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Tsunami Hazards of the Pacific Rim

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ABSTRACT: The Pacific Rim has a well-documented and extensive history of tsunamis, the vast majority of them related to large subduction zone earthquakes. Tsunami hazard analysis poses some unique challenges compared to other hazards due to the long "reach" of the tsunamis and the great importance of large in-frequent events such as the 2004 Sumatra-Andaman and the 2011 Tohoku earthquakes. Methods for probabilistic tsunami hazard analysis (PTHA) have been developed over the last decade and are now being applied for a variety of mitigation purposes, both in engineering as well a public safety in general. Here, we present our methodology, which includes a comprehensive coverage of aleatory variability and epistemic uncertainties. We present the results of several probabilistic tsunami hazard mapping studies that have been carried out across the Pacific basin, for a diverse set of interests such as State planning, transportation safety, building codes and insurance. We will also demonstrate how these results are applied in site-specific inundation studies using both approximate means, such as specified in the new chapter on tsunami loads of the ASCE 7-16 seismic design guidelines, as well as advanced inundation algorithms where full advanced non-linear inundation calculations are combined with high-resolution elevation models for accurate modeling of engineering impact.

1 INTRODUCTION

Probabilistic seismic hazard analysis (PSHA) has been a primary tool in the development of design criteria for buildings and infrastructure in engineering for the last few decades. Its use is intricately linked to the use of Performance Based Engineering (PBE) principles, where building design is based on several levels of performance (safe-use, collapse prevention, etc.), which are linked to a particular probability of exceedance of a ground motion level. Risk based analyses also inherently depend on a probabilistic expression of the hazard, and it is thus desirable to follow a similar framework for tsunami hazard analysis (McGuire, 2004).

For PTHA, the most obvious metric is the exceedance of a water level, wave amplitude or flow depth, as these are the most visible and recorded aspect of tsunami waves. There are however other metrics that may be more suited for certain purposes, such as flow velocities in ports and harbors or momentum for impact on structures. The current methodology has been developed up to compute probabilities of wave height exceedance but can be adapted to analyze other metrics as well.

In performance based engineering, these probability levels may be tied to a specific performance level, for instance a building may be designed to remain operable for 475 yr ARP level ground motions, be temporarily inoperable but repairable within a reasonable amount of time for the 975 year ground motion levels and not collapse (but be permanently in-operable) for 2475 yr events ("life-safety").

Probabilistic tsunami hazard analysis, like its seismic counterpart, follows a dualistic approach to probability. Whereas some aspects are defined in the familiar terms of frequency of occurrence (such as intermediate earthquake recurrence, magnitude distribution), others are more based on judgment, which is a subjective approach (Vick, 2002). For instance, we may characterize the recurrence of intermediate earthquakes in terms of a Gutenberg-Richter distribution, constrained by a catalog of historical earthquakes. The assumption is that the occurrence of earthquakes is a stationary process, and that the catalog represents a homogenous sample of the long-term seismic behavior of a source. For large earthquakes however, the return times are sometimes so long relative to our historic record, even when paleo-seismic data is included, that the recurrence properties of these events cannot be described with a stationary model based on a regression of observed earthquake occurrence. We therefore need to introduce the concept of judgment, where we use our current understanding of earthquake processes, including analyses of similar structures elsewhere and other information, such as local geological conditions, strain rates etc., to make assumptions on the recurrence of large earthquakes. This is a subjective approach to probability, centered on the observer rather than the observations, and will inevitably be different from one practitioner to the other. A rigorous PTHA model therefore includes the use of logic trees to express alternative understandings of the same process, e.g. large earthquake recurrence, weighted by the subjective likelihood of that alternative model ("degree of belief"), where the weights of the alternatives sum to unity. A probabilistic result is always the probability of a hazard level being exceeded due to natural processes and **given our current understanding of the Earth and its processes**. We shall explain in a later section how this distinction is manifested in the handling of uncertainties throughout the analysis.

2 PROBABILISTIC TSUNAMI HAZARD ANALYSIS

In order to ensure consistency with seismic practice, the URS approach closely follows, where possible, the PSHA 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.

2.1 Comparison to PSHA

The most important difference between the two is the impracticality of using something similar to Ground Motion Prediction Equation (GMPE's, aka Attenuation relations) in tsunami hazard due to the very strong dependence of tsunami waveheights on bathymetry, which precludes the use of simple magnitude distance relations. Fortunately, since the global bathymetry is relatively well constrained and computational algorithms are sufficiently accurate and efficient, it is possible to replace the GMPE-type relations with actual computed tsunami waveforms. Another important difference is the different sensitivity to earthquake size. Ground motions do scale up with increasing earthquake magnitude, but in most GMPE's this scaling flattens out towards the largest magnitudes. Therefore, increasing the maximum magnitude in an earthquake model will not raise the hazard proportionally, and in fact in a PSHA, depending on how the earthquake rate is defined, increasing the magnitude may lead to a decrease in the probabilistic hazard. In tsunami hazard, however, the initial waveheights scale proportionally with the amount of slip on the fault for the entire magnitude range, and in fact the volume of water that is displaced increases not only with the increase in waveheight but also the increased extent of the source. Finally, increased length (along strike) of the source leads to a more linear than circular wavefront for the tsunami, which reduces the attenuating effect of geometrical spreading as the wave propagates out across the ocean.

It is therefore of utmost importance to constrain the upper bounds of the earthquake magnitudes and their recurrence rates for an accurate and complete tsunami hazard analysis.

We can summarize the methodology with the following list of steps, with details discussed in later sections:

<u>Step 1: Offshore hazard</u>

- Identification and setup (subfault partitioning) of earthquake sources
- Computation of fundamental Green's functions for every sub-fault to near-shore locations
- Definition of earthquake recurrence model
- Generation of a large set of scenario events that represents the full integration over earthquake magnitudes, locations and sources, for every logic tree branch
- Computation of near-shore probabilistic waveheight exceedance rates (Figure 2)

<u>Step 2: Inundation hazard</u>

- Identification of dominant sources through source dis-aggregation (Figure 3)
- Computation of probabilistic inundation hazard by computing non-linear runup using

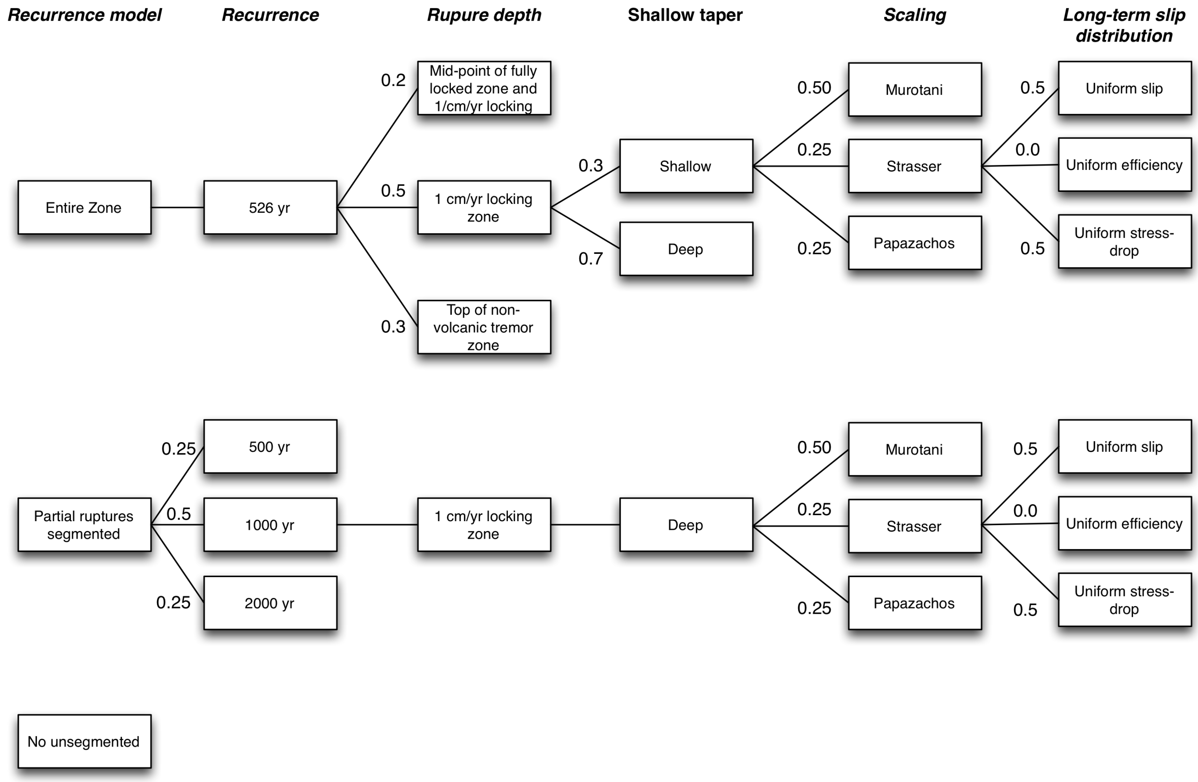

Figure 1. Example of a source logic tree (for the Cascadia subduction zone) showing the different epistemic branches such as depth extent, surface extent and scaling relations.

disaggregated sources and offshore waveheights

3 METHODOLOGY

Since our approach to PTHA is based on numerical simulations rather than empirical relations, we shall first describe the state of practice in tsunami modeling. This process is usually split into two separate processes: source characterization and tsunami propagation. Tsunami formation results from the deformation of the seafloor, which, in the case of an incompressible liquid and rate of deformation that is much faster than tsunami propagation speed, translates directly in an equivalent vertical disturbance of the sea-surface. It is this disturbance that forms the input condition for the tsunami propagation calculations.

3.1 Source characterization

Earthquake sources are often represented as dislocations on rectangular planes defined by strike and dip. This idealized geometry can deviate significantly from the real situation especially in subduction zones, where the dip tends to increase away from the trench (e.g. Ross et al., 2013). Seafloor uplift due to a dislocation source can be computed using a variety of ways, the most common being Okada's (1992) analytical formulation for displacement resulting from a rectangular dislocation in a half-space. Other methods, such as the FK method for computing synthetic seismograms are more versatile as they can accommodate layered crustal structure (Wang et al, 2003/2004).

Recurrence relations for the sources are identical to those used in seismic hazard analysis, and we refer to McGuire (2004) for a discussion on those issues.

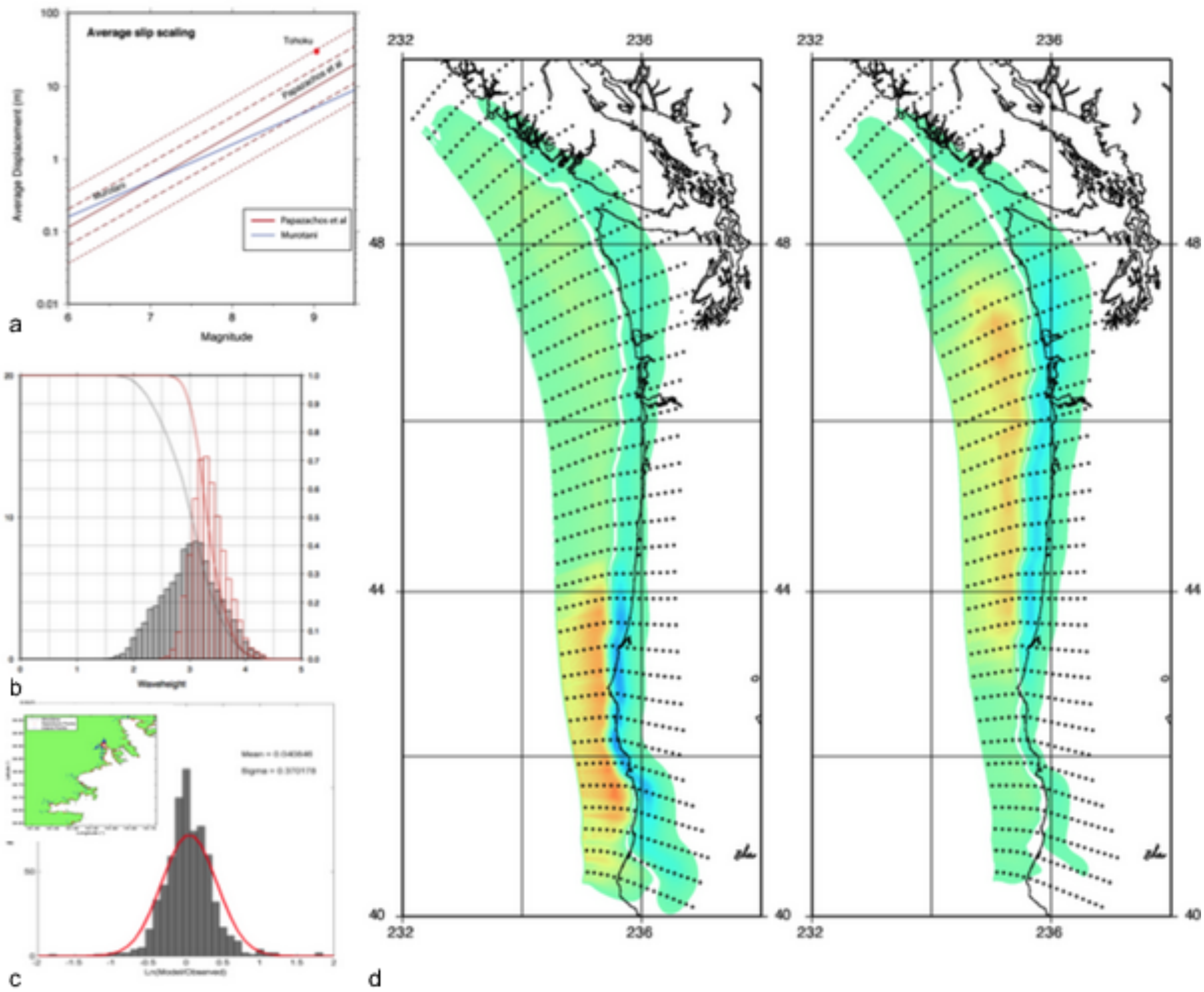

Figure 2. Examples of epistemic uncertainty and aleatory variability. a – different scaling relations (in this case between slip and magnitude) represent a different understanding of a natural process, and thereforeare epistemic uncertainty. The variability in the mean values, expressed by the dashed lines, however, represent an aleatory variability. b – aleatory variability due to tidal variations. The grey bars represent the distribution of the tidal signal, the redbars show the distribution of the convolution of the tidal signal with the timeseries for this particular scenario. c – the aleatory variability due to modeling errors are shown by comparing the observed tsunami heights with the modeled heights for a well-constrained and recorded event, in this case the Tohoku earthquake. d – slip variability is taken into account by using multiple instances (2 out of 3 are shown) for the same type of earthquake with different locations for the asperity.

3.2 **Tsunami models**

Because of their long wavelengths (100's of kilometers), relative to the depth of the oceans (up to 10 km), we can use the long wave approximation to the governing equations of water waves, the Navier-Stokes and continuity equations. For tsunami simulations these equations are typically solved in two dimensions, with vertical accelerations either ignored completely (shallow water or hydrostatic approximation) or approximated in Bousinesq-type models. The simplest (and computationally fastest) form uses the linear shallow water equations. These are generally adequate for tsunami modeling on open oceans but not for near-shore environments as they don't include bottom friction or inundation. Non-linear shallow water equations are generally suitable for nearshore and inundation studies, although details in the algorithms can be important in under certain conditions. For instance, finite volume methods, which preserve momentum tend to be more accurate in situations where bore-formation is prevalent.

For nearshore and runup modeling, bottom friction is an important parameter. This dissipative effect can have a large influence on extent of the inundation and flow velocities.

3.3 Bathymetric models

Accurate bathymetric and topographic models are essential for tsunami hazard studies. For open ocean modeling, global models such GEBCO or ETOPO1 provide sufficient accuracy, but in near-shore regions these are often insufficient, both in term of accuracy as well as horizontal resolution. Likewise, the global topographic models such SRTM and ASTER are not accurate enough for detailed inundation modeling. The errors are one the order of 10-15 meters and especially in the case of SRTM, there appears to be a systematic bias to higher elevations in coastal areas (Figure). It is therefore necessary to use high-resolution data, such as local geodetic data or LiDAR to constrain the topography. For many localities the United States and its territories, NOAA has developed a set of high-resolution (down to 10 m) digital elevation models based on best available data including coastal LiDAR, which provides a consistent dataset for tsunami modeling in the United States.

3.4 Epistemic Uncertainties

As mentioned before, a probabilistic analysis is more than an expression of natural probabilities of a hazard level being exceeded, it also contains a component that expresses limitations in our understanding of natural processes and different opinions regarding these processes. This is refereed to as epistemic uncertainty, and is usually accounted for using a logic tree approach (Figure 1), where every branch represents a potential physical model with an associated weight. Typical aspects of the earthquake process that are included as logic tree branches are:

- rupture segmentation – segmentation models describe whether ruptures on fault systems follow repeated segment, or can break over multiple segments, therefore affecting the maximum magnitude and rupture extent.
- updip and down-dip rupture limits – whether ruptures break to the surface or not can have profound implications for the tsunami generation. The downdip rupture extent has implications for the maximum slip as well as uplift or subsidence patterns along the coast line.
- seismic scaling relations - various authors have established different relations between rupture length, width, slip and magnitude (e.g. Murotani et al., 2008, Strasser et al., 2010) (Figure 2a).
- seismic slip rates – although convergence rates for subduction zones are generally well-known, the fraction of the convergence that accommodated by is seismic (or more accurately tsunamigenic) slip varies between different subduction zones and even within the same subduction zone

3.5 Aleatory variability

Aleatory variability refers to the unpredictability of certain aspects of a process, such as the slip distribution of an earthquake.

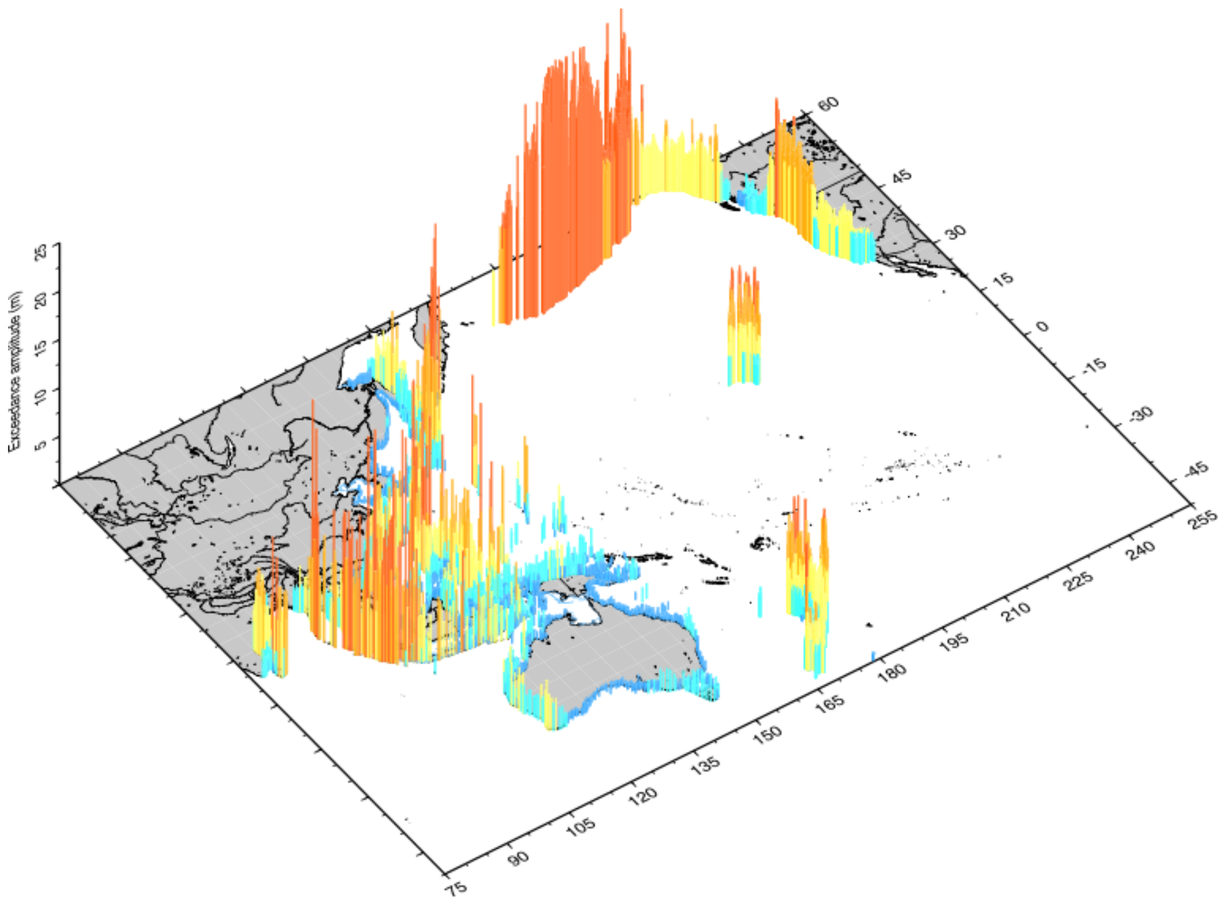

Figure 3. A compilation of offshore hazard values for a 2500 yr return period around the Pacific and Indian Ocean.

- Magnitude – the individual scaling relations mentioned in the epistemic section not only provide mean relations but also the variability about the mean, which usually are typically included as a set of weighted maximum magnitudes around the mean (Figure 2a).
- Tides - For the linear case, tidal variability can most easily be included through a convolution of a sufficiently long tidal record and the actual tsunami timeseries. The convolution is necessary over a simple multiplication of the distribution functions since the tsunami waves tend to consist of multiple arrivals in time with similar amplitudes so that the probability of coincident tsunami and tidal highs increases with increasing "ringing" of the tsunami waves (Figure 2b).
- Modeling – In PSHA, the aleatory variability ("sigma") in the GMPE's is implicitly derived as part of the regression. In PTHA, where we use modeling in lieu of GMPE's, we have to determine the corresponding sigma's explicitly, by modeling tsunamis from well-defined earthquake sources with accurate bathymetric models (Figure 2c).
- Slip –it is still quite common practice to represent earthquake sources with uniform slip on a rectangular fault, even though seismic source studies have shown that the slip is very non-uniform and ruptures consist of patches of high slip (asperities) on a background of lower slip. Murotani et al. (2008) studied the slip distributions of several subduction zone earthquakes and found a ratio of maximum slip over average slip of 2.2. To include this slip variability, we represented every event with three instances of a variable slip rupture model with on third of the rupture as an asperity with twice the average slip and the other two-thirds of the rupture at half the average slip. This way, there is no risk that in some areas the hazard is over- or under-estimated due to incomplete or overlapping asperity coverage offshore (Figure 2d).

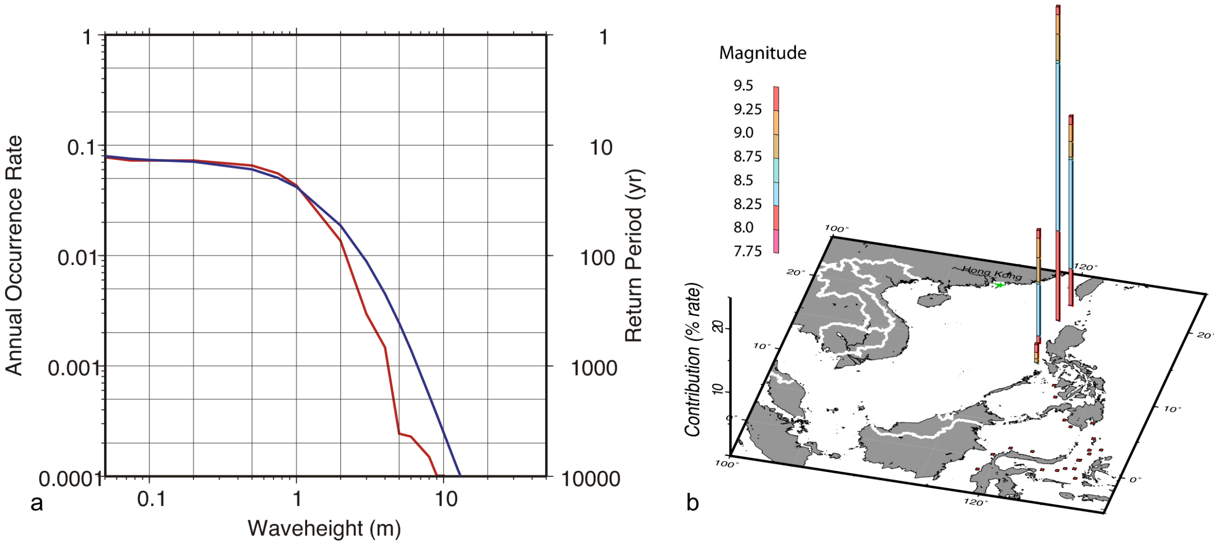

Figure 4. a - example of a tsunami hazard curve for a site near Hong Kong showing both the hazard without the modeling variability (red) and with the modeling uncertainty (blue) applied. b – soure and magnitude disaggregation of the hazard at the same site for 2500 year. Note that the hazard is dominated by the Manila trench and in particular the northern section, and by events with magnitudes between 8.25 and 8.75.

4 APPLICATIONS OF TSUNAMI HAZARD ANALYSIS

4.1 Mapping

In Figure 3 we present an overview map of offshore PTHA results for a return period of 2500 years, compiled from a number of studies by AECOM over the last decade. These maps have been computed using the Green's function summation method (Thio et al., 2010) and represent the integration over thousands of earthquakes. The overall pattern of the hazard is not surprising, with the areas directly offshore major subduction zones showing high hazards. Other areas that are know to have suffered large tsunamis such as Hawaii and Sri Lanka also show up clearly in this map. Note that the different regions have been produced with an evolving set of procedures and therefore one has to be careful to interpret the quantitative differences between different regions. In Figure 4 we present example hazard curves for a site near Hong Kong which shows the hazard steadily increasing even for long return periods, as is expected on the basis of the long recurrence times for very large earthquakes. The source and magnitude disaggregation (Figure 4b) shows that in this case the hazard is dominated by a single source, the Manila trench, with magnitudes around M8.5. This information is crucial in developing maps of tsunami inundation, which require expensive non-linear computations. Being able to reduce the number of computations by using the offshore hazard as a constraint enables us to produce probabilistic inundation maps at high resolution.

4.2 Inundation hazard

In Figure 5, we show an example of a probabilistic inundationmap that is based on the offshore hazard, in this case fo the Port of Los Angeles, California. This is from a preliminary draft inundation map that is being developed for the entire State of California. This map was computed using the GeoClaw code (Leveque et al., 2011) at a resolution of 10m. At this resolution, many important features such as levees and breakwaters are still prepresented as whole structures which greatly improves their accuracy over lower resolutions (even 30m). Without being able to limit ourselves to a few scenarios that are anchored by our offshore exceedance amplitudes, such a probabilistic inundation map would be prohibitiely expensive computationally.

4.3 Regulatory and code issues

The upcoming revision of the ASCE 7-16 "Minimum Design Loads for Buildings and Other

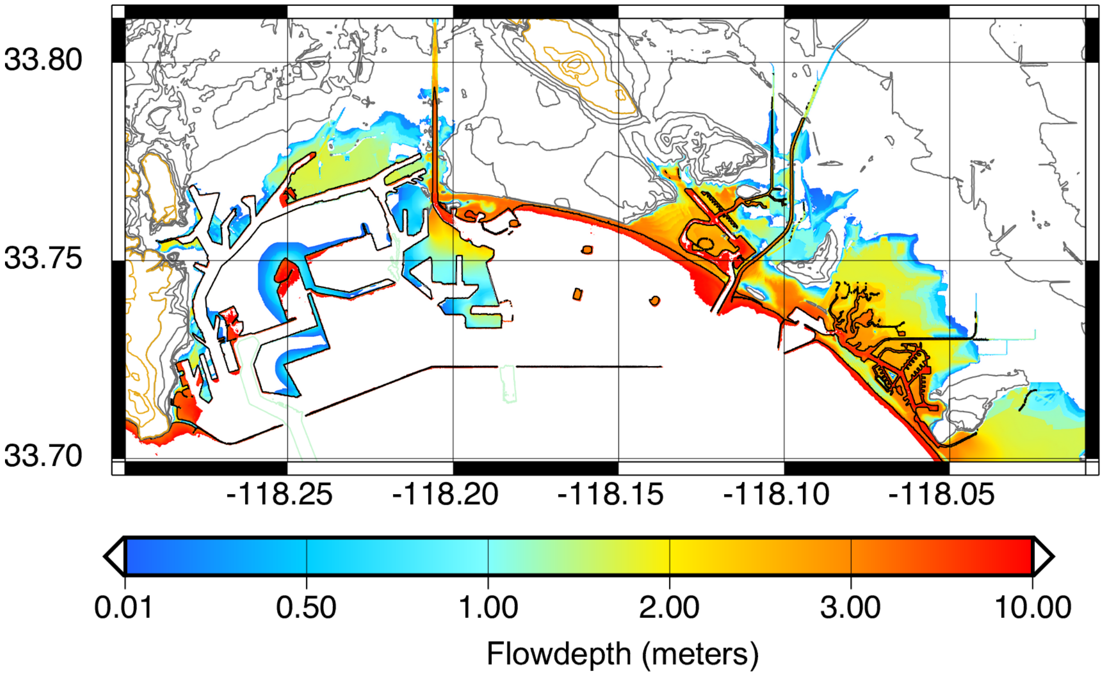

Figure 5. Example of a probabilistic inundation map (2500 yr) for the Port of Los Angeles and Long Beach, California. Note the extensive inundation inland on the low lying easten areas, as well as in substantial parts of the Port complex.

Structures" will include a new chapter on tsunami loads and effects. Similar to the seismic chapter, this will include design maps based on a probabilistic analysis for a return period of 2500 years. The design parameters come in two forms; a map of probabilistic offshore exceedance amplitudes and wave period at the 100 m depth contour and a map of derived tsunami inundation design zones and runup values that can be used as input for a simplified energy grade line procedure to compute conservative inundation parameters such a maximum flow depth and velocity at any point in the design zone (Chock, 2015).

5 CONCLUSION

Probabilistic tsunami hazard anaylsis is becoming a mature and effective way to quantify the hazard from tsunami waves in a framework that is consistent and compatible with other hazard estimates such as seismic hazard. The use of a two-step approach with a full probabilistic treatment for the offshore amplitudes and source disaggregation enables us to produce probabilistic inundation maps with reasonable computational requirements.

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