DEVELOPMENT AND APPLICATIONS OF PROBABILISTIC TSUNAMI HAZARD MAPS FOR THE WESTERN USA

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ABSTRACT

With the adaptation of the tsunami provisions included in ASCE 7-16 into the revision of the International Building Code, and other applications of tsunami hazard for Performance Based Engineering, Probabilistic Tsunami Hazard Analysis has become generally accepted as a method for evaluating tsunami hazard and the determination of tsunami design parameters. In this paper, we present an outline of the probabilistic methodology adopted in ASCE 7-16, which closely follows the seismological practice in practice but deviates significantly from the purely empirical driven approach by using numerical simulations to represent wave propagation in lieu of the traditional ground motion prediction equations (GMPEs).

Computational considerations have so far favored a hybrid approach with an intermediate step that involves the computation of offshore probabilistic hazard where linearity of the propagating medium means that we can efficiently integrate over a very large (tens of thousands) scenarios. Aleatory variability and epistemic uncertainty are integral components of a probabilistic hazard analysis and are given the full treatment in ASCE 7-16. We will demonstrate how the different contributions to the aleatory variability affect the resulting hazard curve, and also show the sensitivity to the epistemic uncertainty. High-resolution inundation maps are produced by sampling the offshore hazard curve with scenarios from sources that correspond to the most significant contributions from the disaggregation. This approach enables us to account for further aleatory variability in the inundation process. We present examples inundation maps for the western US and discuss their application in building design.

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Development and Applications of Probabilistic Tsunami Hazard Maps for the western USA

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\section*{ABSTRACT}

With the adaptation of the tsunami provisions included in ASCE 7-16 into the revision of the International Building Code, and other applications of tsunami hazard for Performance Based Engineering, Probabilistic Tsunami Hazard Analysis has become generally accepted as a method for evaluating tsunami hazard and the determination of tsunami design parameters. In this paper, we present an outline of the probabilistic methodology adopted in ASCE 7-16, which closely follows the seismological practice in practice but deviates significantly from the purely empirical driven approach by using numerical simulations to represent wave propagation in lieu of the traditional ground motion prediction equations (GMPEs). Computational considerations have so far favored a hybrid approach with an intermediate step that involves the computation of offshore probabilistic hazard where linearity of the propagating medium means that we can efficiently integrate over a very large (tens of thousands) scenarios. Aleatory variability and epistemic uncertainty are integral components of a probabilistic hazard analysis and are given the full treatment in ASCE 7-16. We will demonstrate how the different contributions to the aleatory variability affect the resulting hazard curve, and also show the sensitivity to the epistemic uncertainty. High-resolution inundation maps are produced by sampling the offshore hazard curve with scenarios from sources that correspond to the most significant contributions from the disaggregation. This approach enables us to account for further aleatory variability in the inundation process. We present example inundation maps for the western US and discuss their application in building design.

\section*{Introduction}

Over the last decade and a half, several destructive tsunamis have occurred with large loss of life and very significant economic losses. Of the five most significant tsunamis, three (2004 Sumatra-Andaman, 2009 Samoa and 2011 Tohoku) were for one reason or another unexpected, either in occurrence or at least in size, because of which the regions were being caught un- or under-prepared resulting in subsequent large losses. These disasters highlighted the need for comprehensive and systematic tools for tsunami hazard analysis. Probabilistic Tsunami Hazard Analysis (PTHA) has, over the last decade, become an established methodology for quantifying tsunami hazard for global risk analyses, engineering design and emergency preparedness. In this paper, we present the results of

In order to ensure consistency with seismic analysis, our approach closely follows, where

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possible, the Probabilistic Seismic Hazard Analysis practice. For instance, the overall framework and inputs remain quite similar to facilitate model exchange between the PSHA and PTHA. There are however some important differences between PSHA and PTHA. The most important difference between the two is the impracticality of using something similar to GMPEs in tsunami hazard due to the very strong dependence of tsunami wave-heights on bathymetry, which precludes the use of simple magnitude distance relations. Fortunately, since the global bathymetry is well constrained and computational algorithms are sufficiently accurate it is possible to replace the GMPE-type relations with actual computed tsunami waveforms. Especially for wave modeling in deep water the propagation can be approximated using linear methods, which makes it feasible to integrate over thousands of tsunami scenarios similar to PSHA.

The long recurrence times for tsunamis compared to our observational window dictate that the problem is approached in a judgment-based rather than a frequentist approach. The probabilities of the hazard are therefore based on our current understanding of the causation of the hazard (including alternative models) as well as randomness that is inherent on complex physical systems such as the Earth.

Figure 1. Source zones around the Pacific Ocean that are included in the PTHA results presented in this paper.
**Aleatory variability**

Aleatory variability is defined as the natural variability, or randomness, inherent to the physical processes involved. It is often included through probability distributions of the parameter involved, such as magnitude distributions. In other cases, such as slip variations on a fault, they can be solved numerically by summing over a large number instances of the same earthquake with different, possibly stochastic, slip patterns. Due to the significant numerical load of performing a fully stochastic simulation, we have opted for using a simpler asperity model where every event is represented by three instances where one third of the area is characterized by an asperity with larger slip compared to the rest of the rupture.

Tidal level is also an aleatory variability, the coincidence with of a tsunami arrival with a specific tidal stage is a random process, although the tidal record itself can be regarded as a deterministic signal. For the offshore Green’s function based hazard, we can add an aleatory tidal component by convolving the Green’s function with the predicted or measured tidal record for that area over a sufficiently long time period of the Green’s function, to ensure that all the significant arrivals are taken into account, and over a long enough tidal record to ensure that we include all the variability of the tides, including seasonal effects if necessary.

**Epistemic uncertainty**

The epistemic uncertainty, which represents the different understandings of Earth’s processes, including tectonics and earthquake physics, is primarily considered in the source models of the tsunami. These include different maximum magnitudes, segmentation, recurrence times and convergence rates. Ocean propagation is generally a well-understood process, and ocean bathymetric models are sufficiently precise to warrant the use of a single model. For the nearshore regime, there is certainly the possibility of significant epistemic uncertainty, such as bottom friction, nearshore bathymetry, numerical approximations and implementations, etc. For this study, we have used a single (mean) approach for the nearshore/inundation hazard, since currently the uncertainties in the source model dominate the epistemic component and because of computational loads. We expect that in future implementations, some epistemic branching may occur in the nearshore/inundation regime as well.

**Tsunami hazard maps**

**Offshore hazard**

The offshore hazard maps presented here form the basis of the probabilistic inundation hazard maps that are developed for ASCE 7-16 [1], the state of California inundation maps [2], and 1000 year inundation maps that are currently developed for the Western States’ (CA, OR, WA, AK, HI) Departments of Transportation for bridge design. These maps were obtained through the integration over thousands of earthquake instances from all the source zones shown in Figure 1.

**Computing inundation maps**

There are several ways in which we can obtain the probabilistic inundation from the offshore
exceedance amplitudes:

- Onshore projection using empirical relationships or analytical runup laws – These functions typically yield the amplification from the offshore point to the final runup point as function of local parameters such as slope of the topography/bathymetry, period of the wave, offshore amplitude, etc. This method is the least accurate of the three but can handle large areas efficiently and is therefore very useful for large scale loss estimates[3].

- Offshore amplitude matching – Scenarios are selected, using the source disaggregation, with their magnitude adjusted so that their offshore amplitudes match the probabilistic exceedance amplitudes. The inundation is then a direct reflection of the offshore exceedance amplitudes. This is the method used by [4] to obtain the inundation design zones for ASCE 7-16.

- Sampling of the offshore hazard curve – Instead of directly matching the offshore exceedance amplitudes, we define a reduced suite of scenarios that represent the probabilistic hazard

The last method is used for this project and discussed in this report and has the advantage of allowing us to apply an aleatory variability of the inundation to the runup result. We have computed 30 distant scenarios from Alaska, Chile and the Kuriles, the dominant distant sources in California, that span a range of sizes and cover the entire range of offshore exceedance.
amplitudes. For areas along the Cascadia subduction zone, we expanded this set with another 30 Cascadia scenarios. Our assumption is that this event set is representative for the tsunami hazard in California.

To compute the probabilistic inundation from this set, we need to determine the rate of occurrence for each scenario, i.e. the probability distribution of the reduced event set.

The metrics that we use are the offshore amplitudes of these scenarios at the same locations for which we derived the offshore hazard curves. Since we are considering a discrete number of events, the probability distribution of the offshore amplitudes of the reduced set \( (p) \) is a Probability Mass Function (PMF), which can be determined from the offshore hazard curve \( (P) \), a Cumulative Density Function (CDF), since the probabilities of the reduced event set need to satisfy the offshore hazard curves.

In summary:

The probabilities are anchored to the probabilistic offshore amplitudes, so we define the probability for event \( i \), \( p_i \), as the probability of its offshore amplitude \( a_i \): \( p_i = p(a_i) \).

The events are sorted according to their offshore amplitudes: \( a_i < a_{i+1} \), with the number of events in our reduced set \( n \).

The offshore hazard curve (CDF), expresses the probability of exceeding an amplitude \( A \): \( P(a \geq A) \).

Then:

\[
p_i = p(a_i) = P(a \geq a_i) - \sum_{k=i+1}^{n} p(a_k)
\]

Note that this is essentially the inverse of the process by which the offshore hazard curves were obtained from the original, comprehensive, set of events, which was several orders of magnitude larger.

Once the event probabilities, or rates, have been determined, it is possible to compute the inundation hazard curves at every cell in the same way as the offshore hazard curves were computed. We note that at each cell the hazard curve is computed independently, so that in theory the inundation at the same probability level in different cells can be affected by different scenarios from the reduced event set, which is preferable over the other approaches where one or two scenarios determine the inundation in the entire model. Such a situation might arise if different source regions yield very different inundation patterns. In our experience in California, this source dependence does not seem to play a large role for the distant events but may be an
issue in some near-source environments in Cascadia. A comparison between two inundation maps, one produced with the full event set and one with only distant events (Figure 4) suggest that the sensitivity to the sources is small with this method.

**Examples of inundation maps**

In Figure 5 we present the 2500 yr inundation and velocity maps for the south Bay area of Los Angeles, including the Ports of Los Angeles and Long Beach. The inundation maps were computed for grids with a resolution of .32 arcsec (~10m) that were developed by NOAA. Similar map have been developed for almost all inhabited areas along the California coast for return periods between 72-3000 year. For select areas in Oregon (bridge locations), 10m resolution maps for 1,000 year ARP have been developed and for the rest of Oregon, Washington state, Alaska and Hawai‘i 60m resolution maps were developed for the return period.
Conclusions

Currently, probabilistic mapping for the western United States for ASCE 7-16 (2500 yr ARP), the state of California (72-3000 yr ARP), and the Western States Departments of Transportation (1000 yr ARP) have been completed or are in the process of being completed for several

Figure 5. Exceedance flow depths (top) and flow velocities (2475 yr ARP) in the Ports of Los Angeles and Long Beach and northern Orange County.
engineering and general hazard mitigation purposes. These maps are based on a fully probabilistic framework that takes into account both aleatory variability at all stages of the process (source, ocean propagation, inundation) as well as epistemic uncertainties in the source models.

References


