Estimating Losses from Tsunami Risk: Focus on Southern California

P. Grossi[1], P. Watts[2], A. Boissonnade[1], R. Muir-Wood[1]

[1] *Risk Management Solutions, Inc., Newark, CA, USA*
[2] *Applied Fluids Engineering, Inc., Long Beach, CA, USA*

Email: patricia.grossi@rms.com

ABSTRACT

This paper discusses recent work on estimating tsunami risk, with a focus on the coastline of the Western U.S. It is a summary of on-going research, starting with the methodology to model tsunami risk and the hazard along the Southern California coastline. Estimates of loss for various scenario events are presented, illustrating that tsunami losses in the billions of dollars are possible along U.S. coastlines.

KEYWORDS: tsunami, risk, loss

1. INTRODUCTION

In December 2004, a M9.3 earthquake struck off the coast of Indonesia along the Sunda Trench, causing a basin-wide tsunami that reverberated across the Indian Ocean. Local tsunami run-up heights reached over 30 meters in Banda Aceh, Indonesia with smaller run-up heights across India, Sri Lanka, Thailand and other countries across the basin. The occurrence of this event, with its extensive damage and human casualties, sparked worldwide interest in the science of tsunamis.

Tsunamis are generated by large displacements of water, principally by sudden and large scale changes in the configuration of the sea floor associated with earthquake fault displacement, or from significant underwater or subaerial landslides. Other rarer sources include volcanic events, some of which involve a major explosive eruption emptying a large subterranean magma chamber. Massive objects falling into the sea, such as the flanks of island volcanoes and asteroids, can also generate tsunamis. Although such events are anticipated to be rare, in terms of frequency, their consequences can be devastating.

Tsunami hazard along a coastline is therefore a compound of all the potential sources of tsunamis that lie in the neighboring sea or ocean. The large majority of significant tsunamis with run-up of 5 meters or greater (generated by earthquakes and submarine slides) are only damaging locally, generally within 100 to 200 kilometers of the source. The fault or landslide scarp (a line of cliffs produced by faulting or erosion) is typically only tens of kilometers in length, and waves become attenuated as they radiate in all directions out into the ocean. The total volume of sea floor deformation in such local tsunamis (experienced somewhere every few years) is thus typically a few cubic kilometers. The largest tsunami sources, however, can deform tens of cubic kilometers of sea floor and affect coastlines thousands of kilometers away. Sometimes the alignment of the sea floor deformation can focus the energy of the wave in one particular direction like a searchlight. The 2004 Indian Ocean Tsunami, involving an estimated 30 km^3 of sea floor deformation, was one of these ‘basin-wide’ mega-tsunamis (For more information, see RMS, 2006).

Assessment of tsunami consequences, in terms of human and property losses, is important to many stakeholders, including the insurance industry. This paper discusses recent studies conducted on the coastline of the Western U.S., summarizing on-going tsunami risk research. The methodology to model tsunami risk along the Southern California coastline is described, along with the implications for managing this risk in conjunction with other natural perils. Estimates of loss for various scenario events are also presented, illustrating that tsunami losses in the billions of dollars are possible along U.S. coastlines.

2. MODELING TSUNAMI RISK

For any coastline, tsunami hazard reflects the range of possible heights and return periods of expected tsunamis. The run-up height versus return period curve reflects a compound of all the potential sizes and distance ranges of tsunami generating events. Tsunamis will exhibit local variations in height according to the shape of the seafloor, which is only predictable where detailed hydraulic modeling has been undertaken.

For coastlines in the near-field of subduction zones, tsunami hazard will be driven by the expected size and return periods of major earthquakes along the plate boundary. As shown by the 2005 M8.7 earthquake along the Sunda Trench, tsunami heights can be very sensitive to earthquake size, water depth, and centroid parameters. This earthquake only generated a tsunami with 2 to 3 meter run-up heights, in contrast to the 30 meter run-up heights experienced in Banda Aceh following the 2004 M9.3 event, illustrating that tsunami hazards are event-specific.

To calculate tsunami risk at a location, it is necessary to understand how far the tsunami wave will propagate inland, as well as the elevations of buildings and their vulnerability to the force of the water. As with all flooding, risk will depend on the elevation and particular situation. For some low-lying locations along coasts with appreciable tsunami hazard, tsunamis can be a principal driver of risk, particularly for properties deliberately built close to sea level, such as beachfront hotels and port facilities. As with all flood modeling, high resolution information is needed to differentiate risk.

The development of a probabilistic tsunami risk model, therefore, is similar to other peril models (e.g., earthquake, flood, etc.) in defining sources and their recurrence rates, measuring hazard, and calculating damage and subsequent loss. Two general areas of importance in the development of a tsunami risk model are discussed here: probabilistic tsunami hazard analysis (PTHA) and tsunami damage curve generation.

2.1 Probabilistic Tsunami Hazard Analysis

A probabilistic tsunami hazard analysis (PTHA) defines near-field and far-field sources and tsunami propagation models in order to estimate run-up heights along various coastlines. Due to the fact that a number of sources can impact expected tsunami run-up heights, a PTHA can be complex and computationally intensive (Geist and Parsons, 2006). In addition, there are several issues associated with developing a fully probabilistic tsunami hazard model. Recurrence on far-field sources are particularly difficult to estimate, leading to high uncertainties surrounding the expectation of run-up heights along a distant coastline. The measurement of tsunami run-up heights (for model calibration) is limited in nature, where tide gauge stations (measuring waveform amplitudes) and post-event surveys (measuring onshore run-up depths) comprise the majority of data. In addition, these data are fraught with errors and uncertainties.

Nonetheless, approaches similar to those developed by probabilistic seismic hazard analysis (PSHA) pioneers (i.e., Cornell, 1968) have been used to develop PTHA methods. Typically, the maximum tsunami amplitude is first estimated at a source location. Then, the maximum amplitude is propagated to a particular coastal location and modified for attenuation and site effects (e.g., local bathymetry, shoaling). Ideally, the model should include full three-dimensional edge wave effects and onland water wave inundation to accurately estimate the local tsunami risk (Tappin et al, 2008). The amplitude is checked against a particular critical height (e.g., where damage can occur) and integration over all the sources generating wave heights greater than a certain critical height at that particular location can lead to estimates of rates of occurrence.

2.2. Tsunami Damage Curve Generation

Tsunami damage curves available in the literature are primarily based on post-event surveys following significant events with consideration for water flow velocity (e.g., Matsutomi et al., 2001). Flow velocity is a key parameter for damage estimation, as low velocity waves cause less damage than high velocity waves. Post-event surveys, however, do not utilize a consistent parameter for damage measurement. For example, some measurements are based on tsunami run-up heights, while others are based on water depths or structures' inundation depths. One example of a set of damage curves based on post-event surveys in Sri Lanka following the 2004 Indian Ocean Tsunami is illustrated in Figure 1. The empirical data is fit to lognormal cumulative distribution functions, capturing the probability of damage (from 0% to 100%) to unreinforced masonry structures in various districts given the water depth.

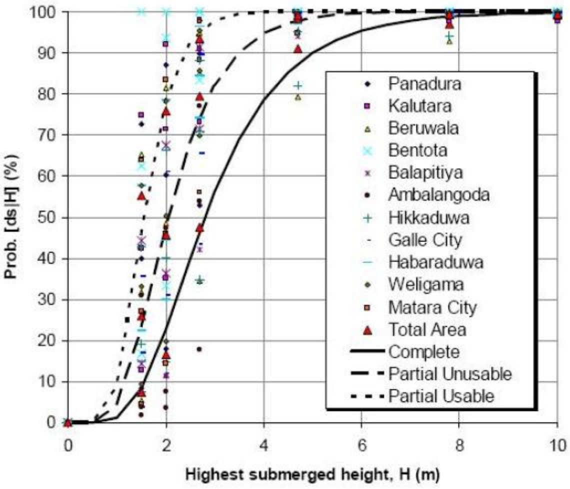

Figure 1 Tsunami damage functions developed for southwest of Sri Lanka (from Peiris, 2006)

3. MODELING TSUNAMI HAZARD IN SOUTHERN CALIFORNIA

Tsunami risk within the San Pedro Basin off the coast of Southern California is the focus of this analysis. For the purposes of this work, catastrophic tsunamis are defined as greater than 1 meter maximum run-up over at least 1 kilometer of shoreline. This definition is based in part on experience gathered from field surveys of tsunami damage, establishing a minimum threat level for the scenarios presented in this work. The chosen tsunami scenarios range from this minimum threat level to a maximum threat level of the greatest possible local tsunami hazard from all tsunami sources.

In order to model tsunami risk, a hazard assessment is first completed, identifying local earthquake and landslide sources, as well as the recurrence of potential tsunami-triggering events. Figure 2 is a vertically exaggerated view of the Los Angeles Basin onshore and part of the San Pedro Basin offshore. The image depicts some of the major local sources of tsunami hazard to this coastline of Southern California (e.g., the Palos Verde Fault and the Palos Verdes underwater slide). In addition, the San Pedro Shelf, an extensive plateau of shallow water that slows the propagation of tsunamis, is highlighted. Tsunami sources are calculated with a numerical model called TOPICS (Tsunami Open and Progressive Initial Conditions System), which uses geophysical constraints to specify tsunami sources for a variety of tsunami-generating processes.

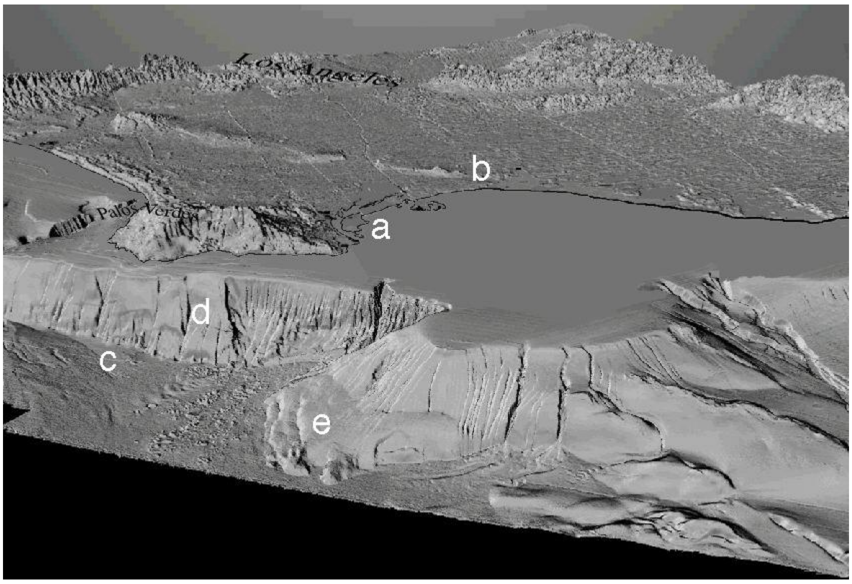

Figure 2 Vertically exaggerated image of (a) the Ports of Los Angeles and Long Beach; (b) the City of Seal Beach; (c) the Palos Verdes Fault; (d) the Palos Verdes underwater slide; and (e) the San Pedro Shelf slump (image courtesy of Jim Gardner, USGS, retired)

3.1. Local Earthquake Tsunamis

Local earthquake tsunamis are potentially produced by two earthquake faults within San Pedro Basin: the Catalina Island Fault and the Palos Verdes Fault. While there are other potential faults that could be considered for a tsunami risk analysis, these two faults are closest to the shoreline of interest, and therefore are more likely to produce catastrophic tsunamis. These tsunami sources were estimated from fault descriptions and parameters as developed by others (e.g., WGCEP, 1995). The hazard assessment model calculates earthquake recurrence intervals, as well as tsunami amplitudes, for these events.

3.2. Local Landslide Tsunamis

Local landslide tsunamis are potentially produced at three locations within San Pedro Basin: an underwater slide off Palos Verdes, an underwater slump off the San Pedro Shelf, and an underwater slide off Catalina Island. There are other potential landslide areas that could be considered in this work. However, these three landslide locations provide the largest mass failures in the closest proximity to the shoreline of interest. These tsunami sources were estimated from expected landslide dimensions (Bohannon and Gardner, 2004; Locat et al., 2004) or typical landslide parameters (e.g., Watts et al., 2005). As with the earthquake sources, the hazard assessment model calculates landslide recurrence intervals, as well as tsunami amplitudes.

3.3. Tsunami Propagation and Inundation Modeling

Tsunami propagation and inundation from the 5 different tsunami sources is modeled with a modified version of FUNWAVE, a 4th order Boussinesq water wave model developed at the University of Delaware (Wei and Kirby, 1995). FUNWAVE includes dissipation from breaking waves and from bottom friction; model predictions of shoreline run-up have been well tested in the case of short wave shoaling and breaking. The benefits of a Boussinesq wave propagation model over traditional nonlinear shallow water wave models is that the horizontal velocity profile over depth is no longer constrained to have a constant value, and vertical accelerations (i.e., non-hydrostatic pressures) are no longer neglected. Dispersive effects are both necessary and manifested during propagation of deep water waves (from landslides) and during propagation of edge waves.

TOPICS and FUNWAVE are combined into a single model referred to as Geowave, in which the tsunami sources predicted by TOPICS are transferred as initial conditions into FUNWAVE. Geowave can simulate multiple tsunami sources with different generation mechanisms, occurring at different times. Geowave has been validated based on case studies of a pyroclastic flow-generated tsunami, several underwater landslide-generated tsunamis (e.g., Tappin et al., 2008), and several earthquake-generated tsunamis (e.g., Ioualalen et al., 2006).

The simulations in San Pedro Basin were performed at mean low low water (MLLW) or low tide; a tide above MLLW may enhance tsunami run-up or inundation. An example of a simulation is shown in Figure 3, indicating the maximum run-up above sea level (expressed in meters) for the largest possible tsunami associated with a landslide off Catalina Island. Maximum water velocity (expressed in meters/second) is also evaluated, in order to calculate impact damage.

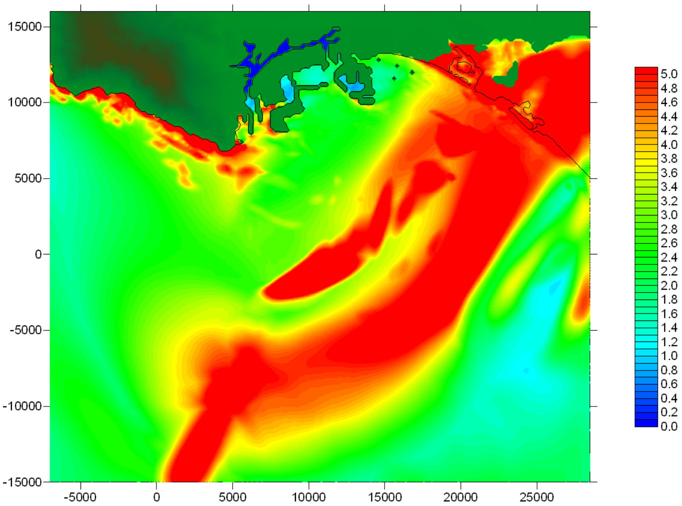

Figure 3 Maximum run-up above sea level in meters for the largest possible catastrophic tsunami from an underwater landslide off Catalina Island

4. DAMAGE AND LOSS ESTIMATES FROM TSUNAMI HAZARD

As previously noted, damage functions due to tsunami waves can be based on run-up heights or water depths. In this research, tsunami damage functions are based on flood or water depth and are classified according to wave velocity (e.g., low versus high), as illustrated in Figure 4. Run-up heights from the tsunami hazard model (described in the previous section) are converted into water depths based on the onshore local topography. If the tsunami wave velocity is greater than 1.5 m/s, it is considered a high velocity wave; otherwise, it is considered low velocity and causing less damage.

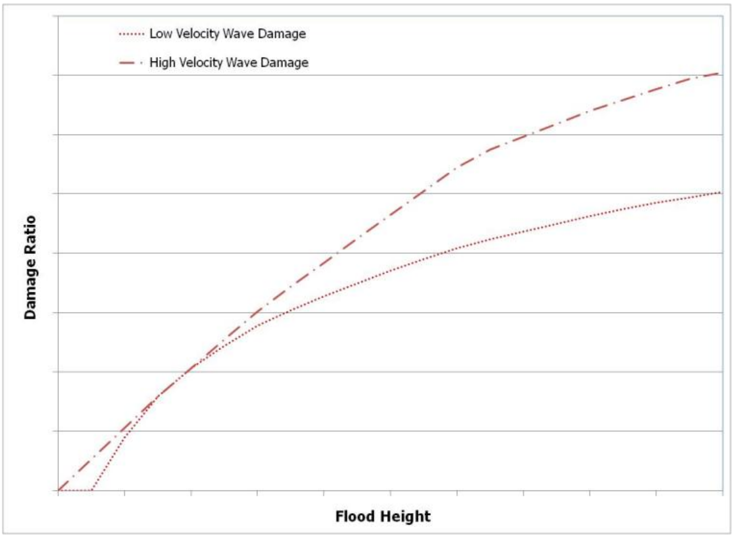

Figure 4 Damage functions utilized to estimate losses from tsunami events off the coast of Southern California

Property exposure at risk is estimated from RMS proprietary data, defining the value of property at a 1-km resolution grid along the coastline subject to tsunami waves. In addition, property is classified according to occupancy (residential, commercial, or industrial), construction type, year built, and height. Based on the damage functions and property at risk, losses for 5 scenario events are summarized in Table 1. These are the 'worst case scenario' events (i.e., maximum threat level) from the 5 local tsunami-generating sources off the coastline of Southern California.

Table 1 Range of loss estimates due to 'worst case scenario' tsunami for 5 sources off the coast of Southern California

Source	Loss Range (in millions)
Catalina Island Slide	\$5,540 – \$7,145
Catalina Island Earthquake	\$360 – \$475
Palo Verdes Slide	\$10 – \$20
Palo Verdes Earthquake	\$15 – \$25
San Pedro Shelf Slump	\$280 – \$400

These results indicate that the displacement of water due to a Catalina Island Slide can cause the largest expected loss among the considered scenarios, causing between \$5.5 billion and \$7.1 billion of expected loss. This scenario event is shown in Figure 5, illustrating the largest water depths near Seal Beach. Note that these impacts do not include business interruption losses resulting from the disruption of the port facilities.

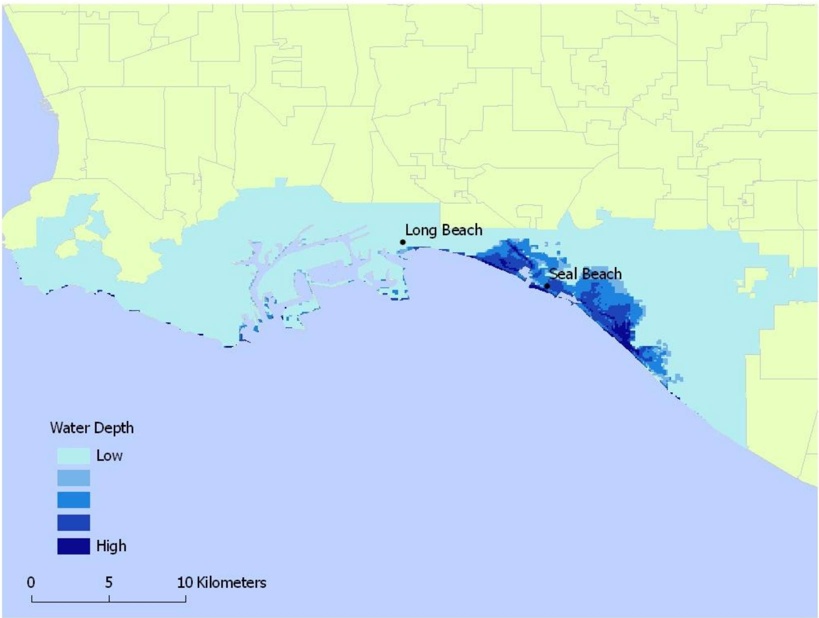

Figure 5 Water depth along the coastline for the ‘worst case scenario’ Catalina Island Slide

5. MANAGING TSUNAMI RISK

In this analysis, tsunami risk within San Pedro Basin is studied. However, Southern California is subject to other natural hazards as well, including earthquakes. Along the coastline, the gradient for tsunami risk is extremely steep and drops to negligible values less than 2 kilometers inland from the coast, whereas the earthquake risk is spread out more evenly across the region. If one considers the overall magnitude of loss from a severe earthquake-generated event off the coastline, tsunami losses would generally comprise a minor component of the total losses, although some specific coastal areas could be devastated by a tsunami, creating total disruption in these areas. Note also that landslide-generated events may cause minor earthquake losses relative to tsunami losses, because landslides can be triggered by relatively small magnitude earthquakes (M5-6). Local tsunamis have event-specific losses that require careful study.

Tsunami risk is a major component of the risk in the exposed Pacific coastal communities along the Western U.S. coastline, where for certain properties, it is likely to dominate total risk. A large Cascadia subduction zone earthquake, with the potential to rupture all or a majority of this plate boundary, would trigger a tsunami that would likely inundate low-lying communities along the neighboring Pacific coast, as happened in 1700.

The 2004 Indian Ocean Tsunami highlighted inherent vulnerabilities of the world’s coastlines and the people who live there. Coastal populations are on the increase in many parts of the world, mostly due to the exploitation of sea resources or tourism-related activities. Adequate mitigation measures from tsunami hazard can be put in place to save lives, property, and the livelihoods of those living on the coast. A wide range of approaches can be used for mitigation, including tsunami warning systems, education, building code standards, land use planning, and other engineering solutions.

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