The Regional Economic Cost of a Tsunami Wave Generated by the Palos Verdes Slide

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Abstract

Recent developments in modeling of tsunami waves and economic impact analysis are combined with data from recent offshore mapping of the Santa Barbara channel and other locations to model the mechanism and economic impact of a tsunamigenic undersea landslide in the vicinity of Los Angeles.

Introduction

The seismic sensitivity of the Los Angeles metropolitan region is well recognized, Fortunately, the densely populated regions of coastal Southern California, including the Los Angeles Basin, and the Santa Barbara -- Ventura regions have been relatively free of severely damaging earthquakes during most of the past 200 years. See Figure 1. Several recent moderate earthquakes however, such as the 1994 M_w 6.7 Northridge earthquake and the 1987 M_w 6.0 Whittier Narrows earthquake, have brought to light the hazard associated with thrust and reverse faulting beneath Southern California (Dolan et al. 1995). There have been several smaller, less damaging thrust and reverse earthquakes in the near shore region that illustrate the possibility of a larger earthquake offshore. The shaking from an earthquake of magnitude 7 or greater on an offshore thrust or reverse fault would undoubtedly be damaging to coastal communities, and its effect would be enhanced by its potential for generating a damaging tsunami.

The hazard to metropolitan Southern California posed by locally generated tsunamis has received considerably less study than the hazards posed by onshore earthquakes. This is likely to change. The mechanisms that generate tsunamis have received considerable study following the unusually large waves associated with the July 17, 1998 Papua New Guinea (PNG) tsunami. As a result of this increasing scientific scrutiny, Southern California's susceptibility to tsunami damage is only recently becoming understood.

Several locally generated tsunamis have been recorded in the region during the past 200 years. One of the first large earthquakes to be recorded in Southern

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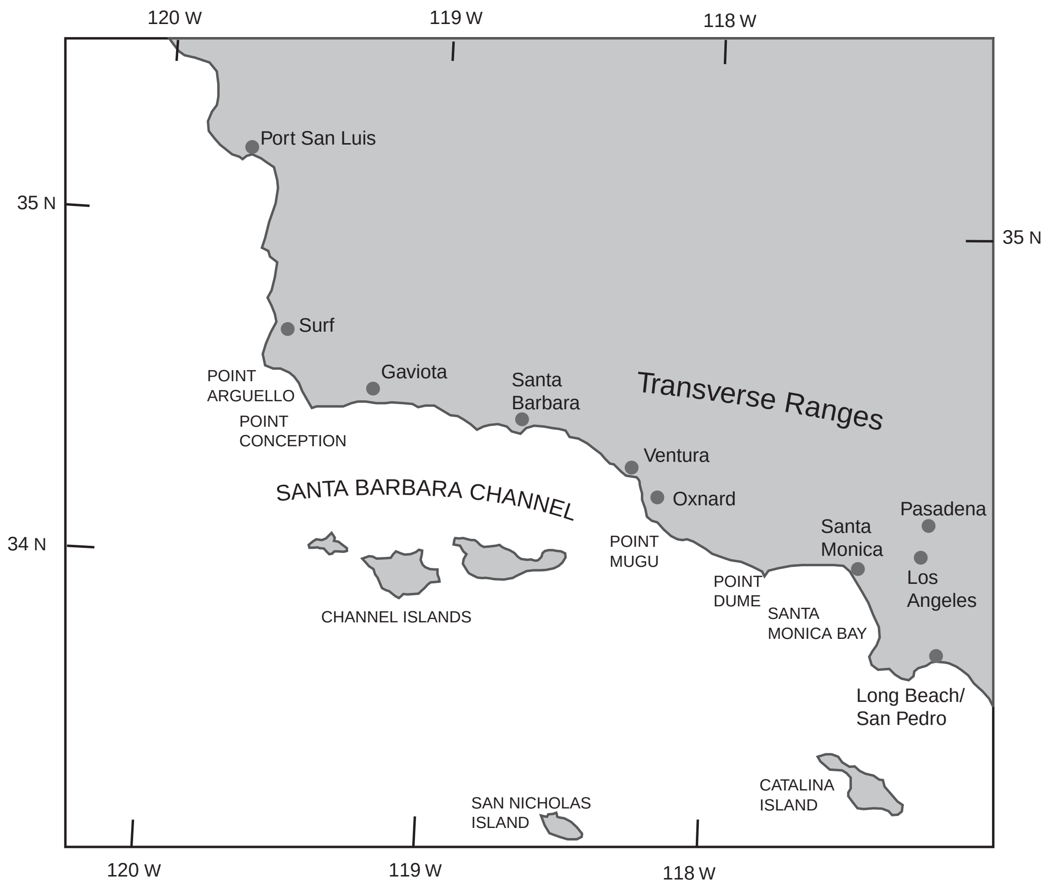

Figure 1: Southern California location map for tsunami and seismic activity over the past 200 years.

California, the December 21, 1812 Santa Barbara earthquake, appears to have generated a moderate tsunami that affected over 60 *km* of the Santa Barbara coast (Toppozada et al. 1981; Lander and Lockridge, 1989). Table 1 summarizes the details of several near-shore earthquakes, some of which generated tsunamis. There will be other such events, and this research focuses on the mechanisms and the potential economic impact of such a large, local tsunami event.

The Role of Reasearch

Figures for 1994 show that the metropolitan Los Angeles area is responsible for nearly $746 billion of economic productivity annually (Cho, et al. 2000). Natural disasters such as earthquakes, fires, floods, and landslides act as agents of economic loss. Quantifying the economic impact associated with natural disasters has long been of research interest to economists, social scientists and engineers, but progress has been slowest in the social sciences. Much of the research on tsunamis has been in the engineering and geological fields. Progress in economic impact research is recent. The physical science of earthquakes and tsunamis is challenging, but it is at least as difficult to explore the social impacts of disasters. Consequently, it is not

Table 1: Local Tsunamis and Nearshore Seismicity in California.

	Fault / Location	Date	Intensity			Tsunami Run-Up	Scientific References
			M_W	M_L	M_S		
Santa Barbara Earthquake[a]	San Andreas Fault, Mojave Segment	December 21, 1812	7.2			Possibly 4 *m* in El Refugio, 2 *m* in Santa Barbara and Ventura, possibly 2-4 *m* in Hilo, Hawaii	Hamilton, et al. (1969) Toppozada, et al. (1981), McCulloch (1985), Ellsworth (1990), Lander, et al. (1993)
Point Arguello-Lompoc Earth-quake	Debated, but likely a North-trending offshore thrust or oblique-reverse fault	November 4, 1927			7.0	2 *m* in Surf and San Luis, 10 *cm* in Hilo, Hawaii	Byerly (1930), Satake and Somerville (1992)
Santa Monica Bay Earthquake	Off Santa Monica, inside Santa Monica Bay	August 31, 1930			5.2	No Tsunami. Unusual wave conditions, possible submarine landslide	Gutenberg, et al. (1932), Huaksson and Saldivar (1986), Huaksson (1990), Lander, et al. (1993)
Long Beach Earthquake	Newport-Inglewood Fault	March 10, 1933			6.4	No Tsunami. Unusual wave conditions, most likely meteorological.	Haukksson and Gross (1991)
Point Mugu Earthquake	Anacapa Dume Fault, possibly the Santa Monica Fault System	February 21, 1973	5.1 - 5.3	6.0		No Tsunami. Unusual wave conditions	Stierman and Ellsworth (1976), Boore and Stierman (1976), Haukkson and Saldivar (1986)
Malibu Earthquake	Off Malibu, inside Santa Monica Bay	January 1, 1979		5.0		No Tsunami. No unusual wave conditions	Haukkson and Saldivar (1986)

Notes: a. The December 21 event was receded by an M_W 7.5 Earthquake on December 13, 1812, also on the Mojave Segment. Additional earthquakes occurred off shore of Santa Barbara on June 28, 1925, M_L 6.3, and June 30, 1941, M_W 5.9-6.0, neither of which generated tsunami waves.

surprising that there has been only limited previous attention to the socioeconomic impacts of natural disasters. This reflects a lag in social science research in this area.

Tsunamis, while obviously related to earthquakes, have never been modeled quantitatively in terms of their potential economic impact. McCulloch (1985) estimated that tsunamis have been responsible for 0.2% of the cost of total earthquake damage between 1812 and 1964. This number, however, is derived primarily from the $32.2 million dollars (adjusted to 1983) of tsunami damage incurred in Crescent City, California after the 1964 Gulf of Alaska Earthquake. California has not suffered any tsunami damage since the 1964 event. However, coastal development has increased dramatically since, placing at risk billions of dollars of additional property, businesses and infrastructure.

The core purpose of applied research in the natural disaster field is to assist policy makers. What types of information are required for creation of cost-effective policies? The large expenditures that are involved in many proposed mitigation programs suggest that a careful analysis of trade-offs is required. This means that the full costs and benefits of prospective mitigation measures should be studied. The benefits of mitigation are the costs avoided by the particular measure. Yet a discussion of costs avoided depends on analysts' ability to determine full costs. Social science research can, therefore, make a substantial contribution by identifying expected full costs with and without various proposed mitigations.

Some of the previous social science-based research on natural disasters has focused on measuring the total economic impacts of structure and contents damage. Work by Gordon, Richardson, and Davis (1998) on the business interruption effects of the 1994 Northridge earthquake indicates that an exclusive focus on structural damage ignores 25 - 30 percent of the full costs. Their analysis also identifies the geographical distribution of these impacts on individual cities and other small area zones. In 1994, business interruption job losses were estimated to be 69,000 person-years of employment, about half of which were jobs outside the area that experienced structural damage. See Table 2. Disregarding values of such magnitudes results in a serious underestimate of the full costs of the event. More recently, Gordon et al. (1998) and Gordon, Moore, and Richardson (2002) examined another distributional question important to policy-making, that of the interpersonal income distribution.

The Southern California Planning Model (SCPM)

The most widely used models of regional economic impacts are versions of inter-industry models. These attempt to trace all intra- and interregional shipments, usually at a high level of industrial disaggregation. Being demand driven, they only account for losses via backward linkages.

The Southern California Planning Model version 1 (SCPM1) was developed for the five-county Los Angeles metropolitan region, and has the unique capability to allocate all impacts, in terms of jobs or the dollar value of output, to 308 sub-regional zones, mostly municipalities. This is the result of an integrated modeling approach that incorporates two fundamental components: input-output and spatial allocation. The approach allows the representation of estimated spatial and sectoral impacts

Table 2: Business Interruption Losses from the 1994 Northridge Earthquake
(Jobs in person-years, Output in thousands of 1994 $)

Area	Direct		Indirect and Induced		Total	
	Jobs	Output	Jobs	Output	Jobs	Output
Impact Zone Total	34605.4	3,117,528	1,904.9	209,591.1	36,510.1	3,327.119.4
Rest of LA City	0.0	0.0	2,119.9	232,021.2	2,119.9	232,021.2
Rest of LA County	0.0	0.0	10,668.2	1,067914.1	10,668.2	1,067914.1
Rest of Region	0.0	0.0	8,260.7	877,532.0	8,260.7	877,532.0
Regional Total	34,605.4	3,117,528	22,953.7	2,387,058.5	57,559.1	5,504,586.9
Rest of the World	11,454.4	1,031,901.9	Not Computable		11,454.4	1,031,901.9
Total	46,059.8	4,149,430.3	22,953.7	2,387,058.5	69,013.5	6,536,488.8

Source: Gordon, Richardson, and Davis (1998).

corresponding to any vector of changes in final demand. Exogenous shocks treated as changes in final demand are fed through an input-output model to generate sectoral impacts that are then introduced into the spatial allocation model.

The first model component is built upon the Regional Science Research Corporation input-output model. This model has several advantages. These include

- a high degree of sectoral disaggregation (515 sectors);
- anticipated adjustments in production technology;
- an embedded occupation-industry matrix enabling employment impacts to be identified across ninety-three occupational groups (This is particularly useful for disaggregating consumption effects by income class and facilitates the estimation of job impacts by race.);
- an efficient mechanism for differentiating local from out-of-region input-output transactions via the use of Regional Purchase Coefficients (RPC); and
- and the identification of state and local tax impacts.

The second basic model component is used for allocating sectoral impacts across 308 geographic zones in Southern California. The key was to adapt a Garin-Lowry style model for spatially allocating the induced impacts generated by the input-output model. The building blocks of the SCPM1 are the metropolitan input-output model, a journey-to-work matrix, and a journey-to-nonwork-destinations matrix. This is a journey-from-services-to-home matrix that is more restrictively described as a "journey-to-shop" matrix in the Garin-Lowry model.

The journey-from-services-to-home matrix includes any trip associated with a home based transaction other than the sale of labor to an employer. This includes retail trips and other transaction trips, but excludes nontransaction trips such as trips to visit friends and relatives. Data for the journey-from-services-to-home matrix includes all of the trips classified by the Southern California Association of Governments as home-to-shop trips, and a subset of the trips classified as home-to-other and other-to-other trips.

The key innovation associated with the SCPM1 is to incorporate the full range of multipliers obtained via input-output techniques to obtain detailed economic impacts by sector and by submetropolitan zone. The SCPM1 follows the principles of the Garin-Lowry model by allocating sectoral output (or employment) to zones via a loop that relies on the trip matrices. Induced consumption expenditures are traced back from the workplace to the residential site via a journey-to-work matrix and from the residential site to the place of purchase and/or consumption via a journey-to-services matrix. See Richardson et al. (1993) for a further summary of SCPM1.

Incorporating the Garin-Lowry approach to spatial allocation makes the transportation flows in SCPM1 exogenous. These flows are also relatively aggregate, defined at the level of political jurisdictions. With no explicit representation of the transportation network, SCPM1 has no means to account for the economic impact of changes in transportation supply and demand. Tsunamis are likely to induce such changes.

We focus on a credible, hypothetical tsunami. Modeling the degree of inundation defines the lengths of time for which firms throughout the region will be non-operational. This allows the calculation of exogenously prompted reductions in demand by these businesses. These are introduced into the inter-industry model as declines in final demand. The I/O model translates this production shock into direct, indirect, and induced costs, and the indirect and induced costs are spatially allocated in terms consistent with the endogenous transportation behaviors of firms and household.

Implementing this approach is a data intensive effort that builds on the data resources assembled for SCPM1. In this case, results of structure damage to businesses are used to drive SCPM2. SCPM2 is a more advanced version of the Southern California Planning Model that endogenizes traffic flows by including an explicit representation of the transportation network. SCPM2 results are computed at the level of the Southern California Association of Governments' (SCAG) 1,527 traffic analysis zones, and then aggregated to the level of the 308 political jurisdictions defined for SCPM1. These jurisdictional boundaries routinely cross traffic analysis zones. Results for traffic analysis zones crossed by jurisdictional boundaries are allocated in proportion to area. Like SCPM1, SCPM2 aggregates to 17 the 515 sectors represented in the Regional Science Research Corporation's PC I-O model Version 7 (Stevens, 1996) based on the work of Stevens, Treyz, and Lahr (1983). Treating the transportation network explicitly endogenizes otherwise exogenous Garin-Lowry style matrices describing the travel behavior of households, achieving consistency across network costs and origin-destination requirements. SCPM2 makes distance decay and congestion functions explicit. This allows us to endogenize the spatial allocation of indirect and induced economic losses by endogenizing choices of route and destination. This better allocates indirect and induced economic losses over zones in response to direct tsunami losses to industrial and transportation capacity. See Cho et al. (2000) for a further summary of SCPM2.

The Geological Framework

The offshore region from Point Conception south to central Baja California is known as the Southern California Borderlands. See Figure 2. The Borderlands are a geologically complex region comprised of different tectonic regimes, complicated bathymetry consisting of deep basins, towering ranges and steep walled canyons. The steep topography that is visible on land does not stop at the water's edge, but rather continues under the sea.

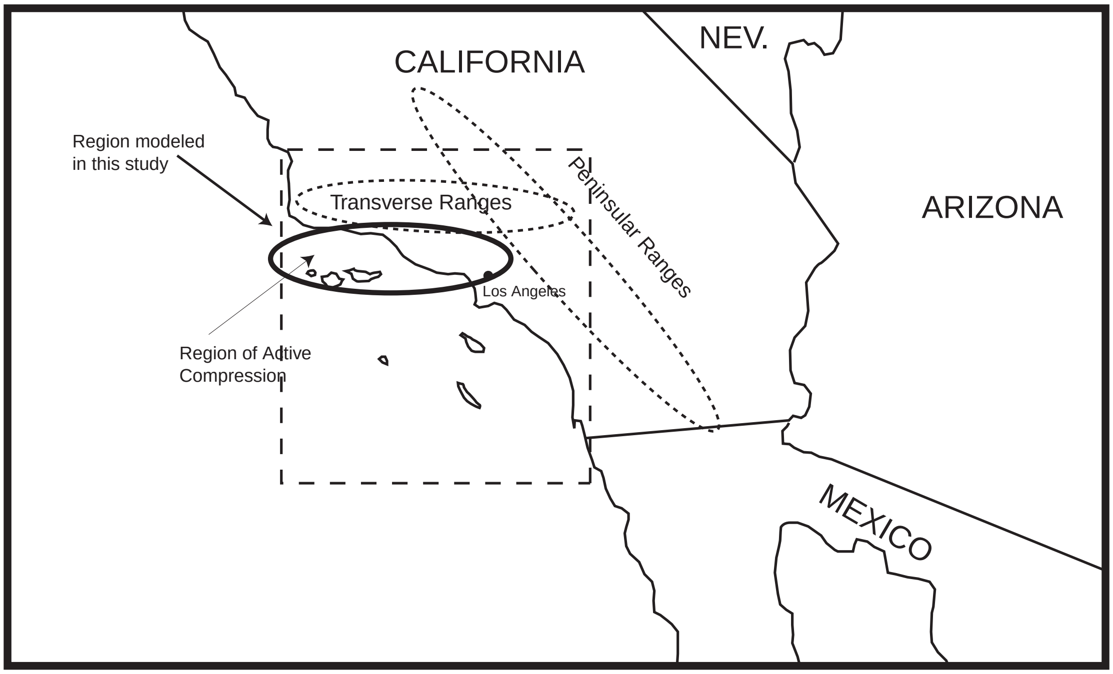

Figure 2: Compressional tectonics offshore of Southern California.

Southern California lies astride a major transition between two tectonic provinces. The region to the south is dominated by northwest-trending, strike--slip faults, whereas the area to the north is characterized by west-trending mountain ranges—the Transverse Ranges--that have developed above west-trending reverse, oblique reverse, and left-lateral strike--slip faults. Where these thrust systems extend offshore, they may represent significant potential sources of tsunamis.

Tsunamis generated by Submarine Landslides. The standard paradigm of large tsunamis generated primarily by tectonic uplift or subsidence has come under increasing scrutiny as a result of the unusually large waves associated with the July 17, 1998 Papua New Guinea (PNG) tsunami. The Papua New Guinea tsunami was generated after a relatively small earthquake with an approximate M_w = 7.0 (Kawata et al. 1999, Matsuyama et al. 1999). The large runup values and extreme inundation, as well as the devastation of coastal communities observed along the PNG coast prompted even the scientists in the International Tsunami Survey Team (ITST) to rethink standard models and search for an alternate explanation for the cause of the wave (Kawata et al. 1999). The runup distribution plotted along the PNG coast showed a very large peak that tapered off rapidly within 10 *km* of the peak. This distribution is unlike that observed in the near field from classic subduction zone earthquakes generating tsunamis, such as the 1995 Jalisco-Colima earthquake (Borrero et al. 1995).

The combination of factors such as the small moment magnitude, unusually large waves, peaked runup distribution plus other seismological clues suggested that a giant submarine mass failure was the causative agent for this tsunami (Synolakis et al. 2002, Tappin et al. 1999, Tappin et al. 2001). The speculation that the PNG tsunami was caused by a submarine mass failure has become a driving force in identifying non -- tectonic tsunami generation sources for various coastal regions around the world, including Southern California.

Submarine Landslides Offshore Southern California. Hampton et al. (1996) give an excellent review of the basic terminology associated with submarine landslides. Submarine landslides are also known as slope failures or underwater mass movements. Regardless of the name, all submarine landslides possess the same two basic features, the rupture surface and a displaced mass of material. The rupture surface is where the downslope motion originated. The displaced material is moved through the acceleration of gravity along a failure plane. There may be several failure planes in one mass movement. The displaced mass can remain largely intact and only slightly deformed or the displaced mass can break apart in to separate sliding blocks. In the extreme case the mass completely disintegrates and becomes a mass flow or a turbidity current. Largely cohesive or block like slope failures in canyon heads may evolve into or trigger turbidity currents in basins (Gorsline 1996).

Submarine landslides are of two general types, the rotational slump and the translational slide. When the rupture surface cuts through a homogeneous material, is scoop-shaped and concave upward, the sliding mass follows a circular arc. This type of slide is known as a *rotational slump*. If the rupture surface is more or less planar and the failure plane is the result of material inhomogeneities, i.e., bedding planes, the motion of the displaced mass is translational and is called a *translational slide*. A series of consecutive failures that propagate upslope is called a *retrogressive* failure (Hampton et al. 1996).

Such submarine landslides can occur in a wide range of sizes, over several orders of magnitude ranging from very small to enormous. As a matter of comparison, Hampton et al. (1996) note that the largest documented subaerial slide might contain tens of cubic kilometers of displaced material whereas one submarine slide mapped off South Africa might contain a displaced volume of over 20,000 km^3.

The near offshore region from Point Conception to the Mexican Border is characterized by a mainland shelf that runs from the shoreline to depths of 70 to 100 *m*. This shelf varies in width from 3 to 20 *km*. It is narrowest in the southern reaches of this zone and broadest in Santa Monica Bay and immediately south of the Palos Verdes Peninsula. The shelf has a relatively gentle slope on the order of a few degrees that runs to a slope break, and then a steeper 5° to 15°slope that drops off into deeper offshore basins of 800 *m* depths or more. The shelf is periodically cross cut by deep canyons along its entire extent. Starting in the north, the major canyons are Hueneme, Mugu, Dume, Santa Monica, and Redondo. South of the Palos Verdes peninsula there are 5 more major canyons, San Gabriel, Newport, Carlsbad, La Jolla and Coronado (Clarke et al. 1985, McCarthy, 1993, Synolakis et al. 1997b).

The slopes offshore of Southern California generally have thick accumulations of under-consolidated sediment of Quaternary age (Clarke et al. 1985). These water-saturated sediments generally have a lower shear strength than comparable onshore sediments. Therefore underwater slope failures are generally larger and occur on lower slopes than on land (Clarke et al. 1985). Decadal and generational floods discharge sediment in amounts one to three orders of magnitude larger than the average annual contribution. These events load the shelf and canyons with material. Seismic activity can trigger slope failures where sedimentation is high and sediments are unstable (Gorsline, 1996). Clarke et al. (1985) note that most offshore slope failures appear to be composite rather than single events. They also mention that it is difficult, if not impossible, to determine the timing and rate of motion of individual slides. They go on to say that " zones of past failure should be viewed as having an unknown potential for renewed movement," in that "some may be more stable than unfailed accumulations of sediment on the adjacent slopes; others, however, may have unchanged or even reduced stability."

Clarke et al. (1985) discuss specific areas of submarine landslides offshore Southern California. Their comprehensive list mentions every offshore canyon, slope and headland from the Santa Barbara Channel to San Diego County. Modeling potential tsunamis from these types of slides is not straight forward, especially since there is no indication whether or not these features were generated as single catastrophic events or through slow gradual movements over time. Nonetheless their morphology is intriguing and further research is necessary to determine the age of these features and the details of their motions.

Scenario Event for this Study. For this study, a tsunami scenario based on waves being generated by a submarine landslide offshore of the Palos Verdes Peninsula is used. A landslide source is chosen for two reasons. First, in the period between 1992 and 2001 several locally generated and destructive tsunamis have been associated with submarine or subaerial landslides. The 1998 Papua New Guinea tsunami was responsible for over 2000 deaths and is believed to have been caused by a large (4 km^3) offshore slump (Tappin et al. 1999, Kawata et al. 1999, Tappin et al. 2001, Synolakis et al. 2002). In August of 1999, a large earthquake near Istanbul Turkey caused significant landslides and slumping along the shores of the Sea of Marmara and contributed to waves, which damaged port facilities. In September of 1999, a large rockfall on the south shore of Fatu Hiva in the Marquesas Islands caused tsunami runup in excess of 2 *m* which inundated a local school and nearly killed several children (Okal et al. 2002a). In December of the same year on Pentecost Island, Vanuatu a highly localized tsunami wave with runup of up to 6 *m* wiped out an entire village and killed 2 people (Caminade et al. 2000).

Second, recent offshore mapping work has found evidence of significant sliding and slumping offshore of Southern California, particularly in the Santa Barbara Channel (Greene et al. 2000) and off of the Palos Verdes Peninsula

(Bohannon and Gardner, 2001). Studies have shown that these events could have been tsunamigenic with wave heights ranging from 5 to 20 *m* (Borrero et al. 2001, Bohannon and Gardner 2001, Locat et al. 2001). Furthermore, due to the proximity to a major port, a tsunami generated off of Palos Verdes would have the greatest impact on economic activity.

Quantifying the Innundation Effects of a Tsunami Disaster

The Palos Verdes Slide. Several researchers, including Bohannon and Gardner (2001), Locat et al. (2001), and Watts et al. (2001), have modeled the waves generated by the Palos Verdes Slide (PVS). Bohannon and Gardner used an energy scaling relationship based on Watts (2000) for a rock avalanche with the following dimensions: T = 70 *m*, D = 350 *m* and L = 4000 *m*. They assumed a 2% transfer of energy from the sliding mass to the generation of tsunami waves. Their analysis resulted in tsunami wave amplitudes of 10 *m* for a landslide density of 1500 kg/m^3.

Locat et al. (2001) analyzed the mobility of the Palos Verdes debris avalanche. Their analysis concluded that the state of the mapped debris field implies that the Palos Verdes debris avalanche must have moved as a large block in a single catastrophic event. They proposed a tsunami wave generation mechanism based on the energy equation of Murty (1979). They proposed initial wave heights of 10 to 50 *m* depending on the value of Murty's μ, "the energy transfer efficiency," which they varied from 0.1% to 1% (.001 to .01).

The analysis of Watts et al. (2001) was based on the Watts (1998, 2000) efforts to fit curves to laboratory data. Their proposed initial wave had an initial drawdown of 9.8 *m* over the sliding center of mass and a positive wave amplitude of 2.5 *m*. Watts et al. (2001) also proposed a range of values for the Palos Verdes slide, giving amplitudes from 6.6 to 19.5 *m*.

Modeling Runup. For this study, the same conditions were used to generate a single case inundation map for a landslide-generated wave off of the Palos Verdes Peninsula. Two cases are modeled, one with the breakwater in place and one without the breakwater. Comparing results shows the effect of the narrow openings between breakwater segments. Modeling suggests current velocities of over 3 *m/sec* in these openings. Instantaneous peak velocities are modeled to be over 10 *m/s*, but generally occur on the steep cliffs of Palos Verdes, west of the entrance to the Ports. The computed runup in the region of the ports is not affected by the presence of the breakwater.

Figure 3 shows the initial wave and the local bathymetry and topography. Figures 4a,b and show the time series of water levels at locations indicated in Figure 3. The maximum drawdown reaches the outer harbor area about 6 minutes after wave generation, with the maximum positive wave arriving one minute later. This illustrates the extremely short time that is available for emergency planners to deal with when considering the effects of landslide-generated tsunamis off of Southern California. Figures 5a,b provide plots of snapshots of the depth averaged velocities at various times.

Figure 3 shows that large peak of up to 25 *m* is seen along the southern tip of the Palos Verdes Peninsula, with the runup value dropping of rapidly to either side. Runup values of 4 *m* are observed in the area of the Ports of Los Angeles and Long Beach. To determine the inundation area, the runup plot in Figure 3 is discretized into 4 zones with 2, 4, 6 and 20 *m* sections. These values are then used in conjunction with topographic maps to generate a GIS layer representing the inundated area. Figure 6 shows the inundation zones plotted with different shadings representing the level of runup. Note that on the steep cliffs of the Palos Verdes Peninsula, the inundation is limited to the fringing shore, however in the low lying areas around the

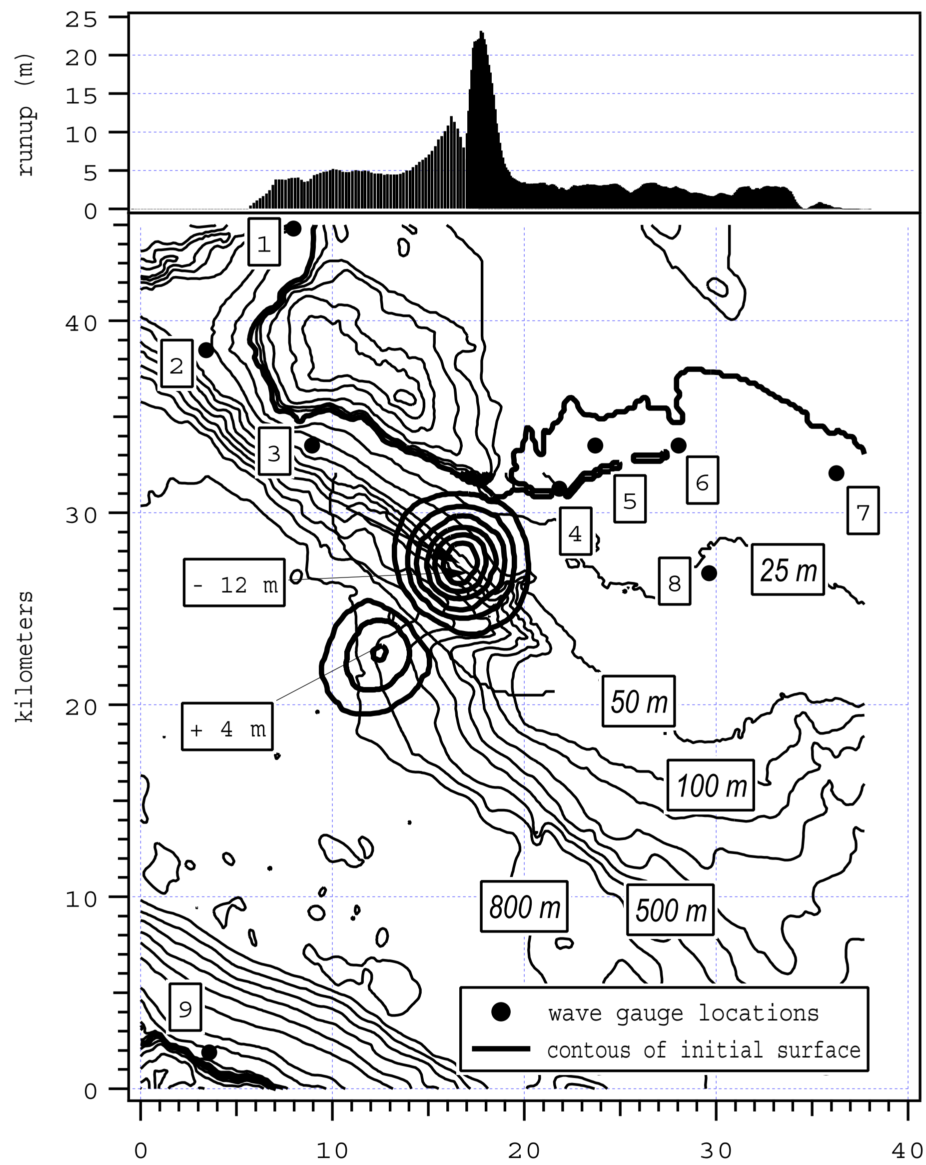

Figure 3: Initial wave used in the Palos Verdes slide simulations and runup along the south facing shoreline boundary: Breakwater included.

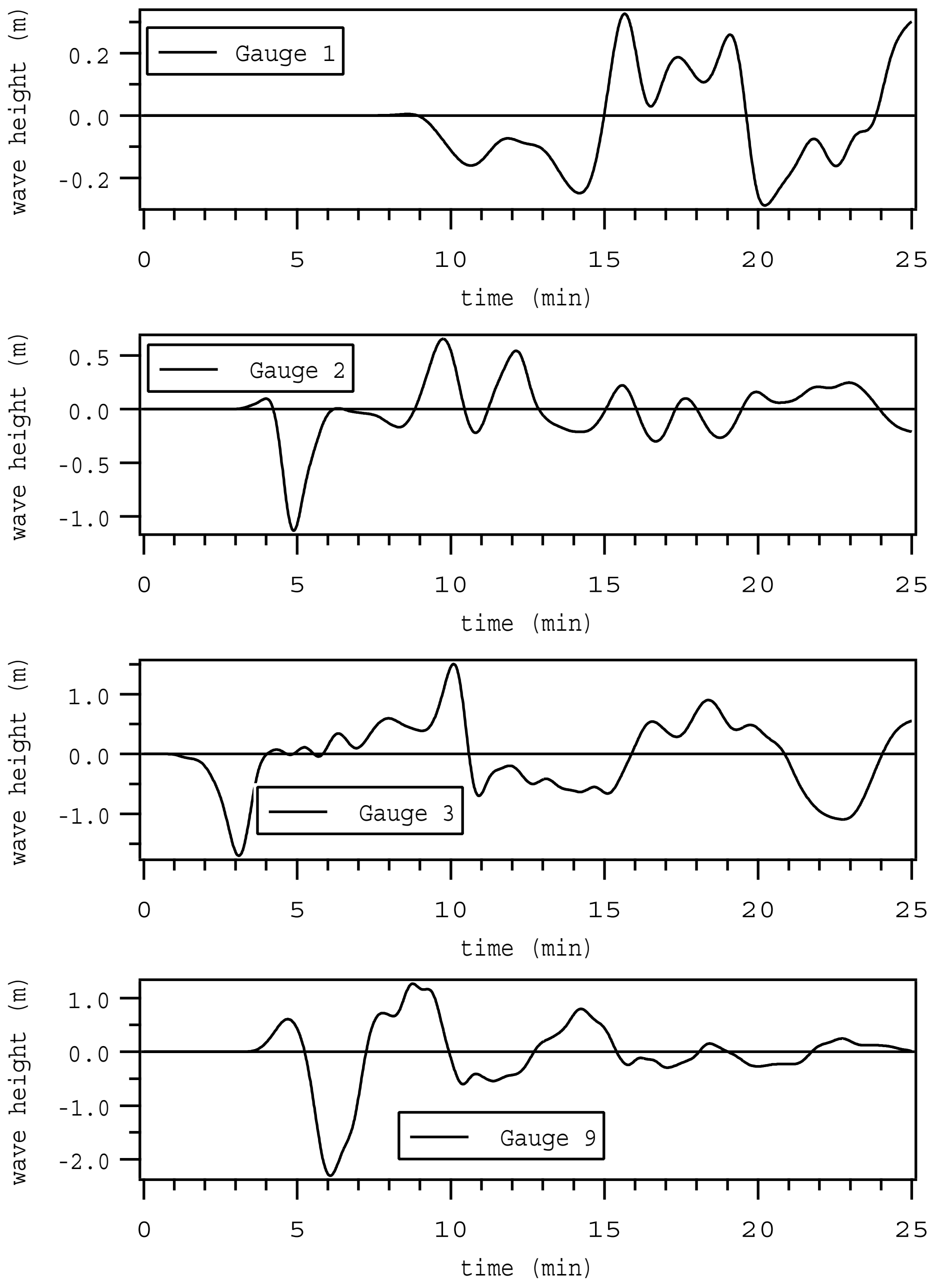

Figure 4a: Wave gauge records 1-4, Palos Verdes slide, with break-water.

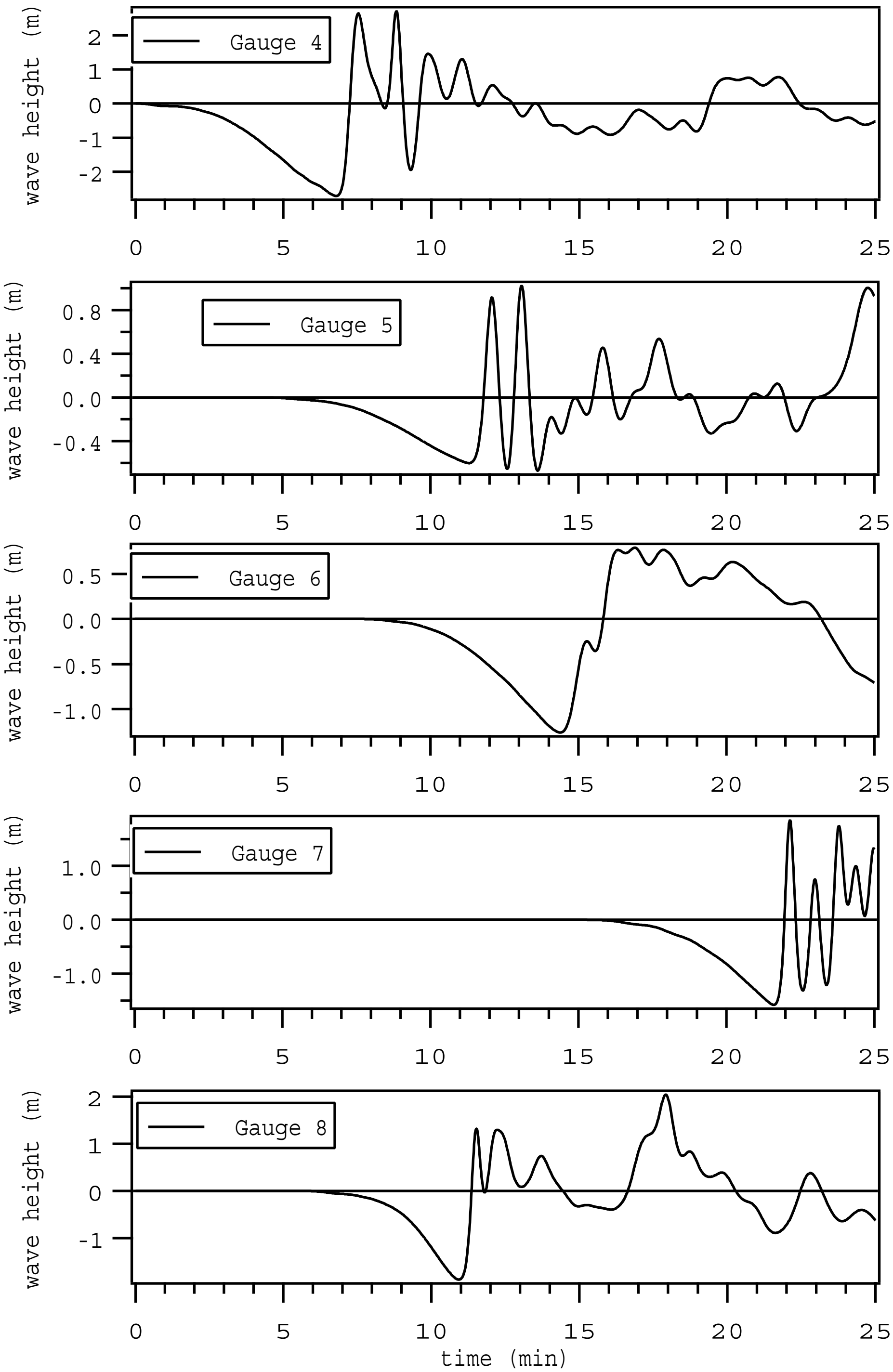

Figure 4b: Wave gauge records 5-8, Palos Verdes slide, with break-water.

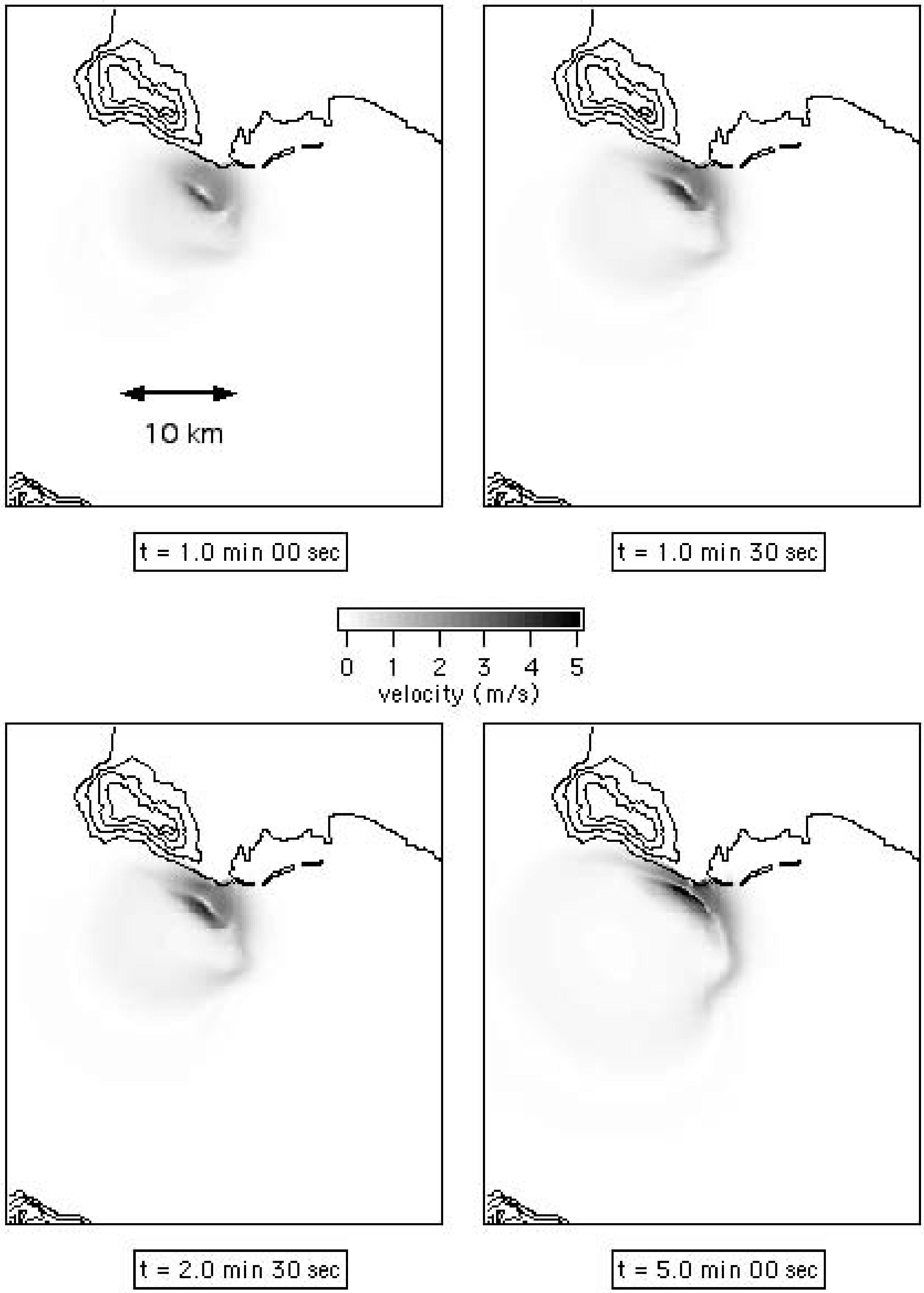

Figure 5a: Depth-averaged water velocities, t = 1.0 minute to t = 5 minutes, with breakwater.

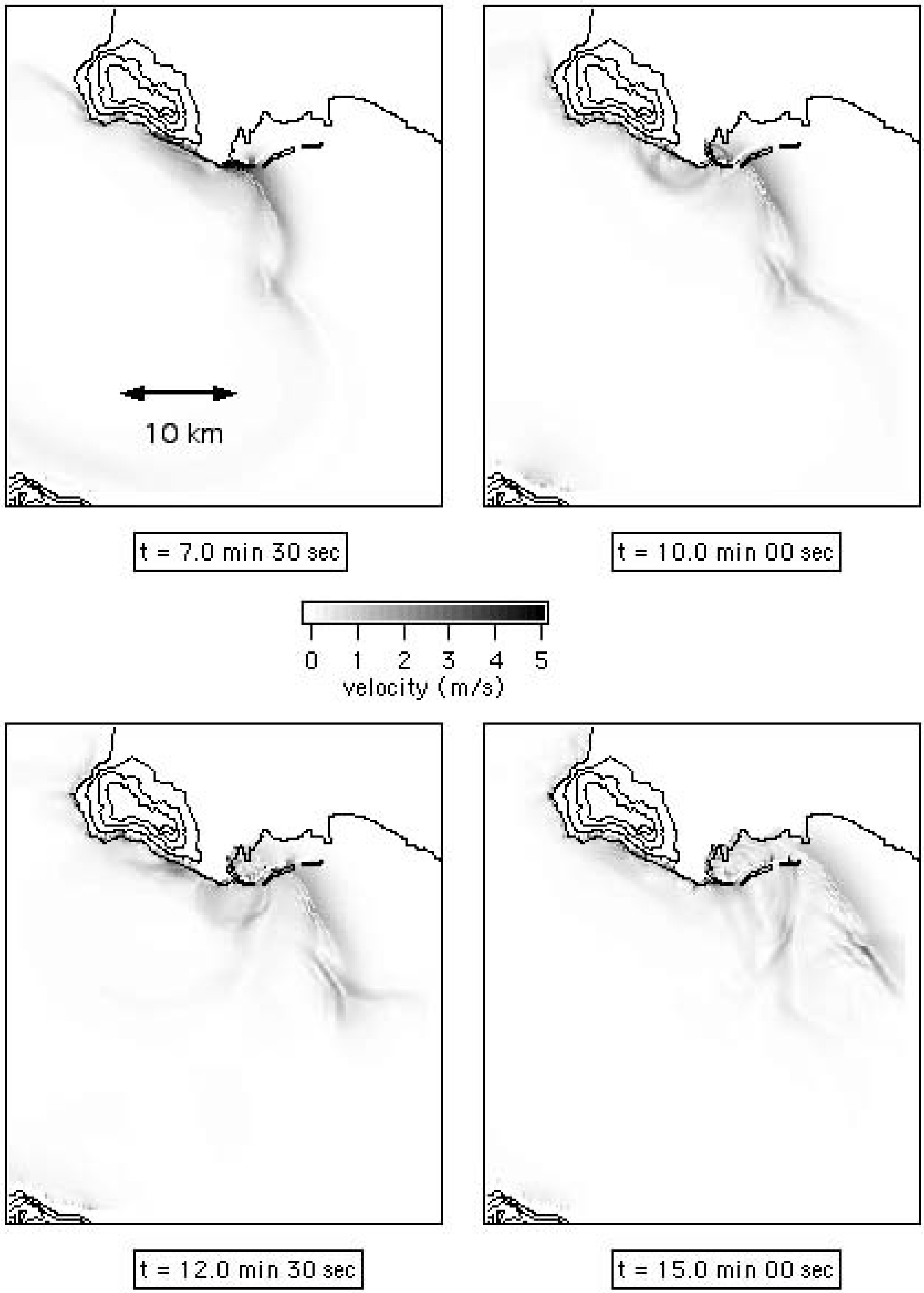

Figure 5b: Depth-averaged water velocities, t = 7.0 minutes 00 seconds to t = 15 minutes, with breakwater.

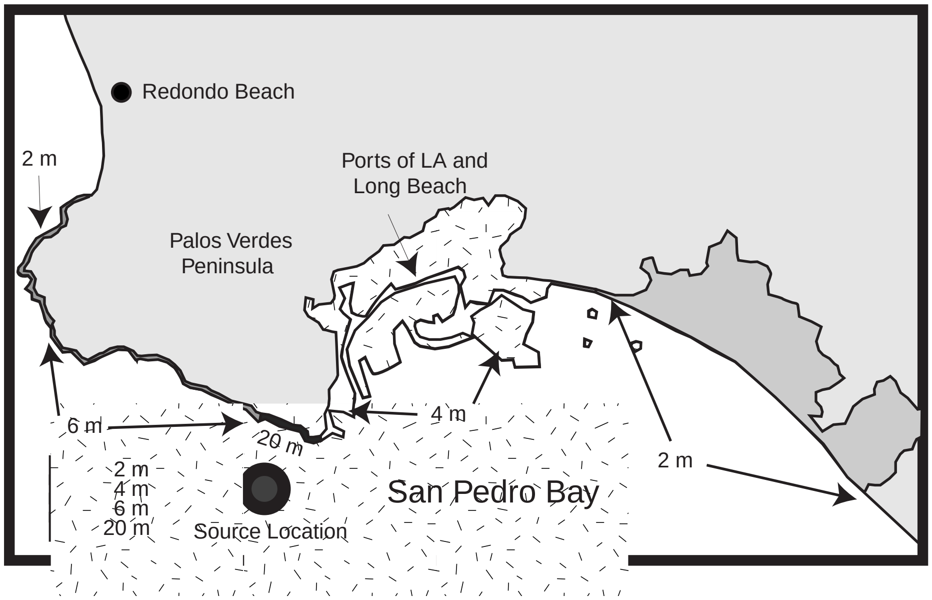

Figure 6: Inundation zones for the Palos Verdes Landslide tsunami.

Ports and to the east near Seal Beach, Surfside and Alamitos Bay, even 2 *m* of runup can produce significant inundation.

Quantifying the Economic Effects of a Tsunami Disaster

The economic impact of a destructive tsunami striking a metropolitan area is the least studied aspect of tsunami hazard mitigation. Previous studies have focused primarily on geological aspects of tsunami generation mechanisms, expected tsunami wave heights, inundation and to a lesser extent, the probability of occurrence. This research applies SCPM2 to quantify potential costs related to a major locally generated tsunami offshore of Los Angeles, California. Tsunami inundation zones are converted to zones of lost economic productivity, and the effects are modeled over the entire Southern California region. The results of the modeling show that distributed losses related to a major tsunami in Southern California could exceed $7 billion, and be as high as $42 billion, depending largely on the degree to which the infrastructure at the Port of Los Angeles and the Port of Long Beach is affected.

Direct, Indirect, and Induced Losses. The inundation map shown in Figure 6 defines the inputs to the Southern California Planning Model 2 (Cho et al. 2000). As noted in Section 1, this spatial economic impact model discretizes the five-county Los Angeles Metropolitan region into 1,527 zones, and reports results for 308 zones corresponding mostly to municipalities and City of Los Angeles council districts. The model is able to calculate direct losses within a damaged area as well as the distributed economic effects of these losses throughout the regional economy. The model also calculates the distributed effect of damage to the transportation network. These quantities are fundamentally different from damage costs. Damage costs are the costs of repairing or replacing damaged or destroyed property. These replacement costs are not considered or quantified in this study. Such costs already receive considerable attention in the literature. Engineering estimates of direct costs are most often replacement costs. The term "direct cost" has a different meaning in the context of an input-output model. Direct losses arise from lost opportunities to produce, or, in the case of the port damage, to ship. Indirect and induced losses arise as people and businesses in the damaged areas become unable to work or generate income as a result of the event. Indirect losses occur to suppliers whose products and services are no longer purchased by damaged firms and households. Induced losses are losses incident to labor.

For this initial study, economic activity is assumed to stop for one year within the inundation zone. Longer or shorter interruption periods can be scaled proportionate to these results. Table 3 shows these values in each of the affected municipal zones represented in SCPM2. Note that the number of inundated zones is small relatively to the number of zone represented in the model. Direct losses accrue only in inundated locations, but indirect losses can accumulate through out the region. SCPM2 is used to establish a baseline representation of ther regional economy, its outputs, and transportation costs. The direct losses associated with inundated locations are introduced into SCPM2 as a reduction in final demand for exports from affected economic sectors. SCPM2 calculates and allocates indirect and induced losses regionwide. Table 4 shows the indirect and induced losses incurred system-wide as a result of the damage cause by inundation. In total, these estimated losses account for 0.99% of the total economic output of the five-county Southern California region.

Impacts on production facilities are only part of the story. A tsunami in this location produces a special threat to the facilities at the Port of Los Angeles and the Port of Long Beach. These ports are of central importance to the regional economy, and the loss of transshipment capabilities at these sites would have a profound effect. In the worst case, export flows currently using seaport facilities would terminate so long as the ports were out of service. This is an upper bound on the economic impact of port damage, since some export flows outside the area of inundation would be shifted to other modes. Table 5 gives the percentage of export flows using Port of Los Angeles / Port of Long Beach facilities within aggregate industrial sectors, and calculates the direct economic loss incurred by eliminating the production of these shares from the local economy. Table 6 shows the model estimates of indirect and induced losses as a result of the direct losses calculated in Table 5.

Transportation Impacts. Potential damage to the transportation infrastructure in Southern California implies additional impacts. In the case of a tsunami, inundation would affect surface streets and might not close elevated freeway segments. However, for the purposes of this study, freeway segments were assumed to be closed. The SCPM2 representation of the transportation network includes freeways, state highways, and high design arterials. Small surface streets are not included in the model.

Some degree of export activity will be possible despite a port closure because the mode of transport can be switched from ship to truck or rail. However, this

Table 3: Direct loss and Annual Baseline Production in Inundated Areas

City	Baseline ($1000)	Direct Loss ($1000)	Direct Loss as a % of Baseline
Carson	6,591,962	85,736	1.30
Hawaiian Gardens	216,150	323	0.15
Long Beach	22,838,571	3,607,647	15.80
Palos Verdes Estates	416,315	32,338	7.74
Rancho Palos Verdes	510,586	26,903	5.27
Wilmington / San Pedro	5,675,587	314,931	5.55
Unincorporated LA County	17,623,822	2,565	0.01
Garden Grove	4,969,415	190	0.00
Huntington Beach	7,031,246	299,580	4.26
Los Alamitos	1,481,826	12,543	0.85
Rossmoor CDP	120,899	5,761	4.76
Seal Beach	1,398,293	103,892	7.43
Westminster	2,238,251	6,908	0.31
Unincorporated Orange County	3,401,272	3,051	0.09
Total	74,513,195	4,502,257	6.04

change may not occur in the short-term. These uncertainties suggest four analysis scenarios of increasing severity.

- Scenario 1:
    - Direct + indirect + induced business loss in the inundated area.
    - No freeway links are closed.
    - Ports Los Angeles and Long Beach are functional.
    - No reduction in export capabilities occurs.
- Scenario 2:
    - Direct + indirect + induced business loss in the inundated area.
    - Freeway links in the inundated area are closed for one year.

Table 4: Direct, Indirect and Induced Losses Throughout the Five-County Region

	Loss ($1000)	Loss as a % of Total Output[a]
Direct	4,502,257	0.60
Indirect	1,541,117	0.21
Induced	1,325,883	0.18
Total	7,369,257	0.99

Note: a. Total 1994 five-county output = $ 745,818.8 M

Table 5: Maximum Direct Losses Due to Loss of Port Services.

Industry	Total Exports[a] ($ Millions)	Port Share of exports (%)	Direct Impact ($ Millions)
Mining	158.5	46.90	74.34
Durable	25,172.7	40.61	10,628.73
Non-Durable	37,595.9	23.23	8,732.27
Wholesale	19,394.3	13.05	2,531.60
Sum	82,321.4		21,966.94[b,c]

Notes: a. Total Exports from PC I-O Transaction Table
b. Total 1994 five-county output = $745,818.8 M
c. Ratio of Direct Impact to total output = 2.95%

Table 6: Direct, Indirect and Inducted Losses in port areas.

	Economic Impact ($ Millions)	Share of Baseline Total Output (%)[a]
Direct	21,966,941	2.95
Indirect	8,762,751	1.17
Induced	5,451,162	0.73
Total	36,180,854	4.85

  - Ports Los Angeles and Long Beach are functional.
  - No reduction in export capabilities occurs.
- Scenario 3
  - Direct + indirect + induced business loss in the inundated area.
  - Freeway links in the inundated area are closed for one year.
  - Ports Los Angeles and Long Beach are closed for one year.
  - No reduction in export capabilities occurs because exported goods are transported by truck and rail rather than ship.
- Scenario 4:
  - Direct + indirect + induced business loss in the inundated area.
  - Freeway links in the inundated area are closed for one year.
  - Ports Los Angeles and Long Beach are closed for one year.
  - Export flows that used to be transported through the ports is now impossible. In addition to the 0.99% decrease in total economic activity implied by damage to production facilities in the inundation area, there is an addition 4.85% reduction in exports from all over the Southern California area.

Tables 7 to 10 summarize the results of these economic impact analyses. Table 7 shows the direct, indirect, and induced losses incurred as a result of tsunami inundation. Scenarios 1 through 3 all have the same impact in these separate loss categories, but different delay costs as a result of variable damage to the transportation network. Scenario 4 adds the direct, indirect, and induced costs associated with a closure of the ports. See Table 6.

Table 7: Summary of Direct, Indirect and Induced Losses for Each Scenario

	Type of Loss			
	Direct Loss ($1,000)	**Indirect Loss ($1,000)**	**Induced Loss ($1,000)**	**Total ($1,000)**
Scenario 1	4,502.257	1,541.117	1,325.883	7,369.257
Scenario 2	4,502.257	1,541.117	1,325.883	7,369.257
Scenario 3	4,502.257	1,541.117	1,325.883	7,369.257
Scenario 4	26,469.198	8,903.868	677.045	43,550.111

Table 8 summarizes the costs of transportation delays incurred due to damage to the transportation network, and the diversion of port flows to the remainder of the road system. Delays are reported in terms of Passenger Car Unit (PCU) hours and $billions. Delay accumulates on an undamaged network, and to even greater degree on a damaged network. Table 9 gives the difference relative to baseline delay values for each scenario. Table 10 summarizes the total of the delay costs associated with

Table 8: Summary of Transportation Network Delay Costs for Each Scenario

	Driver Delay		Freight Delay		Total Delay[b]	
	PCU[a] Hours	**$ Billion**	**PCU Hours**	**$ Billion**	**PCU Hours**	**$ Billion[c]**
Baseline	6,319,364	21.290	762,110	4.550	7,081,474	25.839
Scenario 1	6,323,171	21.302	756,912	4.518	7,080,083	25.821
Scenario 2	6,351,051	21.396	804,195	4.801	7,155,246	26.197
Scenario 3	6,380,809	21.497	852,092	5.087	7,232,901	26.583
Scenario 4	6,329,239	21.323	676,524	4.039	7,005,762	25.361

Notes: a. Passenger Car Units, including both cars and trucks.
b. 365 travel days per year, 1.42 passengers per car, and 2.14 Passengers Car Units per truck.
c. $6.5 per hour for individuals and $35 dollars per hour for freight.

Table 9: Network Losses, Difference (Δ) from Baseline Flows

	Driver Delay		Freight Delay		Total Delay	
	PCU Hours	**$ Billion**	**PCU Hours**	**$ Billion**	**PCU Hours**	**$ Billion**
Scenario 1	3,806	12.824	-5,198	-31.029	-1,391	-18.206
Scenario 2	31,687	106.751	42,085	251.233	73,772	357.984
Scenario 3	61,445	207.006	89,982	537.158	151,427	744.163
Scenario 4	9,874	33.266	-85,586	-510.917	-75,712	-477.651

Table 10: Loss Totals

	Economic Loss	Network Loss	Total
Scenario 1	7,369.257	-18.206	7,351.051
Scenario 2	7,369.257	357.984	7,727.241
Scenario 3	7,369.257	744.163	8,113.420
Scenario 4	43,550.111	-477.651	43,072.460

interruption of the transportation services combined with the direct, indirect and induced costs associated with tsunami inundation of production and port facilities.

Analysis

From the results above, it is clear that the costs associated with a tsunami disaster from a local tsunamigenic landslide source would include substantial direct, indirect, and induced costs associated with lost economic opportunity. This figure is on the order of $7 billion per year, and is separate from the replacement and repair cost of damaged facilities. Furthermore, damage to port facilities could produce much larger losses. If the loss of port services equates to the loss of export services, then the economic impact of the scenario tsunami is approximately $36 billion in losses. The greatest increase in transportation delays occurs in the case where port export flows are forced to switch from the waterways to land based routes, thus creating further congestion and delays on Southern California's transportation network.

Closer inspection of Tables 9 and 10 show some interesting effects. Negative values represent reductions in delay relative to baseline conditions. These reductions in delay are caused by reduced production in inundated areas or are due to loss of port access. However, this improved level of service for the travelers that remain constitutes a rather small positive impact in the face of overwhelming costs.

The difference between scenarios 3 and 4 is that in scenario 3 there is no accounting for the direct cost of damage to the closed ports. The increased losses in scenario 3 consist of increased transportation costs associated with shifting exports from sea to land-based modes. Scenario 4 is the extreme case: the ports are shut down and no exports are shifted to alternative modes. Production associated with these exports simply ceases, even in local facilities outside the inundation area. These losses range from $7 billion to $43 billion and provide upper and lower bounds for the economic impacts associated with this particular tsunami. Neither extreme is likely: Physical damage to wharves, piers and loading facilities would be expected to force some export flows to shift to other modes of transportation, but not all.

Finally the potential economic losses associated with damage to the ports outweigh the totals from the remainder of the inundated region by a factor of five. This figure alone demonstrates the vulnerability of the port infrastructure and pressing need for a comprehensive tsunami hazard assessment in major US shipping ports. This is particularly true along the tsunami prone US west coast, and extremely important in locations exposed to tsunamigenic landslide sources. This includes Southern California.

As a comparison, Cho et al. (2000) used the same method and baseline economic data to calculate economic loss associated with a hypothetical magnitude 7.1 earthquake on the Elysian Park blind thrust fault under downtown Los Angeles. They calculated that an earthquake of this type could produce as much as $135 billion in damage, with a median amount of $102 billion. The scenarios defined here vary between 5 percent and 30 percent of their maximum estimate. However, it is important to remember that these tsunami costs could be incurred *in addition* to the earthquake costs described by Cho et al. (2000). Tsunamigenic landslides are a recently identified risk, but the tsunami risk from seismic sources remains undiminished.

Summary

The example presented here illustrates a methodology for calculating the economic impact of tsunami inundation. Instead of the standard step of merely quantifying the repair and replacement costs associated with tsunami damage, this method distributes the total economic effects of this damage to households and businesses throughout the metropolitan economy. Not all post-event economic behavior is knowable, but this approach makes it possible to calculate the economic impacts associated with a variety scenarios, including changes export modes. The results of this preliminary study suggest that a devastating local tsunami could cause between $7 and $40 billion worth of direct, indirect and induced costs, and transportation related delays.

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