NUMERICAL AND PHYSICAL MODELING OF LOCALIZED TSUNAMI-INDUCED CURRENTS IN HARBORS

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Based on the observations on the recent transoceanic tsunami events, it has been seen that severe damage may still occur in ports and harbors as a result of the strong tsunami-induced currents, even if there is no or limited inundation. Dynamic currents induced by tsunami waves, while regularly observed and known to cause significant damage, are poorly understood. In this paper, it will be discussed that the strongest currents in a port are governed by horizontally sheared and rotational shallow flow with imbedded turbulent coherent structures, and without proper representation of the physics associated with these phenomena; predictive models may provide drag force estimates that are an order of magnitude or more in error. Such an error can mean the difference between an unaffected port and one in which vessels 300 meters in length drift and spin chaotically through billions of dollars of infrastructure. This paper also focuses on tsunami induced currents and seeks to define the relative hazard in specific ports and harbors as a result of these currents.

Keywords: tsunamis, tsunami-induced currents, numerical wave modeling, ports and harbors

INTRODUCTION

Recent transoceanic tsunami events have shown that maritime communities may still be impacted significantly by tsunamis due to strong and erratic currents generated by the tsunami, even when there is no or limited flooding or inundation. Many records of tsunami effects note large shallow coherent turbulent structures, more commonly referred to as whirlpools. Although, tsunami currents are an obviously significant and damaging component of large- scale tsunami inundation from near-field sources, the potential for damage at maritime facilities due to currents induced by tsunami surges not causing inundation (and usually from far-field sources) is much less studied or understood.

Some examples of this phenomenon were occurred after Indian Ocean Tsunami and well documented in Okal et. al. (2006a, 2006b, 2006c). The most remarkable one among those had taken place in Port of Salalah, Oman, where a freight ship Maersk Mandraki broke all its' mooring lines and drifted out of the harbor under the influence of a system of large eddies. Although the incoming tsunami in this case was around 1.5 m, the currents generated were energetic enough to cause 285 m long ship to break its moorings and pull it away from the terminal (Lynett, et. al, 2012). A general conclusion that can be drawn from this incident would be; a tsunami of approximately 1 m was able detach the largest of ships in any given port, the required preparation and mitigation measures would likely be unmanageable and unreasonable.

California coasts were also affected severely by the recent events. In 2006, a tsunami was generated by a M 8.3 earthquake in the Kuril Islands, created strong currents in Crescent City Harbor. These strong currents were reported beginning with the initial waves and intensifying as the larger surges came through, resulting in severe damage to several docks, particularly those located nearest to the entrance of the inner harbor (Dengler et al., 2008). Then in 2010, ports in California were again impacted by tsunami currents following the M ~8.8 Maule, Chile earthquake. Surges began affecting San Diego around midday on 27 February and steadily moved northward over the next several hours. Currents of up to 16 knots (8 m/s), visually estimated by eyewitnesses, caused damage to docks in San Diego, Catalina Island, Ventura, and Santa Cruz and affected passengers boarding a cruise ship in Los Angeles (Wilson et al., 2013).

The 2011 Tohoku tsunami provided one of the most comprehensive and instrumental data sets that describes the effects of tsunamis on ports and harbors (Lynett et al., 2012). It was widely instrumented and recorded tsunami in history, and a handful of flow speed measurements are found in the literature

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(e.g., Fritz et al., 2012; Hayashi and Koshimura, 2013). In the far field, every port, harbor, and maritime facility along the U.S. West Coast was adversely affected by surges and currents induced by

the 2011 Tohoku tsunami (Wilson et al., 2012, 2013). The most severe damages was occurred in Crescent City and Santa Cruz. Very strong currents were created by tsunami surges in Crescent City's inner harbor destroying docks and boats that were inside the harbor when tsunami arrived. On the other side of the Pacific, in New Zealand, the Tohoku tsunami also caused current related damage that primarily affected recreational maritime activities (Borrero et al., 2013). Also, in the Galapagos Islands similar current activity took place (Lynett et al., 2013) among other locations around the Pacific Rim.

Although, the damaging tsunami-induced currents has been observed and described throughout the history (Ludwin and Colorado, 2006), it has not been considered in detail during tsunami hazard mitigation studies.

On the other hand, it is computationally expensive to capture important hydrodynamics related the tsunami currents by numerical modeling, since fine-resolution computational grids are needed which leads to longer simulation times, making them impractical for many modeling efforts. Also, model validation and calibration is difficult due to scarcity of instrumental or observed data on current speeds, besides several estimates of current speed based on eyewitness accounts.

Here, we will present the sample results obtained by numerical simulation tools for hazard mapping purposes to better understand the current-based tsunami hazards in the ports and harbors of California.

NUMERICAL MODELING APPROACH

In the context of this study, both near-field and far-field tsunami model scenarios relative to the California Coast has been we assessed. Sources included real events of the 2010 and 2011 tsunamis originating from Chile and Japan along with hypothetical tsunamis generated by large earthquakes along the Alaska-Aleutian Islands Subduction Zone and the Cascadia /Kuril Subduction Zones for almost all maritime locations along the California Coast..

Most of the hydrodynamic results presented in this study come from the application of the 'Method of Splitting Tsunami' (MOST) numerical model. The MOST model has been used extensively for tsunami hazard assessments in the United States and is currently in operational use at NOAA's Pacific Marine Environmental Laboratory (PMEL). Variants of the MOST model have been in constant use for tsunami hazard assessments in California since the mid 1990's. For select cases, the MOST results are compared to numerical model results from COULWAVE and discussed in Lynett et al. (2014). COULWAVE is a high-order Boussinesq-type model, developed over the past decade, with the particular goal of creating the ability to understand rotational flow in shallow water. While this leads to a far more complex equation model compared to MOST, it includes the physics necessary to simulate boundary shear, and the complete coupling of these effects with a nonlinear, dispersive wave field. It was concluded by Lynett et. al (2014) that, MOST is capable of creating realistic estimates of wave heights. Furthermore, MOST velocity values are on average higher than those of COULWAVE, use of modeled results at this resolution should be sufficiently conservative to generate tsunami current velocity hazard maps

MOST is used to propagate tsunami waves from source to the nearshore region, using a system of nested grids. The outermost grid at 4 arc min resolution covers the entire Pacific basin. Three additional grids of increasingly finer resolution were derived from data provided by NOAA's National Geophysical Data Center specifically for tsunami forecasting and modeling efforts. The innermost nearshore grid with the highest resolution is used with the MOST (10 m resolution).

CURRENT-BASED HAZARD MAPPING IN CALIFORNIA PORTS AND HARBORS

In order to have a quantitative relation between currents speeds and the corresponding damage, Lynett et al. (2014) presented damage index based on the recorded damage observations in ports and harbors are somewhat limited, with good data available only from events of the past decade. As such, this data set is dominated by observations gathered in California following the 2010 Chile and 2011 Tohoku tsunamis (Wilson et al., 2013) and augmented by additional observations found in Lynett et al. (2012, 2013) and Borrero et al. (2013) (Table S1, in the supporting information). Typically, damage observations are accompanied by eyewitness estimates of the local current speed; however, the fidelity of these estimates varies greatly, from a low confidence estimates taken from distances greater than 10 m from the water to those taken at or in the water by experienced boat captains. Furthermore, instrumental measurements of currents in the vicinity of damaged structures are rare, leaving select few

data sets appropriate for model validation. However, with comparison to these measured field data sets in conjunction with experimental benchmarking, we are able to use modeling tools to realistically estimate currents in ports and harbors.

To connect current speed with damage state, we divide the damage state in to six indices, listed in Table 1. While the damage type, and thus the resulting index, is subjective, a review of the observed types of damage suggests that these categories provide a reasonably complete coverage of tsunami impacts in harbors. Based on this damage categorization, we plot current speed versus damage index, as shown in Figure 1. We note that this figure shows only instrumental data and numerical hindcasts and does not include eyewitness estimates since such observations generally report current speeds that are on average twice the numerical or instrumental values. This discrepancy is likely the result of a range of factors but mostly due to overestimation by eyewitnesses inexperienced in estimating current velocities. From the opposite standpoint, there may be a discrepancy due to the inability of numerical simulations to resolve the highly localized strong currents that eyewitnesses may focus on. However, this is a moot point in that current-based hazard maps will ultimately be based on simulated current speeds. Therefore, the correlation between simulated currents and damage states is important while correlation between simulated currents and eyewitness estimates is secondary.

Damage in harbors depend on the several parameters like the age, location and present condition of docks and boats, however, some generalities about the relationship between tsunami currents and damage can be determined. As expected, Figure 1 shows a general trend of increasing damage with increasing current speed. In this data, it can be noticed that threshold for damage initiation at 2-3 knots (1-1.5 m/s). When 3 knots is exceeded, the predicted damage state switches from no damage to minor-to-moderate damage. Thus, in the simulated data, 3 knots represents the first important current velocity threshold. We then argue that the second threshold is at 5-6 knots (2.5-3 m/s), where damage transitions from moderate to major. A third current speed threshold is less clear, but is logically around 8-9 knots (4-4.5 m/s), where damage levels move to the extreme damage category; additional damage observations with correlated current predictions are needed to better define this threshold. These three current divisions will be used to categorize potential damage levels in subsequent analysis of tsunami currents in ports and harbors

Table 1. Damage index and Corresponding Damage Type

Damage Index:	Damage Type:
0	no damage
1	small buoys moved
2	1-2 docks/small boats damaged, large buoys moved
3	Moderate dock/boat damage, mid-sized vessels off moorings
4	Major dock/boat damage, large vessels off moorings
5	Complete destruction

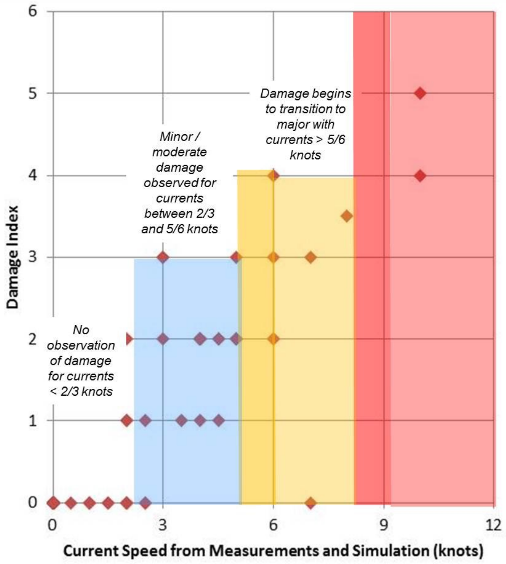

Figure 1. Relationship between current speeds and damage indices

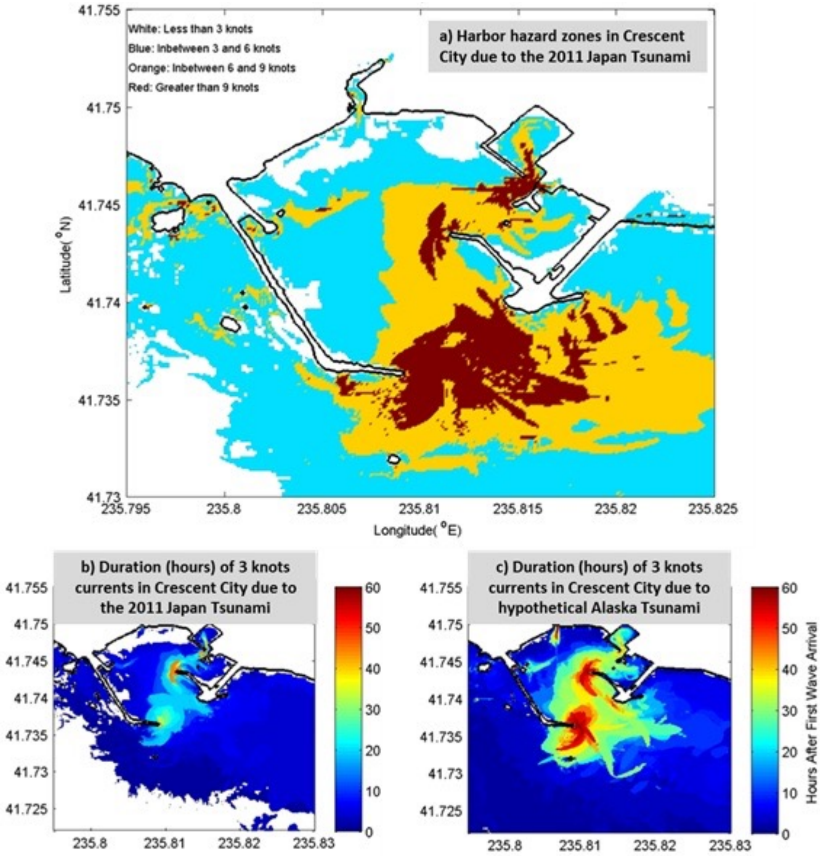

Figure 2. Example uses of the simulation output for hazard assessment. (a) Current speed hazard zones for 3/6/9 knot zonation. (b and c) Time-threshold maps are given

Examples of the types of simulation-based information that should be useful for hazard assessment in coastal areas are shown in Figure 2. In Figure 2a), we plot maximum current speed in Crescent City predicted from the Japan 2011 tsunami

source with solid colors corresponding to estimated damage-current thresholds; i.e. less than 3 knots (no damage), 3 to 6 knots (minor damage), 6 to 9 knots (moderate damage) or 9 knots and above (severe damage). We see that the zonation matches well with observations of currents and damage in Crescent City harbor. Widespread areas of extreme and major damage zones are found in the small boat basin, where the pilings, docks, and remaining vessels were heavily damaged or destroyed.

To determine the duration of damaging currents, "time-threshold" maps are generated; see Figure 2b) and c). For a specified current, these maps will show the time duration during which the current is exceeded based on numerical modeling results run for a 60 hour tsunami scenario. For example, a 6-knot time-threshold map which shows for a particular location a value of 3.4 hours indicates that at that location, flow speeds of 6 knots are not exceeded after 3.4 hours of waves. This metric allows for the estimation of how long damaging current will be active, which could be different depending on the type of maritime assets at stake.

Figures 2b and 2c provide time-threshold maps for a single current speed (3 knots) for two different tsunami sources: the 2011 Tohoku source and a hypothetical Mw ~9.2 earthquake along the Eastern Aleutian Subduction Zone. The simulations predict that for the Tohoku event 3 knots currents should persist for up to 40 h near structures and for 20 h in the main harbor entrance channel, while for the Aleutian event, these values are 60+ h and 45 h, respectively. While this type of information should be very useful for harbor personnel to estimate the duration of potential impacts, the estimates will be highly source dependent.

CONCLUSION

The past events described above highlight the vulnerability of maritime facilities to tsunamis that do not cause inundation, but still may able to create adverse conditions that may exist for many hours after tsunami arrival. Here we presented out approach to better understand the marine hazards related to tsunami-induced currents using numerical tools.

The MOST tsunami model using a 10 m grid satisfactorily reproduces measured tsunami-induced current speeds. The trade off in accuracy is, however, compensated by the tendency for the MOST results to be conservative in terms of hazard assessment and by the fact that MOST is much less computationally demanding.

Model results from a range of scenarios can then be combined with information about tsunami amplitudes, currents, and damage from recent events (i.e., 2006 Kuril Islands, 2009 Samoa, 2010 Chile, 2011 Tohoku, and 2012 British Columbia) to develop an emergency response "decision tree" which will allow forecast information from future tsunamis to be quickly and easily compared to particular real or modeled scenarios and determine an appropriate course of action. The results of this type of analysis are being used to develop a suite of map products and policy guidance documents for maritime communities to know if, when, and where strong tsunami currents will occur and whether vessels should be relocated within or outside of a harbor during and in advance of a tsunami. This maritime mapping plan and guidance will likely also form the basis for national standards through the U.S. National Tsunami Hazard Mitigation Program (Wilson and Eble, 2013).

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