Tsunami Hazards Facing Pier 400

FINAL REPORT

For:

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Executive Summary

We carry out an analysis of tsunami hazards within San Pedro Basin for the local marine operations of Pacific Energy. To do this, we generate probability distributions with a hazard assessment model. Our analysis considers three kinds of tsunami hazards: transoceanic tsunamis, local earthquake tsunamis, and local landslide tsunamis. We establish a rigorous technique for identifying tsunami amplitudes of interest, arriving at a 500 year recurrence interval corresponding to around 3.0 m tsunami amplitudes. We identify four representative tsunami scenarios that span the range of tsunami hazards encompassed by our chosen recurrence interval. We propose that these scenarios form the basis of tsunami propagation and inundation simulations to assist in facility design. We point out the significant opportunity for tsunami warnings being part of tsunami hazard mitigation, and the role our chosen tsunami scenarios can play in designing such a system.

Table of Contents

1. Introduction

Tsunamis are a relatively common natural hazard, although most of the events are small in amplitude and not particularly damaging, if at all. Some of the smallest events are barely detectable by tide gauges and other instruments with thresholds of millimeters to centimeters. For tsunamis of modest amplitude, nearby port facilities tend to receive the most damage, if any, because there is not much coastal runup or inundation, and because ships can experience a range of hazardous responses to tsunami excitation. Ships carrying cargo such as oil are particularly exposed to tsunami hazards, because the impact of even modest damage may be significant, especially during oil transfer operations. Tsunami hazards are therefore of interest to the marine operations of Pacific Energy.

Tsunami hazards facing Southern California have been discounted in the past for reasons that are no longer believed to be valid. First, significant far-field or transoceanic tsunamis may impact Southern California if the tsunami source is sufficiently large, or if the source orientation focuses wave activity onto the region. Second, offshore faults present a larger local tsunami hazard than previously thought, posing a direct threat to nearshore facilities. Third, landslide tsunamis are now perceived as the greatest local tsunami hazard. These three kinds of tsunami hazards are considered one by one for San Pedro Basin and its vicinity below.

This work produces probability distributions within San Pedro Basin for the three kinds of tsunami sources just described. Probability distributions are a natural way to interpret tsunami hazards, because they allow one to choose a meaningful recurrence interval and/or hazard level, with an appreciation of the long term consequences of that choice. We combine the probability distributions with chosen recurrence intervals and/or hazard levels to arrive at a *range* of possible tsunami hazards of interest to Pacific Energy. Specifically, this report identifies four tsunami scenarios that encompass this range of interest. The scenarios will not be simulated here. The modeling of these scenarios will be carried out in future work within the context of facility design and operations, in order to assess appropriate tsunami hazard mitigation measures.

1.1 Summary of Historical Events

Tsunamis generated by earthquakes, landslides, and volcanoes threaten coastal populations and facilities along Southern California previously thought to be immune to significant tsunami hazards. Catalogues of tsunamis impacting Southern California are available (McCulloch, 1985; Lander et al., 1993), although these will not be reproduced here. While detectable tsunamis strike Southern California almost every year, most events arrive from far away and are too small to cause much damage (Lander et al., 1993). Moreover, the last significant local tsunami in San Pedro Basin occurred more than 70 years ago (McCulloch, 1985). Tsunamis tend to be considered in light of these facts, without a careful analysis of what could happen. For example, most studies of waves impacting the POLA/LB (the "Ports") consider either wind waves or tides. Tsunamis can be expected to have wave periods somewhere in between these limits, a region of wave periods called infragravity waves. Harbor response to tsunami attack has rarely been studied (Walker et al., 1998), including the potential disruptions that tsunamis can cause to harbor operations. The recent tsunami in Indonesia promotes the idea of carrying out careful analyses of what could happen.

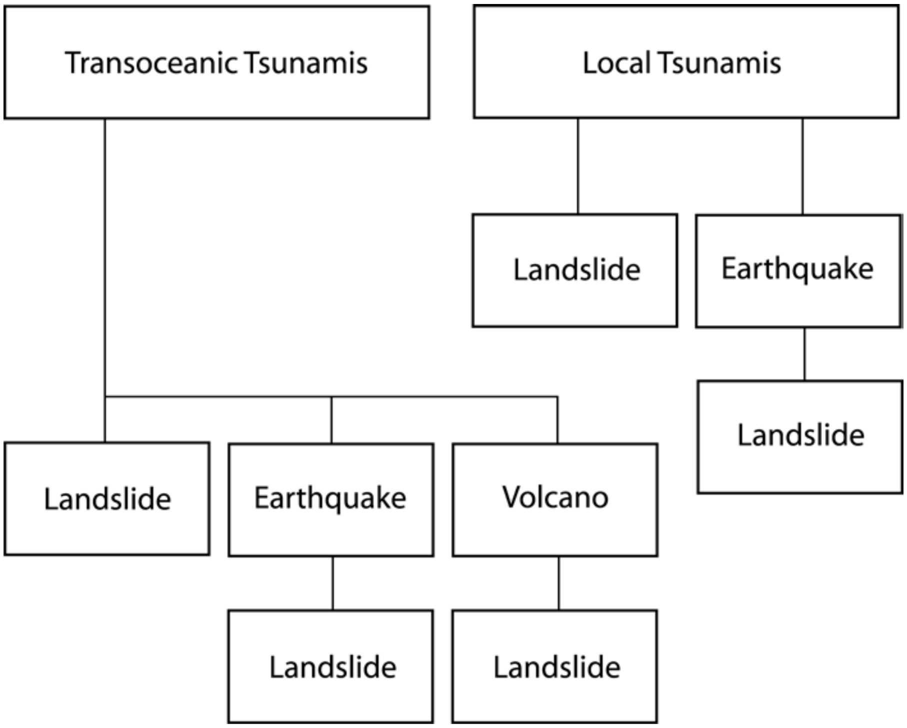


Figure 1. Various tsunami sources that could impact San Pedro Basin. Note that earthquakes and volcanoes can trigger landslides, in addition to spontaneous landslides.

We distinguish local tsunami hazards from transoceanic tsunami hazards (see Figure 1). Wilson (1971) shows wave records from the Ports for four transoceanic tsunamis this century. The Chilean tsunami of November 11, 1922 produced 1.3 m waves just outside of the Ports. Only one of the three existing breakwaters was in place at the time. The Aleutian tsunami of April 1, 1946 generated 1 m wave heights, trough to peak, near the East Channel of the Ports, and slightly smaller waves elsewhere. All three currently existing breakwaters were in place at the time of tsunami attack. The Chilean tsunami of May 23, 1960 generated waves about 2 m in height (1 m in amplitude) throughout the Ports. The Alaskan tsunami of March 28, 1964 generated 3 m wave heights (1.5 m wave amplitudes) at the Ports. These events had tsunami periods between 60-90 minutes and all caused damage to the Ports (Wilson, 1971). Recent numerical simulations of these tsunamis explain their limited impact relative to places such as Hilo, Hawaii: Southern California does not experience bathymetric wave focusing for tsunamis originating from some of these source regions. In general, it is the combined effects of wave directionality, focusing, and shoaling that render transoceanic tsunamis catastrophic (Ben-Menahem and Rosenman, 1972).

Local tsunamis off Southern California have traditionally been dismissed because they were assumed to have small amplitudes (McCarthy et al., 1993). Earthquakes can be expected every 15 years along active offshore faults and may reach up to magnitude 7 in strength (Clarke et al., 1985; Working Group on California Earthquake Probabilities, 1995). Given the Pacific-wide probability that roughly 20% of offshore earthquakes generate measurable tsunamis, at least one local earthquake tsunami can be expected every 75 years off Southern California. This simple estimate agrees with historic records of local tsunamis (McCulloch, 1985) and Monte-Carlo predictions of local tsunami frequency (Watts, 2004). Vertical coseismic displacement during the larger of these events could achieve 2 m for certain rupture mechanisms (Kramer, 1996; Geist, 1998). This also agrees with historic records of local tsunamis (McCulloch, 1985). Coseismic displacement is not the only source of local tsunamis during an earthquake -- there can be many tsunami sources during a single geological event, including numerous underwater landslides (Tappin et al., 2002a; Watts, 2001).

Underwater landslides are usually triggered by offshore or nearshore earthquakes. A magnitude 7.0 earthquake can unleash thousands of landslides on land (Wilson and Keefer, 1985; Kramer, 1996) and numerous landslides offshore (Tappin et al., 2001). Despite an abundance of landslides from an offshore earthquake, observations of landslide tsunamis appear to be less common than those of earthquake tsunamis. For local tsunamis throughout the Pacific Basin, about 30% of maximum runup measurements can be attributed to landslide sources, probably because most landslides are either too small or too deep to generate appreciable waves (Watts, 2003). Time of tsunami arrival (as opposed to tsunami amplitude) is a key means of identifying landslide tsunamis (Plafker et al., 1969; Tappin et al., 2001). The amplitude of landslide tsunamis does not correlate with earthquake magnitude (Watts, 2003, 2004); instead, tsunami amplitude varies over more than six orders of magnitude depending on landslide location and dimensions (Pelinovsky and Poplavsky, 1996; Watts et al., 2003). The theoretical maximum tsunami amplitude corresponds to the vertical center of mass displacement of the landslide (Striem and Miloh, 1976; Watts, 1998). Landslide tsunamis typically have shorter wavelengths and shorter wave periods than earthquake tsunamis (Watts, 2000). Landslide tsunamis also generate highly directional waves, causing most damage at coastlines that are aligned with the axis of failure (Iwasaki, 1997). Away from the axis of failure, the wave front rapidly spreads thin on account of what is often a small tsunami source area. Because most landslides move away from shore, eyewitness observations tend to report a leading depression wave.

1.2 Tsunami Studies for San Pedro Basin

The Ports have been studied extensively by the Army Corps of Engineers. For example, the Army Corps maintains a scale model of the Ports at the Waterways Experiment Station in Vicksburg, Mississippi. Army Corps reports document in situ measurements, experimental model studies, as well as numerical simulations of harbor response at the Ports. They are too numerous to be cited here and generally do not address tsunamis. Long wave activity affecting the Ports, including tsunamis, has been addressed in the scientific literature. Lee (1971) and Chiang (1988) apply numerical models of wave-induced oscillations to the Ports. Raichlen et al. (1997) describe a hydraulic model study of long wave resonance inside the Ports. Walker et al. (1998) model the response of moored ships to these resonance periods. These studies support a more careful examination of tsunami hazards at the Ports.

The response of San Pedro Basin to tsunami attack is part of tsunami hazard assessment. Wilson (1971) has studied the response of the outer harbors, San Pedro Bay, and San Pedro Channel to tsunami attack both theoretically and through tide gauge records of four transoceanic tsunamis this century. The observed peaks below 60 minutes are believed to result from ringing excited by impulsive tsunami arrival. Ringing is an indication of resonance periods that would be relatively independent of the incident tsunami period, and therefore a general part of tsunami response. There is remarkable agreement between theoretical and observed resonance modes: approximately 50 minutes, 38 minutes, 34 minutes, 30 minutes, 25 minutes, and 20 minutes (Wilson, 1971). All tsunamis will excite these wave periods to some degree. Tsunamis with wave periods that match a particular resonance mode could be more damaging than those that do not.

Several studies have addressed tsunami hazards in San Pedro Basin, including all three kinds of tsunami sources considered here. Houston (1980) studied the probabilities of transoceanic earthquake tsunamis impacting the coastline of Southern California. The Working Group on California Earthquake Probabilities (1995) addressed the recurrence of offshore earthquakes as well as the probability for a given earthquake magnitude. Other authors have described potential offshore earthquakes and landslides within San Pedro Basin (e.g., Clarke et al., 1985; Field and Edwards, 1993; Gorsline, 1996; Legg and Kamerling, 2003). Still other authors have analyzed particular underwater landslides off Palos Verdes Peninsula and assessed potential tsunami amplitudes (e.g., Lee et al., 2003; Bohannon and Gardner, 2004; Locat et al., 2004). Watts (2004) carried out a probabilistic analysis of local tsunami hazards off Southern California that is a precursor to the work presented here. This body of work provides much of the background and context for the current analyses.

Watts (2004) found that the cumulative probability distribution of local tsunamis off Southern California follows a log-normal curve similar to that of all Pacific Basin events, but offset in the direction of smaller tsunami amplitudes. The two curves are parallel, implying a similar standard deviation, but have different mean tsunami amplitudes, with Southern California consistently producing tsunami amplitudes half of those elsewhere in the Pacific Basin. Three lobes on the predicted curve were attributed to earthquake tsunamis, underwater slide tsunamis, and underwater slump tsunamis, in order of increasing tsunami amplitude (see Figure 3 below). The results make sense. The earthquake magnitudes off Southern California are generally smaller than those found along many subduction zones of the Pacific Basin. Moreover, the shallow basins off Southern California may limit the size of sediment deposits, thickness of mass failures, and ultimately landslide tsunami amplitudes. The model appears to predict reasonable probability distributions of tsunami amplitudes off Southern California.

1.3 The Role of Breakwaters

Most of the San Pedro Breakwater and the top one third of the Middle and Long Beach Breakwaters are permeable. Wave reflection and transmission by permeable breakwaters is a mature research topic (Madsen and White, 1976; Dalrymple et al., 1991; Huang and Chao, 1992). Established cost/benefit analyses for optimum breakwater design exist (Smith, 1986), but these generally do not consider tsunami costs and benefits. Likewise, transmission coefficients for tsunamis incident on permeable rubble-mound breakwaters are rarely considered (e.g., see Scarlatos and Singh, 1987). As a case in point, Seelig (1980) provides numerous figures of wave transmission coefficients for permeable breakwaters. None of the applicable figures cover wave parameters expected for tsunamis, although it is apparent from these same figures that at least 85% of any given tsunami amplitude can be transmitted through permeable breakwaters. The mathematical algorithm provided by Madsen and White (1976) predicts that almost all incident tsunami energy can be expected to pass through the breakwaters of the Ports.

This is not a surprising result. Tsunamis will almost certainly experience significant transmission through most permeable breakwaters (i.e., a transmission coefficient near unity). Transmission coefficients near unity can be expected on physical grounds (Yu and Chwang, 1994), because tsunamis present a nearly uniform velocity profile over depth, relatively small water velocities, and very small wave steepnesses. The rise and fall of water on either side of the breakwaters is such that pressure gradients and flow velocities remain small (Losada et al., 1998; Liu et al., 1999), conditions that facilitate wave transmission through a breakwater. In addition, the breakwaters appear exceedingly thin to incident long waves such as tsunamis (with wavelengths greater than 0.5 km), which implies that energy dissipated within the breakwaters is dwarfed by the energy of the incident tsunami itself. These results hold for almost all permeable breakwaters built according to the design practices set forth in Smith (1986). We find that the breakwaters around the Ports cannot be construed as an effective protection against tsunami attack, in their current form. Further, we do not consider that modifying the breakwaters is a reasonable means of mitigating tsunami hazards.

The basic reason for discussing the breakwaters is to dispel the idea that the breakwaters will protect the Ports from tsunami attack to any significant degree. In Section 8 below, we recommend that the Army Corps of Engineers carry out an experimental study of tsunamis attacking the Ports at the Waterways Experiment Station in Vicksburg, Mississippi. Such a prospective study would presumably include a closer examination of the role that the breakwaters would play during tsunami attack, if any.

2. Methods

Tsunamis will present from time to time significant hazards to offshore or nearshore structures and activities. Specifically, tsunamis can impact the integrity and operations of pipelines, moorings, storage tanks, and other structures. An effective and manageable use of these structures suggests a careful analysis of tsunami hazards. In general, tsunami hazards are revealed by marine geology studies of offshore morphology (Clarke et al., 1985; Orange et al., 1999; Tappin et al., 2001, 2002a, 2003; Legg and Kamerling, 2003; von Huene et al., 2004). Numerical models compliment these marine geology studies and include various sediment stability models (e.g., Turner and Schuster, 1996; Wright and Rathje, 2003), landslide models (e.g., Imran et al., 2001; Syvitski and Hutton, 2003; Niedoroda et al., 2003), and probabilistic models (e.g., Watts, 2003, 2004). In this work, tsunami hazards are found with a hazard assessment model that provides probability distributions of tsunami amplitudes. Our hazard assessment model incorporates aspects of the different models cited above.

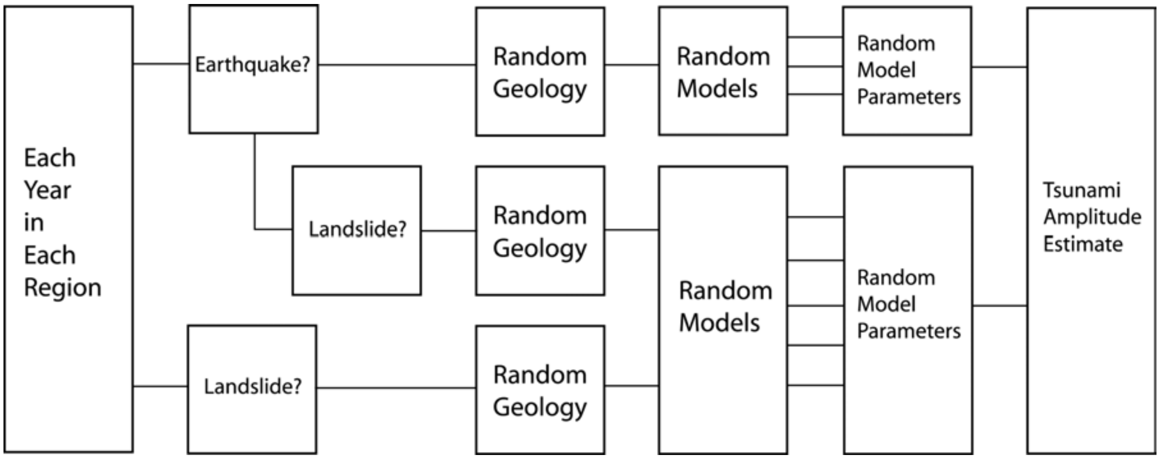


Figure 2. Schematic structure of the hazard assessment model, which incorporates distinct earthquake and landslide tsunami generation models. The geology of each earthquake and landslide is randomized, as are the choice of tsunami generation model and the parameters of that chosen model.

2.1 Hazard Assessment Model

Our hazard assessment model uses realistic probability distributions to span the parameter space of nearshore earthquakes and basin landslides off Southern California (Watts, 2004). We distinguish basin slopes from continental slopes because of the complicated sea floor morphology off Southern California. The hazard assessment model is divided into three sections: earthquake engineering calculations, sediment stability calculations, and tsunami amplitude estimates. Our model is a subset of outbuilding delta models and shares some features of the work of Syvitski and Hutton (2003). However, instead of building a slope year by year and studying its global evolution over time, we ask the simpler question: what tsunami amplitudes could local earthquakes or landslides yield as of now? To address this question, we run numerical experiments based on the current basin conditions, instead of allowing the slope to evolve over time. In our model, each year represents a single numerical experiment in which an earthquake and/or a landslide might trigger a tsunami.

Each hazard assessment model parameter is treated randomly as part of a Monte-Carlo scheme (Watts, 2004). Figure 2 depicts three kinds of model parameters: those related to geophysical quantities, those related to model methodologies, and those related to model assumptions. There are few assumptions built into the model, because of the wide parameter space sampled during hundreds of thousands of numerical experiments, and because there are several different methodologies for predicting a given tsunami event. These facts allow us to discover and sample some of the largest possible tsunami amplitudes. The dependence and sensitivity of tsunami amplitude with respect to each random parameter is also evaluated when running thousands of numerical experiments (Watts, 2004). There are important differences between our earlier work (Watts, 2003, 2004) and the hazard assessment model. First, hazard assessment model computations are carried out explicitly on a yearly basis, directly providing recurrence intervals of practical interest. Second, gas hydrates influence slope stability in the hazard assessment model. Third, additional model methodologies are currently being used to estimate earthquake as well as landslide tsunami amplitudes.

2.2 Characteristic Tsunami Amplitudes

Watts et al. (2003) performed numerical simulations for several tsunami case studies and observed a correspondence between the characteristic tsunami amplitude at the source and the maximum runup above sea level along the nearest shorelines. These and other case studies of tsunami events suggest that this fact holds for both earthquake and landslide tsunamis, and may in fact provide conservative estimates of tsunami hazard. Therefore, our analyses will focus on tsunami generation near the source, rather than on subsequent propagation and inundation. We invoke a Correspondence Principle that states: *The characteristic tsunami amplitude at generation approximates the maximum runup of local tsunamis.* This holds because wave front spreading during propagation, which reduces tsunami amplitude, is more or less compensated for by wave shoaling and focusing during inundation, which rebuilds the tsunami amplitude. The Correspondence Principle is *not* an oversimplification of case studies, it is instead a different *perspective* on tsunami hazard assessment. These facts justify concentrating on tsunami generation in our analyses, because we can analyze thousands of tsunamis over one hundred thousand years of numerical experiments. As such, our work determines the *realm* of tsunami hazards.

The Correspondence Principle is not intended to replace detailed numerical simulations of tsunami propagation and inundation, because it does not indicate *where* maximum runup will occur. However, it is not realistic to perform numerical simulations for *thousands* of possible tsunami scenarios. Nor is it appropriate to declare that a given tsunami scenario *must* be studied without a context for what is possible, and without a rational basis for its choice. At issue is how to choose representative tsunami scenarios before running any given numerical simulation. The first step is to determine the realm of tsunami hazards as mentioned above. We then identify those events that threaten engineering facilities with reasonable tsunami amplitudes over a reasonable span of time. This rigorous technique allows for a much smaller number of tsunami scenarios to be simulated that represent the full range of tsunami hazards of interest. The facility being built by Pacific Energy is at a relatively exposed location of the Ports. Consequently, tsunami propagation and inundation simulations will give important facility design information, but only if representative tsunami scenarios are known in advance.

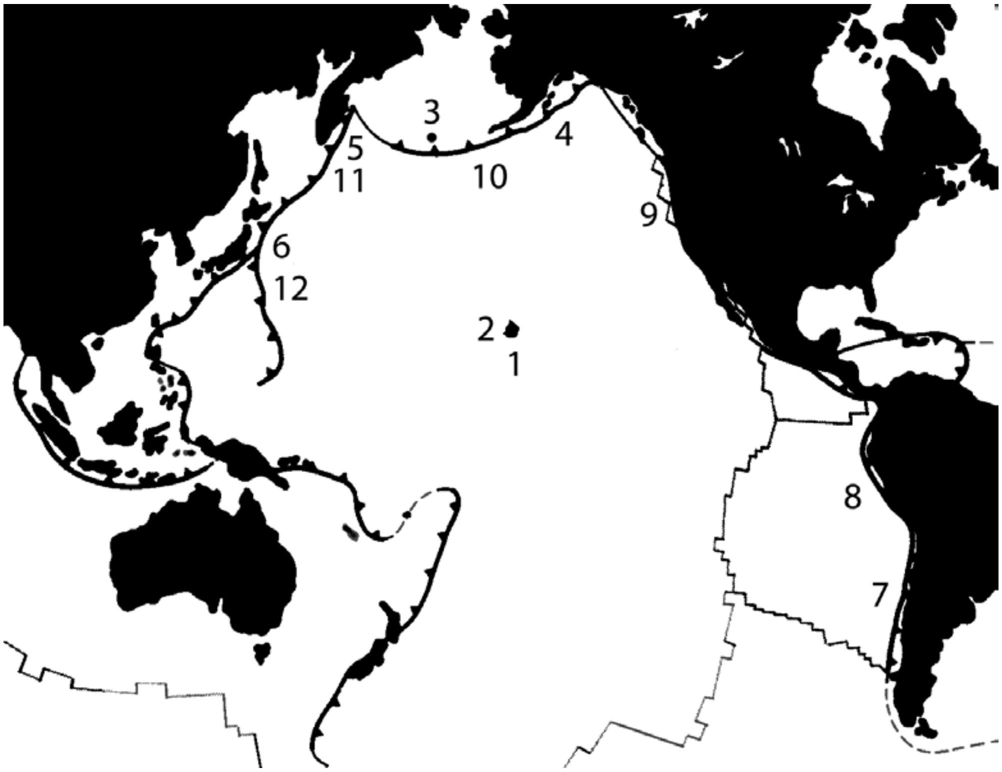
2.3 Tsunami Amplitude Estimates

Tsunami amplitudes of earthquake tsunamis are readily predicted from the earthquake magnitude (McCulloch, 1985; Kramer, 1996; Geist, 1998). This work was assumed to apply foremost to normal and thrust faults, and not to strike-slip faults. Scientists are reconsidering the relationship between earthquake focal plane mechanism and tsunami amplitude, because strike-slip earthquakes are now known to produce significant tsunamis (Tappin et al., 2002b). It appears as if all earthquake mechanisms produce tsunamis of similar amplitude for a given earthquake magnitude, although over different horizontal extents and for different reasons. On the one hand, strike-slip earthquakes produce tsunamis at fault step-overs, at either end of rupture, and at significant bends in the fault (Legg and Kamerling, 2003). In other words, tsunami generation is localized to a small area of sea floor, relative to the extent of rupture. On the other hand, thrust and normal faults produce tsunamis through extensive vertical motion over a large area of sea floor, similar in extent to the length of rupture. These details will not alter our estimates of tsunami amplitude, because they impact primarily the tsunami wavelength.

Tsunami amplitudes of landslide tsunamis are also available from analytical equations. For example, the tsunami amplitude equations of Grilli and Watts (1999) and Goldfinger et al. (2000) were refined and validated by Watts et al. (2003). One of the semi-empirical amplitude equations derived by Striem and Miloh (1976) is used in a case study carried out by Murty (1979). Tinti and Bortolucci (2000) obtain an analytical tsunami amplitude expression from nonlinear shallow water wave equations based on constant velocity motion in a constant depth channel. The theoretical amplitude equation of Pelinovsky and Poplavsky (1996) was shown to produce reasonable experimental predictions by Watts et al. (2000) despite being derived for a constant depth channel. Bohannon and Gardner (2004) base a predictive tsunami amplitude equation on the energetic scaling of Watts (2000) that is similar to the original work of Striem and Miloh (1976). We will be using the equations presented in Watts (2004) for this work.

3. Transoceanic tsunamis

The probability distribution for transoceanic tsunamis will consider large earthquakes along the Pacific Rim (Houston, 1980), large underwater landslides along continental margins (Tappin et al., 2001; Fryer et al., 2004), and volcano collapse events (McMurtry et al., 2004; Watts and Waythomas, 2003). The hazard assessment model calculates earthquake and landslide recurrence intervals as well as tsunami amplitudes. The volcanic events are assumed to occur only once during the one hundred thousand years of numerical experiments being considered here. See Appendix 1 for tsunami source details.



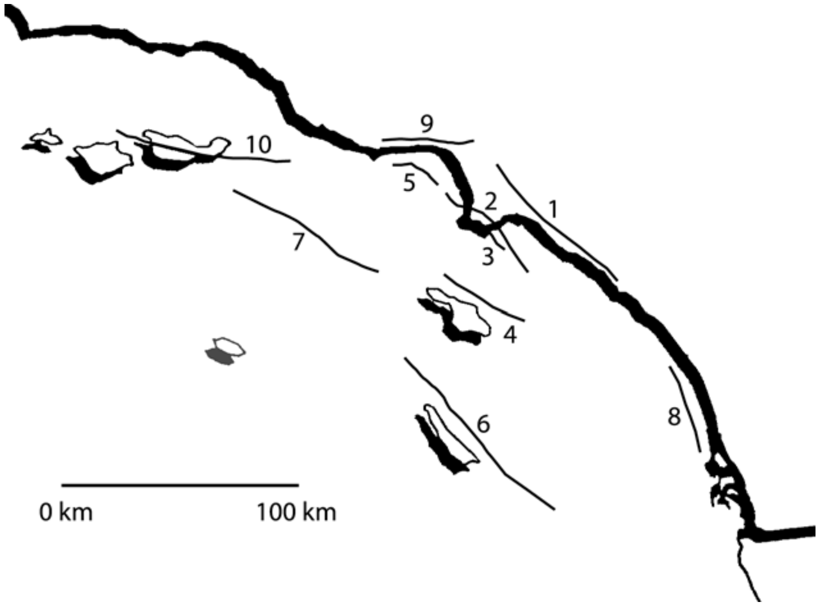
1. Volcano collapse of Kilauea, Hawaii
2. Volcano collapse of Mauna Loa, Hawaii
3. Volcano collapse of Kanaga, Alaska
4. Earthquakes off Alaska
5. Earthquakes off Kamchatka
6. Earthquakes off Japan
7. Earthquakes off Chile
8. Earthquakes off Peru
9. Earthquakes off Oregon
10. Landslides off Alaska
11. Landslides off Kamchatka
12. Landslides off Japan

We have assembled what we consider to be the twelve most important regions of transoceanic tsunamis that could impact the San Pedro Basin. For regions 4-12, the hazard assessment model produces specific tsunami sources from time to time based on randomized parameters. The earthquakes and landslides vary in their intensity and their dimensions in a random manner that mimics the occurrence of real events over time. The tsunami source parameters that result from these random variations are specific to each event, and span the full range of what is possible for that region during 100,000 years of numerical experiments. Each region and tsunami source noted above produces its own probability distribution.

We do not apply the Correspondence Principle to far-field tsunamis. Instead, the far-field directionality of earthquake tsunami energy is estimated from the theoretical work of Ben-Menahem and Rosenman (1972), as well as from case studies of real events described by McCulloch (1985). The far-field directionality of landslide tsunami energy is estimated from the work of Iwasaki (1997). The far-field propagation of all events from the generation region to Southern California is treated analytically according to well-known methods outlined by Dean and Dalrymple (1991). There are sufficient historical records to validate these techniques.

4. Local Earthquake Tsunamis

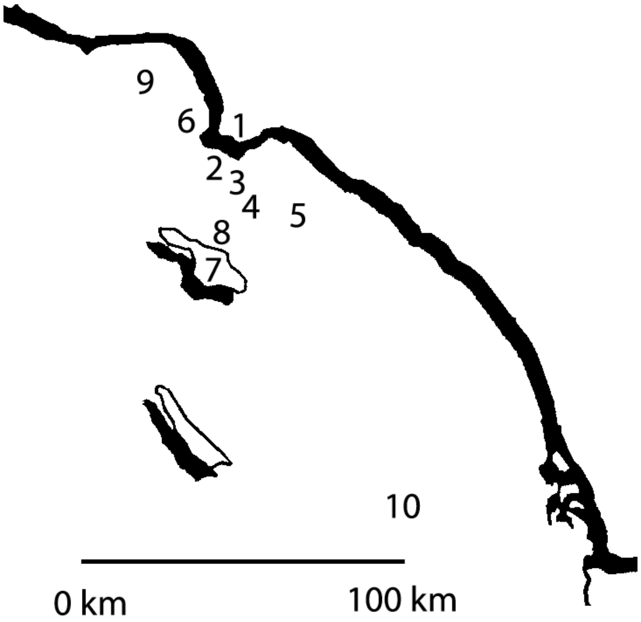
The probability distribution for local earthquake tsunamis will consider earthquake faults nearshore and offshore San Pedro Basin and adjacent basins (Clarke et al., 1985; McCulloch, 1985; Working Group on California Earthquake Probabilities, 1995; Legg and Kamerling, 2003). The hazard assessment model calculates earthquake recurrence intervals as well as tsunami amplitudes. The hazard assessment model produces specific tsunami sources from time to time based on randomized parameters. The earthquakes vary in their intensity and their dimensions in a random manner that mimics the occurrence of real events over time. The tsunami source parameters that result from these random variations are specific to each event, and span the full range of what is possible for that region during 100,000 years of numerical experiments. See Appendix 1 for tsunami source details.



1. Newport-Inglewood Fault
2. Palos Verdes Fault
3. Cabrillo Fault
4. Catalina Fault
5. Santa Monica Fault
6. San Clemente Fault
7. Channel Islands Fault
8. Rose Canyon Fault
9. Malibu Coast Fault
10. Santa Cruz Fault

5. Local Landslide Tsunamis

The probability distribution for local landslide tsunamis will consider potential landslide locations around San Pedro Basin and adjacent basins (Clarke et al., 1985; McCulloch, 1985; Field and Edwards, 1993; Gorsline, 1996; Lee et al., 2003; Legg and Kamerling, 2003; Bohannon and Gardner, 2004; Locat et al., 2004). The hazard assessment model calculates landslide recurrence intervals as well as tsunami amplitudes. The tsunami amplitude of subaerial landslides is calculated with the equations of Walder et al. (2003). The hazard assessment model produces specific tsunami sources from time to time based on randomized parameters. The landslides vary in their location and their dimensions in a random manner that mimics the occurrence of real events over time. The tsunami source parameters that result from these random variations are specific to each event, and span the full range of what is possible for that region during 100,000 years of numerical experiments. See Appendix 1 for tsunami source details.



1. Palos Verdes Subaerial Landslide
2. Palos Verdes Underwater Landslide
3. San Pedro Sea Valley Landslide
4. San Pedro Shelf Landslide
5. San Gabriel Canyon Landslide
6. Redondo Beach Canyon Landslide
7. Catalina Island Subaerial Landslide
8. Catalina Island Underwater Landslide
9. Santa Monica Canyon Landslide
10. Thirty Mile Bank Landslide

6. Probability Distributions

This work produces probability distributions for the tsunami sources described in the previous three sections. Probability distributions are a natural way to interpret tsunami hazards, because they provide an appropriate realm of possible events with known recurrence intervals. In simpler words, one discovers what to expect, and how often to expect it. As mentioned above, Houston (1980) and Watts (2004) have studied probability distributions of tsunamis impacting San Pedro Basin. These works both have shortcomings relative to the present study. Houston (1980) considered only one kind of tsunami source, far-field earthquake tsunamis. Watts (2004) did not identify specific locations for tsunami sources, considering instead Southern California as a whole. These studies stand on their own merits, and our current work must capture some aspects of this earlier work, even as we strive for much more detailed results.

Figure 3 shows a cumulative probability distribution for the Pacific Basin and another for Southern California (see Watts, 1994). These both follow log-normal curves, with tsunamis in Southern California being on average half the amplitude as the Pacific Basin as a whole. The earthquake magnitudes off Southern California are generally smaller than those found along many subduction zones of the Pacific Basin. Moreover, the shallow basins off Southern California may limit the size of sediment deposits, thickness of mass failures, and ultimately landslide tsunami amplitudes. The model appears to predict reasonable probability distributions of tsunami amplitudes off Southern California. The comparison with Pacific Basin tsunamis is important for historical reasons. We can see why tsunamis off Southern California were discounted in the past: tsunamis are in fact less of a threat off Southern California than across the Pacific Basin as a whole. However, in the past, this fact was used to discount *all* tsunami hazards off Southern California. Some of the predicted tsunami amplitudes in Figure 3 are sufficiently large such that tsunami hazards off Southern California need to receive serious consideration.

We calculated the cumulative probability distribution for all tsunami events over all regions considered in this work. To do this, we ran the hazard assessment model for 100,000 years in each source region. We then combined the tsunami events from each source region into a single list of tsunami events from all source regions. This list was sorted by increasing tsunami amplitude and each event was assigned an appropriate cumulative probability according to probability theory. We do not depict these cumulative results graphically in this report, choosing instead to report salient results in the following section. The outcome of this analysis is that we can predict the recurrence interval of tsunamis off Southern California for any given tsunami amplitude. The cumulative probability distribution results suggest posing the following questions. Should one choose tsunami scenarios based on a specific tsunami amplitude (or hazard level)? Or, should one choose tsunami scenarios based on a specific recurrence interval? These questions are addressed in the next section.

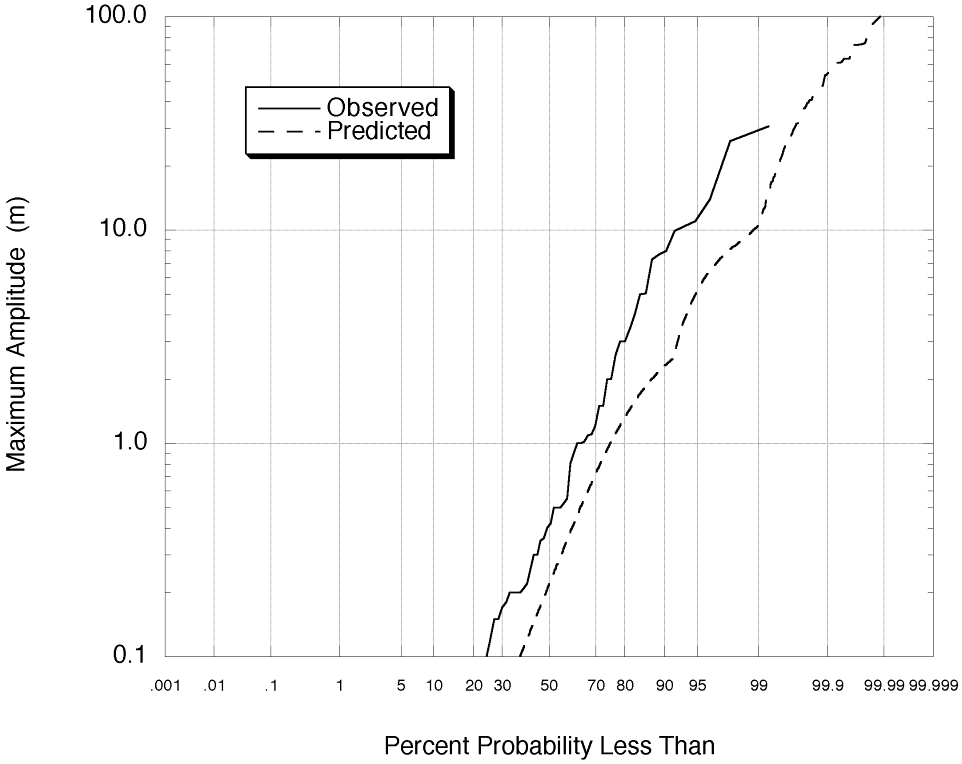


Figure 3. The “observed” cumulative probability distribution of maximum tsunami runup above sea level for the entire Pacific Basin is compared with the “predicted” cumulative probability distribution of local tsunamis off Southern California (from Watts, 2004).

7. Hazard Levels and Recurrence Intervals

We seek a methodology to identify tsunami scenarios that encompass events of potential interest to Pacific Energy. The scenarios will be representative of the range of possible tsunami hazards that are of concern to Pacific Energy. The modeling of these scenarios will be carried out in future work within the context of facility design and operations, in order to assess appropriate tsunami hazard mitigation measures. This report is not concerned with the modeling *per se*. Instead, this report provides the *context* for such modeling. We are faced with two options before identifying specific scenarios (see Figure 4). The options are to choose scenarios based on tsunami hazard level, or based on tsunami recurrence interval. Both will provide an upper bound on tsunami sizes of interest. There is no preference for either option going into the analysis. Likewise, as entirely distinct options, there is no expectation that they will yield similar size tsunamis. Regardless, the analysis will end up identifying representative tsunami scenarios.

The first option is to choose scenarios based on the tsunami hazard level, as represented here by the characteristic tsunami amplitude. The maximum known tsunami hazard levels in the Ports are the 2 m wave heights (or 1 m wave amplitudes) recorded during the May 23, 1960, Chilean tsunami, and the 3 m wave heights (or 1.5 m wave amplitudes) recorded during the March 27, 1964, Alaskan tsunami (McCulloch, 1985). Any reasonable analysis of tsunami hazards must meet or exceed this level, because this level can be met by seismic events that occur relatively frequently. For example, large earthquakes along the Pacific Rim are believed to have recurrence intervals of roughly 500 years in a number of different locations. Figure 3 shows that around 80% of all tsunamis off Southern California have a tsunami amplitude of 1.5 m or less. Therefore, a 1.5 m hazard level encompasses a large majority of tsunami events.

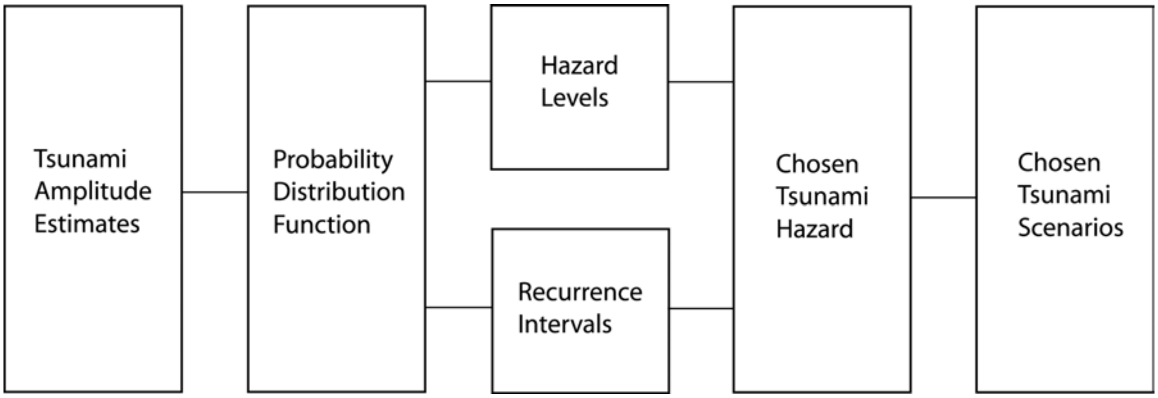


Figure 4. Schematic diagram of the method used to choose tsunami scenarios based on a reasonable assessment of tsunami hazard.

The second option is to choose a tsunami recurrence interval of interest, guided by reasonable arguments or by standards set for other natural hazards. For example, we can choose a 500 year recurrence interval for tsunami design considerations. This recurrence interval is suitably long relative to the lifetime of the project, and therefore provides a reasonable likelihood that the project will reach its term without significant tsunami risks. We can also choose a 500 year recurrence interval on the basis of flood hazard regulations (Houston, 1980), because tsunamis and floods pose related water hazards. The cumulative probability distribution calculated in the previous section suggests that this option corresponds to a tsunami amplitude of around 3.0 m, or twice the amplitude of the maximum known hazard level. This tsunami amplitude also agrees with the findings of Houston (1980), although the technique used is significantly different. Figure 3 shows that around 92% of all tsunamis off Southern California have a tsunami amplitude of 3.0 m or less. We find reasonable alignment of the two distinct options as to the tsunami amplitudes needed to study in the scenarios, because the two options yield similar magnitudes, expressed scientifically as being of order 1 m. The 500 year recurrence interval provides an added degree of safety that appears to be both reasonable and advisable.

We believe that the foregoing analysis needs to be repeated for different locations around the United States and the world, because the transoceanic tsunami context and the local geological context will vary considerably. Having chosen to study tsunamis 3.0 m or less in amplitude in San Pedro Basin, we have established a range of tsunami hazards of concern to Pacific Energy. We assert that tsunami hazards within this range should be considered for tsunami hazard assessment and mitigation. Much larger tsunamis remain a possibility, and these should not be discounted as potential natural hazards. Our analysis suggests that the larger events, sometimes called catastrophic events, are not sufficiently common to be the basis for engineering designs in San Pedro Basin. In other parts of the United States or the world, this may not be the case, because some large earthquakes have recurrence intervals of 500 years or less. Regardless, tsunami hazard preparedness for our chosen 3.0 m tsunami amplitude will almost certainly yield some benefits regardless of actual tsunami sizes.

8. Recommended Scenarios

Up to this point, we have reviewed a significant body of literature, and we have confirmed prior assessments of tsunami hazards at the Ports. In so doing, we have generated a significant amount of new work. We enumerate three novel aspects of our work so far. 1) We have performed this exercise with state of the art tools, such as our hazard assessment model. 2) We have also considered three kinds of tsunami hazards: transoceanic tsunamis, local earthquake tsunamis, and local landslide tsunamis. 3) With the results from the first two aspects, we have established a rigorous technique for identifying tsunami amplitudes of interest, and we have chosen a tsunami amplitude no greater than 3.0 m for all tsunami scenarios. In sum, we consider the work up until now as part of a careful analysis of tsunami hazards facing Pacific Energy in San Pedro Basin.

We now seek representative tsunami scenarios that could happen at any time. The term "scenario" is distinct from "case study", which is understood to be an analysis of a past tsunami event. A "scenario" is a prospective tsunami event, and one must be responsible in proposing scenarios. On the one hand, a scenario cannot represent a catastrophic event unless that is an appropriate context for the work. On the other hand, a scenario cannot minimize the tsunami hazard unless there is a reasonable context for doing so. We believe that our work has addressed these matters. Here, we identify four representative tsunami scenarios that span the range of tsunami hazards being considered by Pacific Energy. We choose four local tsunamis, because their potential impact is not as well understood as those of transoceanic tsunamis. The impact of transoceanic tsunamis at the Ports has been well described by Wilson (1971).

1. Palos Verdes Landslide
2. Catalina Landslide
3. Newport-Inglewood Fault
4. Catalina Fault

The above four scenarios satisfy a number of important criteria. The tsunami waves from these scenarios will approach the Pacific Energy facility from different directions, and with different wavelengths, some of which may resonate within the Ports (see Appendix 1 for details). There are two landslide tsunamis, and two earthquake tsunamis. These scenarios are also events of definite interest, based on recent research activities. All scenarios would have tsunami amplitudes less than or equal to 3.0 m. There is of course no guarantee that the next local tsunami within San Pedro Basin will consist of any of these four events. Instead, these scenarios fill in a gap in our current understanding of tsunamis attacking the Ports. And, these scenarios would presumably pose a wide variety of tsunami hazards for the Pacific Energy facility. We have taken most of this report to identify the realm of tsunami hazards in San Pedro Basin. Now, these scenarios will begin to capture the realm of tsunami hazards facing Pacific Energy for the purpose of facility design.

This report does not address specific operations design and tsunami mitigation work. Instead, the objective has been to *identify representative scenarios* that will enable careful and reasonable facility design. We can take the results from this report and start the process of tsunami hazard assessment and mitigation, because we have clear tsunami source locations and a chosen tsunami amplitude for which to carry out numerical simulations. These numerical simulations will describe tsunami attack at some distance from the source, and identify those regions that are hardest hit by the tsunami. We expect that most of these scenarios will not strike Pier 400 with the full force of the event, whereas a few of them will in fact focus on Pier 400. This behavior can be a natural outcome of different tsunami events, and these differences are the main reason for carrying out numerical simulations of all of our scenarios. Pier 400 will almost certainly be vulnerable to a limited number of tsunami source locations. The connection between tsunami source location and tsunami impact suggests effective tsunami warning strategies, which we will discuss in the next section.

Our tsunami scenarios may also be useful in a broader context than the specific concerns of Pacific Energy. The Army Corps of Engineers may consider running tsunami model experiments at the Waterways Experiment Station in Vicksburg, Mississippi. This would constitute an important step in a general understanding of local tsunamis attacking the Ports. Such a study would presumably use similar wave amplitudes and wave periods as those found in the tsunami scenarios chosen here, and summarized in Appendix 1 below. The prospective study would also confirm the lack of protection provided by the breakwaters during tsunami attack. Recent events in Indonesia provide an impetus to study such wave amplitudes and wave periods. Consequently, this work can serve as a catalyst for future tsunami studies carried out by other agencies and other entities.

9. Tsunami Warnings

Tsunami warning is an integral and important part of tsunami hazard mitigation. Advanced knowledge of tsunami attack allows for plans of action to be executed, especially those that will save lives, and minimize tsunami impact on sensitive facilities and structures. The tsunami warning systems run by NOAA for the Pacific Ocean are currently limited to transoceanic tsunamis generated almost exclusively by large earthquakes. There are few, if any, functional tsunami warning systems for local tsunamis, other than by direct observation, which can provide several minutes to several seconds warning. In the absence of existing warning systems, we are free to assemble such a system from existing technologies. In general, there is a plethora of mature technologies for natural hazard warning systems, water wave detection, earthquake detection, and landslide detection. We will not review these technologies here, nor will we attempt to design a tsunami warning system here. Instead, we describe how the tsunami scenarios will help design a prospective tsunami warning system, and inform its subsequent plans of action.

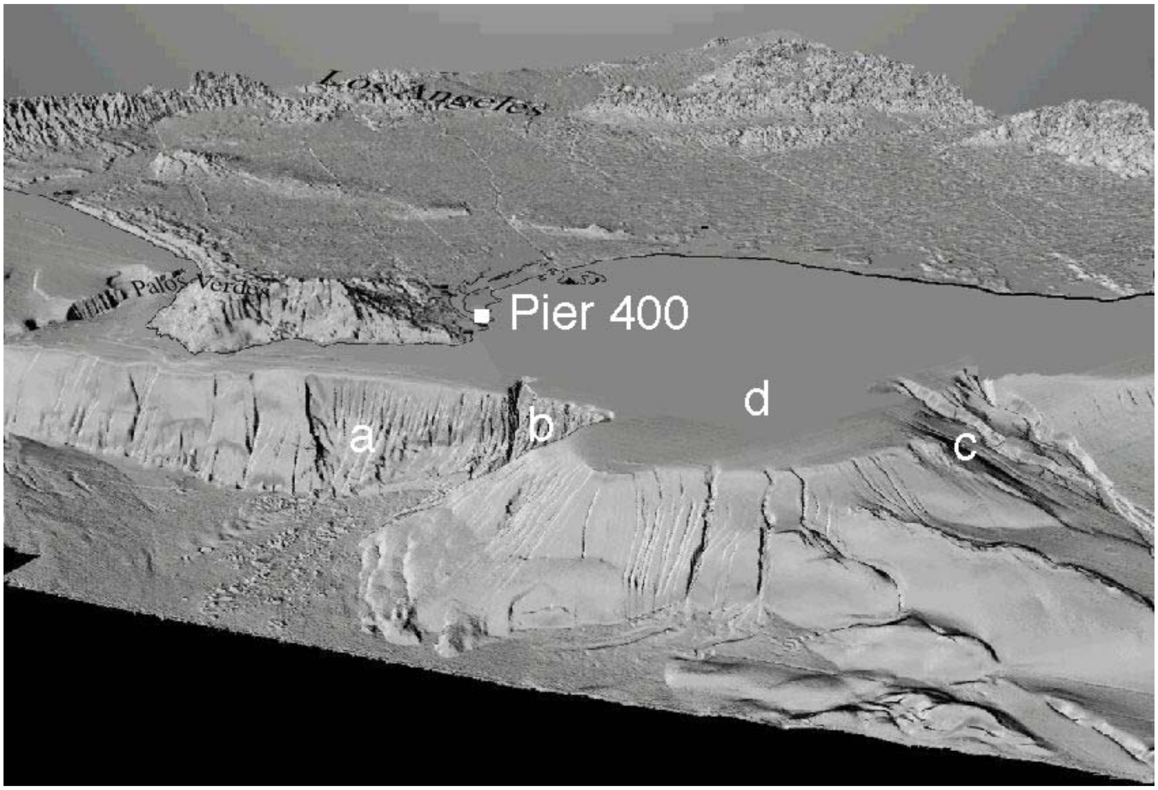


Figure 5. Vertically exaggerated view of the Los Angeles Basin onshore and part of the San Pedro Basin offshore. The image depicts a) Palos Verdes underwater landslides, b) San Pedro Sea Valley landslides, c) San Gabriel canyon, and d) the San Pedro Shelf. The latter is an extensive plateau of shallow water that slows the propagation of tsunamis (image courtesy of Jim Gardner, USGS, retired).

Each tsunami scenario described in Section 8 will almost certainly engage a different plan of action in response to tsunami attack. The reason for this may not yet be apparent, because it relies on the outcome of the numerical simulation of each scenario. Regardless, simulation results will be sufficiently accurate that the impact on Pier 400 will be distinguished from the impact on nearby facilities. In some instances, large amplitude water waves may interact with Pier 400, while in other instances large amplitude water waves may occur elsewhere. As such, the location and type of tsunami source is one of the key features of tsunami warning (Watts, 2001). This suggests that a tsunami warning system should be designed to recognize the geological origin of water waves, in addition to detecting their amplitude and period. This is one reason why we have chosen an equal number of earthquake and landslide tsunami scenarios in the previous section. Comprehensive numerical simulation results of the tsunami scenarios will play a significant role in the design of any future tsunami warning system.

Tsunami warning is predicated on having sufficient time with which to issue an effective warning. During prior research activities, we have simulated a tsunami scenario for a prospective underwater landslide off Palos Verdes just west of the letter “a” in Figure 5. The timing results from this scenario are illustrative of what can be expected in general for local tsunamis within San Pedro Basin. The underwater landslide accelerates and forms the tsunami waves gradually during the first 200 seconds of the event. Tsunami propagation over the San Pedro Shelf (see Figure 5) occurs relatively slowly because of the shallow water. It takes these water waves around 800 seconds (or 13 minutes) from the start of the event to reach Pier 400. As is often the case for tsunamis, the first wave to arrive is much smaller than subsequent waves, and as such it does not pose a significant hazard. It is not until 1100 seconds (or 18 minutes) into the event that the largest water waves are encountered at Pier 400. Some tsunami scenarios can be expected to have even longer available warning times.

For Pacific Energy, the primary use of a tsunami warning system protecting the Ports would be to cease oil transfer operations. The subsequent emplacement of personnel and equipment would follow the specific plan of action being launched. The details of these plans of action remain to be determined, and would respond to specific results from each numerical simulation of each scenario. Regardless, many of these mitigation measures can be expected to take on the order of five minutes to put in place. This turns out to be less than half of the >10-15 minute warning times that should be available from a reasonable tsunami warning system. Figure 5 depicts the shallow San Pedro Shelf, which slows down the advance of an approaching tsunami. This offshore feature virtually guarantees that a local tsunami warning system would be effective for the Ports. The probability distributions calculated here could eventually be used for a cost-benefit analysis of various potential tsunami warning system designs.

10. Conclusions

We carried out an analysis of tsunami hazards within San Pedro Basin for the local marine operations of Pacific Energy. We generated probability distributions with our hazard assessment model. We considered three kinds of tsunami hazards: transoceanic tsunamis, local earthquake tsunamis, and local landslide tsunamis. We established a rigorous technique for identifying tsunami amplitudes of interest. We chose a 500 year recurrence interval corresponding to around 3.0 m tsunami amplitudes. We identified four representative tsunami scenarios that span the range of tsunami hazards encompassed by our chosen recurrence interval. We limit the tsunami amplitude of all scenarios to be no greater than 3.0 m. These scenarios suggest representative tsunami propagation and inundation simulations that will assist in facility design. The suggested simulations are not part of the present work. We showed that our chosen tsunami scenarios could play a significant role in designing an effective tsunami warning system.

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Appendix 1

This appendix provides the geological and geometrical parameters for each tsunami source input into the hazard assessment model and listed in Sections 3-5. We also list the mean characteristic tsunami amplitude as well as the mean tsunami wavelength output by the hazard assessment model during the 100,000 years of numerical experiments. These two quantities give a sense of the hazards associated with each tsunami source. The characteristic tsunami amplitude clearly indicates the size of the tsunami, which will correlate with design considerations such as ship motions, current speeds, and wave forces. The tsunami wavelength is also an important measure of tsunami hazard, in part because some local tsunamis may have resonant responses within San Pedro Basin or the within the Ports. Longer tsunami wavelengths may mimic the tides, whereas shorter wavelengths may form destructive bores. We provide one last output from the hazard assessment model – the maximum tsunami amplitude found by each tsunami source over the course of the 100,000 years of numerical experiments. This quantity is important because it establishes that our work has considered all possible tsunami events, including the most catastrophic tsunamis possible. If these events are not included in the design of facilities for Pacific Energy, this is because they do not occur frequently enough to justify their use based on a 500 year recurrence interval. In general, other facilities with other recurrence interval criteria may need to consider these events.

UNDER CONSTRUCTION

A.1 Transoceanic Tsunamis

Volcano collapse of Kilauea, Hawaii
Volcano collapse of Mauna Loa, Hawaii
Volcano collapse of Kanaga, Alaska
Earthquakes off Alaska
Earthquakes off Kamchatka
Earthquakes off Japan
Earthquakes off Chile
Earthquakes off Peru
Earthquakes off Oregon
Landslides off Alaska
Landslides off Kamchatka
Landslides off Japan

A.2 Local Earthquake Tsunamis

Newport-Inglewood
Fault Palos Verdes Fault
Cabrillo Fault

Catalina Fault
Santa Monica Fault
San Clemente Fault
Channel Islands Fault
Rose Canyon Fault
Malibu Coast Fault
Santa Cruz Fault

A.3 Local Landslide Tsunamis

Palos Verdes Subaerial Landslide
Palos Verdes Underwater Landslide
San Pedro Sea Valley Landslide
San Pedro Shelf Landslide
San Gabriel Canyon Landslide
Redondo Beach Canyon Landslide
Catalina Island Subaerial Landslide
Catalina Island Underwater Landslide
Santa Monica Canyon Landslide
Thirty Mile Bank Landslide