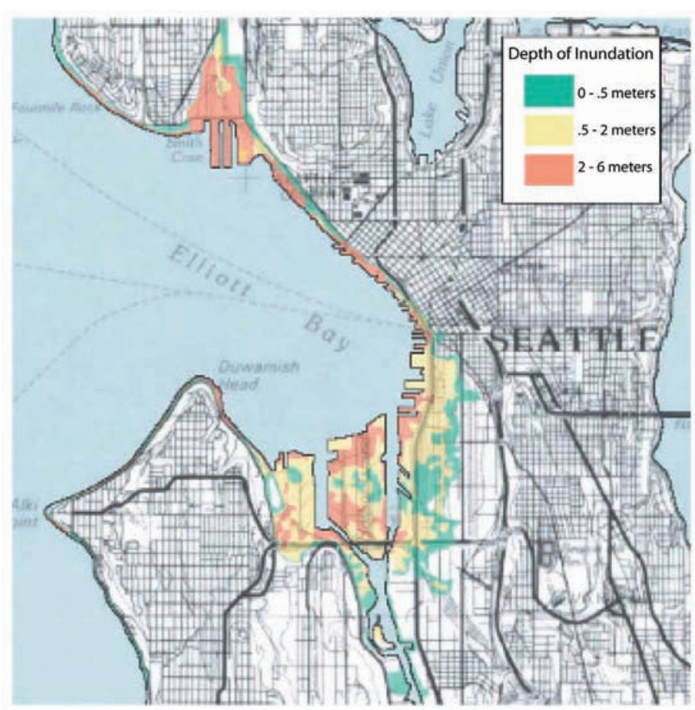


Figure 3-3 Tsunami inundation map for Seattle, Washington produced and published by the state of Washington, using modeling products as guidance (Walsh et al., 2003).

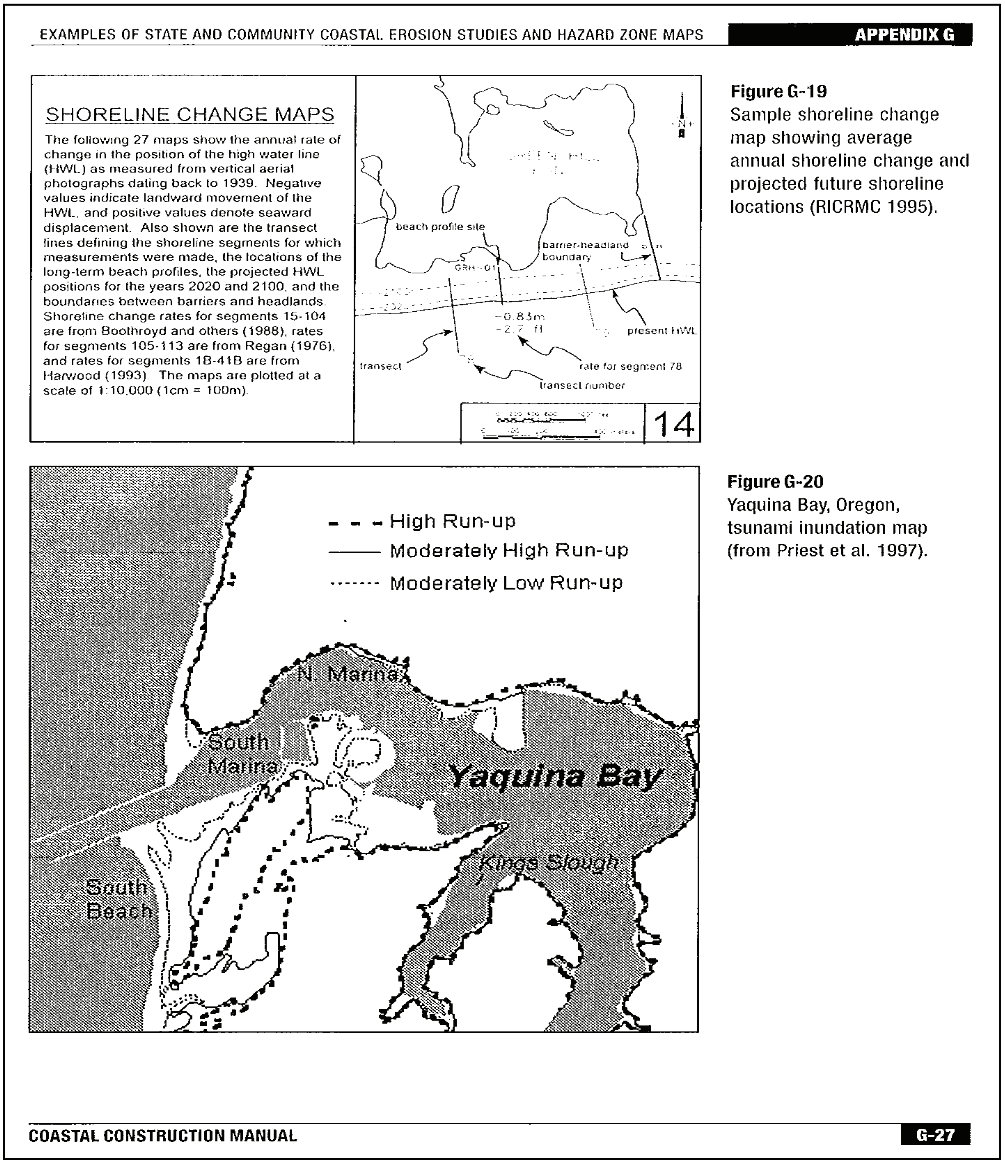
These maps are considered essential for effective disaster planning and development of emergency management products and programs. They guide the development of evacuation maps, educational and training materials, and tsunami mitigation plans. By 2004, the NTHMP Hazard Assessment component had completed 22 inundation mapping efforts and 23 evacuation maps covering 113 communities and an estimated 1.2 million residents at risk (González, et al., 2005a).

There are variations in state products because each state differs in its geophysical setting and the resulting tsunami regime including legislative goals, policies, agency structure, mission, scientific and technical infrastructure, and financial status. Differences between state mapping products include the following:

- Although most credible worst-case scenarios are based on seismic sources, maps generated for Alaska and California also include landslide sources in the tsunami hazard assessment.
- Oregon inundation maps, like the one for Yaquina Bay shown in Figure 3-4, display three inundation lines to depict the uncertainty in the hazard posed by tsunamis from the local Cascadia subduction zone.
- In addition to worst-case scenarios, maps in Alaska also depict inundation from a number of locally generated scenario tsunamis.

Detailed tsunami inundation simulations for credible worst-case scenarios can also be used to derive parameters such as flood depth, velocity, acceleration, and momentum flux, which are used to calculate forces for tsunami-resistant design. These data are archived with the state government hazard mapping agencies, cooperating academic institutions, and the NOAA Pacific Marine Environmental Laboratory. Currently, a central archive for all state mapping products does not exist. However, existing maps and reports are available for viewing, download, or purchase from the following state web sites:

- Alaska: http://www.dggs.dnr.state.ak.us/pubs/pubs
- Oregon: http://www.oregongeology.com/sub/earthquakes/Coastal/Tsumaps.htm
- Washington: http://www.dnr.wa.gov/AboutDNR/Divisions/GER/Pages/home.aspx


EXAMPLES OF STATE AND COMMUNITY COASTAL EROSION STUDIES AND HAZARD ZONE MAPS **APPENDIX G**

SHORELINE CHANGE MAPS

The following 27 maps show the annual rate of change in the position of the high water line (HWL) as measured from vertical aerial photographs dating back to 1939. Negative values indicate landward movement of the HWL, and positive values denote seaward displacement. Also shown are the transect lines defining the shoreline segments for which measurements were made, the locations of the long-term beach profiles, the projected HWL positions for the years 2020 and 2100, and the boundaries between barriers and headlands. Shoreline change rates for segments 15-104 are from Boothroyd and others (1988), rates for segments 105-113 are from Regan (1976), and rates for segments 1B-41B are from Harwood (1993). The maps are plotted at a scale of 1:10,000 (1cm = 100m).

Figure G-19
Sample shoreline change map showing average annual shoreline change and projected future shoreline locations (RICRMC 1995).

Figure G-20
Yaquina Bay, Oregon, tsunami inundation map (from Priest et al. 1997).

COASTAL CONSTRUCTION MANUAL **G-27**

Figure 3-4 Yaquina Bay, Oregon tsunami inundation map with three inundation lines (Priest et al., 1997a; Priest et al.,1997b).

3.4 The FEMA Map Modernization Program: Probabilistic Tsunami Hazard Assessments

On the regional scale, FEMA (1997) presents a probabilistic estimate of the tsunami hazard for the West coast, Alaska, and Hawaii (Figure 3-5). On the local scale, FEMA Flood Insurance Rate Maps (FIRMs) present area-specific flooding scenarios for 100-year and, occasionally, 500-year events (i.e., events with a 1% and a 0.2% annual probability of occurrence, respectively).

The FIRMs provide a basis for establishing flood insurance premiums in communities that participate in the National Flood Insurance Program (NFIP), which is administered by FEMA. These maps were based on tsunami hazard assessment methods developed prior to 1990. To evaluate the underlying methodologies used to assess tsunami and other coastal flooding hazards, FEMA formed focused study groups for each of the flooding mechanisms. The Tsunami Focused Study Group found that the current treatment of tsunami inundation is inadequate, and recommended a joint NOAA/U. S. Geological Survey (USGS) pilot study to develop an appropriate methodology for Probabilistic Tsunami Hazard Assessments (PTHA) that could be used to update FIRMs (Chowdhury, et al., 2005).

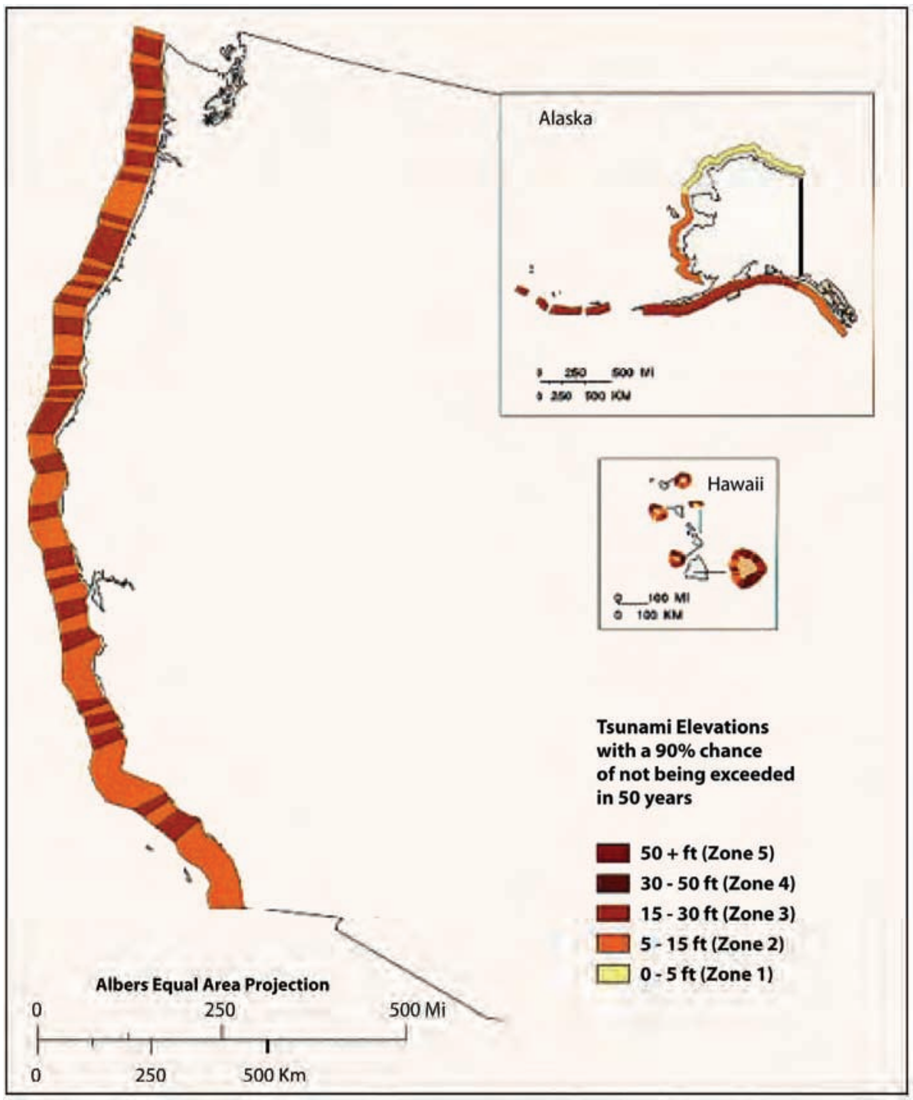


Figure 3-5 Tsunami elevations with a 90% probability of not being exceeded in 50 years (FEMA, 1997).

In the joint NOAA/USGS/FEMA Seaside, Oregon Tsunami Pilot Study (Tsunami Pilot Study Working Group, 2006), USGS and academic colleagues developed a database of near- and far-field tsunami sources associated with a specified probability of occurrence, while NOAA developed a corresponding database of inundation model results based on the sources. The resulting PTHA methodology integrates hydrodynamics, geophysics, and probability theory to meet specific FEMA actuarial needs, and now represents the current state of the art in tsunami hazard assessment for emergency management and engineering design.

The 500-year maximum tsunami wave height map for Seaside, Oregon shown in Figure 3-6 is an example of the type of product that can be

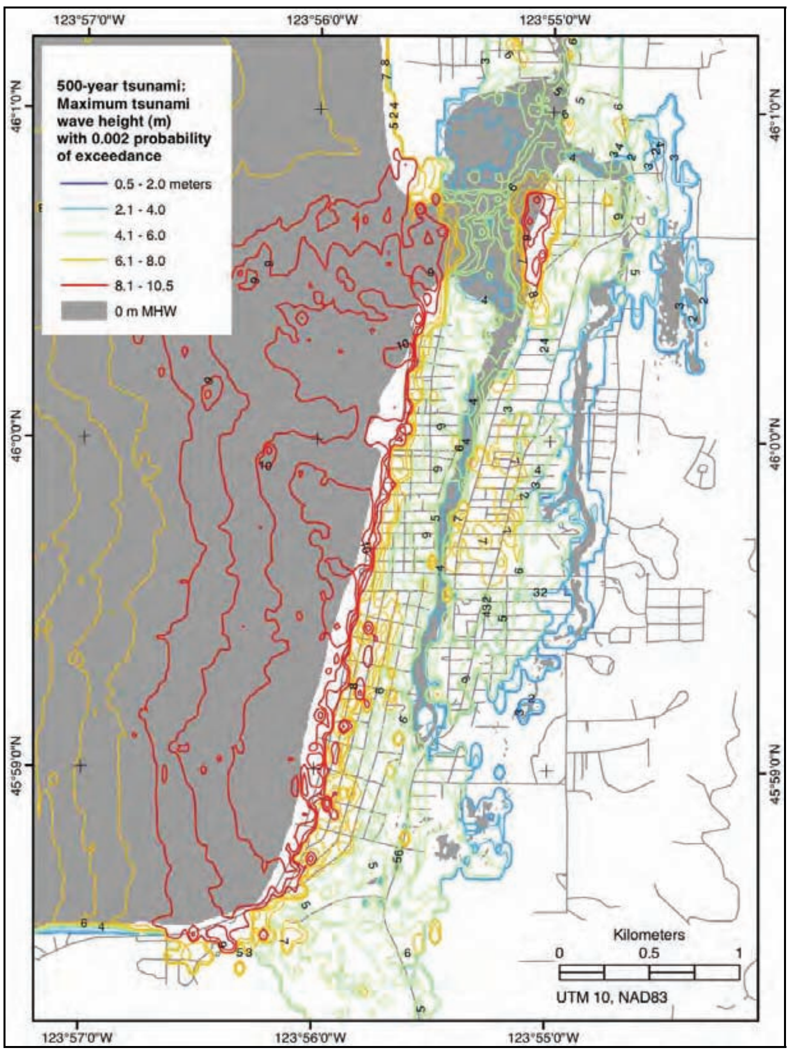


Figure 3-6 The 500-year tsunami map for Seaside, Oregon, depicting maximum wave heights that are met or exceeded at an annual probability of 0.2% (Tsunami Pilot Study Working Group, 2006).

generated by such a study. The resulting GIS database of all model inputs, outputs, and related data can be used to conduct in-depth, site-specific probabilistic studies of tsunami hazard for design of vertical evacuation structures.

3.5 Limitations in Available Modeling and Mapping Products

The quality, content, and availability of currently available modeling and mapping products are limited. Quality varies considerably and, in many cases, cannot be assessed because standard modeling and mapping procedures have not been adopted. Most maps do not provide estimates of currents, so their content is often inadequate for use in design. Digital model products are generally not available to derive the more relevant parameters needed for calculation of forces on structures. Availability of information is limited because a central repository for maps and other model products does not exist.

Limitations in bathymetric and topographic databases are being addressed through coordination of NOAA, USGS, and NTHMP to improve the coverage, quality and availability of the data, but this is an ongoing effort.

3.6 Hazard Quantification for Design of Tsunami Vertical Evacuation Structures

Tsunami hazard can be characterized by:
(1) a probabilistic assessment considering all possible tsunami sources; or
(2) a deterministic assessment considering the maximum tsunami that can reasonably be expected to affect a site.

Given a known or perceived tsunami threat in a region, the first step is to determine the severity of the tsunami hazard. This involves identification of potential tsunami-genic sources and accumulation of recorded data on tsunami occurrence and runup. This can include a probabilistic assessment considering all possible tsunami sources, or a deterministic assessment considering the maximum tsunami that can reasonably be expected to affect a site.

Once potential tsunami sources are identified, and the severity of the tsunami hazard is known, site-specific information on the extent of inundation, height of runup, and velocity of flow is needed. Some of this information can be obtained from available tsunami inundation maps, where they exist; otherwise site-specific tsunami inundation studies must be performed. In the absence of available maps or site-specific inundation studies, analytical solutions can be used to estimate tsunami inundation parameters for preliminary or approximate design. Analytical solutions for flow velocity, depth, and momentum flux are provided in Chapter 6 and Appendix E.

In this document, the design tsunami event is termed the Maximum Considered Tsunami (MCT). There is, however, no firm policy or methodology for setting a Maximum Considered Tsunami at a specified hazard level. For the design criteria contained within this document, it is anticipated that the hazard level corresponding to the Maximum Considered Tsunami will be consistent with the 2500-year return period associated with the Maximum Considered Earthquake used in seismic design.

Existing tsunami hazard assessments in some areas may be adequate for the design of vertical evacuation structures. Even if published hazard maps do not include velocity and depth information, the underlying modeling might. Where the NTHMP has been producing tsunami inundation maps (Alaska, California, Hawaii, Oregon, Puerto Rico, and Washington), the state hazard assessment team (http://nthmp.pmel.noaa.gov) will provide details of the appropriate modeling parameters and can either perform the assessment or provide a referral.

The Maximum Considered Tsunami (MCT) is the design tsunami event. For site-specific tsunami hazard assessments, the Maximum Considered Tsunami should be developed using the Deterministic Maximum Considered Earthquake as the initial condition of the tsunami model.

For site-specific tsunami hazard assessments, the Maximum Considered Tsunami should be developed using the Deterministic Maximum Considered Earthquake (Deterministic MCE) as the source (initial condition) of the tsunami model. At a minimum, the Deterministic MCE for a near-source-generated tsunami in the United States should be the largest potentially tsunami-genic earthquake reported in the "Quaternary Fault and Fold Database of the United States" http://earthquake.usgs.gov/regional/qfaults/.

Otherwise, selection of the Deterministic MCE should conform to ASCE/SEI Standard 7-05 *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2006b), and the following additional guidance proposed for inclusion in the next update of the standard:

- Ground motions for the Deterministic MCE shall be based on characteristic earthquakes on all known active faults in a region.
- The magnitude of a characteristic earthquake on a given fault should be a best estimate of the maximum magnitude capable for that fault but not less than the largest magnitude that has occurred historically on the fault.
- The maximum magnitude should be estimated considering all seismic geologic evidence for the fault, including fault length and paleoseismic observations.
- For faults characterized as having more than a single segment, the potential for rupture of multiple segments in a single earthquake should be considered in assessing the characteristic maximum magnitude for the fault.

Where the greatest threat is from a far-source-generated tsunami, selection of a Maximum Considered Tsunami is more difficult. At a minimum, it should be based on the largest event recorded in the National Geophysical Data Center (NGDC) Historical Tsunami Database (http://www.ngdc.noaa.gov/hazard/tsu_db.shtml) with allowance for the limited accuracy, quantity, and period of time covered by the historic record. It should also consider the largest earthquakes likely in all regions that have generated historic tsunamis affecting the site being considered. The NOAA forecast modeling program may be able to model a Maximum Considered Tsunami for these cases.

Tsunami inundation modeling is not routinely available commercially, but is performed by a number of organizations including government laboratories (USGS, NOAA, Los Alamos National Laboratory), selected universities (Cornell University, Oregon Health and Science University, University of Alaska Fairbanks, University of Rhode Island, University of Southern California, University of Washington), and some consulting companies. An extensive bibliography of past tsunami-related research in modeling is available in Wiegel (2005, 2006a, 2006b, and 2008).

It should be noted that the above recommendations do not include modeling for tsunamis induced by landslides, volcanoes, or meteorite impacts.

3.7 Recommendations to Improve Tsunami Hazard Assessment

Similar to design for other hazards, a possible goal for tsunami-resistant design of vertical evacuation structures is to achieve a uniform level of safety across all communities subjected to tsunami risk. In seismic and wind design, the starting point is probabilistic mapping of earthquake and wind risk. The hazard is further refined by considering local effects such as soil type for seismic design, and topographic effects for wind design. Similar concepts can be used for tsunami design.

Essential tools for tsunami hazard assessment are tsunami inundation models, maps, and comprehensive databases of tsunami inundation parameters. Although difficult to develop, probabilistic maps for tsunami hazard can be made and are needed for reliable design of tsunami-resistant structures for uniform risk.

Chapter 4
Vertical Evacuation Options

A *vertical evacuation refuge from tsunamis* is a building or earthen mound that has sufficient height to elevate evacuees above the level of tsunami inundation, and is designed and constructed with the strength and resiliency needed to resist the effects of tsunami waves. Vertical evacuation refuges can be stand-alone or part of a larger facility. They can be single-purpose refuge-only facilities, or multi-purpose facilities in regular use when not serving as a refuge. They can also be single-hazard (tsunami only) or multi-hazard facilities.

> In concept, vertical evacuation options are applicable to new or existing structures, but it will generally be more difficult to retrofit an existing structure than to build a new tsunami-resistant structure using these criteria.

In concept, these options are applicable to new or existing structures, but it will generally be more difficult to retrofit an existing structure than to build a new tsunami-resistant structure using these criteria. This chapter describes the features of different vertical evacuation options that are available, and provides guidance to assist in choosing between various options.

4.1 Vertical Evacuation Considerations

Vertical evacuation structures can be intended for general use by the surrounding population, or by the occupants of a specific building or group of buildings. Choosing between various options available for vertical evacuation structures will depend on emergency response planning and needs of the community, the type of construction and use of the buildings in the immediate vicinity, and the project-specific financial situation of the state, municipality, local community, or private owner considering such a structure.

4.1.1 Single-Purpose Facilities

> Vertical evacuation facilities can be single-purpose, multi-purpose, or multi-hazard facilities.

The tsunami hazard assessment and inundation study may show that the best solution is to build new, separate (i.e., stand-alone) facilities specifically designed and configured to serve as vertical evacuation structures. Potential advantages of single-purpose, stand-alone facilities include the following:

- They can be sited away from potential debris sources or other site hazards.
- They do not need to be integrated into an existing building design or compromised by design considerations for potentially conflicting usages.

- They are structurally separate from other buildings and therefore not subject to the potential vulnerabilities of other building structures.
- They will always be ready for occupants and will not be cluttered with furnishings or storage items associated with other uses.

Single-purpose, stand-alone structures will likely be simpler to design, permit, and construct because they will not be required to provide normal daily accommodations for people. They can have simplified prototypical structural systems, resulting in lower initial construction costs.

One example of a single-purpose facility is a small, elevated structure with the sole function of providing an elevated refuge for the surrounding area in the event of a tsunami. A possible application for such a facility would include low-lying residential neighborhoods where evacuation routes are not adequate, and taller safer structures do not exist in the area.

4.1.2 Multi-Purpose Facilities

A coastal community may not have sufficient resources to develop a single-purpose tsunami vertical evacuation structure or series of structures, so creative ways of overcoming economic constraints are required. Possible solutions include co-location of evacuation facilities with other community-based functions, co-location with commercial-based functions, and economic or other incentives for private developers to provide tsunami-resistant areas of refuge within their developments. The ability to use a facility for more than one purpose provides immediate possibility for a return on investment through daily business or commercial use when the structure is not needed as a refuge.

Multi-purpose facilities can also be constructed to serve a specific need or function in a community, in addition to vertical evacuation refuge. Examples include elevated man-made earthen berms used as community open spaces. In downtown areas or business districts, they can be specially constructed private or municipal parking structures incorporating tsunami resistant design. On school campuses, vertical evacuation facilities could serve as gymnasiums or lunchrooms on a daily basis. In residential subdivisions, they can be used as community centers.

4.1.3 Multi-Hazard Considerations

Communities exposed to other hazards (e.g. earthquakes, hurricanes) may choose to consider the possible sheltering needs associated with these other hazards, in addition to tsunamis. This could include allowances for different occupancy durations, consideration of different post-event rescue and recovery activities, and evaluation of short- and long-term medical care needs.

Designing for multiple hazards requires consideration of the load effects that might be unique to each type of hazard. This can pose unique challenges for the resulting structural design. For example, the structural system for vertical evacuation structures exposed to near-source-generated tsunamis will likely need to be designed for seismic hazards. Such a structure might include break-away walls or open construction in the lower levels to allow water to pass through with minimal resistance. Open construction in the lower levels of a multi-story structure are contrary to earthquake engineering practice to avoid soft or weak stories in earthquake-resistant construction. Proper design and construction will need to include special accommodations for these and other potential conflicting requirements.

4.2 Vertical Evacuation Concepts

To provide refuge from tsunami inundation, vertical evacuation solutions must have the ability to receive a large number of people in a short time frame and efficiently transport them to areas of refuge that are located above the level of flooding. Potential vertical evacuation solutions can include areas of naturally occurring high ground, areas of artificial high ground created through the use of soil berms, new structures specifically designed to be tsunami-resistant, or existing structures demonstrated to have sufficient strength to resist anticipated tsunami effects.

> Vertical evacuation structures can be soil berms, parking garages, community facilities, commercial facilities, school facilities, or existing buildings.

Nonstructural systems and contents located in the levels below the inundation depth should be assumed to be a total loss if the design tsunami occurs. If the building is required to remain functional in the event of a disaster, the loss of lower level walls, nonstructural systems, and contents should be taken into account in the design of the facility and selection of possible alternative uses.

4.2.1 Existing High Ground

Naturally occurring areas of high ground may be able to be utilized or modified to create a refuge for tsunami vertical evacuation. Large open areas offer easy access for large numbers of evacuees with the added advantage of avoiding the possible apprehension about entering a building following an earthquake. In addition, most coastal communities have educated their populations to “go to high ground” in the event of a tsunami warning. The topography of the existing high ground should be evaluated for the potential of wave runup or erosion. Some modification of the existing topography may be required to address these issues.

4.2.2 Soil Berms

If natural high ground is not available, a soil berm can be constructed to raise the ground level above the tsunami runup height, as shown in Figure 4-1. Although care must be taken to protect the sides of the soil berm from the incoming and outgoing tsunami waves, this option can be relatively cost-effective in comparison to building a stand-alone structure. The height of the berm must be sufficient to avoid becoming inundated, and the slope of the sides must allow for ingress. A ramp slope in the range of one foot vertical rise to four feet horizontal run (1 in 4) is recommended.

Figure 4-1 Soil berm combined with a community open space. Ocean facing walls can deflect incoming waves while sloped sides provide for quick access.

4.2.3 Parking Garages

Parking garages are excellent candidates for use as vertical evacuation structures. Similar to the example shown in Figure 4-2, most parking garages are open structures that will allow water to flow through with minimal resistance. Interior ramps allow ample opportunity for ingress, and easy vertical circulation to higher levels within the structure. Parking garages can also be used to provide additional community amenities on the top level, including parks, observation decks, and sports courts. They are also obvious revenue generating facilities, especially in areas that attract large numbers of tourists.

Parking garages, however, tend to be constructed using low-cost, efficient structural systems with minimal redundancy. If designed with higher performance objectives in mind, and if subjected to additional code review and construction inspection by local jurisdictions, parking garages could be effective vertical evacuation structures.

Figure 4-2 Parking garage. Open structural systems allow water to pass through with minimal resistance, and interior ramps allow for easy ingress and vertical circulation.

4.2.4 Community Facilities

Vertical evacuation structures could be developed as part of other community-based needs such as community centers, recreational facilities, sports complexes, libraries, museums, and police or fire stations. One such example is shown in Figure 4-3. When not in use as a refuge, facilities such as these can be useful for a variety of functions that enhance the quality of life in a community. When choosing alternative uses for a vertical evacuation facility, consideration should be given to potential impacts that other uses might have on the vertical evacuation function. Potential negative impacts could include clutter that could become debris that disrupts ingress. Priority should be given to uses with complementary functions, such as accommodations for large numbers of people.

4.2.5 Commercial Facilities

Vertical evacuation structures could be developed as part of business or other commercial facilities including multi-level hotels, restaurants, or retail establishments, as shown in Figure 4-4. For example, if the refuge area is part of a hotel complex, meeting rooms, ballrooms, and exhibit spaces that are located above the tsunami inundation elevation could be used to provide refuge when the tsunami occurs.

Figure 4-3 Sports complex. Designed for assembly use, this type of structure can accommodate circulation and service needs for large numbers of people.

Figure 4-4 Hotel and convention complex. Meeting rooms, ballrooms, and exhibit spaces located above the tsunami inundation elevation can be used to provide areas of refuge.

4.2.6 School Facilities

Similar to community facilities, public and private school facilities have the benefit of providing useful and essential services to the communities in which they reside. Ongoing construction of schools provides an opportunity and potential funding mechanism for co-located tsunami vertical evacuation structures. This has the added benefit of possible additional public support for projects that increase the safety of school-age children.

4.2.7 Existing Buildings

Historic damage patterns suggest that many structures not specifically designed for tsunami loading can survive tsunami inundation and provide areas of refuge. It is possible that some existing structures could serve as vertical evacuation structures or could be made more tsunami-resistant with only minor modifications. An assessment of both the functional needs and potential structural vulnerabilities would be required to determine if an existing building can serve as a vertical evacuation structure.

In some situations, providing some level of protection is better than none. An example of this concept is shown in Figure 4-5. In a tsunami evacuation map for Waikiki, concrete and steel framed buildings six or more stories in height are considered to provide increased protection on or above the third floor, and are identified as potential areas of refuge.

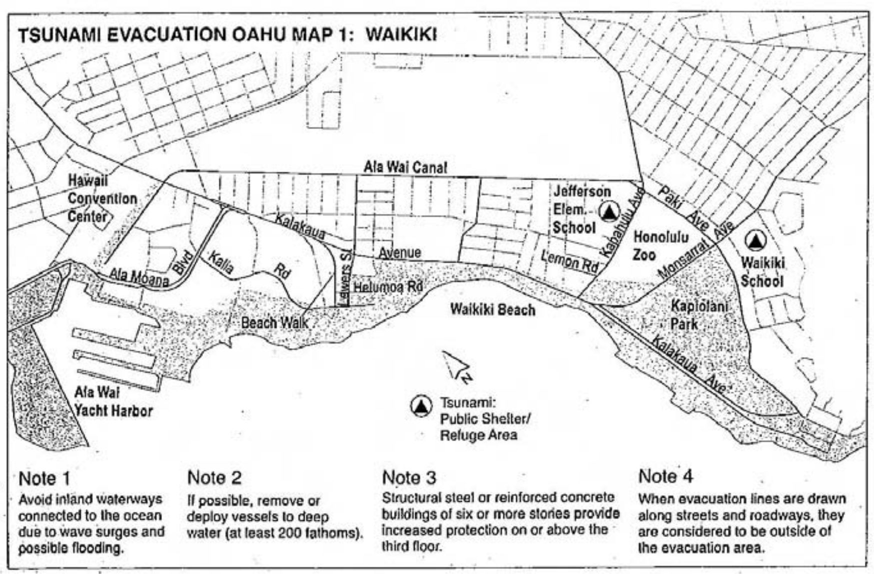


Figure 4-5 Evacuation map for Waikiki, Hawaii, indicating use of existing buildings for vertical evacuation.