The *SAFRR* Tsunami Scenario

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ABSTRACT

The U.S. Geological Survey and several partners operate a program called Science Application for Risk Reduction (SAFRR) that produces (among other things) emergency planning scenarios for natural disasters. The scenarios show how science can be used to enhance community resiliency. The SAFRR Tsunami Scenario describes potential impacts of a hypothetical but realistic tsunami affecting California (as well as the west coast of the United States, Alaska, and Hawaii) for the purpose of informing planning and mitigation decisions by a variety of stakeholders. The scenario begins with an Mw 9.1 earthquake off the Alaska Peninsula. With Pacific basin-wide modeling we estimate up to 5m waves and 10 m/sec currents would strike California 5 hours later. In marinas and harbors, 13,000 small boats are damaged or sunk (1 in 3) at a cost of $350 million, causing navigation and environmental problems. Damage in the Ports of Los Angeles and Long Beach amount to $110 million, half of it water damage to vehicles and containerized cargo. Flooding of coastal communities affects 1800 city blocks, resulting in $640 million in damage. The tsunami damages 12 bridge abutments and 16 lane-miles of coastal roadway, costing $85 million to repair. Fire and business interruption losses will substantially add to direct losses. Flooding affects 170,000 residents and workers. A wide range of environmental impacts could occur. An extensive public education and outreach program is underway, as well as an evaluation of the overall effort.

SAFRR PROJECT

The U.S. Geological Survey's Science Application for Risk Reduction (SAFRR) project, in collaboration with the California Geological Survey, the California Emergency Management Agency, the National Oceanic and Atmospheric

Administration, and other entities, are developing the SAFRR Tsunami Scenario to detail the impacts to California of a tele-tsunami generated by a hypothetical but realistic M 9.1 earthquake near the Alaska Peninsula.

SAFRR aims to help communities reduce losses from natural disasters. A primary approach has been comprehensive, scientifically credible scenarios that start with a model of a geologic event and extend through estimates of damage, casualties, and societal consequences. The 2008 ShakeOut Scenario addressed a hypothetical southern San Andreas earthquake and spawned the annual Great ShakeOut, the nation's largest emergency preparedness drill. The 2011 ARkStorm scenario addressed winter storms, California's other "big one," whose destructive potential surpasses hurricanes.

The Tsunami Scenario's goals include developing advanced inundation and currents models; spurring Alaskan earthquake source research; engaging maritime interests; understanding the societal, environmental, ecological, and economic impacts; and creating enhanced communication products. The State of California is using the scenario process to evaluate policies regarding tsunami impact. The scenario will serve as a long-lasting resource to teach preparedness and inform decision makers. Development began in January 2011 and will conclude in 2013. This paper summarizes our approach to and status of the SAFRR Tsunami Scenario.

SOURCE

Tsunami modeling has shown that earthquakes along the Alaska Peninsula have the greatest impacts on southern California for a given magnitude event. The most probable sector for an Mw ~9 source within this subduction segment is between Kodiak Island and the Shumagin Islands, called the Semidi Sector. GPS observations indicate that the sector between the 1964 Mw 9.2 Alaska rupture and the Shumagin sector is currently creeping. Key geological and geophysical features in the Semidi sector are remarkably similar to those where the destructive Mw 9.1 tsunamigenic Tohoku, Japan earthquake occurred. Accordingly, we created an earthquake source in the Semidi Sector similar to the well-characterized Tohoku event. The resulting slip model (Figure 1) has an average slip of 18.6m and a moment magnitude of Mw 9.1. The Tohoku earthquake was not anticipated, despite superb seismic and geodetic networks and the world's best historical record over the last 1500 years, because of a lack of adequate paleogeologic data on prehistoric earthquakes and tsunamis. Such investigations could improve our appraisal of potential tsunami sources in Alaska.

PALEOTSUNAMI SUPPORT

Geoscientists from the USGS, CGS, and Humboldt State University completed collaborative reconnaissance field studies at over twenty localities along the California coast to determine if paleotsunami deposits exist and can be used to validate the impact and recurrence of teletsunamis from the SAFRR (eastern

Aleutians) source region. This study constitutes the first concerted regional effort to document the presence (or absence) of tsunami deposits in California coastal marshes.

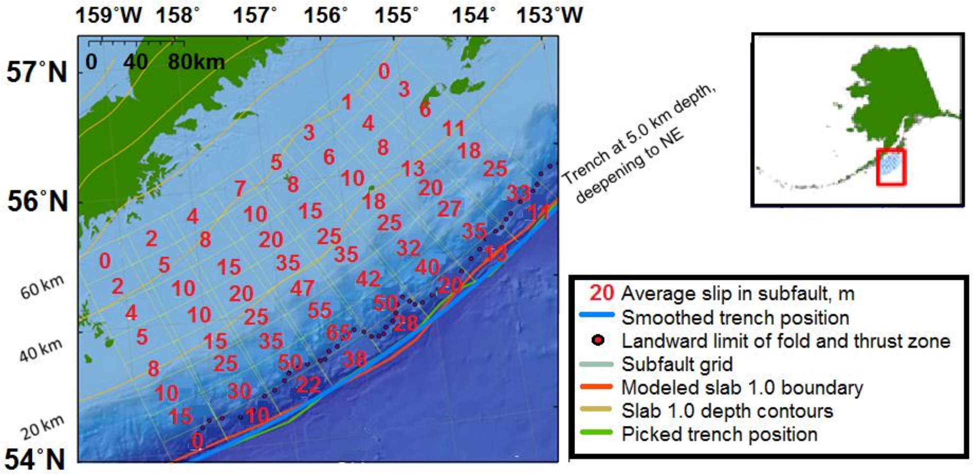

Figure 1. Surface projection of subfaults with co- seismic slip (red) given in m. After Kirby et al. (2012).

Field results to date show that inundation from distant-source tsunamis is evident in marshes near Half Moon Bay and Crescent City. Preliminary evidence from Half Moon Bay suggests a preserved deposit from the 1946 Aleutians tsunami, and possibly older, similar events. In the Crescent City area, sedimentary evidence for the 1964 (Alaska) distant source event is found at several sites, and preliminary observations suggest occurrences of other anomalous, possible tsunami deposits younger than the 1700 AD Cascadia Subduction Zone event.

TSUNAMI MESSAGES

NOAA's West Coast/Alaska Tsunami Warning Center (WCATWC), located in Palmer Alaska, issues tsunami messages for the U.S. West Coast, British Columbia, and Alaska. The Center issues Warnings, Advisories, Watches, and Information Statements. Warnings indicate that an inundating tsunami is expected or that the impact is unknown. Advisories indicate strong currents and danger to those in or near the water, without significant inundation. Watches mean that a large earthquake has occurred elsewhere in the ocean basin and that the impact for the region is being determined. A Watch is canceled or upgraded to Warning or Advisory at least two hours before impact. Information statements normally indicate that no tsunami is expected in the areas referenced by the message. In the SAFRR Tsunami Scenario, WCATWC will issue Warnings for the source area with a Watch for the U.S. West Coast within 5 minutes after the rupture occurs. The Watch is upgraded to Warning or Advisory 1 to 2 hours after the rupture as real-time forecast models are calibrated with observations.

HYDRAULIC AND HYDROLOGIC MODELING

Simulation of the scenario tsunami includes basin-wide modeling from the source to target regions, high-resolution inundation modeling, and high-order modeling of selected ports and harbors. Earthquake parameters described above are used to provide initial conditions for basin-wide propagation, modeled using several previously developed codes, including the ComMIT tool (Titov et al. 2011). A series of nested numerical computation grids were implemented, with the highest resolution of ~10-m used for inundation modeling. A line correcting the potential inundation limits was created using a new 1m-resolution LiDAR topography.

In southern California, tsunami waves arrive approximately 6 hours after the earthquake, with the largest waves occurring within the first five hours of the initial arrival. Overall the strongest tsunami effects occur in the POLA/LB, an area vital to commerce and economics nationwide (Figure 2). The effects in this area include strong currents in the vicinity of coastal structures and overland inundation. Significant currents and coastal flooding are also predicted outside of southern California, including the San Francisco Bay region.

Using the dispersive, rotational, and turbulent flow model of Kim and Lynett (2011), high-resolution simulations are performed at San Diego Bay, POLA/LB, and Ventura Harbor, using the results from the basin-wide simulations as boundary conditions. A uniform numerical grid of 5m resolution is used, and the tsunami signal is super-imposed over the tidal signal, such that complete hydrodynamic forcing is included. Results indicate that highly localized current features such as jets and whirlpools tend to drive the greatest flow speeds. Maximum currents through the Ventura Harbor channel exceed 14 knots, with maximum speeds greater than 8 knots in many parts of the harbor. In POLA/LB and San Diego, maximum currents also exceed 8 knots, with areas near structure transitions and breakwater gaps experiencing the worst conditions (Figure 3).

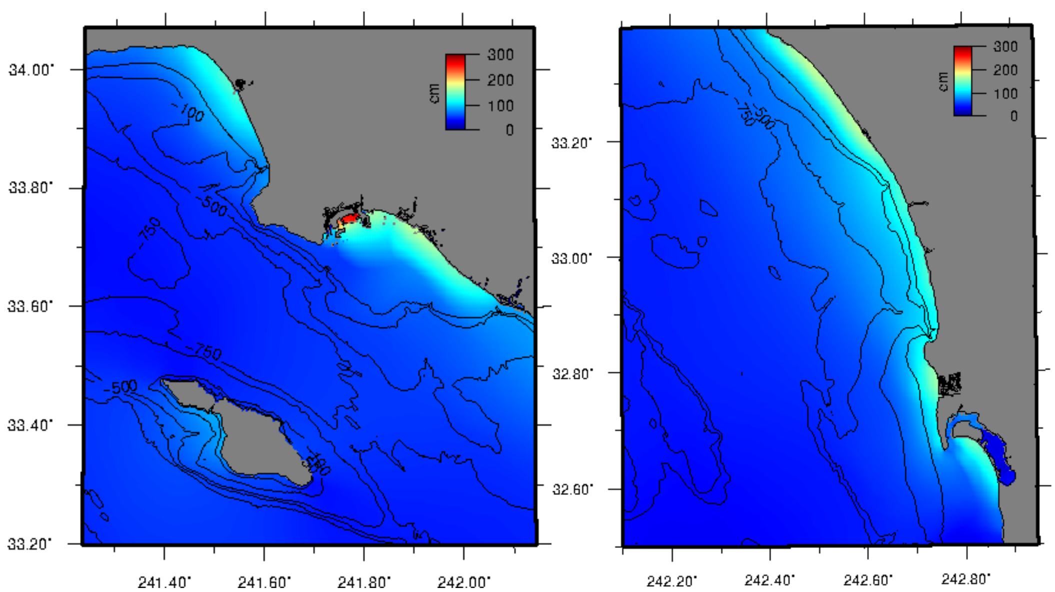

Figure 2. Overview of maximum tsunami wave heights in southern California. Left: Santa Monica/San Pedro Bays. Right: Oceanside-San Diego region. Grid resolution: 9 arc-seconds.

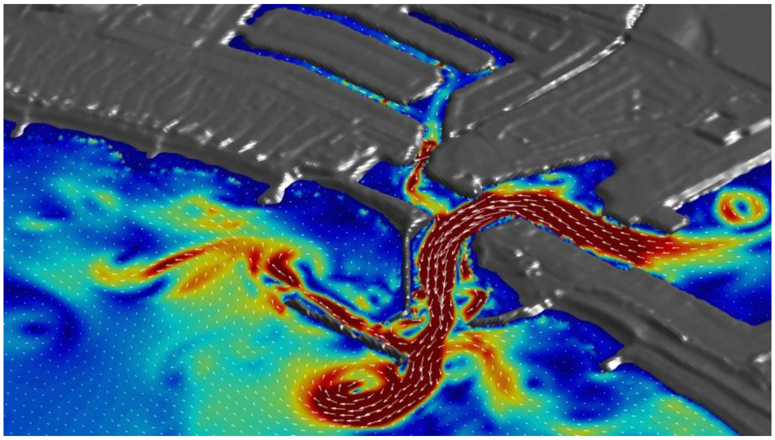

Figure 3. Snapshot from a simulation of tsunami-induced currents in Ventura Harbor. Red indicates the areas of greatest current speeds, and the circular features are large rotational structures, or whirlpools.

MARINAS AND HARBORS

At least 37,000 small craft are kept in California coastal marinas and harbors. High currents could damage or sink them; high wave heights could cause floating docks to overtop their pilings. Reviews of California boat damage data in the 2010 Chilean and 2011 Tohoku tsunamis were used to create new fragility functions for boats and docks, and harbormasters were consulted to inform and critique damage estimates. It appears to be realistic for this tsunami to sink on the order of 5,300 boats (1 in 7 boats) and damage an additional 7,500 (1 in 5), at a cost of $350 million. The debris represents a significant environmental and navigation hazard.

PORTS OF LOS ANGELES AND LONG BEACH

Well engineered port facilities generally fare better than older or less well-maintained ports. This was evident in Chile and Japan where tsunamis are relatively common and building codes are geared towards minimizing shaking and tsunami damage. The Ports of Los Angeles and Long Beach are among the most modern in the United States and are designed to strict structural and navigation standards which go a long way towards minimizing tsunami damage. Overall, it is expected that the ports will return to service within a day or two following the tsunami with the exception of a few terminals where flooding is expected to damage operations buildings and some warehouses. Debris from damage to small craft harbors and boats within the Ports is expected to cause some disruption of shipping activities following the tsunami.

As shown in Figure 4, inundation at the Ports of Los Angeles and Long Beach is limited to the fringes of wharves, except for low-elevation portions of both ports that store containerized cargo and automobiles. Flow there is too shallow to damage cranes or float containers or vehicles, but would damage the container contents and cause the loss of 2,700 vehicles. These effects represent half ($55 million) of the $110 million in property loss at the ports. Fast tsunami currents adjacent to some marine oil terminals are of concern; these may be sufficient to displace moored tankers from their berths during the tsunami. Recommendations are being formulated to take tankers to sea prior to the tsunami arrival during the 4- to 5-hour warning time.

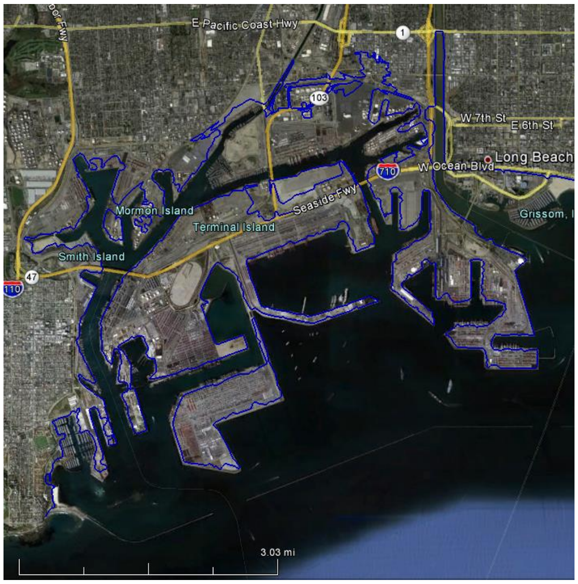

Figure 4. Extent of hypothetical inundation in the Ports of Los Angeles and Long Beach.

OTHER DAMAGE

Tsunamis scour bridge embankments and erode their fill; scour roads; displace or uplift bridge superstructures; scour bridge foundations; and cause debris impact. Here, the first two modes are most likely. Bridge abutment damage occurs where the abutment intrudes into flow and velocity exceeds a few m/sec. Scour washes out roads where the road has a crown or culverts and is overtopped. Here it damages 16 lane-miles of highway at US101 near Eureka, I80 near the Oakland-San Francisco Bay Bridge toll plaza, I5 near Camp Pendleton, and CA1 near Costa Mesa. It damages 12 bridge abutments, mostly on CA1 but also at I5 near Camp Pendleton. Repairs could cost $85 million and take 3 days. We estimated building damage as well. Flooding of coastal communities is hypothesized to occur in 1800 city blocks, affecting 100 million square feet of buildings valued at $13 billion replacement cost new and $8 billion of contents replacement cost new. The total building and content repair cost (using draft HAZUS-MH tsunami vulnerability functions) is $230 million. Loss of function is generally nil, with up to 3 days loss of function in a few locations.

Tsunamigenic fires have been observed in many earthquakes at least since 1755 in Lisbon. In modern times they are typically fueled by spreading water-borne liquid fuels released from petrochemical facilities damaged by the tsunami. This scenario affects 47 major tank farms and other petrochemical facilities, especially in the Ports of Richmond, Los Angeles and Long Beach. One or more fires would likely result at these facilities. If a tank were to rupture and a fire were to ignite on Mormon Island in the Port of Los Angeles, a 5-km^2 fire could cause the loss of product, tanks, control systems and other assets at 7 berths housing 28 million barrels of storage of petroleum products and lubricants in 48 tanks, plus 350,000 tons of industrial borates.

Figure 5. Left: railroad bed and rail on either side of a commuter rail platform were scoured away in the Tohoku earthquake. Right: 1 mile of Japan coastal Route 38 had bridges and roadway on levees destroyed by the 2011 Tohoku tsunami.

POPULATION EXPOSURE

A geospatial analysis of population exposure to scenario inundation was conducted to provide insight on the magnitude and hot spots of at-risk individuals along the California coast. This information helps emergency managers understand where evacuations may be most challenging. Over 90,000 residents are in areas prone to tsunami inundation, many of them in Long Beach, San Diego, and Newport Beach. The type of at-risk resident varies substantially along the California coast in terms of race, ethnicity, age, renters, and group quarters, indicating a need to tailor evacuation-message content and dissemination channels to the needs of local audiences.

The SAFRR Tsunami Scenario inundation also threatens 79,000 employees, many in Long Beach, Newport Beach, and San Francisco. The largest fraction of at-risk employees is in the accommodation and food-services sector, suggesting the presence of tourists. Customers and visitors also will need to be evacuated from the substantial number of government offices, retail stores, banks, libraries, religious organizations, and social organizations that are in the scenario-hazard zone. Finally, the scenario-hazard zone includes several facilities with populations that require evacuation assistance, such as K-12 schools, child day-care centers, adult residential-care centers, and medical offices.

ECONOMIC CONSEQUENCES

Business interruption will occur during the warning period and from damage to coastal infrastructure. We will examine the economic impacts from cargo damage at inundated berths and disrupted operations within the San Pedro port complex. Disruptions pertain to two days of port shut down, and subsequent channel surveying, shipping logistics, rail and road repairs, and terminal downtime. The immediate attention on the San Pedro ports is justified by the local, regional, and national significance of the two ports that handled $300 billion of trade in 2011 (BST 2012).

Impacts to the California economy will be modeled using a computable general equilibrium model that was developed for the ARkStorm scenario (Porter et al. 2010;

Sue Wing et al. 2012). The model can evaluate the effects of damage and disruption on transactions between sectors and supply chain ripple effects throughout the state economy. Important features of the modeling methodology are forms of economic resilience including substitution and conservation of inputs in response to shortages, inventories, and changes in relative prices. Economic impacts will be modeled across time periods to reflect the dynamics of the tsunami event and recovery. Future work will address business interruption from damages to infrastructure along the rest of the west coast. These impacts may add greatly to the property losses.

ENVIRONMENTAL IMPACTS

Because of the anticipated evacuation of low-lying coastal areas, it is likely that there would be few human casualties, injuries, or illnesses (such as tsunami lung) resulting directly from the tsunami. A potentially wide range of environmental and ecological impacts could occur, however. For example, the nearshore marine environment could suffer physical disruption from bottom sediment erosion, redistribution and deposition, and from debris washed into the ocean from the built environment. Contamination of nearshore marine and onshore coastal environments by diverse debris, chemicals, and pathogens could result from: redistribution of contaminated sediments from harbor bottoms; releases of contaminants from damaged port facilities, berthed ships, and coastal communities; tsunami-triggered fires, and; sewage releases from damaged wastewater treatment infrastructure. Some short-term environmental health impacts could result from exposures to these contaminants, although effective public health response and cleanup measures would minimize risk of infectious disease outbreaks or serious longer-term illnesses.

PUBLIC ASSISTANCE

Losses will be partially reimbursed through FEMA’s Public Assistance Grant Program (PA). PA provides cost reimbursement for the eligible permanent repair, replacement, or restoration of disaster-damaged, publicly owned facilities and the facilities of certain private non-profit organizations. When PA is triggered by Presidential disaster declaration, the federal cost-share is not less than 75% of eligible expenses. The California Emergency Management Agency administers a similar program, the California Disaster Assistance Act (CDAA) supplementing the non-federal share of eligible PA costs. California determines whether CDAA will be implemented and how much of the non-Federal share will be covered by the state.

PUBLIC POLICY

Public policy can be described as what governments choose to do or not to do. U.S. public policymaking is the responsibility of elected local, state, and federal bodies. Government managers also participate, helping to conceptualize and create policies. Policymaking evolves in response to problems perceived by citizens, interest groups, and political leaders. Within government, it can be described as a cycle of agenda setting, policy formulation, implementation, and evaluation. SAFRR’s tsunami policy assessment largely corresponds with agenda setting and policy formulation. It examines policy issues highlighted by the scenario and explores the consequences of policy options. These issues are organized around the functions of disaster management: warning and preparedness, mitigation, response, recovery, and risk awareness. Concurrent with SAFRR, California has established a Tsunami Policy Working Group, a voluntary advisory body to the California Natural Resources Agency's Department of Conservation, and comprising experts in earthquakes, tsunamis, flooding, engineering and policy. The working group advises State programs addressing tsunami hazards. It acts as a consumer of insights from SAFRR and provides input into the policy section of the scenario. It serves to raise awareness and facilitate transfer of policy concepts to other U.S. coastal states.

EMERGENCY MANAGEMENT AND OUTREACH

Essential to every SAFRR project are efforts to improve understanding and use of science. This project employs various methods to engage key stakeholders, including emergency managers and port operators, and reach new users of science. With Art Center College of Design, SAFRR is producing a messaging campaign and an animated movie to raise awareness and inspire change. Leaders within State and Federal tsunami mitigation programs are convening workshops to involve emergency managers and first responders and identify needed tsunami information products. An evaluation of the scenario process will determine the effectiveness of strategies and activities as the project seeks to engage decision makers, foster inter- and intra-agency coordination, build networks, enhance awareness, and stimulate change. A key ongoing strategy is collaboration with non-traditional partners—local government, private companies, and community organizations—who are more typically seen as downstream users rather than colleagues and co-messengers.

USE WITH OTHER HAZARD PROGRAMS

California's Tsunami Hazard Mitigation and Preparedness Program is helping coastal communities become "Tsunami Ready" and is developing products that will facilitate local tsunami hazard mitigation through safer land-use and construction practices while reducing the vulnerability of ports and harbors and improving emergency preparedness and response for the maritime community. The Tsunami Policy Working Group serves a dual purpose as an advisor to the State program and as a consumer of insights from the SAFRR Tsunami Scenario project, acting to resolve vulnerability issues and formulate policy recommendations. SAFRR's comprehensive scenario-based risk assessment not only helps to discover gaps and barriers in preparedness, but provides an enhanced focus on potential disaster consequences that can motivate policy-makers to take action on working group recommendations.

CONCLUSIONS

The SAFRR Tsunami Scenario will help California communities, maritime interests, and other constituencies understand their tsunami risk and make decisions about reducing losses. It begins with a hypothetical Mw 9.1 earthquake along the Alaskan Peninsula, which represents a large but realistic event for preparedeness and mitigation purposes. The project is spurring Alaskan earthquake source research and field studies of paleotsunami deposits. It has produced advanced inundation and currents models, with high-resolution modeling in four major harbors. Currents there would exceed 8 knots, representing a danger small craft, liquid bulk shipping, and other vessels. We are examining the potential environmental impacts from vessel damage, debris, and release of contaminants from various sources. In addition to maritime interests, such a tsunami would threaten several stretches of coastal roadway and bridges, and buildings housing 170,000 residents and employees. Repair costs of $1.2 billion have been estimated for ports, harbors, marinas, coastal buildings, bridges, and roads. Coastal areas that have not been modeled might add another $200 million. Business-interruption losses are being estimated with a computable general equilibrium model. Fire losses will also be added. We are creating products to communicate tsunami risks, including Google Earth maps of the tsunami effects; simulated NOAA tsunami warnings; and public-information videos. Like its predecessors the ShakeOut and ARkStorm scenarios, the SAFRR Tsunami Scenario will serve as a long-lasting resource to teach preparedness and inform risk-management decision-making. For more information, see http://urbanearth.usgs.gov/.

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