DEVELOPMENT OF PROBABILISTIC TSUNAMI DESIGN MAPS ALONG THE U.S. WEST COAST FOR ASCE7

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ABSTRACT: To date, a national standard for engineering design for tsunami effects has not existed, and this significant risk is mostly ignored in engineering design. The American Society of Civil Engineers (ASCE) 7 Tsunami Loads and Effects Subcommittee is completing a chapter of *Tsunami Loads and Effects* for the 2016 edition of ASCE/SEI 7 Standard. This study describes the development of 2,500-year probabilistic tsunami design zone maps for the U.S. West Coast (Washington, Oregon and California) for use with the ASCE design provisions. These new maps will define the coastal zones where structures of greater importance would be designed for tsunami resistance and community resilience.

1. Introduction

Probabilistic hazard maps are the key criteria necessary to establish risk-consistency for engineering design provisions. Past efforts in the tsunami field have largely focused on deterministic assumptions of scenarios for evacuation planning purposes. However, the inherent vulnerability in this deterministic practice, which does not explicitly account for aleatory uncertainty, has been revealed by unsustainable losses in the last decade due to “unexpected” tsunamis. Probabilistic Tsunami Hazard Analysis (PTHA), adapted from the Probabilistic Seismic Hazard Assessment (PSHA), assesses tsunami risks based on a reliability analysis that considers the uncertainty and variability of seismic events (Geist and Parsons, 2006). The Seaside, Oregon, study by González et al. (2009) showed the PTHA is a viable approach for tsunami hazard assessment. González et al. (2013) applied a similar approach to assess the tsunami hazards for Crescent City, California. Thio et al. (2010) established a different PTHA approach consisting of a large number of tsunami scenarios that included both epistemic uncertainties using logic trees as well as aleatory variability. Their study provides probabilistic offshore tsunami heights along California's coastline. Thio et al. (2010) also extended their tsunami offshore heights to estimate tsunami inundation for a few coastal communities in California. PTHA methods are also widely used in Japan (Annaka et al., 2007), Australia (Burbridge et al., 2008) and New Zealand (Power et al., 2012). Cardno (2012) carried out detailed inundation modeling and risk assessment for several coastal communities in Australia based on Geoscience Australia's tsunami risk assessment for New South Wales. For critical facilities and structures of greater importance, the PTHA method provides a probabilistic design of flow characteristics, hydrodynamic and geometric factors affecting the forces imparted to the structure and variability in the as-built capacity of the structural elements subjected to the flow. Thus, the hazard is probabilistic and the corresponding design methodology is risk-based on structural performance.

In the U.S., there has never been a national standard for engineering design for tsunami effects. The American Society of Civil Engineers (ASCE) 7 Tsunami Loads and Effects Subcommittee (TLESC) is presently completing a comprehensive chapter with the ASCE/SEI 7 Standard, *Minimum Design Loads for Buildings and Other Structures*, for proposed incorporation into the 2016 edition of the Standard. Chapter 6, *Tsunami Loads and Effects*, would become the first national tsunami design provisions established in a standard referenced in the International Building Code. States included in the scope of these provisions would be Alaska, Hawaii, California, Washington and Oregon. These provisions will emphasize essential facilities and critical infrastructure. ASCE7 design provisions are urgently in need of PTHA maps associated with probabilistic 2,500-year offshore wave amplitude based on PTHA methods. The 2,500-year Annual Recurrence Interval is chosen for consistency with the PSHA earthquake hazard studies in the U.S.

The new ASCE standard recommends two procedures to obtain the inundation depth and velocities at a site of interest The first procedure uses the PTHA offshore tsunami amplitudes, wave periods and other waveform parameters as input for a two-dimensional model to compute the tsunami inundation. The second procedure, named the Energy Grade Line (EGL) analysis, is much simplified and easy to execute in an Excel spreadsheet. The EGL approach uses the PHTA runup elevation and associated inundation distance as input for a hydraulic analysis along topographic transects through the onshore structure. The runup elevation and inundation distance are indicated by the probabilistically based tsunami design zone maps provided in this study.

In the next sections, we describe the methodology, procedure and results of the development of the ASCE 2,500-year Tsunami Design Zone (TDZ) maps for all of the U.S. West Coast based on PTHA maximum tsunami amplitudes at 100 m depth offshore.

2. Methods and Procedure

2.1. PTHA Offshore Maximum Tsunami Amplitude

Thio et al. (2010) detail the process of obtaining the 2,500-year offshore maximum tsunami amplitude. The methodology used by Thio et al. (2010) is adopted, for the most part, from the PSHA proposed by McGuire (2004), except the PTHA is interested in the exceedance of maximum tsunami amplitude. Thio et al. (2010) employed shallow water wave models to establish a database of Green's function for each of a set of subfaults that adequately describe the earthquake rupture. They then quickly synthesize tsunami waveforms for any slip distribution by summing the individual subfault tsunami waveforms, and thus the maximum tsunami wave amplitude, along the 100 m water depth offshore. Thio et al. (2010) methods include consideration of both aleatory and epistemic uncertainties, which account for uncertainties resulting from the random nature of modeling, as well as uncertainties due to incomplete understanding of natural processes of the earthquake sources. As the first step of developing the ASCE TDZ maps, the method of Thio et al. (2010) is used to obtain the ASCE PTHA offshore amplitudes for all five Pacific states of the U.S., including Alaska, California, Hawaii, Oregon and Washington. This approach also provides source disaggregation, identifying the source regions and magnitudes that contribute the most to those offshore tsunami amplitudes. Based on the PTHA source disaggregation, we reconstruct tsunami sources to the detail of source parameters so that the reconstructed tsunami scenarios provide good approximation of the PTHA offshore amplitudes at a site of interest. As a result, we are able to extend the PTHA offshore amplitudes to obtain the 2,500-year TDZ using tsunami inundation models. Figure1 shows an example of the PTHA maximum tsunami amplitude at 100 m depth offshore of Crescent City, California. In Fig.1, the color bars indicate the PTHA offshore maximum tsunami amplitude and the gray bars are the corresponding wave periods. Clicking on one of the circles brings up a pop-up window showing the values of the maximum tsunami amplitude in feet and wave period in min at that location. The typical 2500-year maximum tsunami amplitude at 100 m water depth is about 25 ft (~ 7.6 m).

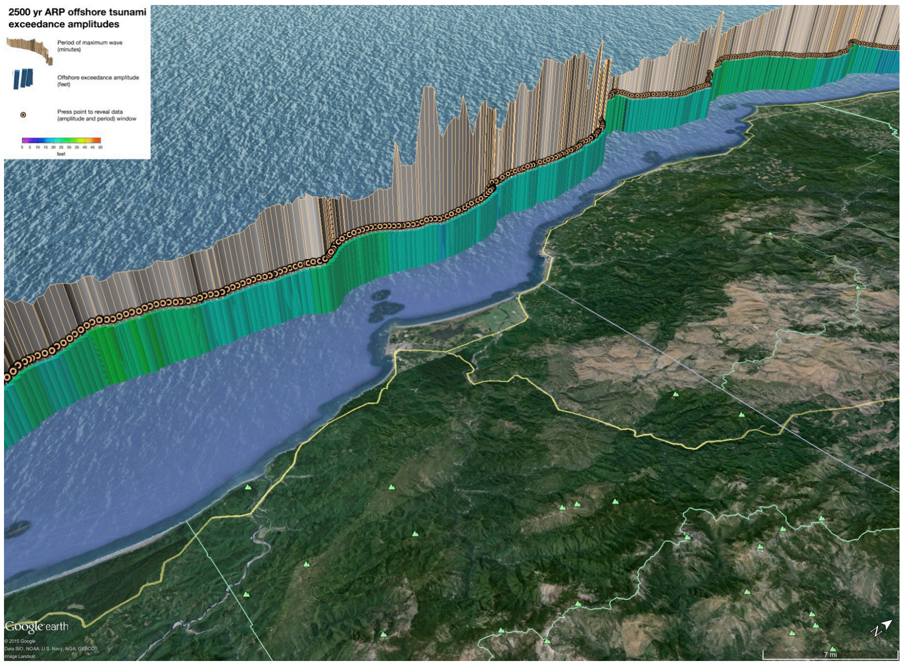

Fig. 1 – PTHA offshore maximum tsunami amplitude for Crescent City, California

2.2. Tsunami Model

We use the Method of Splitting Tsunami (MOST) for tsunami propagation and inundation modeling. MOST is a suite of integrated numerical codes capable of simulating tsunami generation, transoceanic propagation and subsequent inundation of coastal area (Titov and González, 1997). The model employs a finite-difference approximation of the characteristics form of the shallow water wave equations by use of the splitting method (Titov and Synolakis, 1997). For propagation, MOST uses the shallow water wave equations in spherical coordinates with numerical dispersion to account for different propagation wave speeds at different frequencies. The physical process of frequency dispersion can be approximated by numerical dispersion in the MOST model (Burwell et al., 2007). Zhou et al. (2012) showed that dispersive waves during the 2009 Samoa tsunami were successfully modeled with the numerical dispersion in MOST, whereas shallow water equations without dispersion overpredicted the wave amplitude by 50%. MOST uses nested computational grids to telescope down to the high-resolution area of interest for inundation computation. Nested grids are used to generate a sufficient number of nodes per wavelength to enable solution of the equations with minimum error. The numerical coupling between all nested grids in MOST is unidirectional from the outer grid. That is, the inner grid has no effect on the outer grid, and the outer grid provides the inner grid with computed wave amplitudes and flow velocities at all four boundaries by linear interpolation from coarser resolution. We note that the downstream boundary conditions from the outer grid require no overlapped marginal areas between grids. MOST has been extensively tested against a number of laboratory experiments and benchmarks, and was successfully used for simulation of many historical tsunami events (Synolakis et al., 2008; Tang et al., 2009, 2012; Titov, 2009; Wei et al., 2008, 2013; Zhou et al., 2012).

2.3. Tsunami Propagation Database

By implementing MOST, the NOAA Center for Tsunami Research (NCTR) has developed a database of pre-computed unit tsunami propagation scenarios (Fig. 2). A unit tsunami propagation contains results of a model tsunami propagation scenario generated by a unit tsunami source with 1 m slip over an area of 100 km x 50 km. These unit sources are all placed along subduction zones and known tsunamigenic faults, and are aligned to fit known fault geometries (Fig. 2). Gica et al. (2008) provide detailed descriptions of all unit sources with tabulated source parameters for each unit source, including their locations (longitude and latitude), focal depths, strikes and dips. The rake angles are all set to 90° for all unit sources. These parameters are used as model input for an elastic deformation model of Okada (1985) to compute the vertical deformation resulting from a 1 m slip. This deformation is assumed to be instantaneously transferred to the ocean surface, and is considered a unit tsunami source. The tsunami propagation database consists of thousands of sets of pre-computed model results of tsunami propagation, generated by the unit tsunami sources. Each of these unit tsunami scenarios is computed using MOST at a grid resolution of 4 arc min (~ 7.2 km). Because of the linearity of tsunami waves in deep water, we can reconstruct a tsunami source (usually a combination of the unit scenarios) inverted from deep-water waveforms obtained from either observations or numerical solutions.

It is worth pointing out that the existing propagation database should not be directly used as solutions for water depth shallower than 1000 m due to the coarse resolution of the grids. However, all PTHA offshore amplitudes are available at the 100 m water depth. To solve this issue, we extended the existing database to include an additional database of tsunami waveforms computed using a grid resolution of 24 arc sec (~ 720 m). For coastlines of interest, we develop model grids of 24-arc-sec resolution to compute waveforms at the PTHA offshore points, adopting boundary conditions provided by the existing propagation database.

In the present study, we use the existing unit tsunami scenarios and the extended propagation database to reconstruct the disaggregated PTHA sources through an inversion method. This inversion process searches for a best match between the PTHA offshore wave amplitudes and the MOST-computed results, the details of which are provided in Section 2.4.

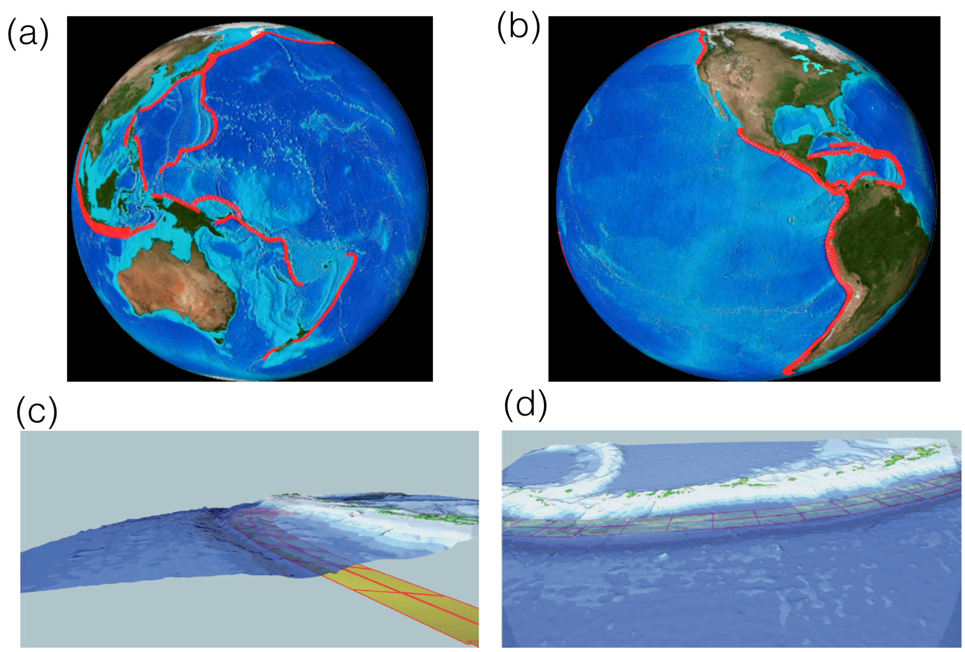

Fig. 2 – Tsunami unit sources. (a) Unit sources developed for western Pacific. (b) Unit sources developed for eastern Pacific. (c) Aerial side view of unit sources along the Aleutian trench (courtesy of Gica et al., 2008). (d) Aerial view of unit sources along the Aleutian trench (courtesy of Gica et al., 2008).

2.4. Tsunami Source Reconstruction and Inversion

The PTHA approach of obtaining 2,500-year offshore maximum tsunami amplitude consists of tens of thousands of numerical results of synthetic scenarios (Thio et al., 2010). For an inundation study, it is unnecessary and time consuming to compute all synthetic scenarios used to derive offshore amplitudes. Alternatively, a small subset of these synthetic scenarios is used to compute the inundation zone. For example, Thio et al. (2010) applied only scenarios that were selected based on their source disaggregation study, and Power et al. (2012) chose the largest 100 tsunamis for their probabilistic inundation study. Similarly, we only choose the source regions and magnitudes contributing the most to those offshore tsunami amplitudes at sites of interest. Figure 3 shows an example of the source disaggregation obtained by the PTHA method of Thio et al. (2010). For a site (118.34°W, 34.146°N) in California, this source disaggregation map indicates that the most dominating source regions are the Aleutian Trench and the Alaska subduction zone. Therefore, for this California site, we aim to reconstruct tsunami sources only in these two rupture areas, to produce model results matching the PTHA offshore amplitudes.

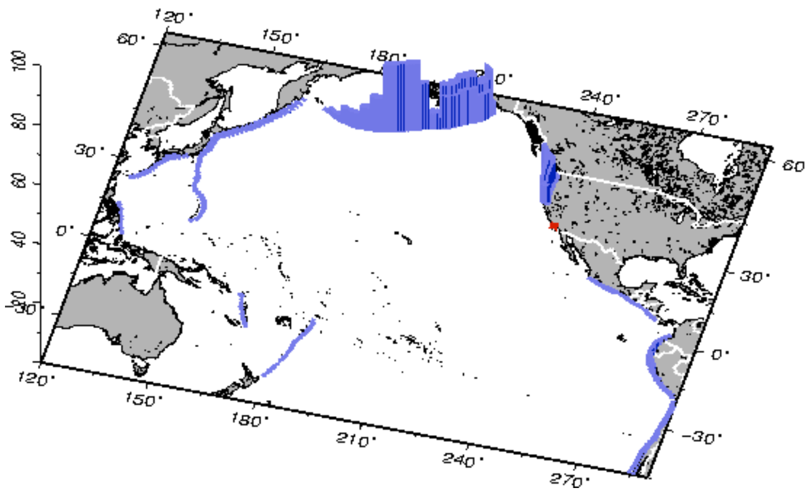

Fig. 3 – 2500-year PTHA source disaggregation for a site (118.36°W, 34.136°N) in California, where the blue bars denote the source contributions (%) to the site indicated by the red circle.

We use a nonlinear least squares method to realize the reconstruction of the tsunami sources, which in turn will be used for inundation computation. Based on the PTHA source disaggregation, we first select a group of unit sources in the dominating rupture zones. By the use of the pre-computed propagation database (described in Section 2.3), the inversion method then adjusts the combination of the slip amount of each unit source until the model results match the PTHA offshore amplitudes. The nonlinear least squares method, expressed in Eq. (1), starts with an initial guess of slips for selected unit sources. This provides an initial tsunami source. We can then quickly obtain the maximum tsunami amplitudes at every PTHA offshore point through a linear combination of the pre-computed propagation waveforms weighted by the slip amount. These model results are then compared with the PTHA values. The inversion method iteratively modifies the slip combination for those selected unit sources until a least squares error is reached between the model results and the PTHA offshore amplitudes. We then further fine tune this solution of the slip combination at the source region until two conditions are satisfied: (1) the absolute error between the model results and the PTHA is less than 20%; and (2) all individual model results are greater than 80% of the PTHA values. As a result, the final solution of slip combination for the selected unit sources gives us a workable tsunami source to compute the tsunami inundation.

$$\min_x \| f(x) \|_2^2 = \min_x \left(\sum_{j=1}^{n} f_j(x)^2 \right)$$

$$f_j(x) = \max\left[\sum_{i=1}^{m} \eta_{ij}(t) \cdot x_i \right] - A_j \tag{1}$$

where $\eta_{ij}(t)$ is the wave amplitude time series at point j due to i_{th} unit source; x_i is the slip coefficient on the i_{th} unit source; and A_j is PTHA offshore amplitude at j_{th} point.

2.5. Digital Elevation Models (DEM)

The National Geophysical Data Center (NGDC) has been building high-resolution digital elevation models (DEMs), mostly at a grid resolution of 1/3 arc sec (~ 10 m) of bathymetry and topography for selected U.S. coastal regions (Eakins and Taylor, 2010). The DEMs are part of the U.S. tsunami forecast system developed for NOAA's Tsunami Warning Centers. These DEMs have 1) a global, geographic coordinate system; 2) a mean high water (MHW) vertical datum for modeling of maximum flooding; 3) a grid file format of the ESRI Arc GIS; and 4) bare earth with buildings and trees excluded from the DEM. Figure 4 shows the coverage of the tsunami DEMs in the Pacific developed by NGDC. Most coastal regions along the U.S. West Coast are covered by these high-resolution DEMs. In Hawaii, 1/3-arc-sec DEMs are developed for most of the islands. The exceptions are east of Maui, which has a coarser grid resolution at 1 arc sec (~ 30 m), and western and central Molokai and the southern tip of the Island of Hawaii have a grid resolution of 6 arc sec (~ 180 m). In Alaska, high-resolution DEMs are only available for populated areas, and nearly 90% of these "high-resolution" DEMs only have a grid resolution of 1 arc sec (~ 30 m) or lower. Each DEM is provided with a detailed report describing the procedure, data sources and analysis of the development (http://www.ngdc.noaa.gov/mgg/inundation/tsunami/inundation.html).

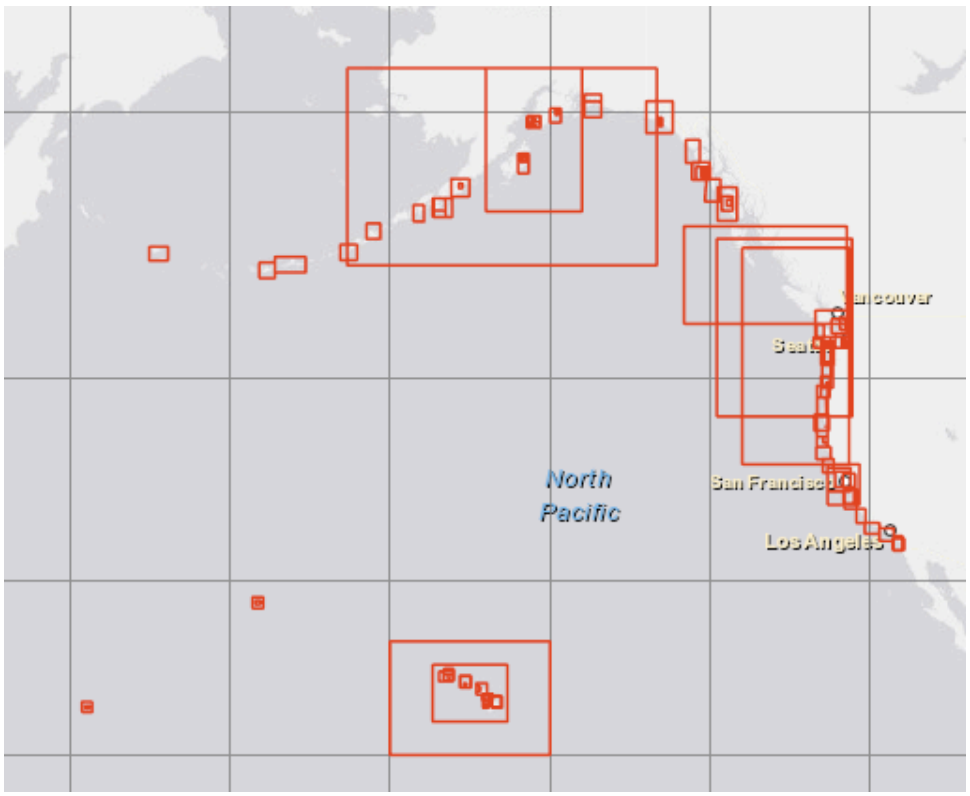

Fig. 4 – Coverage of the tsunami DEMs developed by NGDC (courtesy of NGDC).

2.6. Setup of the Tsunami Inundation Models

MOST is used to compute the ASCE TDZ after the tsunami sources for coastal regions of interested are determined by the method described above. It is not realistic to carry out all inundation computations at a grid resolution of 1/3 arc sec (~ 10 m) for all coastlines due to the large coverage area of the coastlines and time frame for completing the ASCE TDZ. Instead, we use an optimal grid resolution of 2 arc sec (~ 60 m) for inundation computation in MOST. A typical grid resolution of 2 arc sec (~ 60 m) is used for forecast models developed for NOAA's Tsunami Warning Centers to forecast inundation along U.S. coastlines. In many cases, the inundation areas obtained using 2 arc sec (~ 60 m) are similar to those using a grid resolution of 1/3 arc sec (~ 10 m; Tang et al., 2009).

As discussed in Section 2.2, MOST uses telescoped grids (A, B and C grids) to account for tsunami wave transformation from deep water to onshore flooding. For a coastline of interest, we use the 24-arc-sec grid described in Section 2.3 as the A grid of MOST. A smaller B grid, with a grid resolution of 6 arc sec (~ 180 m), is nested within the A grid to further capture tsunami wave characteristics at water depths of hundreds of meters. The 2-arc-sec (~ 60 m) grid is used at the innermost level, the C grid, to compute tsunami inundation. Figure 5 illustrates all C grids used to develop the ASCE TDZ for the U.S. West Coast. In the present study, we use a total number of 19 models to provide full coverage for the coastal regions of U.S. West Coast. The bathymetry and topography of all model grids, including the A, B and C grids, are derived from NGDC's DEMs based on their best-available data at the site, so the vertical datum for all inundation computation is the MHW. A constant Manning's coefficient of 0.03 is applied to all inundation computation.

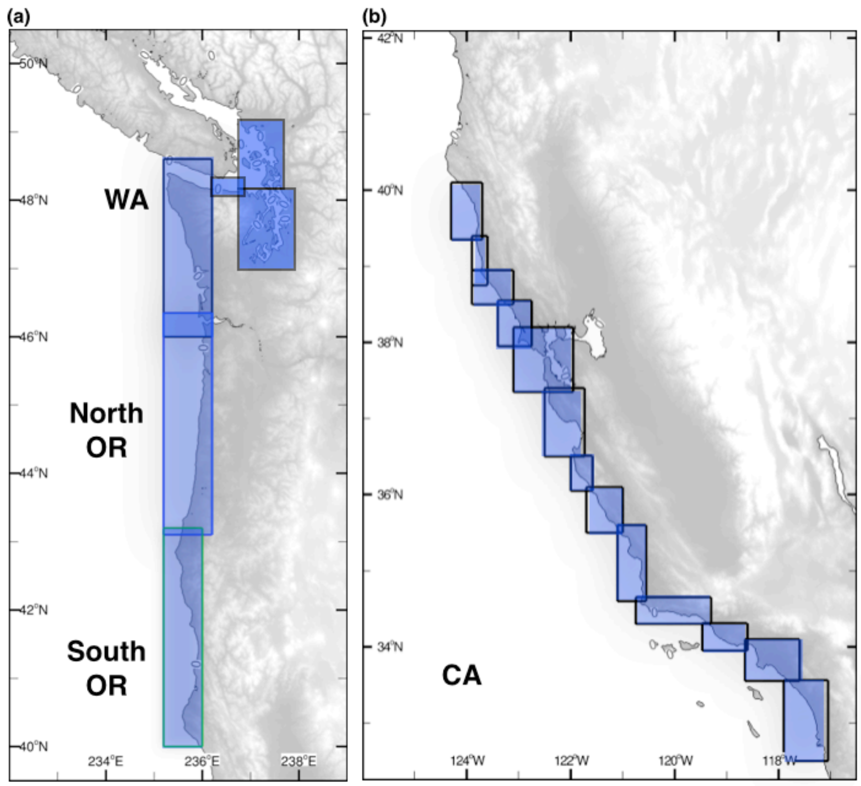

Fig. 5 – Model coverage of all C grids for MOST inundation computation along the U.S. West Coast. (a) Washington and Oregon; (b) California.

3. Results and Discussion

3.1. Reconstruction of Tsunami Sources

3.1.1. Dominating near-field sources: Cascadia Subduction Zone

The PTHA analysis indicates that the 2500-year tsunami hazards along the coastal regions of Washington, Oregon and northern California are dominated by tsunamis generated in the Cascadia Subduction Zone (CSZ). The PTHA maximum tsunami amplitudes at 100 m water depth offshore are in the range of 4 to 12 m (blue circles in Fig. 6a). For near-field sources, we assume the maximum tsunami amplitudes offshore are mostly dominated by earthquake ruptures near the site of interest, e.g., within a couple of hundred kilometers. The impact caused by ruptures at farther distances than that is considered to be secondary. As a result, we break down the coastlines of Washington, Oregon and northern California into eight segments. We then use the inversion procedure described in Section 2.4 to obtain the valid source(s) for each of these segments. Figure 6 shows that these reconstructed tsunami sources give reasonable comparison between the model results and the PTHA values along the coastlines of the CSZ.

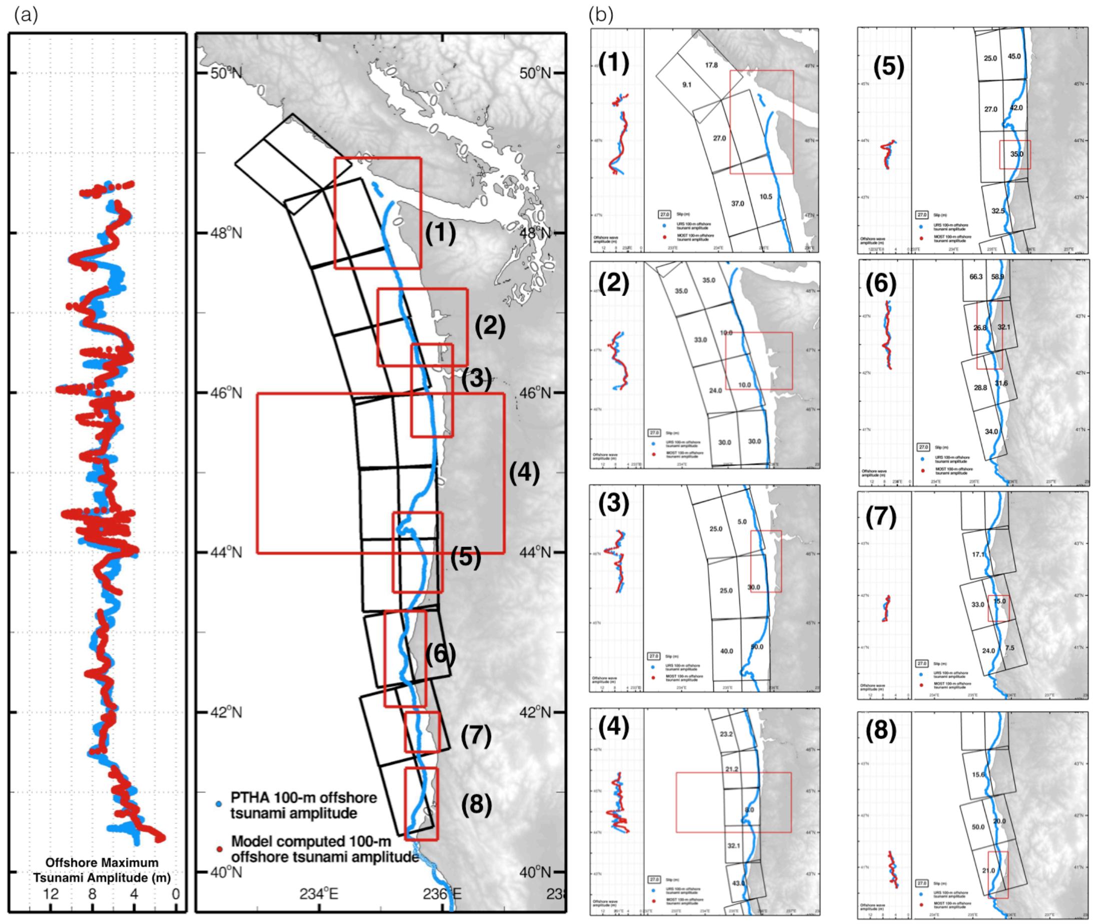

Fig. 6 – Reconstruction of the tsunami sources for coastlines dominated by the Cascadia Subduction Zone (CSZ), where the black boxes are the unit tsunami sources with dimensions of 100 km in length and 50 km in width, and red boxes are the 24-arc-sec grids to compute the maximum tsunami amplitudes for comparison with the PTHA values. (a) The left panel shows the comparison between model results (red circles) and the PTHA values (blue circles); the right panel shows the tsunami unit sources along the coastline of the CSZ, and the red boxes indicate the model coverage of the 24-arc-sec grids. (b) The breakdown of individual sources used to match the model results with the PHTA tsunami amplitudes. The value shown on the unit source is the slip associated with that unit source.

Table 1 summarizes some characteristics of the reconstructed source for each segment of coastlines. One can see that the range of average slip is between 19.3 m and 39.8 m, with the largest slip of 66.3 m and the smallest slip of 5.0 m. The equivalent earthquake magnitudes of these sources are between 8.79 and 9.09.

Table 1 – Characteristics of the reconstructed tsunami sources in the CSZ

Segment of coastlines	Average slip (m)	Largest Slip (m)	Smallest Slip (m)	Length of Source (km)	Equiv. EQ Magnitude
1	20.3	37.0	9.1	300	8.80
2	25.9	35.0	10.0	400	9.01
3	29.2	50.0	5.0	300	8.96
4	25.5	43.0	8.0	500	8.87

5	34.4	45.0	25.0	400	9.01
6	39.8	66.3	26.8	400	9.09
7	19.3	33.0	7.5	300	8.79
8	26.7	50.0	15.6	300	8.88

3.1.2. Dominating distant sources: California (south of 41°N)

The tsunami hazards in California (south of 41°N) are dominated by large tsunamis generated from distant earthquake zones in Alaska and the Aleutians (Thio et al., 2010). Different from the near-field CSZ sources discussed in Section 3.1.1, these distant sources are featured by longer source lengths, larger slips and as a result, much greater source magnitudes.

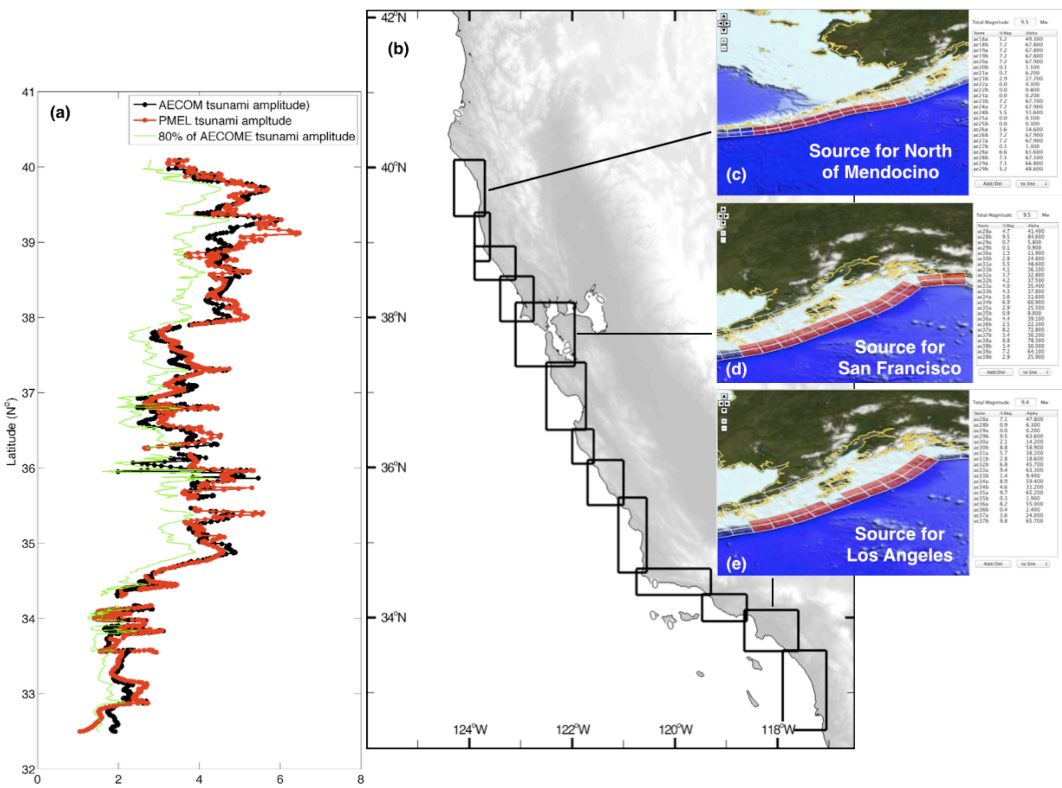

Fig. 7 – Reconstruction of the tsunami sources for the coastlines of California dominated by distant tsunamis. (a) Comparison between model results (red circles) and the PTHA values (black circles); the green circles indicate 80% of the PTHA amplitudes. (b) The 13 segments of coastlines for source reconstruction. (c) Example tsunami source (Alaska Subduction Zone) for north of Mendocino. (d) Example tsunami source (Alaska Subduction Zone) for San Francisco and its vicinity. (e) Example tsunami source (Alaska Subduction Zone) for Los Angeles and its vicinity.

Figure 7a shows good comparison between model results and PTHA amplitudes. In Fig. 7c-e, we show some example solutions of the tsunami sources reconstructed using the inversion procedure described in Section 2.4. These sources have rupture lengths of 1000 km to 1200 km, and a rupture width of 100 km. The magnitudes of these three sources are 9.5, 9.5 to 9.4, with average slips of 39.2 m, 36.9 m and 35.3 m, respectively. These are the representative distant tsunami sources dominating the 2500-year hazards along California's coastlines.

We emphasize that the 2500-year offshore tsunami amplitudes resulting from the PTHA accommodate the statistical uncertainty of inundation map modeling. Therefore, the tsunami sources to match the specific offshore tsunami amplitudes may require seismic source displacements that are greater than the mean 2500-year earthquakes. The offshore tsunami amplitudes play an important role in the reliability calibration of the whole design methodology. To achieve a targeted reliability to maintain a low probability of failure, the statistical uncertainty of inundation map modeling is embedded in the prescribed amplitude of the offshore tsunami. The uncertainty of inundation map modeling reflects the statistical degree of fit of the inundation model compared to actual tsunami records and runup heights. Although they may not be fully consistent with the earthquake rupture characteristics in a specific subduction zone, the reconstructed tsunami sources provide information on the extent of the offshore fault affecting the match of the PTHA offshore tsunami amplitude for a particular inland region.

3.2. TDZ Maps Developed for ASCE7

Once the tsunami sources are determined, the tsunami models described in Section 2.6 are used to compute the TDZ. We note here that the computational results obtained from a tsunami source are only valid for the segment of coastline used to reconstruct that source. When a segment of coastline is dominated by multiple tsunami sources, an envelope of the inundation areas is then used to define the final TDZ.

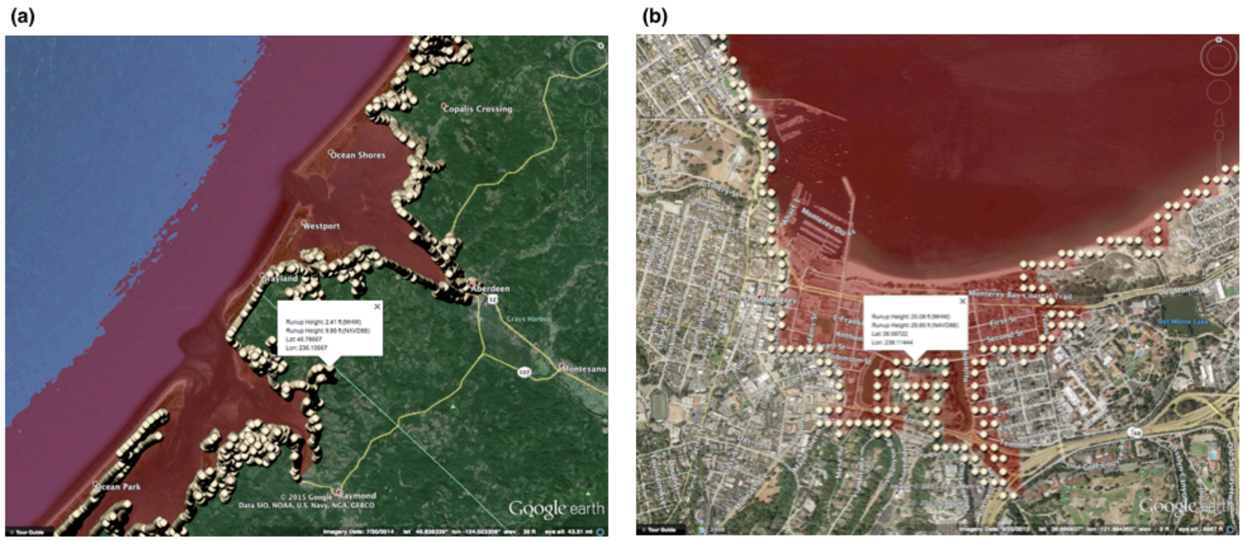

Fig. 8 – (a) TDZ for Ocean Shores, Westport, and Long Beach, Washington; (b) TDZ for Monterey, California.

Figure 8 shows the TDZ for Ocean Shores, Westport and Long Beach, Washington, and Monterey, California. The TDZ is displayed in Google Earth kmz, with tsunami inundation shaded in red. The TDZ is defined as the inundated areas between the shoreline and the inundation limit. The circles in Fig. 8 are runup heights obtained at the grid nodes of the model's C grid along the inundation limit. Clicking on any of the runup points in Google Earth brings up a pop-up window showing the coordinates of the location (longitude and latitudes) and two runup heights, one referenced to the MHW and the other referenced to the North America Vertical Datum 1988 (NAVD88).

Figure 9 shows examples of the TDZ maps for Puget Sound, Washington. Inundation hazards from both distant and local sources are considered in Puget Sound TDZs. The distant tsunami impact comes from the 2500-year tsunami scenario in the CSZ, the tsunami source (1) shown in Fig. 6. The local impact comes from three potential local faults, the Seattle Fault, the Tacoma Fault, and the Rosedale Fault. The TDZ shown in Fig. 9 is the envelope of inundation hazards produced by all four scenarios. The model results show that, although the distant CSZ source may produce inundation in the Puget Sound, the inundation hazards are mostly dominated by tsunamis caused by the local faults.

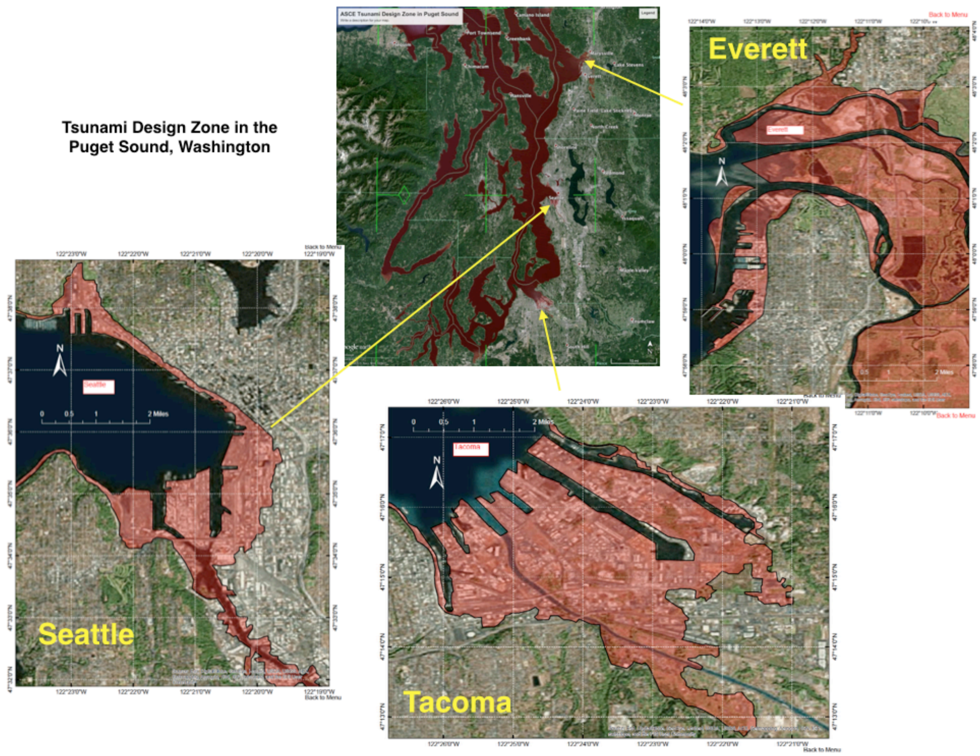

Fig. 9 – TDZ for Puget Sound, Washington.

4. Conclusions and Future Work

The ASCE TLSEC is completing a chapter of *Tsunami Loads and Effects* for the 2016 edition of ASCE/SEI 7 Standard to establish a national standard of engineering design for tsunami loads and effects. As a critical part of the ASCE 7 Standard, this study develops TDZ maps based on the 2500-year PTHA maximum tsunami amplitudes at 100 m water depth offshore. The TDZ maps provide fundamental input of inundation distance and runup elevations for ASCE's EGL analysis for engineers to calculate the tsunami effects on specific structures in the TDZ. The TDZ maps are developed for a majority of coastlines of the five Pacific states of the U.S.: Alaska, Washington, Oregon, California and Hawaii. In this study, we have examined the methodology, procedures and example results of the TDZ development for the U.S. West Coast. We used an inversion process to reconstruct tsunami sources to match the model results with PTHA 2500-year maximum tsunami amplitudes offshore. These tsunami sources are employed in inundation models to compute the TDZ at a grid resolution of 2 arc sec (~ 60 m). A total of 19 such large tsunami inundation models were developed and used for the entire coastlines along the U.S. West Coast. Examples of the established TDZ maps are shown in the format of Google Earth kmz for their use for ASCE's EGL analysis. It is worth pointing out that, although we only discuss TDZ development for the U.S. West Coast, the ASCE TDZ maps also include most of the coastlines of Alaska and Hawaii.

The TDZ maps developed through this study are currently under review by experts, geologists and emergency managers from the states of California and Oregon. The TDZ maps are being compared with state tsunami inundation maps that were developed using deterministic (Witter et al., 2011) or probabilistic (Thio et al., 2010) methods. The format of the TDZ products will include metadata, Google Earth kmz and GIS layers, as well as paper example maps. Future efforts of improving these TDZ include higher-resolution inundation modeling using a grid resolution of 1/3 arc sec (~10 m) or finer for selected sites. Systematic modeling efforts to update the TDZ are to be carried out in coordination with the National Tsunami Hazards Mitigation Program.

5. Acknowledgements

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6. References

ANNAKA, T., et al., "*Logic-tree approach for probabilistic tsunami hazard analysis and its applications to the Japanese Coasts*" Pure and Applied Geophysics, 164, 2007, pp. 577-592.

BURBRIDGE, D., CUMMINGS, P.R., MLECZKO, R. and THIO, H.K., "*A probabilistic tsunami hazard assessment for western Australia*". Pure and Applied Geophysics, 165, 2008, pp. 2059-2088.

BURWELL, D., TOLKOVA, E., and CHAWLA, A, "*Diffusion and dispersion characterization of a numerical tsunami model*". Ocean Modelling, 19(1–2), 2007, pp 10–30.

CARDNO, C.A., "*NSW tsunami inundation modeling and risk assessment*", LJ2874/Rep2703, prepared for NSW Office of Environmental and Heritage and NSW State Emergency Service, 2012, 56 pp.

EAKINS, B.W., and TAYLOR, L.A., "*Seamlessly integrating bathymetric and topographic data to support tsunami modeling and forecasting efforts"*, in Ocean Globe, ed. by J. Breman, ESRI Press, Redlands, 2010, pp. 37-56.

GEIST, E.L. and PARSONS, T., "*Probabilistic analysis of tsunami hazards*". Natural Hazards, 37, 2006, pp. 272-314.

GICA, E., SPILLANE, M., TITOV, V.V., CHAMBERLIN, C., and NEWMAN, J.C., "*Development of the forecast propagation database for NOAA's Short-term Inundation Forecast for Tsunamis (SIFT)"*. NOAA Tech. Memo. OAR PMEL-139, 2008, 89 pp.

GONZÁLEZ, F.I., et al., "*Probabilistic tsunami hazard assessment at Seaside, Oregon, for near- and far-field seismic sources*", *J. Geophys. Res.*, *114*, 2009, C11023, doi:10.1029/2008JC005132.

GONZÁLEZ, F.I., LeVEQUE, R.J., ADAMS, L.M., "*Probabilistic Tsunami Hazard Assessment (PTHA) for Crescent City, CA (Final Report on Phase I), Pilot Study funded by BakerAECOM*", 2013, 70 pp.

MCGUIRE, R.K., "Seismic hazard and risk analysis", Earthquake Engineering Research Institute, Oakland, CA, 2004, 240 pp.

OKADA, Y., "Surface deformation due to shear and tensile faults in a half space", Bull. Seismol. Soc. Am. 75(4), 1985, pp. 1135–1154.

POWER, W., WANG, X., LANE, E., and GILLBREAND, P., "*A probabilistic tsunami hazard study of the Auckland region, Part I: propagation modeling and tsunami hazard assessment at the shoreline*", Pure and Applied Geophysics, 170, 2012, pp. 1621-1634.

SYNOLAKIS, C.E., et al., "Validation and verification of tsunami numerical models". Pure Appl. Geophys., 165(11–12), 2008, pp. 2197–2228.

TANG, L., TITOV, V.V., and CHAMBERLIN, C.D., "Development, testing, and applications of site-specific tsunami inundation models for real-time forecasting", J. Geophys. Res., 114, 2009, C12025, doi:10.1029/2009JC005476.

TANG, L., et al., "*Direct energy estimation of the 2011 Japan tsunami using deep-ocean pressure measurements*". J. Geophys. Res., 117, 2012, C08008, doi:10.1029/2011JC007635.

THIO, H.K., SOMERVILLE, P. and POLET, J., "*Probabilistic tsunami hazard in California*", PEER report 2010.108, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, 2010.

TITOV, V.V., "*Tsunami forecasting*". Chapter 12 in The Sea, Volume 15: Tsunamis, Harvard University Press, Cambridge, MA and London, England, 2009, pp 371–400.

TITOV, V.V., and GONZÁLEZ, F.I., "Implementation and testing of the Method of Splitting Tsunami (MOST) model", NOAA Tech. Memo. ERL PMEL-112 (PB98-122773), NOAA/Pacific Marine Environmental Laboratory, Seattle, WA, 1997, 11 pp.

TITOV, V.V., and SYNOLAKIS, C.E., "*Extreme inundation flows during the Hokkaido-Nansei-Oki tsunami*". Geophys. Res. Lett., 24(11), 1997, pp 1315–1318.

WEI, Y., et al., Real-time experimental forecast of the Peruvian tsunami of August 2007 for U.S. coastlines. Geophys. Res. Lett., 35, 2008, L04609, doi:10.1029/2007GL032250.

WEI, Y., et al., Modeling of the 2011 Japan tsunami - Lessons for near-field forecast. Pure Appl. Geophys., 170(6–8), doi: 10.1007/s00024-012-0519-z, 2013, pp. 1309–1331.

WITTER, R.C., et al. "Simulating tsunami inundation at Bandon, Coos County, Oregon, using hypothetical Cascadia and Alaska earthquake scenarios", Special Paper 43, State of Oregon Department of Geology and Mineral Industries, 2011, 57 pp.

ZHOU, H., WEI, Y., and TITOV, V.V., "Dispersive modeling of the 2009 Samoa tsunami". Geophys. Res. Lett., 39(16), 2012, L16603, doi:1029/2012GL053068.