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TSUNAMI HAZARD ESTIMATES IN CENTRAL CALIFORNIA USING A PROBABILISTIC APPROACH

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Abstract: This study presents a probabilistic analysis and extreme-value procedure for estimating seismic hazard from a tsunami induced wave or run-up for central California and the City of Pacifica. The procedure is useful for engineers and property owners who are considering one or more levels of risk and want the tsunami design level of hazard consistent with other design parameters. The purpose of this paper is to investigate the potential tsunami hazard in central California based on historical observations of run-up. We obtained tsunami run-up data between 1854 and 2007 for the region from San Francisco to Monterey, California from the National Geophysical Data Center. Only data with high validity numbers were used in this study.

INTRODUCTION

The purpose of this paper is to investigate potential tsunami run-up in central California (Figure 1), based on a probabilistic approach that incorporates historical data. We estimated the return period of given tsunami run-up elevations for the entire 130 km reach between the Cities of San Francisco and Monterey, and specifically for the city of Pacifica located approximately 15 km south of San Francisco. A probabilistic approach was adopted for this study because it enables engineers, planners, and property owners to estimate run-up amplitudes associated with various levels of hazard. In contrast, a deterministic approach is often used to prepare tsunami evacuation maps assuming a worst-case scenario for tsunami occurrence (Synolakis et al., 1997; Titov & Synolakis, 1998; Borrero et al., 2006).

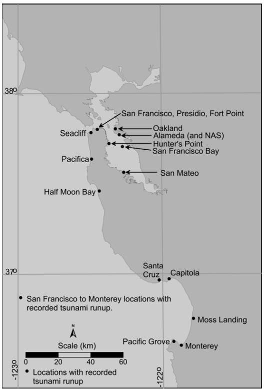

Fig. 1. Map of central California

A tsunami is a gravitational sea wave produced by a rapid disturbance of the sea floor and/or a sudden displacement of a large volume of water. In the open ocean the waves are often difficult to measure because they may be only a few feet high and traveling at speeds in excess of 800 km/hr. In coastal regions, as the waves enter shallow waters, the potential damage can be catastrophic. Processes that can generate tsunamis include submarine earthquakes, volcanic eruptions, submarine and aerial slumping, and meteoric impact. Tsunamigenic earthquakes are relatively rare and are classified as either distant (far-field) or local (near-field). Slumping or landslides are generally considered a local, near-field source.

Locally generated tsunamis allow for only minimal warning periods and may be accompanied by damaging seismic shaking, surface faulting, liquefaction, and landslides (Ryan et al., 2001). Far-field tsunamis may travel for hours before striking a coastline. On average, tsunami wave periods vary from a few minutes to as long as 30 minutes. As a tsunami enters the shallow water, its speed diminishes, its wavelength decreases, and its height greatly increases. Previous studies of tsunami hazard in California have been conducted by Magoon (1962 & 1966) and McCarthy et al. (1993 & 2003). Additional useful information regarding these hazards has been published by the California Seismic Safety Commission (2005) and the Governor's Office of Emergency Services Earthquake Program (1997).

Once the seismic data, including the historic number of tsunamigenic earthquakes and associated run-up levels, are processed, the hazards associated with a tsunami can be considered in quantitative terms. This hazard is defined as the probability that a "T-year" return period event will occur at least once during a given "n-year" long time period. The resultant run-up frequency curve can then be used to estimate the hazard for any selected "n-year" long time period and the probability of a run-up of a given size during a specified time period. The probability of a T-year run-up in any one year is P = 1/T. In other words, there is a 1% chance that the 100-year run-up will occur during a given year. The probability of at least one flood occurring in n years is referred to as the risk (Bendient and Huber, 1988).

TSUNAMIGENIC EARTHQUAKE SOURCES

Seismically active regions, like the Pacific region including western North America, contain a number of near-field and far-field faults that are potential sources of tsunamigenic earthquakes. A far-field tsunamigenic earthquake originates at a great distance from the region considered for analysis, limiting the potential damage to only the tsunami. On the other hand, a near-field tsunamigenic earthquake is relatively close to the potentially affected area, and there may be damage from seismic shaking and surface fault rupture as well as from the tsunami. Far-field sources include events in the Alaska-Aleutian zone, the Kurile Islands and Japan subduction zones, and the Chile-Peru subduction zone. In central California, potential near-field sources include shoreline and submarine landslides as well as active faults.

Far-field sources

Numerous large ruptures have occurred along the central and western portions of the Alaska-Aleutian subduction zone during historic times, including the 1964 Alaska earthquake. The Andreanof and Rat Island segments are capable of producing earthquakes of magnitudes between 8 and 9 M_w. To the west, large earthquakes have originated in the Kurile-Kamchatka subduction zone and off Japan, resulting in trans-Pacific tsunamis. Convergence along the Nazca and South American plates (Figure 2) has resulted in a number of large tsunamigenic earthquakes, including events in Chile in 1960 and most recently in 2010 (Wilson et al., 2010).

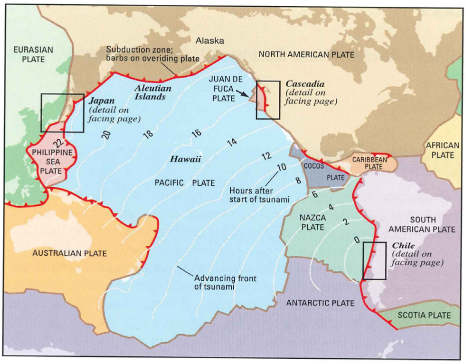

Fig. 2. Map showing the Pacific Plate and subduction zones in the Pacific Ocean region (from USGS, 1999). Map shows predicted hours after significant earthquake off the coast of Chile when a tsunami would potentially impact other areas

Near-field sources

The Cascadia subduction zone (CSZ) is the boundary between the Pacific and North American tectonic plates along the Pacific Northwest margin of North America (Figure 2). The CSZ extends along the Pacific coast of North America from Cape Mendocino, California, to Vancouver Island in British Columbia, Canada. The CSZ is believed to produce infrequent earthquakes of magnitudes 8.5 or larger, with the most recent in 1700. The Cascadia subduction zone is a potential far and near-field source depending on the location and size of the earthquake.

The San Andreas Fault is a seismogenic structure that extends roughly 800 miles (1300 kilometers) through western and southern California in the United States. This fault, a right lateral strike-slip fault, marks a transform (or sliding) boundary between the Pacific plate and the North American plate (Figure 2). The presence of this fault in northern California was first identified by UC Berkeley geology professor Andrew Lawson in 1895, who named it after a small lake which lies in a linear valley formed by the fault just south of San Francisco called the Laguna de San Andreas. Following the 1906 earthquake in San Francisco, it was again Lawson who discovered that the San Andreas Fault stretched southward well into Southern California. The 1989 Loma Prieta earthquake occurred on a structure within the San Andreas Fault system and generated a local tsunami (Figure 3).

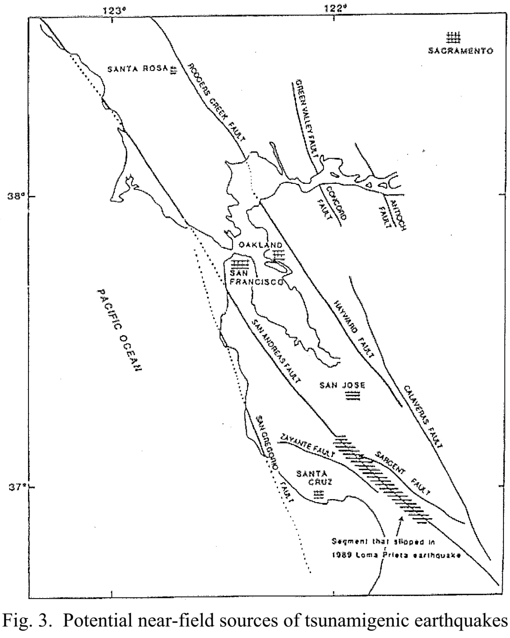

Fig. 3. Potential near-field sources of tsunamigenic earthquakes

The San Gregorio Fault is part of an offshore fault system that approximately parallels the coast from Point Arguello to Bolinas Bay. While the coseismic vertical displacement of both the San Andreas and San Gregorio faults is expected to be relatively small, the proximity of these two faults to Pacifica presents a potential hazard. Figure 3 shows the locations of the two faults.

Submarine and coastal landslides can generate local tsunamis. Unfortunately, without detailed maps, it is difficult to locate areas where submarine and coastal landslides could occur.

DATA ANALYSIS

Data set for tsunami run-up

Tsunami run-up values for the region from San Francisco to Monterey between 1854 and 2007 were obtained from the National Geophysical Data Center (NGDC) at WWW.NGDC.NOAA.GOV (this database is periodically updated). This website displays earthquake dates, magnitude, distance from run-up site, location of run-up measurements, maximum water height values (run-up), and the validity of the run-up measurements. The validity parameters take values between 0 and 4, as follows: 0 = erroneous entry, 1 = very doubtful tsunami, 2 = questionable tsunami, 3 = probable tsunami, and 4 = definite tsunami. In this study, we have used only the data associated with validity levels 3 and 4. Table 1 shows the number of tsunami run-ups recorded per site with validity levels of 3 or 4 in the area from San Francisco to Monterey between 1854 and 2007.

Table 1. Tsunamis recorded in the area between San Francisco and Monterey from 1854 through 2007 (total = 96) from the NOAA/NGDC tsunami database

Location of Tsunami Run-up	Number of Recorded Tsunamis
Alameda (NAS), CA	1
Alameda, CA	8
Capitola, CA	1
Fort Point, CA	1
Half Moon Bay, CA	2
Hunters Point, San Francisco, CA	2
Monterey Bay, CA	9
Moss Landing, CA	3
Oakland, CA	1
Pacific Grove, CA	3
Pacifica, CA	2
Presidio, CA	6
San Francisco Bay, CA	1
San Francisco, CA	42
San Mateo, CA	1
Santa Cruz, CA	6
Seacliff, CA	1

Earthquake–caused tsunamis

Figure 4 is a map showing the sources and distances of observed tsunamis in central California. Figure 5 shows the magnitudes of the recorded earthquakes that caused run-ups along the northern California coastline from 1854 to 2007. Recorded earthquake magnitudes ranged from 5.5 to 9.5 M_w. Distances between earthquake sources and the coastline are presented in Figure 6. For the purposes of this report, earthquakes designated as "from 0-1000 km" are considered to be local earthquakes.

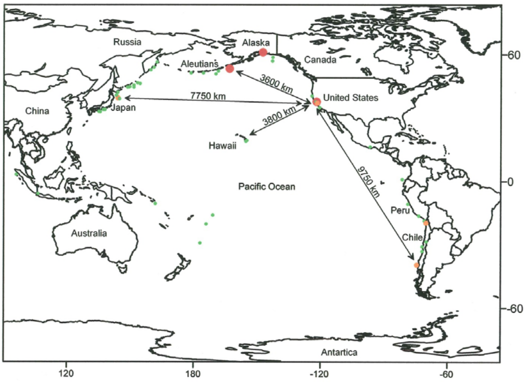

Fig. 4. Showing the sources of observed tsunamis in central California

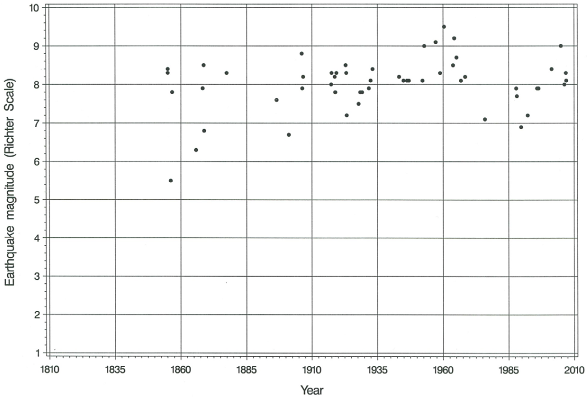

Fig. 5. Magnitude of earthquakes that caused tsunami waves along the northern coast of California

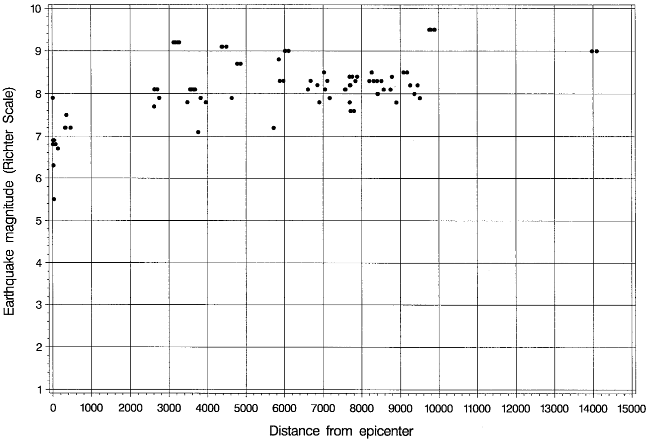

Fig. 6. Magnitude versus distance from epicenter of earthquakes that caused tsunami waves along the northern coast of California

Tsunami run-up

A histogram of the recorded run-up is shown in Figure 7. In this figure for each event, only the largest measured run-up was included. The percentage of the run-up that is less than 0.25 m is 65%. Eighty percent of the tsunami run-up is less than 1 m, and 90% is less than 1.5 m.

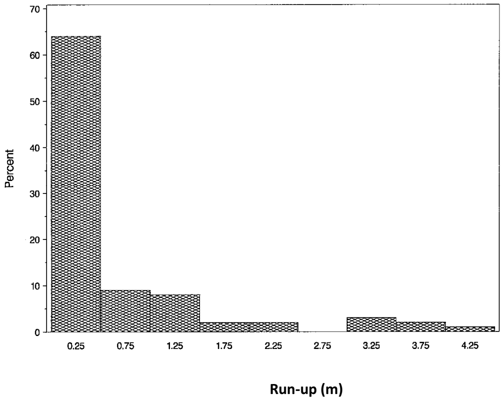

Fig. 7. Histogram of tsunami run-up that occurred in the area between San Francisco and Monterey between 1854 and 2007

Run-up vs. earthquake magnitude

No direct relationship can be seen. Earthquake magnitudes range from 5.5 to 9.5, while run-up values range from 0.01 m to 4.60 m. Both far-field and near-field earthquakes can cause run-ups. In 1868, a 6.8 magnitude earthquake caused a 4.5 m tsunami within a source distance of 15 km at San Francisco Bay, demonstrating the potential threat of near-field sources.

DESIGN RUN-UP HEIGHT FOR VARIOUS RETURN PERIODS

Estimates of extreme values of run-up

The entire NGDC dataset of run-up values for the area from San Francisco to Monterey with validity parameters of 3 and 4 was used to estimate run-up return periods for northern California and the City of Pacifica. For northern California (San Francisco to Monterey), we used the whole dataset, and for Pacifica, we used the data for San Francisco, Presidio, and Pacifica. The data set we used extends from 1854 to 2007, covering 153 years. Maximum run-up values per event were extracted. The event maxima were ranked from lowest to highest as follows: Y1, Y2, …YN. The value of F(Yi) is approximated as k/(N+1), with k being the rank and N the number of points in the maxima dataset. N is equal to the number of years from the first year to the last year.

Extreme values of many one-sided random variables that arise from measurements of natural phenomena are well represented by a double exponential:

$$F(y) = exp\ [-exp\ [\ -(a+by)]\} \qquad (1)$$

The straight-line equivalent was obtained by taking logarithms of both sides twice:

$$-log\ \{-log[F(y)]\} = a + by \qquad (2)$$

There are N values of y, and the constants a and b were calculated by least square regression analysis of Xt on Yt, where Xt and Yt stand for observed values of y and -log $\{-\log[F(y)]\}$, respectively.

With values of a and b determined, Equation (1) allows the maximum distribution $F(y)$ to be determined for arbitrary values of the run-up, y.

Recurrence intervals (RI) for a specific run-up y (Figure 8).were then determined using

$$\mathrm{RI} = 1/[1-F(y)] \qquad (3)$$

HAZARD ANALYSIS

The hazard associated with flooding from a tsunami at a specific site such as the City of Pacifica can now be considered in quantitative terms. This hazard is defined as the probability that a "T-year" return period event will occur at least once during a given "n-year" long time period. The run-up frequency curve in Figure 8 can be used to estimate the hazard for any selected "n-year" long time period. The frequency curve can also be used to estimate the probability of a run-up of a given size during a specified time period.

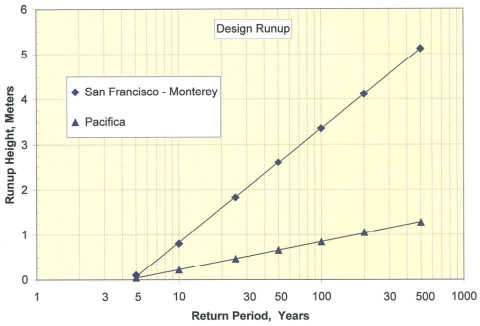

Fig. 8. Estimated run-up for various return periods

The probability of a T-year run-up in any one year is P = 1/T. In other words, there is a 1% chance that the 100-year run-up will occur during a given year. The probability of at least one flood occurring in n years is referred to as the hazard (Bendient and Huber, 1988). The hazard is equal to the sum of the probabilities of having 1 run-up, 2 run-ups, ... n run-ups, etc., occurring during n years of interest, or to 1 minus the probability of having no run-ups. The hazard can be calculated from Equation (4):

$$\text{Hazard} = 1 - (1 - 1/T)^n \qquad (4)$$

Equation (4) indicates that there is a 63% chance that the 100-year magnitude run-up will occur at least once during any 100-year time interval. Similarly, Equation (4) can be used to calculate the risk associated with any T-year run-up during any time period.

Figure 9 gives the probability of occurrence of 25-year, 50-year, and 100-year run-ups in an n-year period based on Equation 4.

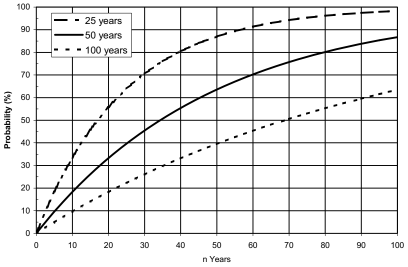

Fig. 9. Probability of 25-year, 50-year and 100-year run-up occurring within n-years

SITE-SPECIFIC ISSUES

Shore development would be reasonably safe from small to moderate tsunami and inundation hazards, such as those experienced in central California, depending on (National Tsunami Hazard Mitigation Program, 2001): 1) setback distance from shoreline; 2) existing shore protection; 3) elevation of improvements; 4) protection created by existing structures seaward of proposed development; and 5) construction quality. Revetment structures may dissipate some of the small tsunamis energy.

Table 2 gives observed tsunami run-up from two major earthquakes, recorded at Crescent City located at North of California, for the City of Pacifica and nearby locations. It is interesting to note that the run-up at the City of Pacifica is smaller than that at nearby locations. There are three possible reasons: 1) the region's bathymetry (Figure 10); note that the coast by the cities of San Francisco and Pacifica is fronted by a wider shelf); and 2) the presence of the seawall in Pacifica.

Table 2. Run-ups for the 1960 and 1964 tsunamis recorded at the City of Pacifica and at other locations from Monterey to San Francisco.

	5/22/1960	3/28/1964
Location	Run-up (m)	Run-up (m)
Pacifica, CA	0.99	0.91
Alameda, CA	0.31	0.72
Capitola, CA	Missing	2.13
Half Moon Bay, CA	Missing	3.08
Monterey Bay, CA	1.25	1.43
Moss Landing, CA	0.76	1.4
Oakland, CA	–	1.22
Pacific Grove, CA	0.91	1.37
San Francisco, CA	0.46	1.13
Santa Cruz, CA	0.91	3.05
Seacliff, CA	Missing	1.52
Crescent City, North CA	1.68	4.79

SUMMARY AND CONCLUSIONS

This study presents an analysis and procedure for estimating tsunami run-up and hazard risks for central California and the City of Pacifica. Historical northern California run-up data from 1854 through 2007, collected by the National Geophysical Data Center (NGDC), were used in this study. The procedure is useful for engineers and property owners who are considering one or more levels of risk and want the tsunami design level of hazard consistent with other design parameters.

In this study, we identify the far- and near-field sources of tsunamis (Figures 2, 3 and 4). The historical tsunami run-up data were analyzed, and estimates of run-up for various

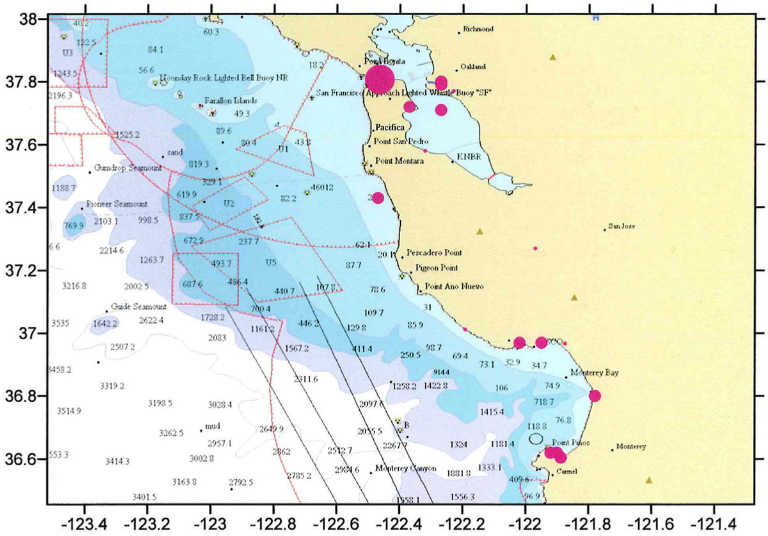

Fig. 10. Bathymetry of the California coastline with dots showing locations of reported tsunami run-up; diameter is proportional to number of events

return periods are presented in Figure 8. The 100-year run-up values in central California (from San Francisco to Monterey) and the City of Pacifica are 3.4 m and 0.85 m, respectively. The hazards associated with flooding from a tsunami in the City of Pacifica are considered, and the probability of occurrence of 25-year, 50-year, and 100-year tsunamis in an n-year period is presented in Figure 9.

Tsunamis are infrequent events, but they can cause substantial damage (State of California, Seismic Safety Commission, 2005). Tsunamis are primarily caused by tsunamigenic earthquakes and marine landslides. Earthquakes are difficult to predict and tsunamigenic earthquakes are a minor subset limited by location and size. However, there is a reasonably large database extending from 1810 to 2008, which provides confidence in the results presented here. Tsunamis recorded from 2008 to the present, including the 2010 Chilean tsunami (Wilson et al., 2010), provide a valuable data set to test the results of this analysis.

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