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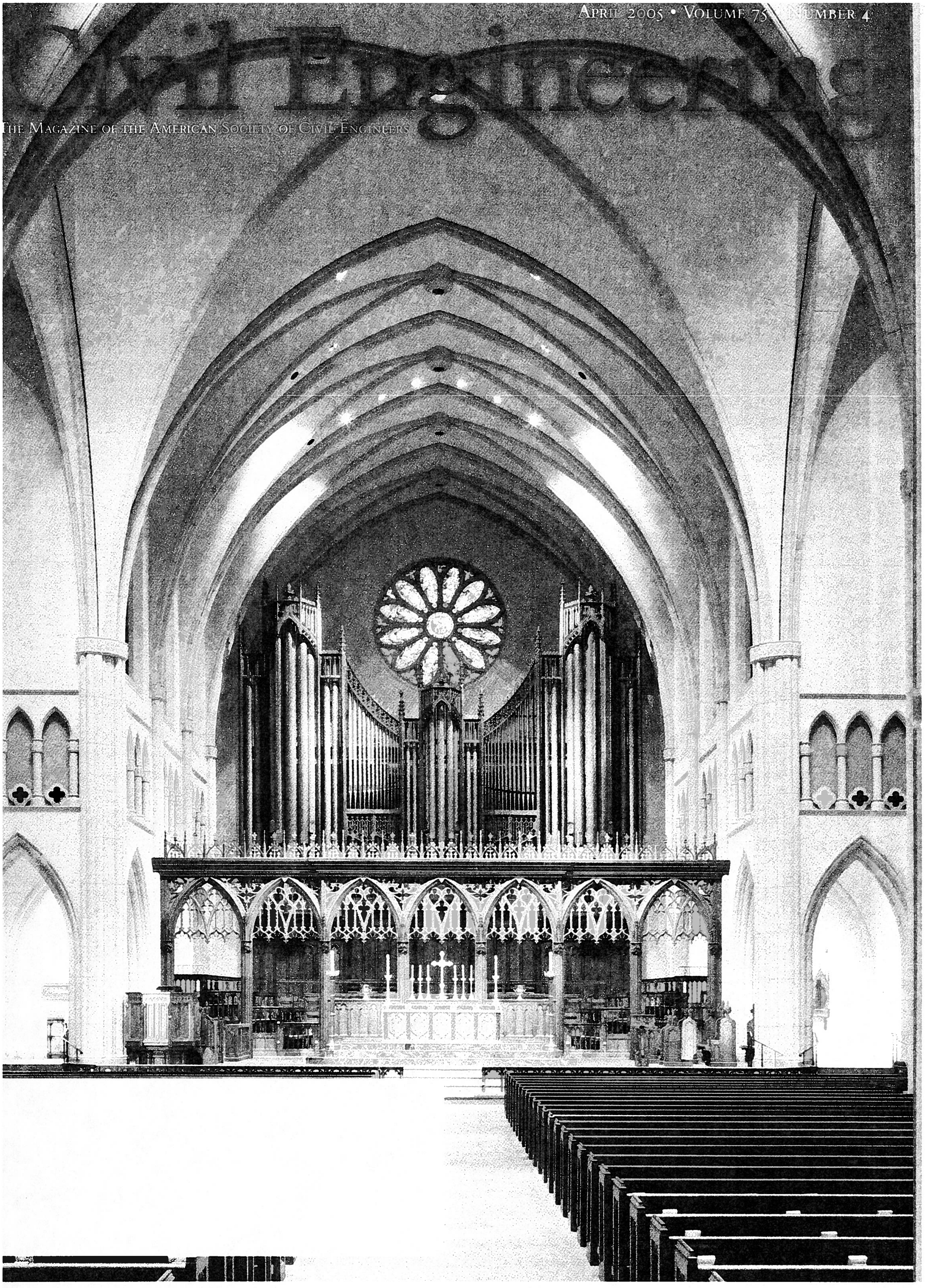

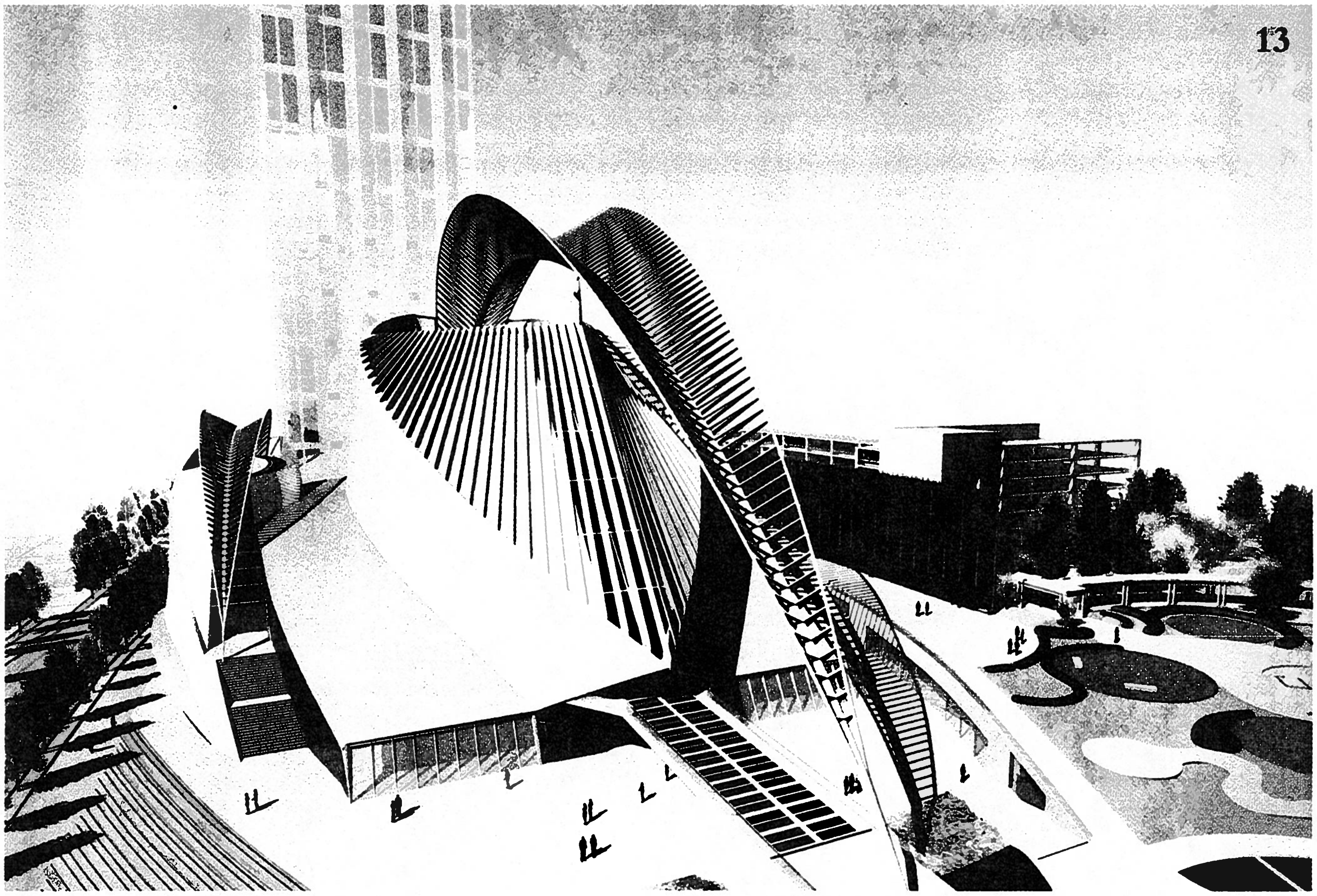

Courtesy of Santiago Calatrava, S.A.

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FEATURES

ON THE COVER *St. Martin's Episcopal Church, in Houston, presented its structural engineers with many challenges, chief among them how to frame the nave—which runs from the entrance to the altar and custom-designed organ—with only a few columns spaced far apart and no horizontal braces to span the space. Photograph by Mark Scheyer. (See page 36.)*

Could It Happen Here?

The catastrophic tsunami that struck southern Asia on December 26, 2004, underscored the extraordinary social and economic havoc that such an event can wreak. Could it happen here in the United States—in particular, off the coast of Southern California? The disturbing answer is that, yes, it could. Although the National Oceanic and Atmospheric Administration's National Ocean Service has 13 continuously operating tide stations in the state of California that are capable of producing real-time data for tsunami warnings, there is no way to prevent a strike. Recent developments in the modeling of tsunami waves and the analysis of their economic consequences, combined with data from recent offshore mappings of the Santa Barbara Channel and other locations, suggest the mechanism and economic effect of an undersea landslide in the vicinity of Los Angeles that would spawn a tsunami. **By Jose Borrero, Ph.D., Sungbin Cho, James E. Moore II, Ph.D., Harry W. Richardson, and Costas Synolakis, Ph.D.**

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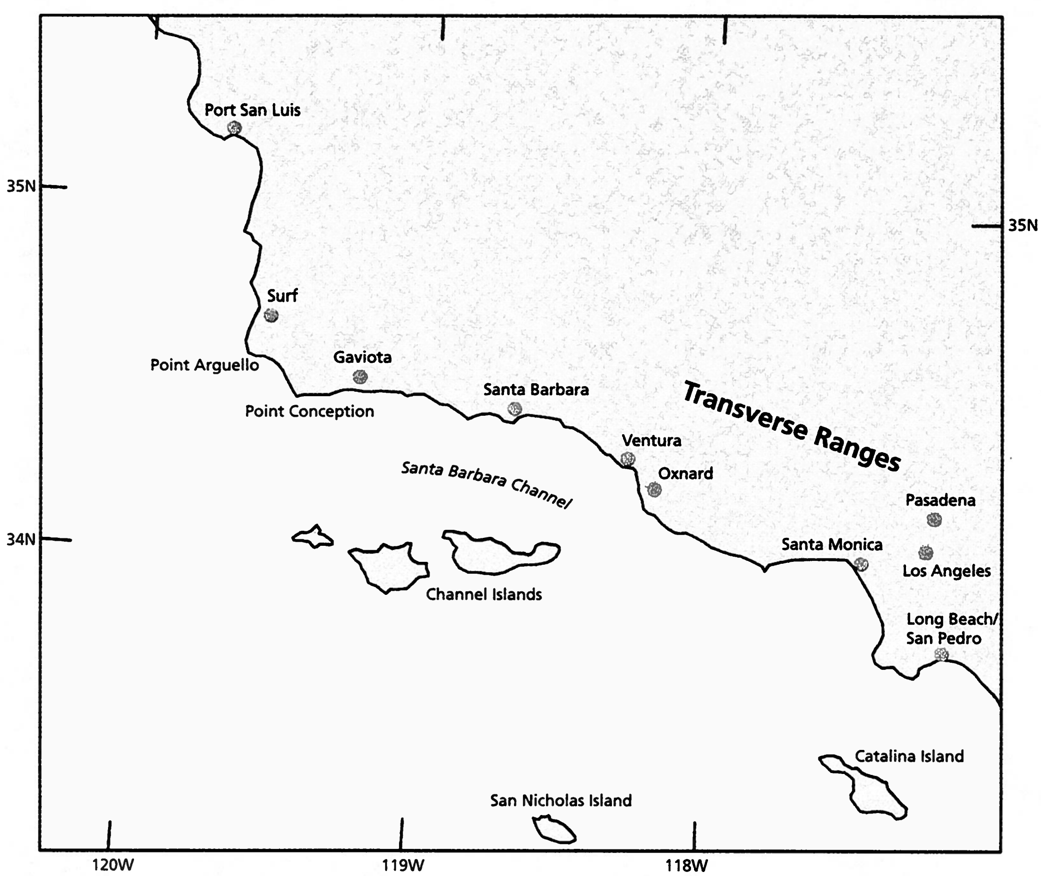
The seismic sensitivity of the Los Angeles metropolitan region is well recognized, although the densely populated regions of coastal Southern California have been relatively free of severely damaging earthquakes during the past 200 years (see figure 1). However, several recent moderate earthquakes—the Northridge earthquake, which occurred in California in 1994 and had a seismic moment (M_w) of 6.7, and the M_w 6.0 Whittier Narrows earthquake, which occurred in 1987—have brought to light the hazards associated with thrust and reverse faulting beneath Southern California. There have been several smaller, less damaging thrust and reverse earthquakes near the shore 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 could be greatly magnified if it were to generate a 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 tsunami that struck Papua New Guinea on July 17, 1998. As a result of this increasing scientific scrutiny, Southern California's susceptibility to tsunami damage is becoming better understood.

Several locally generated tsunamis have been recorded in the region over the past 200 years. There will be others, and the research outlined in this article focuses on the likelihood and the potential economic effect of a large tsunami. One of the first large earthquakes to be recorded in Southern California—the temblor that struck Santa Barbara on December 21, 1812—appears to have generated a moderate tsunami that affected more than 60 km of the Santa Barbara coast. Table 1 summarizes the details of several nearshore earthquakes, some of which generated tsunamis.

Figures for the year 1994 indicate that the annual economic output of metropolitan Los Angeles is $746 billion. Such natural disasters as earthquakes, fires, floods, and landslides have serious economic ramifications. Quantifying the economic effects of natural disasters has long been of theoretical interest to economists, social scientists, and engineers, but progress has been slowest within the social sciences. The physical science of earthquakes and tsunamis is challenging, but it may be far less difficult than assessing the social consequences of disasters. Consequently, it is not surprising that only limited attention has been focused on the socioeconomic effects of

Figure 1



natural disasters. This reflects a lag in social science research in this area.

Much of the research on tsunamis has been in the engineering and geological fields. Progress in assessing economic effects is recent. Tsunamis, while obviously related to earthquakes, have never been modeled quantitatively in terms of their potential economic consequences. In 1985, David S. McCulloch estimated that tsunamis were responsible for 0.2 percent of the total cost of earthquake damage between 1812 and 1964. This number, however, is derived primarily from the $32.2 million (1983 dollars) of tsunami damage sustained by Crescent City, California, after the earthquake that occurred in the Gulf of Alaska in 1964. California has not suffered any tsunami damage since that 1964 event; however, coastal development has increased dramatically since that time, placing billions of dollars' worth of property, businesses, and infrastructure at risk.

The core purpose of applied research in the natural disaster field is to assist policy makers. What types of information are required for the establishment of cost-effective policies? The large expenditures 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 if a particular measure is implemented. Yet any discussion of costs avoided depends on the ability of analysts to determine full costs. Social science research can, therefore, make a substantial contribution by defining expected full costs with and without various proposed mitigation measures.

Much of the research in the social sciences on natural disasters has focused on measuring the total economic effects of damage to structures and to the contents of those structures. Work conducted by Peter Gordon, Harry W. Richardson, and William Davis in 1998 on the business interruption effects of the Northridge earthquake indicated that an exclusive focus on structural damage ignored 25 to 30 percent of the full costs. Their analysis also delineated the geographical distribution of these effects on individual cities and other small areas. Job losses in 1994 caused by interruptions to business were estimated to be 69,000 person-years of employment, roughly half the jobs being outside the area that experienced structural damage (see table 2). Disregarding such numbers seriously underestimates the full costs of the event. More recently, Gordon, James E. Moore II, Richardson, and Masanobu Shinozuka (in 1998) and Gordon, Moore, and Richardson (in 2002) examined another important question relating to distribution, that of income distribution.

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

Version 1 of the Southern California Planning Model (SCPM1), developed by Gordon and Richardson for the five-county Los Angeles metropolitan region, has the unique ability to allocate all effects—in terms of jobs or the dollar value of output—to 308 zones, mostly municipalities. This is the result of an integrated modeling approach that incorporates two fundamental components: I/O and spatial allocation. The approach allows the representation of estimated spatial and sectoral effects corresponding to any changes in final demand. Exogenous shocks treated as changes in final demand are fed through an I/O model to generate sectoral consequences that are then introduced into the spatial allocation model.

The first model component is built upon the I/O model developed by West Virginia University's Regional Science Research Institute. This model has several advantages:

- A high degree of sectoral disaggregation (515 sectors);
- Incorporation of anticipated adjustments in production technology;
- An embedded occupation-industry matrix enabling employment effects to be defined across 93 occupational groups (particularly useful for disaggregating consumption effects by income class and for estimating job consequences by race);
- An efficient mechanism for differentiating local I/O transactions from those outside the region through the use of what are called regional purchase coefficients;
- Determination of state and local tax consequences.

The second basic model component is used for allocating sectoral consequences across 308 geographic zones in Southern California. The key was to adapt a model of the type developed by Ira Lowry and extended by Robert Garin (Garin-Lowry model) for spatially allocating the effects generated by the I/O model. The I/O model provides economic detail. Garin-Lowry style models provide spatial detail by generating estimates of employment, population, and land use for the subareas of a defined region. The building blocks of the SCPM1 are the metropolitan I/O model, a journey-to-work matrix, and a journey-to-nonwork-destinations matrix. This last matrix 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 such nontransaction trips as those to visit friends and relatives. Data for the journey-from-services-to-home matrix includes all the trips classified by the Southern California Association of Governments (SCAG) 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 the incorporation of the full range of multipliers obtained via

Table 1: Local Tsunamis and Nearshore Seismicity in California

	Fault/location	Date	Intensity[a]			Tsunami run-up	References
			M_W	M_L	M_S		
Santa Barbara earthquake[b]	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 Borrero et al. 2001
Point Arguello-Lompoc earthquake	Debated, but likely a north-trending offshore thrust or oblique-reverse fault	November 4, 1927			7.0	2 m in Surf and San Luis, California, 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, Richter, and Wood 1932 Hauksson and Saldivar 1986 Hauksson 1990 Lander, Lockridge, and Kozuch 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

[a] M_W denotes moment magnitude, M_L local magnitude, and M_S surface wave magnitude.
[b] The December 21 event was preceded by an M_W 7.5 earthquake on December 13, 1812, also on the Mojave Segment. Additional earthquakes occurred offshore 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.

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Toppozada, T., C. Real, and D. Parke. 1981. Preparation of isoseismic maps and summaries of reported effects for pre-1900 California earthquakes. *Annual Technical Report, California Division of Mines and Geology, #81-11SA:* 34, 136–40.

Table 2: Business Interruption Losses from the 1994 Northridge Earthquake

Area	Direct		Indirect and induced		Total	
	Jobs	Output	Jobs	Output	Jobs	Output
Impact zone total	34,605.4	3,117,528.0	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	1,067,914.1	10,668.2	1,067,914.1
Rest of region	0.0	0.0	8,260.7	877,532.0	8,260.7	877,532.0
Regional total	34,605.4	3,117,528.0	22,953.7	2,387,058.5	57,559.1	5,504,586.9
Rest of world	11,454.4	1,031,901.9	Not computable	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: Data from Gordon, P., H.W. Richardson, and B. Davis. 1998. Transport-related impacts of the Northridge earthquake. *Journal of Transportation and Statistics* 1: 21–36.

Note: Jobs in person-years; output in thousands of dollars (1994).

I/O techniques so as to produce detailed economic effects 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 or consumption via a journey-to-services matrix.

Incorporating the Garin-Lowry approach into spatial allocation makes the transportation flows in the SCPM1 exogenous. They are also relatively aggregated, defined at the level of political jurisdictions. With no explicit representation of the transportation network, the SCPM1 has no way of accounting for the economic consequences of changes in transportation supply and demand. Tsunamis are likely to induce such changes.

The focus in what follows is on a credible, hypothetical tsunami. Modeling the degree of inundation defines the lengths of time for which firms throughout the region will be nonoperational. This allows the calculation of reductions in demand by these businesses. These are introduced into the interindustry 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 households.

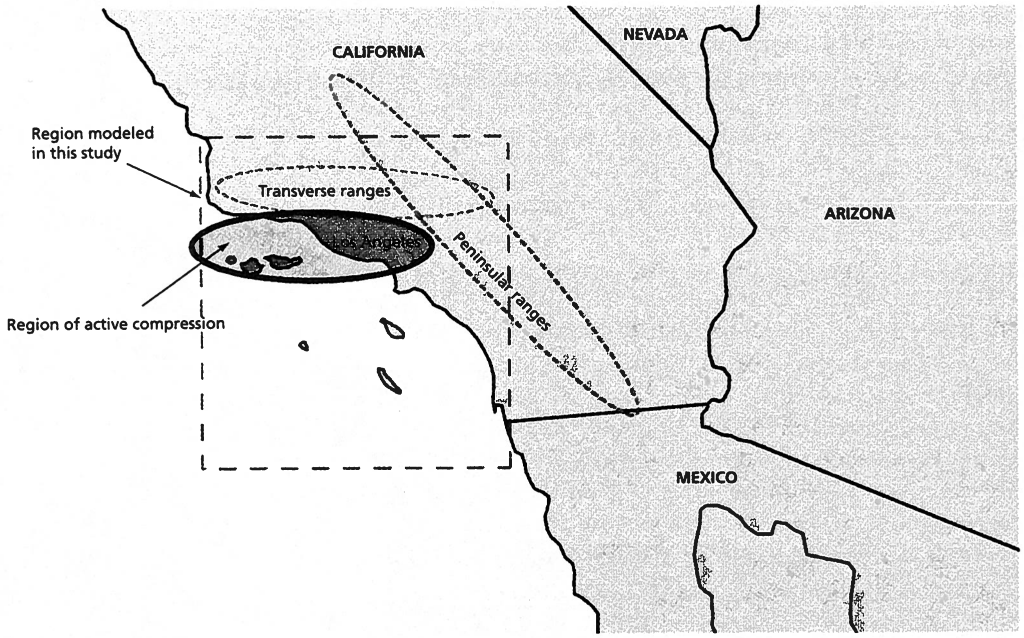
Implementing this approach is a data-intensive effort that builds on the data resources assembled for the SCPM1. In this case, results of structural damage to businesses are used to drive the SCPM2, a more advanced version of the Southern California Planning Model that "endogenizes" traffic flows by including an explicit representation of the transportation network. SCPM2 results are computed at the level of the SCAG's 1,527 traffic analysis zones and then aggregated to the level of the 308 political jurisdictions defined for the 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 the SCPM1, the SCPM2 aggregates to 17 the 515 sectors represented in version 7 of the Regional Science Research Institute's I/O model on the basis of the 1983 work of Benjamin Stevens, George Treyz, and Michael Lahr. Treating the transportation network explicitly endogenizes otherwise exogenous Garin-Lowry style matrices describing the travel behavior of members of households, thereby achieving consistency across network costs and origin-destination requirements. The SCPM2 makes distance decay and congestion functions explicit. This makes it possible to endogenize the spatial allocation of indirect and induced economic losses by endogenizing choices of route and destination. Such an approach better allocates indirect and induced economic losses over zones in response to direct losses of industrial and transportation capacity caused by the impact of the tsunami.

The offshore region from Point Conception, California, south to central Baja California is known as the Southern California Borderlands (see figure 2). This geologically complex region is composed of different tectonic regimes, and its complicated bathymetry includes deep basins, towering ranges, and canyons with steep walls. The steep topography that is visible on land does not stop at the water's edge; rather, it continues under the sea.

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 that have developed above west-trending reverse, oblique reverse, and left-lateral strike-slip faults. Where these thrust systems extend offshore, they may be potential sources of tsunamis.

In view of the unusually large waves associated with the tsunami that struck Papua New Guinea on July 17, 1998, the standard paradigm defined by large tsunamis generated

Figure 2



primarily by tectonic uplift or subsidence has come under increasing scrutiny. That tsunami was generated after a relatively small earthquake with an M_w of approximately 7.0.

The large run-up values and extreme inundation, as well as the devastation of coastal communities observed along the coast of Papua New Guinea, prompted even the scientists in the International Tsunami Survey Team, established under the auspices of the United Nations Educational, Scientific, and Cultural Organization's Intergovernmental Oceanographic Commission, to rethink standard models and search for an alternative explanation of the wave. The run-up distribution plotted along the coast of Papua New Guinea 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 temblor centered in Jalisco, Mexico.

The combination of such factors as the small moment magnitude, unusually large waves, and peaked run-up distribution, along with other seismological clues, suggested that a giant submarine mass failure was the cause of this tsunami. The speculation that the Papua New Guinea tsunami was caused by a submarine mass failure has become a driving force in delineating nontectonic tsunami generation sources for various coastal regions around the world, including Southern California.

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: a 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; alternatively, it can break apart into separate sliding blocks. In the extreme case the mass completely disintegrates and becomes a mass flow or a turbidity current. Largely cohesive or blocklike slope failures in canyon heads may evolve into or trigger turbidity currents in basins.

Submarine landslides are of two general types: the rotational slump and the translational slide. When the rupture surface cuts through a homogeneous material and 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, that is, 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.

Submarine landslides, the general term that will be used here for any underwater mass movement, can occur in a wide range of sizes, the orders of magnitude ranging from very small to enormous.

The offshore region from California's 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 its southern reaches 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. From there a slope of 5 to 15 degrees drops off into basins where depths can exceed 800 m. The shelf is periodically crosscut by deep canyons along its entire extent. Heading south from Point Conception, the major canyons are Hueneme, Mugu, Dume, Santa Monica, and Redondo. South of the Palos Verdes Peninsula are five more major canyons: San Gabriel, Newport, Carlsbad, La Jolla, and Coronado.

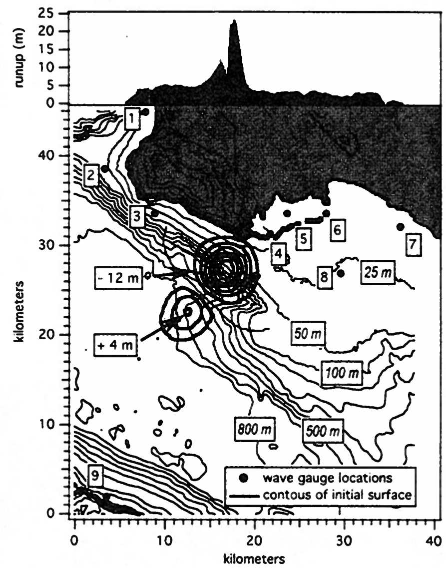
The slopes offshore of Southern California generally have thick accumulations of underconsolidated sediment of Quaternary age. These water-saturated sediments generally have a lower shear strength than comparable onshore sediments. Therefore underwater slope failures are generally larger and occur on lower slopes than on land. 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.

In work published in 1985, Samuel H. Clarke, H. Gary Greene, and Michael P. Kennedy noted that most offshore slope failures appeared to be composite rather than single events. They also mentioned that it was difficult, if not impossible, to determine the timing and rate of motion of individual slides. They went 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." They discussed particular areas of submarine landslides offshore of 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 straightforward, especially since there is no indication whether these features were generated as single catastrophic events or through 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.

For this article, a tsunami scenario based on waves 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 tsunami that struck Papua New Guinea was responsible for more than 2,000 deaths and is believed to have been caused by a large (4 km^3) offshore slump. In August 1999 a large earthquake near Istanbul, Turkey, caused significant landslides and slumping along the shores of the Sea of Marmara and contributed to waves that damaged port facilities. In September 1999 a large rockfall on the south shore of Fatu Hiva, one of the Marquesas Islands, caused tsunami run-up in excess of 2 m, which inundated a local school and nearly killed several children. In December of that year on Pentecost Island, Vanuatu, a highly localized tsunami with run-up of up to 6 m wiped out an entire village and killed two people.

Figure 3

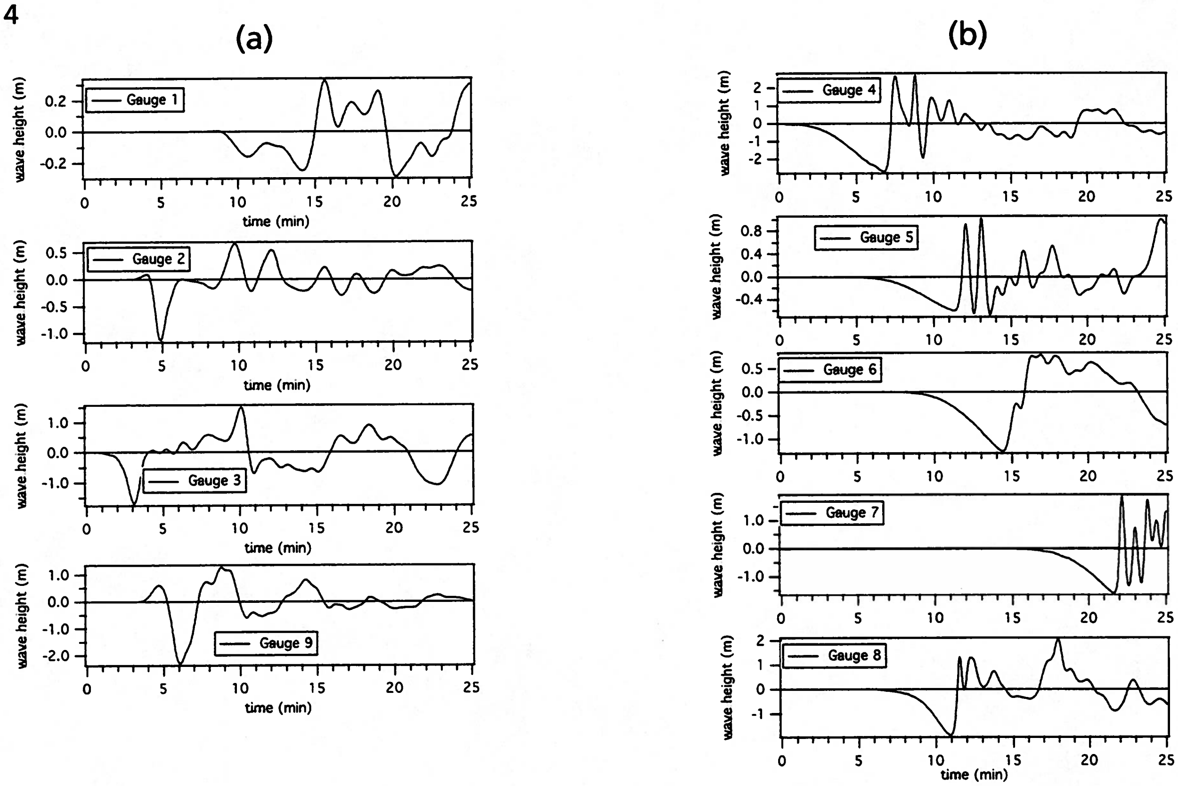


Second, recent offshore mapping work has found evidence of significant sliding and slumping offshore of Southern California, particularly in the Santa Barbara Channel and off the Palos Verdes Peninsula. Studies have shown that these events could have given rise to tsunami wave heights ranging from 5 to 20 m. Furthermore, given the proximity to a major port, a tsunami generated off the Palos Verdes Peninsula would have grave economic consequences.

While the signature of the Palos Verdes debris avalanche had been identified by the mid-1980s, its potential for generating destructive tsunamis had not, owing to an arithmetic error in calculations. Back then, there were few documented landslide waves and hence little engineering intuition as to whether the numbers made sense. In the aftermath of the 1998 Papua New Guinea disaster, there was a critical reevaluation of existing formulations, and the error was discovered by Jose Borrero in 2000. At the same time, various marine geologists, including Homa J. Lee, Robert G. Bohannon, James V. Gardner, Jacques Locat, and Gary Greene, were doing additional work on the Southern California bight and were using newer relationships to calculate the initial waves. Steve Ward and Costas Synolakis have also estimated the impact.

In work published in 2001, Jacques Locat, Pascal Locat, and Lee analyzed the mobility of the Palos Verdes debris avalanche. Their analysis concluded that the state of the mapped debris field implied that the avalanche must have moved as a large block in a single catastrophic event. They proposed a tsunami

Figure 4



wave generation mechanism based on the energy equation published by Tad S. Murty in 1979. They proposed initial wave heights of 10 to 50 m, depending on the value of Murty's *m*, "the energy transfer efficiency," which they varied from 0.1 percent to 1 percent (0.001 to 0.01).

The sliding mass paradigm for modeling submarine landslides is based on the classic work of Bob Wiegel at Berkeley. Another analysis—also using a sliding mass—was based on more recent curve fits to laboratory data, originating from the laboratory of Fred Raichlen at Caltech. The proposed leading depression wave (initial drawdown) was of the order of 10 m and a leading elevation wave of the order of 3 m.

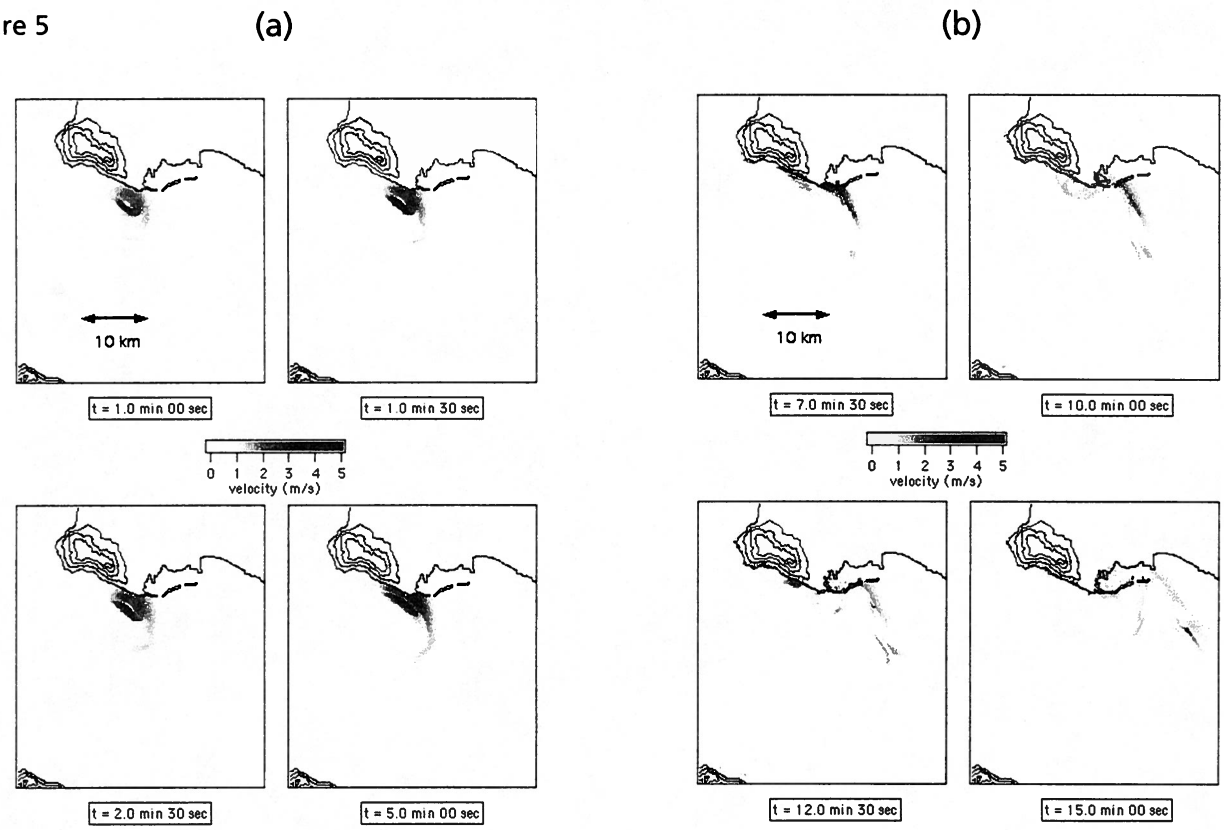
For this article, the same conditions were used to generate a single-case inundation map for a landslide-generated wave off the Palos Verdes Peninsula. Two cases are modeled, one with the breakwater in place and one without the breakwater. A comparison of results shows the effect of the narrow openings between breakwater segments. Modeling suggests current velocities of over 3 m/s in these openings. Instantaneous peak velocities are modeled to be over 10 m/s but generally occur on the steep cliffs of the Palos Verdes Peninsula west of the entrance to the ports. The computed run-up 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. The two parts of figure 4 show the time series of water levels at the locations indicated in figure 3. The maximum drawdown reaches the outer harbor area about six minutes after wave generation, the maximum positive wave arriving one minute later. This illustrates the extremely limited amount of time that would be available to emergency planners. Plots of snapshots of the depth-averaged velocities at various times are given in figure 5.

Figure 3 shows that a large peak (up to 25 m) is seen along the southern tip of the Palos Verdes Peninsula, the run-up value dropping off rapidly to either side. Run-up values of 4 m are observed in the area of the ports of Los Angeles and Long Beach. To determine the inundation area, the run-up plot in figure 3 is discretized into four zones with sections of 2, 4, 6, and 20 m. These values are then used in conjunction with topographic maps to generate a geographic information system (GIS) layer representing the inundated area. Figure 6 shows the inundation zones, the different shadings representing the level of run-up. 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 ports and to the east near Seal Beach, Surfside, and Alamitos Bay, even 2 m of run-up can produce significant inundation.

The economic toll that would be exacted if a destructive tsunami struck a metropolitan area is the least studied aspect of tsunami hazard mitigation. Previous studies have focused primarily on the geological aspects of tsunami generation mechanisms, expected tsunami wave heights, inundation, and, to a lesser extent, the probability of occurrence. This research applies the SCPM2 to quantify potential costs related to a major locally generated tsunami offshore of Los Angeles. Tsunami inundation zones are converted to zones of lost economic output, 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

Figure 5



$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 was affected.

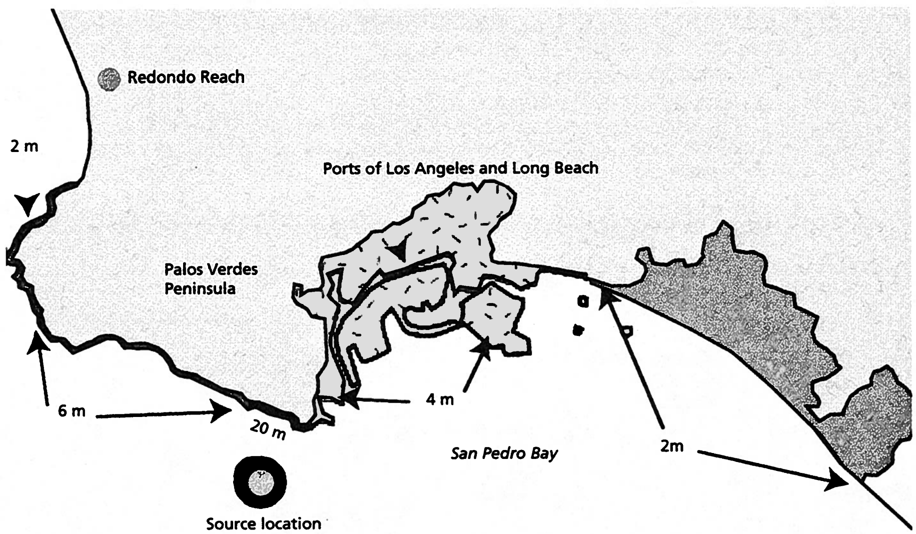
Figure 6 is an inundation map defining the inputs to the SCPM2. This spatial economic effect model discretizes the five-county Los Angeles metropolitan region into 1,527 zones and reports results for 308 zones corresponding mostly to municipalities and City of Los Angeles council districts. The model is able to calculate direct losses within a damaged area as well as the distributed economic effects of these losses throughout the regional economy. It also calculates the distributed effect of damage to the transportation network. These quantities are fundamentally different from damage costs. Damage costs pertain to the value of repairing or replacing damaged or destroyed property. These replacement costs are not considered or quantified in this study. Such costs have already received considerable attention. Engineering estimates of direct costs are most often replacement costs. The term "direct cost" has a different meaning in the context of an I/O model. Direct losses arise from lost opportunities to produce or, in the case of 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 are incurred by 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 in proportion to these results. Table 3 shows these values in each of the affected municipal zones represented in the SCPM2. Note that the number of inundated zones is small relative to the number of zones represented in the model. Direct losses accrue only in inundated locations, but indirect losses can accumulate throughout the region.

The SCPM2 is used to establish a baseline representation of the regional economy that includes its outputs and transportation costs. The direct losses associated with inundated locations are introduced into the SCPM2 as a reduction in final demand for exports from affected economic sectors. The SCPM2 calculates and allocates indirect and induced losses regionwide. Table 4 shows the indirect and induced losses incurred systemwide as a result of the damage cause by inundation. In total, these losses account for 0.99 percent of the total economic output of the five-county Southern California region.

The effect on production facilities is 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

Figure 6



sites would have profound effects. In the worst case, export flows from these seaport facilities would cease while the ports were out of service. This is an upper bound on the economic effects of port damage, since some export flows outside the area of inundation would continue through other channels. Table 5 gives the percentage of export flows using facilities at the ports of Los Angeles and Long Beach 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.

Potential damage to the transportation infrastructure in Southern California implies additional consequences. In the event of a tsunami, inundation would probably affect surface streets but not 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-volume arterials, but small surface streets are not included.

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 change may not occur in the short term. These uncertainties suggest four increasingly severe analysis scenarios.

Scenario 1:

- Direct, indirect, and induced business loss in the inundated area;
- No freeway links closed;
- Ports of Los Angeles and Long Beach remain functional;
- No reduction in export capabilities.

Scenario 2:

- Direct, indirect, and induced business loss in the inundated area;
- Freeway links in the inundated area closed for one year;
- Ports of Los Angeles and Long Beach remain functional;
- No reduction in export capabilities.

Scenario 3:

- Direct, indirect, and induced business loss in the inundated area;
- Freeway links in the inundated area closed for one year;
- Ports of Los Angeles and Long Beach closed for one year;
- No reduction in export capabilities—exported goods transported by truck and rail rather than ship.

Scenario 4:

- Direct, indirect, and induced business loss in the inundated area;
- Freeway links in inundated area closed for one year;
- Ports of Los Angeles and Long Beach closed for one year;
- Export flows formerly transported through the ports now impossible. (In addition to the 0.99 percent decrease in total economic activity implied by damage to production facilities in the inundation area, there is an additional 4.85 percent reduction in exports from all over Southern California.

Tables 7 to 10 summarize the results of these economic analyses. Table 7 shows the direct, indirect, and induced losses incurred as a result of tsunami inundation. Scenarios 1 through 3 all have direct, indirect, and induced business loss in the inundated area, but the delay costs are different because the extent of damage to the transportation network differs.

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

City	Baseline ($ thousands)	Direct loss ($ thousands)	Direct loss as percentage 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 (census designated place)	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

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

	Loss ($ thousands)	Loss as percentage 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

[a]Total 1994 five-county output = $745,818.8 (millions).

Table 5: Maximum Direct Losses from Loss of Port Services

Industry	Total exports[a] ($ millions)	Port share of exports (percent)	Direct impact ($ millions)
Mining	158.5	46.90	74.34
Durable	25,172.7	40.61	10,628.73
Nondurable	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]

[a]Total exports from input-output.
[b]Total 1994 five-county output = $745,818.8 (millions).
[c]Ratio of direct impact to total output = 2.95 percent.

Scenario 4 adds the direct, indirect, and induced costs associated with a closure of the ports (see table 6).

Table 8 summarizes the costs of transportation delays incurred because of 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 in billions of dollars. (One passenger car in traffic for one hour is one PCU hour.) Delays accumulate on an undamaged network, the accumulation being even greater on a damaged network. Table 9 illustrates the difference relative to baseline delay values for each scenario. Table 10 summarizes the total of the delay costs associated with interruption of the transportation services and the direct, indirect, and induced costs associated with tsunami inundation of production and port facilities.

From the results above, it is clear that the costs associated with a tsunami generated by a local landslide 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 costs 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 losses from the scenario tsunami are approximately $36 billion. The greatest increase in transportation delays occurs in the case where port export flows are switched 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 reveals 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 by the loss of port access. However, this improved level of service for the travelers that remain constitutes a rather small positive effect 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 incurred in scenario 3 derive from the 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 consequences associated with this particular tsunami. Physical damage to wharves, piers, and loading facilities would be expected to force some, but not all, export flows to be shifted to other modes of transportation.

Finally, the potential economic losses associated with damage to the ports outweigh the totals *(continued on page 133)*

Table 6: Direct, Indirect, and Induced Losses in Port Areas

	Economic impact ($ thousands)	Share of baseline total output (percent)
Direct	21,966,941	2.95
Indirect	8,762,751	1.17
Induced	5,451,162	0.73
Total	36,180,854	4.85

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

	Type of loss			
	Direct loss ($ millions)	Indirect loss ($ millions)	Induced loss ($ millions)	Total ($ millions)
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: Summary of Transportation Network Delay Costs for Each Scenario

	Driver delay		Freight delay		Total delay[b]	
	PCU[a] hours	$ billions	PCU hours	$ billions	PCU hours	$ billions[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

[a]Passenger car units, including both cars and trucks.
[b]Calculated assuming 365 travel days per year, 1.42 passengers per car, and 2.14 PCUs per truck.
[c]Calculated assuming $6.50 per hour for individuals and $35 per hour for freight.

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

	Driver delay		Freight delay		Total delay	
	PCU hours	$ millions	PCU hours	$ millions	PCU hours	$ millions
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 ($ millions)	Network loss ($ millions)	Total ($ millions)
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

(continued from page 65) from the remainder of the inundated region by a factor of 5. This figure alone demonstrates the vulnerability of the port infrastructure and the pressing need for a comprehensive tsunami hazard assessment at all major U.S. ports. This is particularly true along the tsunami-prone West Coast and extremely important in locations that could be subjected to tsunamis as a result of landslides. This includes Southern California.

For purposes of comparison, consider the economic loss associated with a hypothetical earthquake of magnitude 7.1 on the Elysian Park blind thrust fault under downtown Los Angeles. Using the same method and baseline economic data to calculate economic loss, an earthquake of that type could produce as much as $135 billion in damage, the median amount being $102 billion. However, it is important to remember that these tsunami costs would be incurred *in addition* to the earthquake costs. Landslides that give rise to tsunamis have only recently come to be seen as a risk, but the tsunami risk from seismic sources remains undiminished.

The example presented here illustrates a methodology for calculating the economic effects of tsunami inundation. In contrast to the standard approach 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 postevent economic behavior is knowable, but this approach makes it possible to calculate the economic consequences associated with a variety of scenarios, including changes to export modes. The results of this preliminary study suggest that the direct, indirect, and induced costs of a devastating local tsunami, together with the costs arising from delays in transportation, could range from $7 billion to $40 billion. ■

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