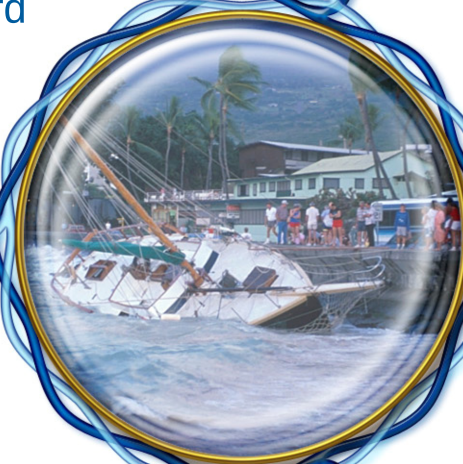
Tsunami Hazards

FEMA Coastal Flood Hazard Analysis and Mapping Guidelines Focused Study Report

February 2005



Focused Study Leader

Shyamal Chowdhury, Ph.D., CFM

Team Members

Eric Geist
Frank Gonzalez, Ph.D.
Robert MacArthur, Ph.D., P.E.
Costas Synolakis, Ph.D.

Table of Contents

Tables

Figures

Acronyms

CCM	Coastal Construction Manual
CFR	Code of Federal Regulations
ERDC	Engineer Research and Development Center
FEMA	Federal Emergency Management Agency
FD	finite-difference
FE	finite-element
FIRM	Flood Insurance Rate Map
FSG	Focused Study Group
LSW	linearized shallow-water wave
MOST	numerical inundation model
NFIP	National Flood Insurance Program
NSF	National Science Foundation
NTHMP	U.S. National Tsunami Hazard Mitigation Program
NOAA	National Oceanic and Atmospheric Administration
PTHA	Probabilistic Tsunami Hazard Analysis
SG	Study Group
USGS	U.S. Geological Survey

1 INTRODUCTION

Guidelines do not currently exist for defining tsunami hazard zones for incorporation into FEMA Flood Insurance Rate Maps (FIRMs). This study is therefore focused on recommendations for developing tsunami hazard assessment methodologies for the Pacific Coast, through close coordination and collaboration of the FEMA National Flood Insurance Program (NFIP) with the U.S. National Tsunami Hazard Mitigation Program (NTHMP), a partnership led by the National Oceanic and Atmospheric Administration (NOAA) with participation from FEMA, the U.S. Geological Survey (USGS), NSF, and geotechnical and emergency management agencies of the five Pacific states (Alaska, California, Hawaii, Oregon, and Washington).

This report provides recommendations for preparing guidelines and a preliminary time estimate for four tsunami-related topics grouped under the Tsunami Focused Study. The table below shows the four topics and associated need and priority level.

A critical, short-term (6-month) activity is recommended to develop a methodology to incorporate existing NTHMP products into FIRM by combining Tasks 15 and 16 into a pilot study for a specific locale in California, Oregon, and Washington. The preliminary assessment will also allow for evaluation of the adequacy of existing guidelines, related to wind waves or riverine flows, to account for tsunami hazards. The current FEMA effort to update FIRMs focuses on California, Oregon and Washington, but will consider future efforts in other states, as appropriate. The seriousness of the tsunami threat to the states of Alaska and Hawaii are well-documented, and a rapid expansion of the FIRM update effort to these states is therefore strongly recommended.

Tsunami Hazard Topics and Priorities

Topic Number	Topic	Topic description	Priority Level		
			Atlantic / Gulf Coast	Pacific Coast	Non-Open Coast
15	NTHMP	Address use of NTHMP products and approaches in the NFIP	H	C	Pacific C
16	100-year Recurrence	Develop methodology for determining the 100-year inundation line	H	C	Pacific C
20	Structure-Debris Interaction	Tsunami structure–debris interaction to define hazard zones.	H	I	Pacific I
29	Tsunami-Induced Erosion.	Review methodology for predicting erosion	H	I	Pacific I

Key: C = critical; A = available; I = important; H = helpful

The Focused Study Group (FSG) is made up of Frank Gonzalez of NOAA, Eric Geist of the USGS, Shyamal Chowdhury of Northwest Hydraulic Consultants (Team Leader), Costas Synolakis of the University of Southern California, and Robert MacArthur of Northwest Hydraulic Consultants. The FSG had several teleconferences and one meeting and exchanged numerous emails with documents and ideas. This preliminary work discusses the scope and NOAA's current and future plans for preparation of tsunami inundation mapping and possible venues of cooperation between FEMA, NOAA, USGS, and other agencies to address FEMA's needs for guidelines to incorporate tsunami hazard zones on FIRMs, both in the interim and long term.

1.1 DESCRIPTION OF THE HAZARD

Prior to discussing the topics from the Workshop a description of the tsunami hazard is included here to provide necessary background for developing guidelines to incorporate tsunami hazard assessments into FEMA maps.

Tsunamis are long waves of small steepness generated by impulsive geophysical events of the seafloor and of the coastline, such as earthquakes and submarine and aerial landslides. Volcanic eruptions and asteroid impacts are less common but more spectacular triggers of tsunamis. The determination of the terminal effects of tsunamis as they strike shorelines and coastal structures is one of the quintessential problems in earthquake engineering and has profound implications for mitigating their effects and saving lives.

Tsunamis are notorious for exporting "death and destruction at distant coastlines," as they sometimes travel across the world's oceans without dissipating sufficient energy to render them harmless. When striking at distances greater than 1,000 miles, tsunamis are referred to as teletsunamis or farfield tsunamis. An example of coastal inundation from teletsunami is shown in Figures 1 and 2.

Tsunamis generated within 200 miles of the coast and striking the adjacent shoreline, are referred to as nearfield tsunamis. Tsunamis originating between 200 to 1,000 miles off the target coastline are known as regional tsunamis. The characterization (farfield, nearfield, or regional) is thus dependent on the target coastline at risk. For example, a Cascadia Subduction Zone tsunami is nearfield in the Pacific Northwest, regional for California, and farfield or teletsunami for Hawaii or Japan.

The recorded tsunami history of the United States is quite short by world standards. In Washington, Oregon, and California, it is at best 180 years long, while a few older events are identifiable from paleotsunami studies. Until 1998, a total of 63 farfield tsunamis had been reported in the Western states, and 47 of them have been recorded instrumentally. Eleven have caused damage and fatalities (Lander et al., 1993) (Table 1). A total of 53 nearfield tsunamis have been reported in the same period, with 17 of them causing damage (Table 2) (Lander et al. 1993; McCarthy et al., 1993; Borrero, 2002).

Figure 1. Inundation in Crescent City, California, from a tsunami triggered by the 1964 Great Alaskan earthquake.

In the past 10 years, 12 major tsunamis have struck coastlines around the Pacific Rim, causing more than 3,000 deaths and an estimated $1 billion US (2001) in damage. Fortuitously, these tsunamis have either struck less developed coastlines or developed coastlines at low season with few or no visitors along the coast. Within the contiguous 48 states of the United States, the most significant event was the 1964 Great Alaskan tsunami that killed nine people in Crescent City, CA, and caused more than $30 million US (1984) in damage. Before the 1995 Kobe, Japan and 1999 Izmit, Turkey, earthquakes, it had been estimated that tsunamis cause between 5% and 15% of earthquake damage worldwide. During the past century, tsunamis have killed more people in the United States than earthquakes.

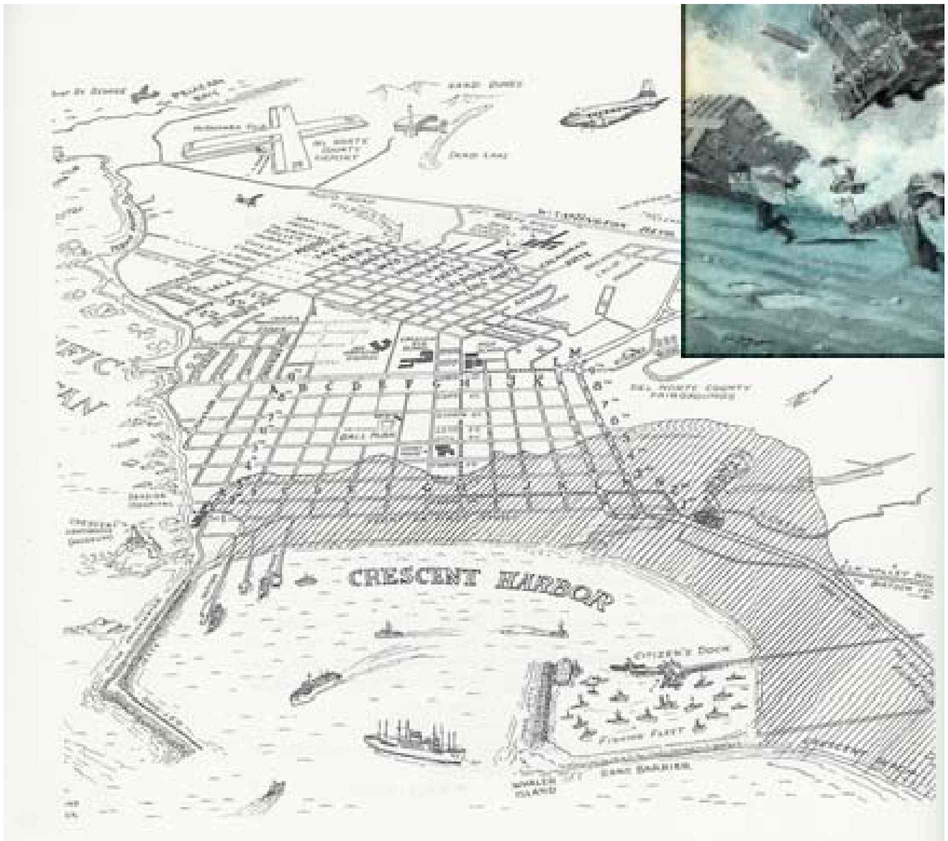


Figure 2. The inundation line in Crescent City, California from a farfield tsunami triggered by the 1964 Great Alaskan earthquake.
The inset (upper right) is an artist's rendering of the nearfield impact around Cook Inlet, Alaska, and is based on eyewitness accounts.

The term tsunami—also known as seismic sea wave or tidal wave—comes from the Japanese and translates as "harbor wave". Since ancient times, harbors have long been centers of commercial activity, and even a relatively small tsunami entering a harbor can trigger substantial harbor oscillations by bouncing off the harbor's embankments and combining together to form larger waves. Alaska's 1964 infamous Good Friday earthquake triggered large tsunamis that entered harbors throughout the region, including those at Anchorage, Valdez, and Seward, Alaska, and caused catastrophic destruction. The same tsunami manifested itself as a teletsunami in Crescent City, California where it killed nine people and devastated the downtown area, and was even recorded in Long Beach.

Table 1. Farfield Tsunamis (teletsunamis) impacting Washington, Oregon, and California		
Date	Generation Area	Impact in the United States
August 13, 1868	Arica, Peru	San Diego, CA
May 10, 1877	Chile	San Pedro, CA
June 15, 1896	Sanriku, Japan	Santa Cruz, CA
January 31, 1906	Ecuador	San Diego, CA
April 1, 1946	Unimak Island, Alaska	Scott's Cap, Tahola, WA; Seaside, OR; and Noyo Harbor, Half Moon Bay, Santa Cruz, Port Huaneme, Catalina Island, CA
November 4, 1954	Kamchatka, USSR	Brandon, OR; Crescent City, CA
March 9, 1957	Unimak Island, Alaska	San Diego, CA
May 22, 1960	Chile	Seaside, Gold Beach, OR; and Crescent City, Noyo Harbor, Pismo Beach, Morro Bay, Santa Barbara, Los Angeles, and San Diego, CA
March 28, 1964	Prince William Sound, Alaska	$1.75M damage in Washington and Oregon; over $15M damage in Crescent City; $1M in San Francisco, CA 17 people killed
November 29, 1975	Kanapala, Hawaii	Catalina Island, CA
Source: Lander et al., 1993		

Table 2. Nearfield tsunamis impacting Washington, Oregon, and California	
Date	Generation Area/Impacted Area
December 21, 1812	Santa Barbara, CA
May 31, 1854	Santa Barbara, CA
October 21, 1854	San Francisco, CA
July 10, 1855	San Juan Capistrano, CA
February 15, 1856	San Francisco, CA
May 27, 1862	San Diego, CA
October 8, 1865	Santa Cruz, CA
October 21, 1868	San Francisco, CA
November 22, 1873	Oregon and Northwest CA
November 29, 1891	Puget Sound, WA.
March 2, 1901	Monterey, CA
April 18, 1906	San Francisco, CA
November 4, 1927	Point Arguello, CA
August 30, 1930	Santa Monica, CA
April 13 and 16, 1949	Tacoma, WA
October 19, 1989	Monterey, CA
April 25, 1992	Cape Mendocino, CA
Source: Lander et al., 1993; McCarthy et al., 1993; Borrero, 2002	

Such large earthquakes frequently generate strong seismic waves with periods of a few to tens of seconds that propagate outward from the epicenters along the surface of the earth. The ground motions from these seismic surface waves can cause the water in small harbors, marinas, navigation channels and coastal rivers to go into oscillation, sometimes hundreds or even thousands of kilometers from the earthquake epicenters. Called seismic seiches, these oscillations have the potential to cause substantial damage to shoreside facilities, acting either independently or enhancing the destructive power of tsunamis. Local oscillations induced by the seismic waves of the 1964 Alaska earthquake were observed at numerous sites throughout the US. Therefore, seismic seiches should also be included in the long-term plan to map tsunami and other water wave hazards.

Tsunamis also occur in lakes and reservoirs through seismic local ground shaking that triggers resonant oscillations (also known as seiching); by coseismic generation of subaerial or submarine mass movements (landslides, debris flows, slumps); or by aseismic mass movements or passing weather fronts. Lake Geneva (Lac Leman), Switzerland, is the textbook case of meteo-triggered lake oscillations. During the 1755 Lisbon earthquake, significant seiching was triggered in lakes as distant as Loch Lomond in Scotland and persisted for several days, while the 1964 Great Alaskan earthquake reportedly triggered oscillations in numerous reservoirs operated by the U.S. Army Corps of Engineers (Synolakis, 2002). Lander et al. (1993) list eight “reservoir” tsunamis in Franklin D. Roosevelt Lake, Washington, between 1944 and 1993. In Puget Sound, Washington, the inland waterways are exposed to multiple potential tsunami sources, in the form of active seismic fault systems and potential landslide and river delta failures; in Lake Washington and Lake Sammamish, sidescan imagery and seismic profiles have identified subaqueous landslides, submerged forests, coherent block slides, debris flows, sand flows and mixed slumps (Gonzalez et al., 2003). The January 17, 1994 Northridge earthquake triggered waves that sloshed up to 19 feet in the Los Angeles Reservoir, while unconfirmed reports published in the *Los Angeles Times* on January 18, 1994, described 30-foot waves and overtopping of the reservoir. Flooding from overtopping appears to be of growing concern, particularly for smaller reservoirs located in the midst of densely populated cities in many California locales.

1.2 TSUNAMIS VERSUS WIND WAVES

It is important to describe briefly the differences between wind waves and tsunamis, because a tsunami with heights comparable to those of swell often has substantially higher impact.

Tsunamis are created by sudden movements or disturbances of the water column by a number of mechanisms, including submarine explosions or impacts of large objects such as landslides from the coastline or asteroids, and/or aerial or submarine mass movements. These events trigger a series of fast-moving, long waves of initial low amplitude that radiate outward similar to the waves radiating when a pebble is dropped into a pond. In contrast, most of the swell waves observed on beaches are generated by wind disturbing the surface of the sea. Tsunamis are generated by disturbing the seafloor, wind waves by disturbing the ocean surface. Another mechanism for triggering tsunamis is shaking of a closed basin such as a reservoir, a lake, or a harbor, also known as sloshing or seiching.

Both wind waves and tsunamis are characterized by a wavelength, the horizontal distance between crests or peaks; a period, the time it takes successive peaks to pass a fixed point; and a height, the vertical distance from the wave trough to its crest. Wind waves tend to have a wavelength from a few inches to about a mile and periods of about 1/2 second to 30 seconds (Prager, 2000). In contrast, tectonic tsunamis near the source typically have a wavelength of hundreds of kilometers and periods of tens of minutes. Wind waves vary in height from tiny ripples on the sea surface to the rare rogue waves imagineered in the movie *The Perfect Storm*. Tsunamis, on the other hand, race across the open ocean as a series of long, low-crested waves, usually less than one meter high. Their steepness is so small that a ship at sea may not feel a tsunami passing beneath the hull.

In general, waves are considered deep-water waves if their wavelength L is relatively small compared to the water depth d through which they travel. Wind waves do not "feel" the seafloor until they are within one to several kilometers from the coastline, depending on the slope of the beach. In the open ocean, where depths average about 2.5 miles, all wind waves with period less than 30 seconds are deep-water waves—a short wavelength relative to depth ($d/L>1$). In contrast, shallow-water waves are those with a long wavelength relative to depth ($d/L<1/20$). The depth and nature of the seafloor strongly influence how shallow-water waves propagate or travel. Because tsunamis have such long wavelengths, even when traveling through very deep water, they are considered shallow-water waves. Thus, although geometric spreading initially reduces the height of tsunami waves, variations in ocean depth can focus or de-focus energy at a distant point. Because the earth is a sphere, simple divergence and convergence of orthogonals can also de-focus and focus tsunami energy over transoceanic distances; in fact, this mechanism will intensify tsunamis at sites antipodal to the source, so that the threat can actually increase at great distances.

In wind-generated waves, the orbital motion of the water particles decreases with depth from the water surface. As energy is transferred through the motion of the water particles, the energy of wind waves traveling through deep water is concentrated near the surface. By contrast, the energy imparted to the water during tsunami formation sets the entire water column in motion. Tsunami orbital velocities do not decrease significantly with depth, and although the wave height at the surface in the open seas is relatively small, the energy contained throughout the entire water column is substantial. Furthermore, the rate at which water waves lose energy is inversely proportional to their wavelength. Hence, tsunamis not only contain a significant amount of energy and move at high speeds (often reaching 450 mph), but they can also travel great distances with little energy loss.

As they move toward the coast, tsunamis pass through varying depths and over complex seafloor topography. Changes in the ocean depth and seafloor cause them to continuously evolve and change shape. A tsunami generated from an earthquake off Peru may look entirely different along the Peruvian coastline compared to when it enters a bay in California and still different, when it strikes a beach in Hawaii. Tsunamis are characterized by much greater length scales than wind waves and this can give rise to differences in nearshore propagation. For example, nearshore tsunamis are almost never forced waves, but it is not uncommon for shallow-water wind waves to be forced and, as a consequence, deviate from the usual free wave propagation characteristics. However, some mechanisms governing nearshore transformation are shared by both tsunamis and wind waves as they approach a coastline; in particular, both undergo refraction and shoaling. Shoaling is the process in which the wave front steepens and the wave height increases. The front of the wave enters shallower water and moves more slowly than the tail of the wave because the depth is smaller, hence the speed slower, at the front. If the wave is sufficiently steep and the continental shelf is wide, the wave eventually breaks, in essence tripping over itself. However, the crest lengths of tsunamis often cause unexpected wave patterns in refraction compared to those of wind waves. Also, because of their long wavelengths, tsunamis dissipate less than wind waves as they evolve up sloping beaches, and frictional effects are less important.

When tsunamis advance up on dry land, they can snap trees, destroy engineered structures, and carry boats far inland. Their impact is often described with the inundation distance and the runup height. The inundation distance refers to the maximum penetration inland of the entire tsunami wave train. Not unexpectedly, Tsunamis can penetrate farther on flat beaches than they do on steep beaches.

Tsunami runup is the maximum elevation the wave climbs up a coastline. One of the highest tsunami runup recorded in the United States occurred during the 1946 Aleutian tsunami at Unimak Island, Alaska. The tsunami destroyed the Scotch Cap lighthouse, killing all four U.S. Coast Guard officers. This nearfield event for Unimak was a teletsunami in Hilo, Hawaii, where it killed more than 150 people and ushered in the modern era of tsunami mitigation studies in the United States. The site of the disaster, along with a picture of the lighthouse as it stood before the event, is shown in Figure 3.

At times, the tsunami runup and inundation distance do not fully describe the tsunami impact. The large sustained currents associated with tsunamis can carry large objects and use them as projectiles to destroy structures behind them. The 1946 tsunami carried large debris, the impact force of which bent several parking meters along the Hilo coastline. During the 1994 Mindoro, Philippines, event, a 6-foot tsunami broke a 6,000-ton power generating barge off its moorings at the delta of the Baryan River, carried it one mile inland, and left it there, so that when the water level receded, there was not sufficient freeboard to tow the barge back to the delta (Imamura et al., 1995). During the 1995 Manzanillo, Mexico, tsunami, another 7-foot wave carried large recreational vehicles 600 feet inland and smashed them against palm trees (Borrero et al., 1995).

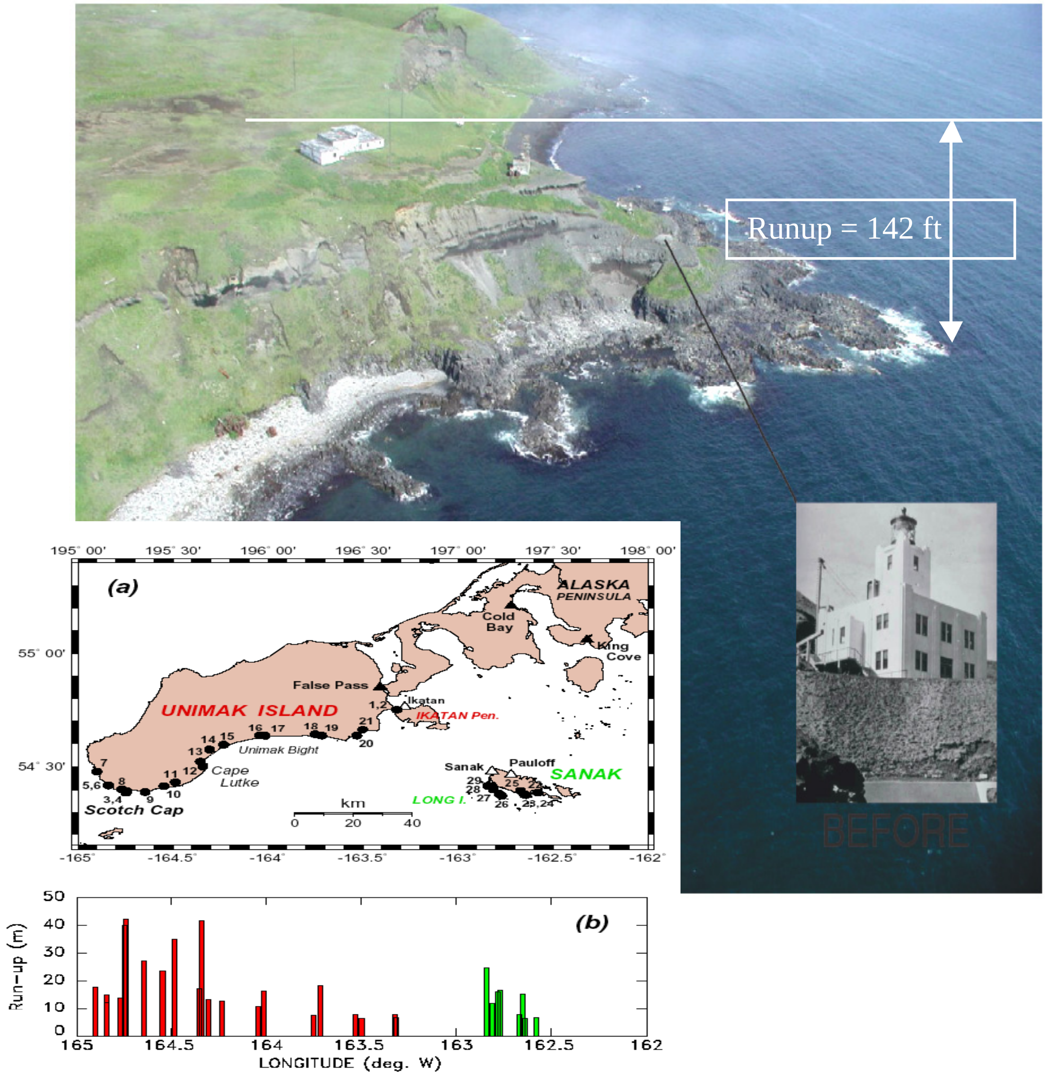


Figure 3. Aerial view of Scotch Cap, on Unimak Island, Alaska.

The lighthouse that was destroyed during the 1946 Aleutian tsunami, killing all four U.S. Coast Guard officers, is shown in the inset at lower right. The inset at lower left shows Unimak and Sanak Islands and the runup distribution along the south side of Unimak Island. Scotch Cap is at the lower left tip of the island. Tsunami runup reached 142 ft. (Photo results from Okal et al. 2003; lighthouse photo from NOAA.)

Tsunamis can also cause erosion and deposition of sediment or they can rip apart coral reefs that are in their path. Coastal regions that are low lying or located between steep cliffs or bodies of water are particularly vulnerable to tsunami damage. The September 1, 1992, Nicaraguan tsunami deposited a vast sediment blanket over many lowlands along the affected areas. On June 3, 1994, a magnitude 7.2 earthquake triggered a large tsunami that struck the coast of southeast Java and rolled on to hit southwest Bali (Synolakis et al. 1995). About 200 people were killed and 400 injured. Post-tsunami surveys identified watermarks, such as trees with sand-encrusted bark and leaves, indicating that runup reached about 17 feet in west Bali and up to 40 feet in southeast Java. Several beaches were completely washed away, while rivers effectively blocked evacuation routes. The same tsunami was documented along the northwestern Australian coast where a surge of 10 feet of water carried fish and rocks nearly 1,000 feet inland. The 1998 Papua, New Guinea, tsunami deposited a sediment layer that, in some areas, was 3 feet thick (Kawata et al., 1999; Gelfenbaum and Jaffe, 2003).

1.3 TECTONIC TSUNAMIS VERSUS LANDSLIDE-GENERATED WAVES

Predicting the initial wave generated by a seafloor motion or mass movement is the first step in modeling tsunami generation and assessing its possible impact. Until the last few months, when a NOAA DART buoy–also known as a tsunameter–recorded a tsunami in the open ocean, there were no measurements of tsunamis near the generation region, and tsunami hazard mitigation relied on untested models. The current state of knowledge differs substantially in reconstructing *ex post facto* tsunamis from tectonic sources and from submarine mass movements. Understanding the limitations of accurately predicting the initial tsunami wave is important in evaluating the accuracy of the predictions and is equally important in proposing recurrence intervals.

Earthquake-induced seafloor deformation was long believed to be the primary cause of most tsunamis, even though numerous major landslides and associated waves were triggered in fiords and lakes of southern Alaska by the 1964 Great Alaska earthquake (Plafker, 1965). It is now suspected that landslides play a much greater role in tsunami generation than was earlier believed. This should not have been all that surprising; Gutenberg suggested in 1939 that “submarine landslides are to be considered at least as one of the chief causes, if not indeed the major cause of tsunamis.” Landslide-generated tsunamis differ from the classic long waves in that they are steeper and disperse (break down) rapidly, particularly in shallow water. Also, mass movements often trigger tsunamis unexpectedly and sometimes aseismically. The 1994 Skagway, Alaska, tsunami was triggered by sediment instabilities at extreme low tides without associated seismic motions.

There are several important differences in the character of tsunamis triggered by mass movements compared to those triggered by earthquakes (tectonic tsunamis) (Prager, 2000). Tectotsunamis tend to have longer wavelengths, longer periods, and a larger source area than those generated by mass movements of earth. Whereas it is clear that the timing of the seafloor deformation is not important to first order in calculating tsunami evolution, it is also clear that the timing of mass movements is more important in the wave evolution; very slow movements will not generate large waves. Nonetheless, this is a parameter that cannot be determined very accurately (Okal and Synolakis, 2003).

When a potential tsunami-triggering earthquake occurs, sufficient information is often available to predict whether or not a massive wave will be created. This is all that can be inferred, however reliably. There are at least four characteristics of a mass movement that determine whether or not a tsunami will form; its length, width, thickness, and the inclination of the slope that fails and triggers the landslide. Controversy remains regarding the ways in which the generated waves are affected by the geomechanical characteristics of the sliding material. This controversy is partially attributable to the lack of knowledge about the effects of the timing of seafloor motion, but is more importantly related to the lack of validated constitutive models. None of these characteristics can yet be accurately predicted; the relevant information on geometric slide characteristics may sometimes be difficult to determine even after the event (Synolakis et al., 2002a) A few empirical and computational methods exist to predict initial waves generated by underwater mass movements (Chiang, et al, 1981).

Compared with the understanding of earthquake induced initial tsunami waves, the understanding of landslide-induced initial waves is marginal. A few empirical and computational methods exist to predict initial waves generated by underwater mass movements. The lack of understanding limits intuition, leading to inadvertent errors. In 1985, a purely arithmetic error in a simple algebraic formula led to underestimating the size of a possible tsunami from the Palos Verdes, California, debris avalanche by a factor of 100 in official U.S. government reports. The error was quoted freely until the arithmetic was redone in 2001. The PV wave, calculated in 1985 at 0.14 m, was found to be 14 m using the identical algebraic formula and the identical landslide parameters. Because no field data are available for verification, the degree of understanding or the lack of understanding embodied in the algebraic formula is unknown. But this interesting anecdote, involving solutions that differ by two orders of magnitude, does demonstrate the lack of intuition mentioned above.

While landslide-induced tsunamis may not be as uncommon as believed before the 1998 Papua, New Guinea, event (Synolakis et al., 2002a), it is now accepted that the most common cause is submarine earthquakes. Note that not all submarine earthquakes generate tsunamis. According to Okal (2002), in the past 31 years, there have been one submarine earthquakes per year of magnitude 8 or higher and about 10 of magnitude 7, yet only 20 of these have reportedly created tsunamis. The pattern and extent of vertical ground deformation from an earthquake uniquely determines whether a tsunami is formed or not. Most seismic faults combine both strike-slip and thrust motions, but primarily only faults that have predominantly vertical displacement and create sufficiently large seafloor deformations appear to trigger a tsunami.

1.4 FACTORS IN TSUNAMI MODELING

Generally, the larger the magnitude of an earthquake, the larger the deformed area is, and this deformed area usually contains an area of uplift and subsidence that defines the dipole shape of the wave. The deformation area refers to the horizontal extent of deformation, while slip length is a measure of vertical change. Strong earthquakes not only deform larger areas, but do so by a greater amount of slip, thus producing disproportionally larger tsunamis than smaller events. Tsunami generation is discussed in detail in Geist (1997, 2003) and Geist and Dmowska (1999).

In addition to an earthquake's magnitude, the depth of the earthquake affects tsunami generation. The deeper the hypocenter or focus of an earthquake, the smaller the vertical deformation of the Earth's surface. A deeper hypocenter allows the seismic energy to spread over a larger volume, so that less energy reaches the ground surface. Earthquakes deeper than about 30 km rarely cause sufficient deformation to generate tsunamis.

An earthquake whose epicenter lies inland will only generate a tsunami if it produces sufficient vertical deformation offshore on the seafloor. Therefore, only very strong inland thrust earthquakes, as compared to even moderate offshore earthquakes, are potential tsunami generators (unless they trigger a massive landslide into the sea). For example, the 1994 Northridge earthquake resulted in vertical ground deformations of up to 6 feet but did not produce a tsunami. Had the fault ruptured with the same strength about 40 miles west offshore, it would have probably created a substantial tsunami inside Santa Monica Bay.

Tsunami models use the energy released; the size of the deformed area; the mean displacement at the surface; and the dip, strike, and slip angles, to infer a seafloor displacement pattern. Then, the models assume that water motion occurs instantaneously and, therefore, the initial tsunami wave will have the same shape as the seafloor displacement. Whatever mass of fluid is displaced by the seafloor moving up or down causes an equivalent displacement of the water in the same direction. The instantaneous assumption is based on the fact that tsunamis propagate at speeds up to 700 feet per second (fps), while seismic waves cause rupture at typical speeds of 1 to 2 miles per second.

Once the initial wave conditions are established, tsunami models estimate the evolution of the tsunami from its source to the target coastline, over the underlying seafloor bathymetry. When the simulated wave arrives at the coastline, tsunami models become inundation models and calculate the evolution of the tsunami as it moves inland. Tsunami models are really the synthesis of earthquake, wave evolution, and flood inundation models.

2 CRITICAL TOPICS SECTION

2.1 TOPIC 15: ADDRESS USE OF NATIONAL TSUNAMI HAZARD MITIGATION PROGRAM PRODUCTS AND APPROACHES IN THE NFIP. (HELPFUL FOR THE ATLANTIC AND GULF COASTS, CRITICAL FOR OPEN AND NON-OPEN PACIFIC COASTLINES.)

The National Tsunami Hazard Mitigation Program (NTHMP) conducts site-specific tsunami inundation modeling efforts for hazard assessment, based on "credible worst-case" tsunami generation scenarios (Bernard et al., 1996). The scenarios are based on identified tsunamigenic sources, typically earthquakes and/or landslides near the threatened site. Source development is key in this approach and involves research into historical and prehistorical events, including geologic fieldwork such as paleotsunami investigations and shallow sediment coring of the seafloor, as well as geophysical investigations such as multibeam bathymetric and seismic reflection surveys. Then numerical computations are undertaken that evolve the wave from its source to the target coastline (either nearshore or farfield), which sometimes involves transoceanic propagation. Model output includes wave height and current speed over the computational domain; from these, various products can be derived, including a line of maximum inundation that occurs over the duration of the simulated event. Tsunami inundation models are tested by simulating historic tsunamis and comparing model results with available tide gauge records. Simulations are also tested using field measurements of tsunami deposit distribution and estimates of tsunami current speed from sediment transport modeling of deposits as described in Section 3. Recommended best practices and quality control procedures for official NTHMP hazard assessment products are discussed by González et al. (2003). The current approach is outlined below, with the state of California as a case study.

2.1.1 Description of the Topic and Suggested Improvement

Inundation maps provide emergency managers in coastal communities with the necessary tools to plan for and mitigate tsunami disasters. Inundation maps are not only useful in assessing the population and facilities at risk, but also helpful in planning for emergency response. The preparation of inundation maps involves the assessment of the local geologic hazards, the interpretation of those hazards in terms of tsunami initial conditions, and the calculation of the resulting potential coastal inundation. Inundation maps now exist for most coastal areas of the Pacific states of the U.S., most coastal areas of Japan, and several other vulnerable areas around the world.

In this section, as a case study, the preparation of tsunami inundation maps in California will be presented. Even using these state-of-the-art inundation prediction tools, California presents unique challenges in assessing tsunami hazards: 1) There is an extremely short historic record of tsunamis in the state. Whereas some areas in the Pacific have 1,000-year-long records, in California there are none known before the 19th century. Although 28 more-than-credible tsunami "hits" have been reported, only the impact of the 1964 event has been well documented. 2) The geologic work in the state has been concentrated on identification of the risks associated with onshore faults. There is scant and mostly unpublished information on offshore faults or landslide and slump scars suggestive of past submarine mass failures. 3) Earlier estimates of tsunami hazards had relied almost entirely on farfield sources and had used pre-1980s inundation mapping technology. This had created the impression among policy planners and the general public that the tsunami hazard was small.

The most comprehensive calculation of tsunami hazards for California is the work of Houston and Garcia (1974) and of Houston (1980), both of which focused on the hazard in Southern California from farfield events. McCulloch (1985) also focused on the hazards in the Los Angeles region, primarily from farfield events, but also considered several nearfield events. Satake and Sommerville (1992) analyzed the Lompoc 1927 earthquake and the associated local hazards. In a seminal review, McCarthy et al. (1993) analyzed the historic records of tsunamis in California and predicted qualitatively the hazard over the entire state. Synolakis et al. (1997) reviewed pre-1997 studies and observed that the earlier runup estimates did not include inundation calculations. When performed with the new generation of inundation models, runup estimates were occasionally up to 100% higher than what the earlier calculations suggested, depending on the nearshore topography. Borrero et al. (2001, 2002, 2003) studied nearshore tectonic, landslide, and slump sources in East Santa Barbara channel and produced runup estimates ranging from 6 to 40 feet. For the San Pedro Bay, Borrero et al. (2004) estimated losses ranging from $7 to $40 billion provide estimates for the leading wave heights for landslide-generated waves off Palos Verdes ranging from 30 feet to 120 feet depending on the initiation depth. The bathymetry off Palos Verdes (shown in Figure 4) has features suggestive even to non-marine geologists of landslide scarps.

The current state of understanding is reviewed in Borrero (2002) and in Synolakis et al. (2002c). They have argued that the 100-year hazard in California is dominated by distant events, similar to the assumption of the earlier FEMA studies. However, given the recent results of offshore landslide hazards, which have yet to be accurately timed, they argued that the 500-year hazard is dominated by local events, hence revising Houston and Garcia's estimates.

In 1996, the Tsunami Hazard Mitigation Federal/State Working Group prepared a report to the U.S. Congress recommending the preparation of inundation maps for the five Pacific states (Alaska, Hawaii, California, Oregon, and Washington). The report led to mobilization of significant federal resources for tsunami hazards mitigation, and to the establishment of the U.S. National Tsunami Hazard Mitigation Program (NTHMP), which provides resources in all five states for mitigating tsunami hazards. The NTHMP was the focus of a program review during the International Tsunami Symposium held on August 5-7, 2001, in Seattle, Washington (Gonzalez et al, 2001).

As early as 1997, California's Coastal Region Administrator of the Governor's Office of Emergency Services (OES), through a series of workshops and publications, informed local governments and emergency agencies of the plans to address tsunami hazards and presented the NTHMP. OES solicited input as to the levels of hazards to be represented on the maps because

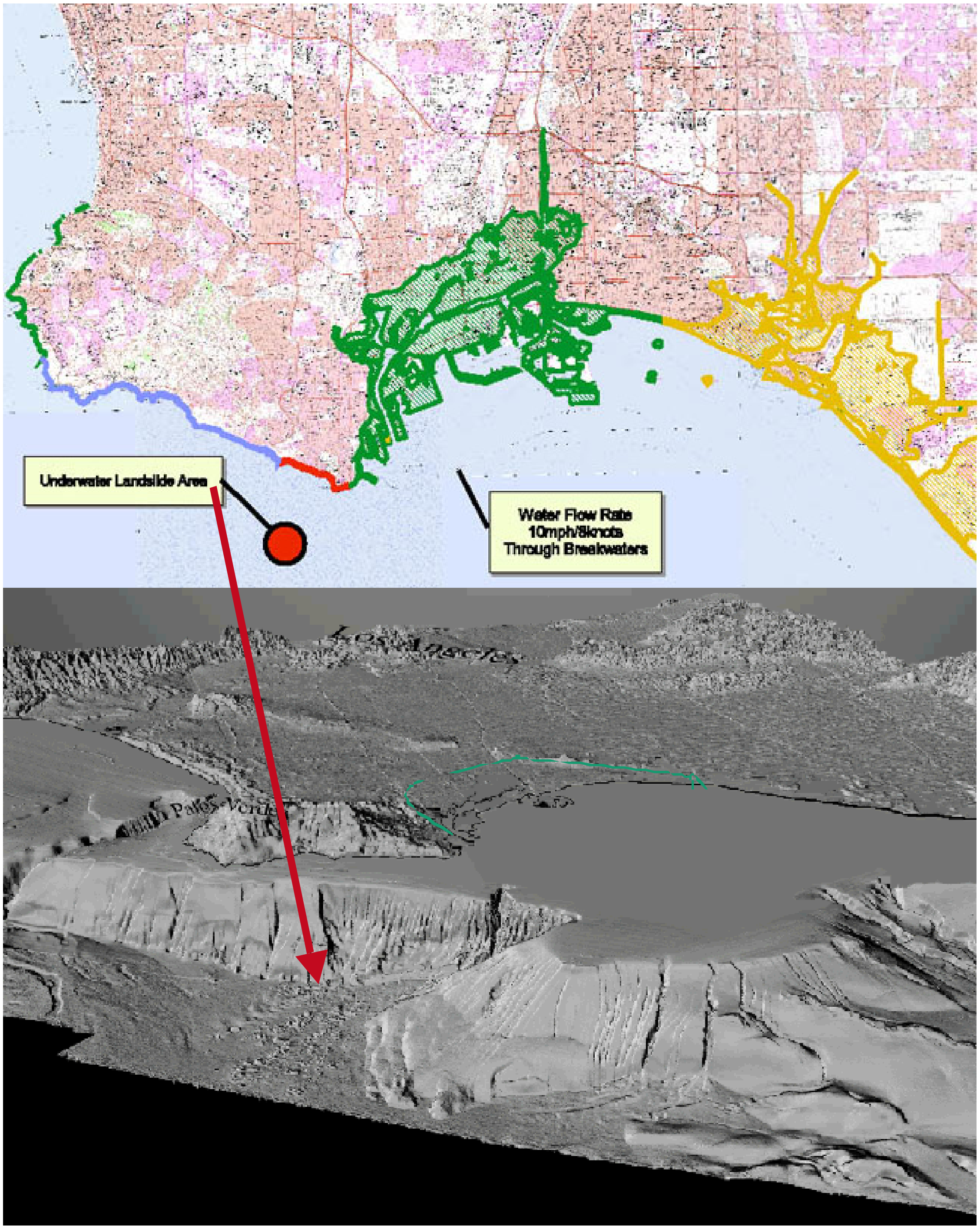


Figure 4. Images of Santa Monica and San Pedro bays, California.

Inundation zone from a tsunami generated from a failure of the Palos Verdes, California debris avalanche in green (i. e. the zone on the left). The "standard" flood zone from a dam break is shown in yellow (inundation zone on the right of the top figure). The lower figure shows the topography off Palos Verdes and identifies the so-called PV debris avalanche. The economic impact ranges from $7 to $40 billion U.S.

the short length of the historic record did not permit a comprehensive probabilistic hazard assessment. It was decided that the maps would include credible worst-case scenarios, to be identified further in the mapping process. In 1998, as funding became available for the state, OES contracted with the Tsunami Research Program of the University of Southern California for the development of the first generation of inundation maps for the state.

The State of California has the most densely populated coastlines among the five states in the NTHMP. The state had to use the same limited resources as the other four but assess offshore tsunami hazards over a much longer coastline. A comprehensive tsunami hazard evaluation involves both the probabilistic hazard assessment of different farfield and nearfield, onshore and offshore sources and the hydrodynamic computation of the tsunami evolution from the source to the target coastline. Given the level of funding, this was not feasible, and this presented another challenge for California.

Given the limited resources, it was decided to focus on nearshore tsunami hazards, which had never been modeled; even with the acknowledged limitations, the impact from farfield events had at least been attempted by Houston and Garcia (1974). Although return periods for these nearshore sources were not estimated, they are likely longer than the 100-year return period of the Houston and Garcia sources. But current NTHMP hazard assessment policy is to develop “credible worst case” scenarios, rather than events characterized by a specific return period. Thus, if inundation predictions from nearshore events proved smaller than twice the farfield tsunami results of Houston and Garcia, then farfield sources would have to be considered as well. As it turned out, nearfield sources produced inundation predictions more than twice those of Houston and Garcia. Hence, the effort was focused on identifying credible nearfield events, such as submarine mass movements, and then developing the state inundation maps for these nearfield scenarios only.

The state was also faced with the decision of choosing its mapping priorities. By considering the geographic distribution of population centers, the state opted to perform modeling of the Santa Barbara and San Francisco coastlines in year one, of Los Angeles and San Diego in year two, and of Monterey Bay in year three. The next decision was the resolution of the numerical grids to be used in developing the maps. The technology existed for high-resolution maps with grids of sizes as small as 17 feet, but this would result in a relatively small spatial coverage with large computational grids and painful computations. It was decided that the goal would be to produce maps at 400 feet resolution, based on information from Titov and Synolakis (1997, 1998), who had argued that dense grids may improve numerical accuracy but do not improve the realism if the available bathymetric/topographic sets are not of similar resolution. In California, the best available sets varied in resolution between 170 feet and 500 feet. Also, given the uncertainties in locating and understanding source mechanisms for submarine mass movements results with higher resolution would be misleading.

The next question was whether to provide emergency planners with inundation results at different levels of risk. For example, one suggestion was to include low and high risk lines on the inundation maps. Another suggestion was to provide separate lines for nearfield and farfield events. After discussing these issues with emergency preparedness professionals across the state, it was decided that a single line representing a worst-case scenario was preferable, for it simplified the preparedness response of city officials and better informed the general public.

The inundation mapping effort first identified offshore faults and offshore landslide and slump hazards. Difficulties encountered included the lack of detailed high-resolution marine surveys over all target coastlines. Marine surveys have been undertaken by the USGS off Santa Monica Bay and by the Monterey Bay Aquarium Marine Institute (MBARI) off Santa Barbara and Monterey Bay (Greene et al., 2000); high resolution surveys are not available for other parts of the state, if indeed they exist at all. Hence, given that onshore earthquakes can trigger submarine landslides, in regions where marine geology data did not exist, steep submarine soft-sediment slopes were considered as possible sources. Data on offshore faults and slide-prone areas were then used to develop initial tsunami waves as discussed in Borrero et al. (2001), and then the inundation model MOST was used to obtain inundation heights and penetration distances along the target coastline.

Once draft versions of the maps became available, the California OES presented them in regional meetings with emergency preparedness officers and other interested parties such as the State Lands, Seismic Safety, and Coastal commissions. Further input was solicited, and an emergency response manual was produced by OES (2002) with guidelines for mitigation. OES also produced a videotape for school use and distributed numerous copies of other commercial video programs describing tsunami hazards. The development of the state’s inundation maps was featured in four Discovery Channel documentaries and in numerous national and local news stories.

2.1.2 Description of Procedures in the NTHMP Guidelines

NTHMP tsunami hazard assessment products draw on the collective expertise of NOAA, USGS, and the community of academic scientists and engineers actively involved in tsunami research and hazard mitigation (Bernard et al., 1996; Gonzalez et al., 2003). Thus they represent the best available methodology and information for tsunami hazard assessment. In each state, the historic and prehistoric record is examined to determine whether the worst credible event is likely to occur from a farfield or nearfield tsunami. In summary, the program has identified the following points:

A. Southern and Central California are at risk from local and distant earthquakes and from coseismic or aseismic subaerial and subaqueous slides.

B. Northern California to Northern Washington and Straits of Juan de Fuca are at risk from Cascadia Subduction Zone earthquakes and from coseismic of aseismic subaerial and subaqueous slides.

C. Puget Sound is at risk from local earthquakes (i.e., along the Seattle, Tacoma, and other local fault systems) from coseismic and aseismic subaerial and subaqueous slides and from delta failures.

D. For Alaska, the primary sources of tsunamis are local earthquakes and landslides. In Hawaii, distant earthquakes and local landslides are the primary sources of tsunamis.

To date, 22 inundation modeling efforts have been completed, covering approximately 108 coastal communities in California, Oregon, and Washington with an estimated at-risk population of 1.2 million residents. Work continues on the estimated 40 additional modeling efforts needed to cover the remaining 2.2 million residents at risk.

2.1.3 Application of Existing NTHMP Guidelines to Topic–History and/or Implications for the NFIP

Alternatives for Improvement

Because the NTHMP methodology does not fit a current FEMA template for the assessment of other flooding hazards, we recommend a focused, collaborative FEMA/NTHMP effort to develop such a methodology for incorporation of NTHMP tsunami hazard assessments into the FEMA National Flood Insurance Program–perhaps as a special overlay on existing FIRMs (i.e., development of a separate Tsunami Hazard Zone Delineation) or some other use of the NTHMP products. We have identified the following areas that are critical for this integration.

A. Probabilistic hazard assessment, 100-year-return period

The current NTHMP approach does not explicitly address the probability of occurrence of events. In particular, no formal effort is made to develop a “100-year event” or an estimated recurrence period for a particular source. Rather, the focus is on creating a scientifically defensible scenario for generation of a tsunami that poses a potential threat to the community that can be used for emergency management purposes. This critical need is addresses in Task 16 in detail.

B. Producing inundation maps versus evacuation maps

Without a probabilistic hazard assessment element in the NTHMP’s existing inundation maps, it has been difficult to rank the relative risk from different scenarios. Some states have felt that lines identifying risk zones for nearfield and farfield events would prove cumbersome and confusing for the public. In these cases, it was decided to consider, for every locale in each study region under consideration, the worst credible event based on the available historic earthquake and tsunami information.

The inundation predictions for any given event are highly dependent on bathymetry and topography and vary substantially along the coast. Because the location of the source is seldom accurately known, the source was moved around but remained within the range of uncertainty of its location. Along California’s flat coastlines, this relocation of the tsunami sources resulted in relocation of the maximum along the coast. When asked, emergency planners preferred to have a single value for each region identifying the maximum elevation that tsunami waves from the different local offshore sources would attain. This practice would simplify the communication of the risk to the public and would provide information that is easy to remember and implement in regional emergency preparedness. For example, a region could plan for tsunami evacuation areas above a certain minimum elevation across its jurisdiction. Hence, in the development of the maps, sources were relocated along the coast and the highest inundation value among different runs was identified.

Interestingly, in the areas studied, there were no areas that consistently experienced higher runup that adjacent locales. Synolakis et al. (2002c) found that most low-lying coastal areas could experience high runup if the source was relocated in an appropriate direction, within the uncertainties of defining the source. Thus, the inundation maps for California do not represent the inundation from any particular event or characteristic earthquake, but the locus of maximum penetration distances from relocating worst-case scenario events. For the Palos Verdes tsunami, Borrero et al. (2004) estimated direct, indirect, and induced losses ranging from $7 to $40 billion. An interim procedure for incorporating NTHMP maps into FIRMs would be to use the existing 100-year-return maps and designate a separate hazard zone for tsunami risks. The NTHMP boundaries would then be the tsunami hazard zone limits.

Substantial effort would have to be expended to identify the predicted hazard zone limits within existing inundation maps. Because the NTHMP maps are used for evacuation planning and emergency preparedness, most often they reflect local conditions. For example, to effectively implement evacuation plans, if the inundation zone is close to a major highway, the state maps extend to the highway, which is then designed for evacuation. Also, the existing maps often portray an inundation zone that is larger than the zone predicted from the models. For example, if the highest credible tsunami runup within a region is 40 feet, the evacuation maps attempt to follow the 40-foot-elevation contour everywhere. While this is important for evacuation planning, it is not adequate for flood insurance mapping, where detail might be important.

2.1.4 Preliminary Time Estimate for Guideline Improvement Preparation

Supplementary support for NOAA, USGS, and FEMA activities will be required to appropriately expand ongoing work and include efforts specific to NFIP needs–conduct a comprehensive review of the relevant literature, examine in-house geologic and geophysical data create the digital database, develop an appropriate methodology, relocate the existing inundation line as appropriate, and produce a report. Interagency discussions will determine the source of new funds. Table 4 at the end of this report presents estimates of times required to accomplish the tasks in this topic.

2.2 TOPIC 16: PROBABILISTIC HAZARD ASSESSMENT FOR THE OPEN AND NON-OPEN COASTLINES OF THE PACIFIC STATES

A methodology is recommended for completing a comprehensive probabilistic tsunami hazard assessment for the Pacific Coast, considering both farfield events and nearfield events triggered by seismic sources. For the Pacific Coast, farfield events are those generated a long distance away by seafloor displacement during earthquakes, such as the 1964 Alaska and 1960 Chile earthquakes; and nearfield events are those generated by submarine landslides triggered by earthquakes offshore and onshore, such as the Cascadia Subduction Zone earthquakes that triggered the 1992 Cape Mendocino tsunami along the California coast. Existing FIRMs for the Pacific Coast depict only risk associated with farfield events and the method relies on the definition of a 1% annual-chance-event and a 0.2% annual-chance-event tsunami for the farfield events.

Traditionally, FEMA's policy has been to incorporate tsunami-induced hazard and other storm-related coastal hazard into one coastal high hazard zone, which is defined in 44 Code of Federal Regulations (CFR) Part 59.1 as follows:

> *Coastal high hazard area means an area of special flood hazard extending from offshore to the inland limit of a primary frontal dune along an open coast and any other area subject to high velocity wave action from storms or* ***seismic*** *sources.*

During the course of this study, it became imperative to address not only the statistical aspects of tsunami generation, but the associated geological, numerical modeling, regulatory, and institutional aspects and available resources at NOAA, USGS, and in academic institutions.

2.2.1 Description of the Topic and Suggested Improvement

There is no existing guideline for tsunami hazard assessment for the Pacific Coast. However, Houston and Garcia (1974) and Houston (1980) conducted tsunami hazard studies that can be construed as FEMA's methodology on effective studies for the Pacific Coast. In a Type 19 Flood Insurance Study for Southern California, Houston (1980) conducted tsunami prediction studies for the 100-year and 500-year tsunamis based on events in Chile and Alaska. A similar approach was adopted for Type 16 Flood Insurance Studies for the West Coast of the Continental United States and for Monterey and San Francisco bays and Puget Sound.

The runup frequency relationship for tsunamis was combined statistically with combined frequency relationships for swell and wind waves to produce a single runup frequency relationship along a transect. Thus, the resulting coastal hazard zones represented hazards associated with high-velocity wave action from storms or seismic sources. The biggest limitation of this method is that it incorporated only farfield events.

Houston and Garcia (1974) used a combination finite-difference (FD) solution and analytic solution of the linearized shallow-water wave (LSW) equations to calculate tsunami propagation, except in Santa Monica and San Diego bays, where they used a finite-element (FE) solution to resolve possible local resonance effects. They argued that the only reliable data for defining source characteristics at that time were from the 1964 Alaskan and the 1960 Chilean earthquakes. At the time, the tsunamigenic potential of the Cascadia subduction zone had not been recognized (Geist, 1998; Satake et al., 2003). Based on these data, they approximated the initial ground deformation by a hypothetical uplift mass of ellipsoidal shape, about 600 miles long with an aspect ratio of 1:5 and maximum vertical uplift of 25–33 feet. They then divided the Aleutian trench into 12 segments and calculated the wave evolution from each segment, and repeated the procedure for tsunamis from the Peru-Chile trench.

It is important to note that, for their time, the methodology used by Houston and Garcia (1974) was ground breaking, not only in its scope, but also in the combined use of analytical and numerical methods. Houston and Garcia (1974) first solved a linear-form spherical long wave and then propagated the tsunami from the source to the edge of the continental shelf, by using a finite difference model; at the continental shelf, they derived an analytic expression to match the outer and inner wave amplitudes, and then they used that expression to derive a simple amplification factor for a sinusoidal tsunami. Even though they did not match the slope of the water surfaces in the inner and outer continental shelf regions, their results compared extremely well with measurements from tidal gauge records, whenever suitable tidal were available that did not need additional signal processing to filter harbor resonance effects.

The good comparisons with tidal gauge data for the 1964 Alaskan event provided encouragement for the extrapolation of the results for nearfield events, despite Houston and Garcia’s (1974) own disclaimers, thereby masking three important aspects of the “inundation” calculations used: 1) Nearfield events are “extremely dynamic in three dimensions,” and for this reason the methodology used for farfield events may not be appropriate for nearshore quakes. 2) In the mid-1980s it became apparent that superposition of sinusoids is not as straightforward as had been previously assumed; the reason is that during the reflection process (not accounted for in Houston and Garcia's calculation) a phase lag is introduced that is frequency dependent (Synolakis, 1987; Liu et al., 1991). 3) Comparisons of numerical model predictions with data from the field surveys of the 1992–1996 tsunamis suggested that even small-scale nearshore features can influence inundation to first order, casting doubt on predictions from coarse grid computations because they may miss extreme events.

Houston performed another comprehensive study of tsunami predictions in California in a series of two reports (Houston and Garcia, 1978; Houston, 1980). By this time, numerical solutions of the shallow-water wave equations had begun to be available; they solved, using finite difference algorithms, the nonlinear form of the shallow-water (NSW) wave equations including frictional terms. Still, because of computational power limitations, no runup was evaluated. Instead, computations treated the shoreline as a vertical wall. Houston (1980) noted that the runup elevations (i.e., the elevation of the maximum inland penetration of the tsunami) may not equal shoreline elevations at locations where dunes prevent flooding, or if the land is flat, where inland flooding maybe extensive. As has been shown by Titov (1997) and Titov and Synolakis (1997, 1998), wall-type calculations (as shown in Figure 5) not only underpredict the runup substantially, but may also miss extreme events. Although the degree of underprediction varies with the local topography, it is often a factor of two and sometimes it has been reported as large as five.

Even though these newer computations were a substantial improvement over the 1974 study, it is important again to revisit the computational assumptions used to arrive at these 1978 and 1980 predictions:

1. Only farfield events from Alaska and South America were considered because the potential of the Cascadia Subduction Zone had not been recognized at the time.

2. Faults were modeled simply as an uplift of the seafloor.

3. The entire Pacific Ocean was modeled as a 1,600-foot constant-depth basin with a 2-mile-square grid. In the nearshore region, the bathymetry was also modeled with a 2-mile-grid (i.e., no coastal topography was included).

4. The computational boundary was a vertical wall at the shoreline (i.e., there were no inundation computations).

5. No values were provided for tsunami currents.

To evaluate the possible effects of these limitations, the Focused Study Group looked at results from field measurements and modeling from the 15 tsunamis in the 1992–2003 period. The contemporaneous field surveys that were initiated following every event have provided a high-quality data set with actual inundation measurements. They have thus allowed not only the assessment of earlier assumptions, but also the means to visualize what the impact of even small tsunamis can be. Some of the conclusions from review of the field surveys in the past 15 years are summarized below.

1. Small-scale coastal features have first-order effect on runup, particularly for extreme events. To obtain quantitative agreement with measurements, computational grids of less than 150 feet are needed.

2. Excellent predictions for fault movements now exist. Comparisons with field data (for nearfield events only) suggest that, for first-order accuracy, the details of the three-dimensional fault displacement on the seafloor need to be incorporated in the model (Geist, 2002).

3. Threshold-type computations with vertical boundaries at some reference offshore depth or at the shoreline, as used earlier, may underpredict measurements by factors up to five.

4. Overland flow is a significant hazard, as demonstrated in Wurhing during the 1992 Flores event, or in Sissano, during the 1998 Papua New Guinea tsunami. Residents of narrow

spits of land, such as in Eureka or Coronado Island in San Diego, California, are at higher risk, and extreme care is needed to evaluate inundation areas in such locales.

5. Tsunami currents are important in defining inundation zones. Even small tsunamis can generate large currents.

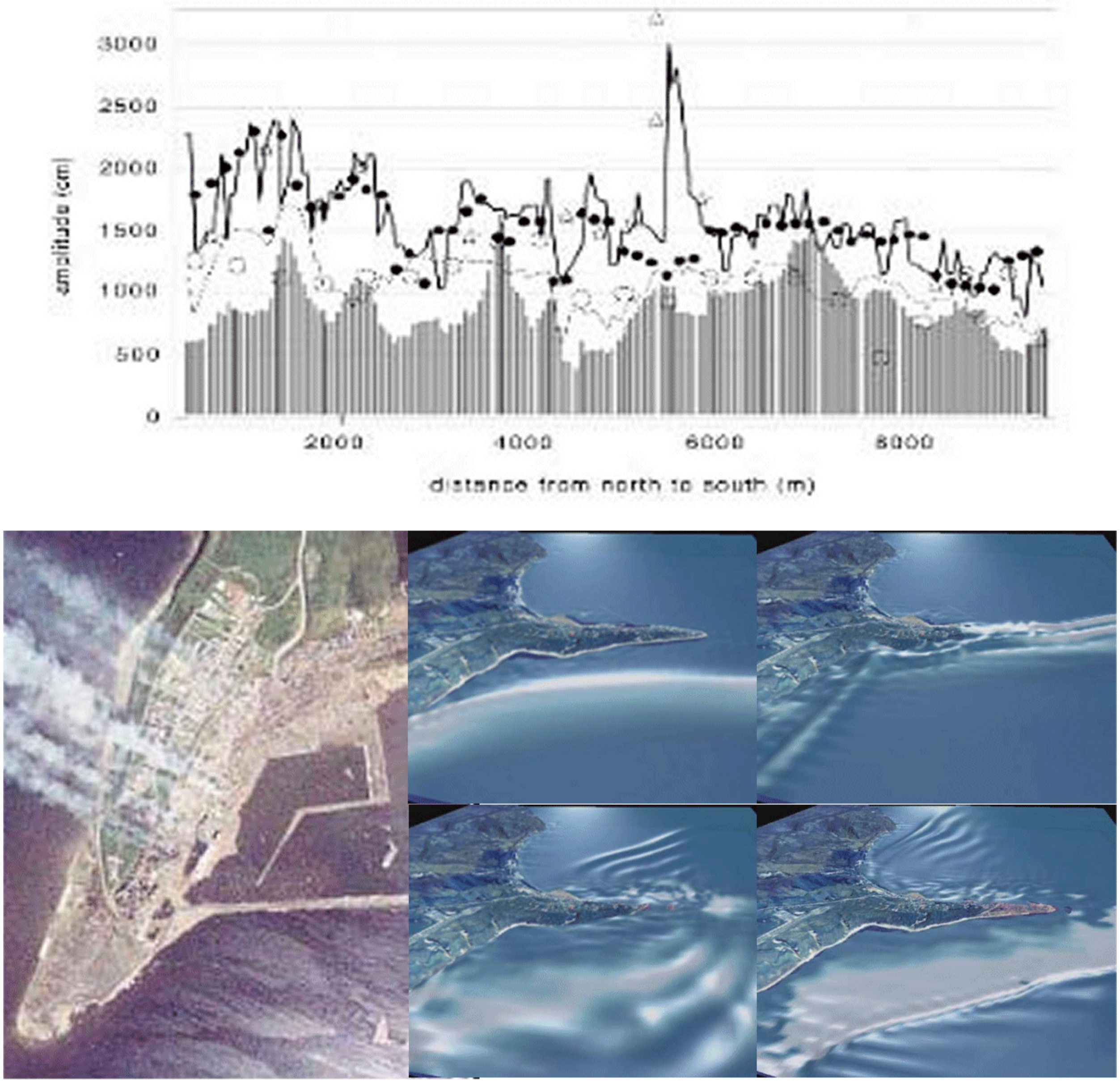


Figure 5. The lower left panel shows the damage at the town of Aonae at the southern tip of Okushiri Island, Japan, during the 1993 Hokkaido-Nansei-Oki tsunami.

The photo was taken the next morning, and fires are still smoldering. Notice the complete devastation of the eastern tip of the peninsula. The lower right panel shows numerical simulations from MOST that accurately display the overland flow that destroyed Aonae. Notice how the wave approaches (upper right), flows over (upper left), and then reflects back (lower right). The upper panel shows a comparison of results from numerical predictions with actual measurements. The solid vertical lines (1) are the predictions of a threshold model such that used by Houston and Garcia (1974) and then by Houston (1978). The empty circles (□) show model predictions at a resolution of 1,600 feet, the solid circles ( ) at 800 feet, and the solid line (–) at a resolution of 1,000 feet or less. The stars indicate the field data. Notice that only at a resolution of 100 feet it is possible to capture the extreme runup, which reached more than 100 feet. The threshold models appear inadequate for modeling extreme runup, which is exactly when accuracy is most needed. Results from Titov and Synolakis (1997, 1998).

The recent findings stated above are a cause of concern. In view of the large differences with the inundation predictions from nearfield events, it is important to assess what improvements can be made in the existing methodology to determine an inundation line with 100-year return period using the best available technology, in terms of geologic, geophysical, and hydrodynamic computational resources.

2.2.2 Alternatives for Improvement

Four preliminary alternatives are articulated, in order of increasing preferences:

A. Do nothing for tsunami hazard assessment and rely on local, state, and NOAA programs to map tsunami risks. For instance, a recent Flood Insurance Study on Sandy Point, Washington, did not include a tsunami hazard assessment.

B. Maintain the same tsunami-related risk assessment in the coastal areas for which Houston developed runup frequency elevations. Update the method used by Houston only for farfield events.

C. As an interim procedure, consider separating tsunami risks from storm-induced risks. Designate a separate hazard zone for tsunami risks. Use NOAA’s Tsunami Inundation Map boundaries as hazard zone limits.

D. As a longer term procedure, develop a methodology for comprehensive tsunami hazard assessment for farfield and nearfield events triggered by earthquakes, both offshore and onshore. This includes the analysis of tide gage data, when available, to determine the tsunami anomalies along the Pacific Coast and transfer these results to open coast areas of interest. The tsunami events listed in Tables 1 and 2 will serve as a basis for searching the tide gage data for tsunami anomalies.

Approach A

Approach A ignores the risk altogether and is not advisable.

Approach B

Approach B maintains the status quo of hazard identification of effective FIRMs, with tsunami hazard identified, as the new FIRMs under FEMA’s Map Modernization Program will also include same type of farfield tsunami hazards as the currently effective FIRM. In this approach, necessary modifications should be applied to the Houston method in terms of event description and numerical models. This approach is better than the first because it incorporates the farfield tsunami hazard; however, it does not incorporate comprehensive tsunami hazard analysis involving both farfield and nearfield events and is based on earlier results that differ substantially with recent finding.

Approach C

Approach C would involve identifying a tsunami risk hazard zone as the maximum credible tsunami inundation. Although this approach would show a hazard zone, NOAA's current tsunami inundation maps would not serve the actuarial purpose of a FIRM. This approach is analogous to creating a FIRM for maximum possible flood rather than the one-percent-annual chance flood for a riverine hazard. However, if return periods can be assigned to NOAA's tsunami inundation maps, actuarial rates may be worked out separately for the tsunami hazard. In this approach, the NFIP would need to change its regulations to redefine coastal high-hazard zones and add new regulations for tsunami hazard zones.

The argument for designating a tsunami hazard zone merits some investigation because the damage potential of tsunami waves may be much greater than that of storm waves, for which the current guidelines were developed. The rationale for a new tsunami hazard zone is as follows:

1. The definition of V-Zone is based on at least a 3-foot breaking wave during a 100-year storm event. This definition should be reevaluated for tsunami waves because tsunamis are associated with large velocities. Further, empirical relationships often used to associate velocities with wave heights may not be applicable for tsunamis.

2. Current V-zones frequently exclude adjoining areas with virtually indistinguishable hazard characteristics. It is probable that damages from a tsunami would extend beyond a V-Zone limit line because tsunamis are known to induce debris and fire damage in adjacent areas. Statistical combination of tsunami-induced runup with storm-induced runup may mask the actual risk posed by tsunamis because damage may extend beyond mathematically computed elevations and zones.

3. Floodplain management regulations may need to be reevaluated for tsunami-prone coastal communities under the NFIP to reflect appropriate precautions necessary for reducing damages from a tsunami. For new construction and substantial improvement within V-Zones, 44 CFR 60.3 provides certain minimum standards, which may have been developed based on hurricane-induced conditions of the Atlantic and Gulf coasts. Relevant regulations, particularly those under Section 60.3(e), need to be reevaluated for tsunami-prone areas. Some criteria may be developed under the Community Rating System for rewarding "tsunami-ready" communities that undertake precautionary steps beyond the minimum necessary under the NFIP. These evaluations should include conditions from all tsunami-prone states, including Alaska and Hawaii.

4. Because tsunami events are infrequent, the insurance rate structure in a tsunami hazard zone may be less costly than that for the more frequent coastal storm events, which include El Ninos.

5. Designation of a different hazard zone for apparently similar flooding scenarios is not new to the NFIP. In riverine situations, separate zone designations are available for alluvial fans with high velocity debris hazards.

Approach C3 is better than the first two because it includes nearfield events, at least in California, where these events are known to be more hazardous than farfield events. The definition of a new coastal hazard zone for tsunami may be more time consuming because it involves changes to federal regulations. To have the effective regulations ready for use in the Pacific Coast flood studies under the Map Modernization Program, activities leading to tsunami-related floodplain management regulations should start soon. The weakness of adopting NOAA's inundation maps is that the hazards they address are not comprehensive; for instance, they do not include farfield events for California or nearfield events in Alaska.

Approach D

Approach D would attempt to incorporate comprehensive tsunami hazard assessment for nearfield and farfield events. The Probabilistic Tsunami Hazard Analysis (PTHA) framework (for example, as proposed by Downes et. al.,2001) can be adopted with some modifications. The framework this Focused Study Group proposes consists of four steps:

1. Identify farfield and nearfield sources: The sources might be submarine landslides and fault sources. State-of-the-art model (Geist, 2002) would be used to predict initial conditions for the numerical computations.

2. Estimate recurrence interval: In this step, recurrence interval of seafloor displacement and landslide volumes would be estimated. This step produces the initial condition for the propagation model and is deemed to be the most formidable step in the process because of the large uncertainties in the underlying rupture process of fault or landslide.

3. Develop runup (or wave height) frequency curves. These can be developed for the shorelines by using numerical models that account for wave transformation from each source (i.e., faults and landslides).

4. Combine runup frequency curves. These can be generated by statistically combining all runup frequency curves developed in Step 3.

In computing recurrence intervals for infrequent events such as tsunamis, one can also consider conditional probabilities and this approach may be the most realistic for tsunami hazard assessment as it represents real risk from infrequent events. For the Pacific Northwest, Priest (2001) argues that "with the known condition that 301 years of strain has already accumulated on the subduction zone, the conditional probability of a recurrence in the next 100 years is much higher than a random event with a 400-600 year recurrence." This approach is a departure from traditional hazard assessment, which is based on purely random events.

Although there are difficulties and uncertainties with recurrence interval estimates, given the lack of sufficient data, groups of scientists in academia, research institutions, and federal agencies are actively working on this problem (Bardet et al., 2003). Most notable are the USGS, the University of Southern California, Northwestern University, and Lawrence Livermore Laboratory. A study can be undertaken comprising national and international tsunami research scientists to assess the state of the art and associated uncertainties of recurrence interval prediction for tsunami sources along the Pacific Coast for California, Oregon, and Washington.

Approach D could take several to many years to perfect, and it is recommended that FEMA remain an active partner with other federal agencies and research institutions and help set the goals and objectives of the PTHA.

2.2.3 Recommendations

The Focused Study Group believes that the Approach D is the only defensible approach to tsunami hazard assessment and that a probabilistic hazard assessment can be performed in 2–4 years for all Pacific states. However, before embarking on a large-scale up/down–coast analysis, it is recommended that a focused study be performed within a 6-month period to redo the existing simulations for farfield events done 25 years ago. Tsunami modeling technology has evolved rapidly, particularly in the last ten years, and comparison of new simulations with the 25-year-old results would allow evaluation of the margin of error of the hydrodynamic predictions. Depending on the results, the Focused Study Group will recommend to FEMA a larger followup study to address the needs of all five Pacific states and possibly the Atlantic and Gulf states as well.

The Focused Study Group believes that a good candidate for this interim pilot study is Santa Monica Bay in Southern California. Not only does it have the largest population density on the west coast, but on a Sunday afternoon in the summer months, hundreds of thousands of people are at risk. The property values are some of the highest along the Pacific Coast, and the pilot study results would be extremely useful in local emergency preparedness. However, from the epistemological point of view, any locale at risk in Washington, Oregon, or California would serve the purpose of the pilot study.

It is noted that this pilot study would be useful under either Approach C or D. Even if a probabilistic hazard study is not conducted, the pilot study would determine a better 100-year-return inundation line by improving the farfield estimates of Houston and Garcia (1974, 1978). If, for example, Approach C is used and a different hazard zone defined, the limits of this zone would be calculated using contemporary inundation technology, eliminating most of the significant known limitations of the earlier maps.

Inundation modeling for hazard assessment, based on tsunami source probabilities, will exploit the advanced numerical modeling technology and essential infrastructure developed and maintained in each state by the NTHMP. It will employ NOAA's model MOST. Organization and planning of this multiyear effort in an efficient and cost-effective way will be a primary objective of the FEMA/NTHMP working group.

NOAA's historical database requires extensive quality control and expansion, including systematic historical research to assess and characterize the nature of tsunami-event sources. Similarly, to identify and characterize additional tsunami events and the nature of their sources, the prehistoric database requires an accelerated effort to acquire and analyze field measurements. Characterization of tsunami events will include estimates of inundation and tsunami currents based on field and laboratory measurements of tsunami deposits and on tsunami sediment transport modeling. This collaborative FEMA/NTHMP effort to assess tsunami hazards will clearly advance the primary goals of each agency–those of FEMA related to insurance rates, those of the NTHMP related to emergency management, and those of both agencies related to mitigation.

Specific goals of this pilot study for a selected locale in Washington, Oregon, or California are the following:

1. Significantly improve estimates of recurrence interval by increasing the coverage and quality of the historic and prehistoric tsunami record. Analyze farfield sources in Alaska and South America and regional sources in Cascadia.

2. Develop probability distributions for tsunamigenic earthquake and landslide sources.

3. Conduct inundation modeling to evaluate the consequences of events from the appropriate sources.

4. Determine the 100-year-recurrence line for communities in one selected locale as a pilot study.

2.2.4 Preliminary Time Estimate for Guideline Improvement Preparation

Accelerated research and development focused on joint NFIP/NTHMP goals will require supplementary support for USGS, NOAA, and academic efforts. These efforts will include (a) significant improvement of database coverage and quality, (b) development of probability distributions, (c) tsunami modeling, and (d) FEMA/NTHMP Working Group activities. Interagency discussion and agreement will identify the level and sources of both new and matching in-kind support required for this effort.

3 IMPORTANT TOPICS SECTION

3.1 TOPICS 20 AND 29: TSUNAMI STRUCTURE–DEBRIS INTERACTION TO DEFINE HAZARD ZONES AND TSUNAMI-INDUCED EROSION.

Debris impact causes the greatest amount of structural damage during tsunami attack, at least for tsunamis with overland flow depths less than 10 feet. As the tsunami evolves in the terminal stages of upwash up a beach, it transports debris such as logs, cars, and the remains of coastal structures, which then become waterborne missiles. An example of waterborne debris damage is shown in Figure 6. An example of tsunami-induced erosion is shown in Figure 7. No guidelines exist for calculating forces from the impact of tsunami-borne debris impact on structures. A comprehensive review of tsunami-debris interaction is recommended, along with a preliminary assessment of the adequacy of guidelines published in FEMA's Coastal Construction Manual (CCM).

3.1.1 Description of the Topic and Suggested Improvement

Tsunamis can generate large onshore currents and move large objects far inland. Historic examples from large tsunamis abound. The most notorious is the report of the U.S. Navy ship Watery, which was moved by the 1868 Arica, Chile tsunami two miles inland and then moved back to shore during the 1877 Arica tsunami so that the ship could sail on. A measure of what even small tsunamis can do is the 1994 Mindoro, Philippines tsunami (Imamura et al., 1995). In an area where the vertical inundation heights did not exceed 10 feet, the generated tsunamis floated a 6,000-ton power-generating barge, broke its mooring lines, and carried it one mile inland down the Baryan river. Impact forces can cause collapse of coastal structures; an excellent visualization of the process can be observed in detail in the videotape Discovery's Tidal Wave (1998). The estimation of impact forces and currents is still an art and far less well understood than hydrodynamic evolution and inundation computations. In what follows, different methods and formulae are described in the literature, although none has been truly validated by comparisons with field data.

Existing analyses extend only so far as suggesting methods for calculating forces on piles and impact forces on seawalls and structures with provisions available for breaking wave loads. No methods exist for calculating debris impact, beyond the suggestions provided in the CCM, which were derived from results from steady flows. The results are discussed in detail in Synolakis (2003).

Tsunami forces on piles are usually calculated in accordance with the classic work of Dean and Harleman (1966), as the sum of a drag and added mass terms developed for periodic waves. To date, no equivalent published analysis exists for transient waves. Research work is under way in a National Science Foundation Collaborative Research study with the University of Washington, Cornell, Southern Methodist University, and the University of Southern California. Preliminary results exist only for solitary waves.

Figure 6. An example of impact from waterborne debris in Hilo, Hawaii, from the attack of the tsunami triggered by the 1946 Aleutian earthquake, the same tsunami whose impact in Scotch Cap is shown in Figure 3.

Figure 7. Rajekwesi, East Java, after the 1994 tsunami.

The tsunami eroded a strip about 100 feet wide off the shoreline. The damage seen is from the tsunami; there was no earthquake ground shaking, as this was a slow offshore earthquake. The tsunami penetrated more than 1/2 mile inland. Its height here was estimated (from watermarks inside the only surviving structure) as 12 feet. (Imamura et al., 1995).

For tsunami forces on seawalls, the existing methodology follows the classic work of Cross (1967). Ramsden and Raichlen (1990) and Ramsden (1993) used Cross's formulation and results from laboratory experiments to calculate the forces of an impinging bore on a vertical seawall. They cautioned against extrapolating their specific results for walls of finite height and horizontal extent.

No published results exist for tsunami loads on rectangular structures. To calculate the hydrodynamic load on a rectangular structure, the CCM recommends using an equivalent "dynamic" flow depth, d_{dyn}, calculated from

$$d_{dyn} = (1/2g)\ C_d\ V^2 \quad (1)$$

where C_d is the drag coefficient, g is the acceleration due to gravity, and V is the velocity. The CCM recommends that $V^2 = 4gd_s$ where d_s is the design flow elevation (DFE). When the velocity $V < 10$fps, $d_{dyn} = 2\ C_d\ d_s$. While it is unclear how C_d or d_s are to be calculated for a highly transient wave, the velocity of which varies rapidly as it evolves up a shoreline, it is presumed that one would use the maximum flow velocity calculated from the hydrodynamic computational models at the locale of interest. Then the hydrodynamic force is given by

$$F = \rho g\ d_s\ d_{dyn}\ w \qquad (2)$$

in which ρ is the water density and w is the structure width. The drag coefficient depends on the relative ratio of width of the structure w to the DFE depth d_s at the front of the structure.

For overland flow velocities $V > 10$fps, the CCM recommends that the force be calculated by

$$F = (1/2)\ \rho\ C_d\ V^2\ A \qquad (3)$$

in which A is the surface area of the structure normal to the flow.

The CCM describes a methodology for calculating debris impact forces through the calculation of the impact load F_p, given by

$$F_p = W\ V / gt \qquad (4)$$

where W is the weight of the object impacting the structure, V is its velocity, g is the acceleration of gravity, and t is the duration of impact. The formula in essence calculates the impulse force. The CCM recommends that, in the absence of any criteria, one use w=1,000lb with $V=(g\ d_s)^{1/2}$. Assuming that one is careful with the calculation of the DFE, the formula might produce a conservative estimate. One issue that needs clarification is the calculation of the local DFE. As the wave evolves up on dry land, its velocity is not simply related to the square root of the gravitational acceleration times the depth, which is simply the long wave velocity. During tsunami attack, the velocity in the runup zone can be as high as 10 fps, yet the local depth might be smaller than 1 foot.

There are no existing guidelines for erosion due to tsunamis. Scientists from the USGS have performed comprehensive surveys of several historic tsunamis and of most 1992–2002 events. A large amount of data has been accumulated on erosion and deposition during tsunami attack, but the data have yet to be translated into standards and guidelines for engineered structures. While there are many studies of scour around cylindrical piers for steady flows and combinations of steady flows and waves, the Focused Study Group identified only one for tsunamis, by Tonkin et al. (2003). It describes a laboratory experiment with erosion from solitary waves attacking a circular cylinder. The study concluded that the time scale of the tsunami attack is critical in the scouring process. However, given the well-established difficulties with extrapolating sediment scouring experiments from small-scale laboratory measurements to the prototype, it is not possible to draw conclusions from this study

3.1.2 Description of Potential Alternatives

There are three preliminary alternatives to mitigating the hazard:

A. Do nothing and rely on the CCM recommendations and on existing guidelines for evaluating coastal structures.

B. Do a preliminary study to determine how relevant and appropriate the CCM recommendations are for tsunamis, in view of recent field observations.

C. Develop standards and guidelines for calculating debris impact loads on structures during tsunami attack.

D. Perform an interim study to determine whether sufficient data exist to develop empirical guidelines for tsunami scour and to suggest a methodology for calculations.

Despite the fact that there are no published studies disputing the CCM recommendations for tsunamis, even casual examination of tsunami damage photos reveals that tsunami impact is a substantial hazard, even for tsunamis of small height. For this reason, Approach A is not recommended.

Approach B involves calculating specific tsunami heights and velocities during tsunami attack on actual coastlines. Numerical models such as MOST calculate velocities in both propagation directions as the tsunami evolves, in addition to the local flow depth. Note that the latter is not known a priori, when the wave advances on dry land. For example, the tip of the advancing wave has very small depth but very high velocity. As the wave reaches its maximum, the flow depths over the inundation area are the largest, but the velocities are smaller than their extreme values. It is possible to obtain numerical data, then compare different methodologies for evaluating the local DFE and velocities, and compare them with the CCM recommendations.

Approach C involves resorting to both numerical modeling and large-scale experiments to determine debris impact forces from tsunamis. Both the Network for Earthquake Engineering Simulation and the Engineer Research and Development Center (ERDC, formerly CERC) basins, have directional wave spectrum generators that have the capability to generate large-scale transient waves. Experiments in these facilities can help validate numerical results on impact forces.

In terms of tsunami scour, it is recommended that an interim study be performed that computes predictions using existing methodology for scour from steady flows using the recent laboratory data and existing field measurements.

The study group believes that the second approach is the most advisable and feasible as an interim measure. If results for force calculations using flow depths and velocities from numerical models differ substantially from the CCM results or are not consistent with existing guidelines for evaluating coastal structures for wind waves, then the Study Group will recommend to FEMA a suggested methodology.

3.1.3 Preliminary Time Estimate for Guideline Improvement Preparation

If this preliminary assessment is undertaken in the context of the interim analysis to develop a 100-year-recurrence line for a specific area, as outlined in Section 2.2, numerical modeling results will be readily available to perform a preliminary assessment of the CCM guidelines as they pertain to tsunami debris impact forces. The additional effort involves only comparison of results with the values derived from the methodology in the CCM.

In terms of tsunami-induced scour, it is recommended that the preliminary studies of this Focused Study Group be expanded with the help of the USGS, which has substantial experience in evaluating tsunami erosion and deposition (Jaffe and Gelfenbaum, 2002; Gelfenbaum and Jaffe, 2003). Again, in the context of a pilot study, the USGS could recommend a cohesive approach.

4 SUMMARY

This Focused Study had four items to consider that also involve the NTHMP's products and approaches. These are Task 15, to address use of the NTHMP products into FEMA FIRMs; Task 16, to evaluate the possibility of performing probabilistic tsunami hazard analyses to better define the NTHMP hazard zone lines: Task 20, to develop new hazard zones for tsunamis-born debris impact; and Task 29, to assess tsunami induced erosion. Of the four, the first two items have been treated as critical, the third and fourth as important.

The main findings of the study are:

- FEMA's current maps use 25-year-old methodology and only consider farfield tsunami events. They do not reflect hazards from nearfield tsunami events, which may be more dominant in Washington, Oregon, and California. Further, inundation mapping technology did not exist 25 years ago and the potential of the Cascadia Subduction Zone had not been recognized; hence, there are significant known limitations in the earlier projections.

- Current NFIP regulation defines Coastal high-hazard zones as inclusive of both storm wave and tsunami wave hazards. However, since the hazards posed by tsunamis are very different temporally and spatially from storm-related hazards, a case can be made for defining a new hazard zone for tsunamis.

- NTHMP inundation maps use state-specific sources and represent hazard zones of varying recurrence intervals across the five Pacific states. They represent worst credible scenarios, with unspecified return periods. None combine nearfield and farfield events or multiple hazards. Hence, these maps cannot be used in NFIP as they currently exist. Yet, the existing maps would be very useful to the NFIP if return periods could be estimated and included.

- Comprehensive probabilistic tsunami hazard analysis, which includes farfield and nearfield events from both offshore and onshore sources, is the only way for reliable and cross-hazard consistent tsunami risk assessments in NFIP. However, suitable methods have not yet been fully developed for the idiosyncrasies of the Pacific Coast.

This Focused Study Group strongly recommends an integrated, interdisciplinary, and highly focused six-month pilot study to define the national problem of tsunami flooding, forces, and erosion, by carefully examining the limitations of existing NTHMP and NFIP tools, in the context of evaluating the hazards in one specific locale in Washington, Oregon, or California. The proposed study will demonstrate the need and methods for national implementation, which we believe can be accomplished within 2–4 years. Specific tasks for the initial six-month period (to September 30, 2004) are the following six.

1. Significant improvement of recurrence interval estimates by increasing the coverage and quality of the historic and prehistoric tsunami record. Analysis of farfield sources in Alaska and South America and regional sources in Cascadia, and inclusion of nearfield sources. Estimation of credible probabilities for nearfield events.

2. Development of probability distributions for both tsunamigenic earthquake and landslide sources.

3. Inundation modeling to evaluate the consequences of the generated tsunamis for relevant geologic sources for the locale under study.

4. Determination of 100-year recurrence line in one selected locale as a pilot study. If appropriate storm hazard data are available, these will be included because NFIP guidelines allow for combining runup estimates from both storm and seismic sources. Other possible tsunami hazard zone delineations based on both water depth and velocity will be investigated for their potential to improve hazard assessment.

Inundation modeling for hazard assessment, based on tsunami source probabilities, will exploit the advanced numerical modeling technology and essential infrastructure developed and maintained in each state by the NTHMP. It will employ NOAA’s model MOST and the state-of-the-art fault models recently developed by USGS to provide estimates of source motions and initial conditions. Efficient and cost-effective organization and planning of this multiyear effort is a primary objective of this FEMA/NTHMP Working Group.

At the conclusion of this pilot study, FEMA will have a methodology that meets its present 100-year-return criteria. FEMA will also have a more realistic cost estimate for properly incorporating tsunamis with other flooding hazards.

This collaborative FEMA/NTHMP effort to assess tsunami hazards will clearly advance the primary goals of each agency–those of FEMA related to insurance rates; those of the NTHMP related to emergency management, and those of both agencies related to mitigation, saving lives, and protecting property.

Table 3. Summary of Findings and Recommendations for Tsunami Hazards

Topic Number	Topic	Coastal Area	Priority Class	Availability / Adequacy	Recommended Approach	Related Topics
15	NTHMP	AC	H	--	The recommended approach includes: (1) develop digital database, and (2) develop a methodology, including recurrence interval estimation, for use of NTHMP products for NFIP for tsunami hazard zone delineation.	16, 20, 29
		GC	H	--		
		PC	C	MIN		
		SW	C	MIN		
16	100-year Recurrence Develop method to predict 100-year tsunami events	AC	H	--	The recommended approach is to perform a comprehensive probabilistic tsunami hazard assessment at a pilot site in California or Oregon or Washington: (1) recurrence interval estimate of forcing functions (2) propagation of tsunamis from Alaska, Chile, Cascadia Subduction Zones; (3) inundation calculations, (4) probability distributions and integration of hazards, (5) Include the analysis of tide gage data, when available, to determine the tsunami anomalies along the Pacific Coast and transfer these results to open coast areas of interest.	15, 20, 29
		GC	H	--		
		PC	C	MAJ		
		SW	C	MAJ		
20	Structure-Debris Interaction	P	I	PRODAT	Evaluation of Coastal Construction Manual recommendations for impact forces using data for overland flow depths and velocities for the numerical simulations from Topics 15 and 16 for one specific locale	15, 16
29	Erosion	SW	I	PRO	Evaluation and integration of USGS data into empirical relationships for the specific locale under study	

Table 4. Preliminary Time Estimate for Guideline Improvement Preparation

Topic Number	Item	Time
15	Digital database development	3 months for one NOAA support scientist
	Recurrence interval development	3 months for one USGS scientist
	Develop methodology, FEMA, NOAA, USGS and consultants	3 months for NOAA and USGS scientists, one month for consultants
16	Recurrence Interval Estimate	2 months of one NOAA and one USGS scientists, consultants.
	Propagation of tsunamis from Alaska, Chile, CSZ	6 months of one NOAA scientist, consultants and/or USGS
	Inundation calculations	3 months of one NOAA scientist, 3 months of consultants
	Probability distributions and integration	2 months of one NOAA scientist, 2 months of a USGS and 1 month for consultants
20, 29	Evaluation of CCM recommendations for impact forces using data for overland flow depths and velocities of the numerical simulations from Topics 15 and 16 for one specific locale.	1 month of combined NOAA and consultants.
	Evaluation and integration of USGS data into empirical relationships for the specific locale under study.	4 months of combined USGS and consultants.

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