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Title: PROBABILISTIC TSUNAMI HAZARD ANALYSIS

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Abstract

We have developed a method for Probabilistic Tsunami Hazard Analysis (PTHA) based on the traditional Probabilistic Seismic Hazard Analysis (PSHA) and therefore completely consistent with standard seismic practice. In lieu of attenuation relations, it uses the summation of finite-difference Green's functions that have been pre-computed for individual subfaults, which enables us to rapidly construct scenario tsunami waveforms from an aggregate of subfaults that comprise a single large event. For every fault system, it is then possible to integrate over sets of thousands of events within a certain magnitude range that represents a fully probabilistic distribution.

1 Introduction

The recent tsunami disaster caused by the 2004 Sumatra-Andaman earthquake (Ammon et al, 2005) has focused our attention on the hazard posed by large subduction zone earthquakes and the tsunamis that they generate. Even before this destructive event, a significant amount of work was carried out in this field, primarily through deterministic modelling of tsunami scenarios (e.g. Borrero et al., 2005). Such studies often address worst-case scenarios or some type of maximum credible event. In order to put these types of studies on a firm basis, it is necessary to conduct a comprehensive review of tsunamigenic sources that can affect a certain locality, and determine the probabilistic hazard level based on this set of sources. Also, notwithstanding the great usefulness of individual scenario maps, in order to assess the hazard for a certain region, it may be more appropriate to start with a map of the tsunami hazard, analogous to the seismic hazard maps that are published by government agencies such as the United States Geological Survey and statewide agencies in the US, or the Global Seismic Hazard Assessment Program. Even though events like the Sumatra-Andaman earthquake and tsunami are rare, the very large loss of life (> 200,000 dead or missing) and tremendous material destruction over large geographical areas warrant a significant effort towards the mitigation of the tsunami hazard. In recent years, the risk posed by tsunami to United States coastal communities from a variety of sources have also become apparent and the need for a comprehensive and consistent methodology to evaluate this aspect of earthquake risk, which so far has been neglected compared to the attention paid to the hazard from strong ground motion, is obvious. On the other hand, where there is concern about tsunami damage, the lack of a consistent framework to evaluate this hazard has given rise to unnecessarily conservative estimates of the hazard, which can result in an economic barrier to development of coastal communities and facilities.

Given the maturity and widespread acceptance of Probabilistic Seismic Hazard Analysis (PSHA) in seismic hazard mitigation, we believe it would most beneficial to cast our methodology for tsunami hazard mitigation in a similar framework. By exploiting the commonality between tsunami and seismic hazard models, such as the earthquake recurrence models, we assure maximum consistency across the two disciplines, which facilitates the evaluation of the combined hazard posed to coastal communities, facilities and infrastructure.

2 Tsunami sources

Even though the occurrence of large tsunamis is rare, the potential for extensive loss of life and damage, as was demonstrated by the 2004 Sumatra-Andaman earthquake, merits a strong commitment toward tsunami hazard mitigation issues. The vast majority of tsunamis are caused by earthquake-induced displacement of the seafloor. Most of the world's largest tsunamis, which have caused damage at locations thousands of miles away, have been caused by megathrust (subduction interface) earthquakes around the Pacific Rim. These include the 1960 Chile earthquake, the 1964 Alaska earthquake and the 2004 Sumatra-Andaman earthquake. On a local scale, smaller earthquakes can cause significant tsunamis as well (Borrero et al., 2004). Generally, the hazard from these events is lower because of the longer recurrence rate, but is not negligible.

Earthquakes are by no means the only sources of tsunami. Submarine landslides, whether triggered by earthquakes or not, are another important source for tsunamis (Watts, 2004), and although their effects tend to be more localized (e.g. 1996 Flores earthquake), there is speculation that major submarine landslides (e.g. in Hawaii, Satake, 2001) and asteroid impacts (Ward and Aphaug, 2000) could generate giant tsunamis that could devastate coastal regions thousands of miles away. We have limited the scope of the current study to include only tsunamis that are directly generated by earthquakes but the method that we are developing will be able to address the problem of submarine landslides or catastrophic collapse as well as we will show later. Based on the much lower recurrence rates for these latter sources, we feel confident that the current model includes all the significant sources for return periods of up to 2500 years.

3 Probabilistic tsunami hazard analysis

Probabilistic Seismic Hazard Analysis (PSHA) has become standard practice in the evaluation and mitigation of seismic hazard to populations in particular with respect to structures, infrastructure and lifelines. Its ability to condense the complexities and variability of seismic activity into a manageable set of parameters greatly facilitates the design of effective seismic resistant buildings but also the planning of infrastructure projects. Probabilistic Tsunami Hazard Analysis (PTHA) achieves the same goal for hazards posed by tsunami. Although this field is not very developed yet, we believe there are great advantages of implementing such a method to evaluate the total risk (seismic and tsunami) to coastal communities, facilities and infrastructure.

Previous work on PTHA includes Downes and Stirling (2001) who proposed to use an empirical attenuation relation similar to ground motion attenuation relations. They recognize that such attenuation relations would have to be source and site specific, and we believe it doubtful whether there would ever be enough data available for such attenuations relations to be derived consistently. On the other hand, Geist and Parsons (2005) developed a method that uses the full linear calculations for a limited number of scenarios for earthquakes near the site. The main difference with their work is that through the Green's function summation, we can generate many more fault scenarios and at arbitrary distances including teleseismic, which allows us to run full probabilistic analyses over a much wider area. Also, our method is very efficient for the analysis of many sites simultaneously, which allows us to quickly identify areas at elevated risk. Such information is indispensable for the effective allocation of funds for tsunami hazard mitigation work.

The method that we have developed is based on the traditional PSHA and therefore completely consistent with standard seismic hazard practice. It provides an overview of the tsunami hazard along entire coastlines, and helps identify the specific tsunami source regions for which a particular site on the coastline is sensitive to.

3.1 Methodology

The methodology behind PSHA is well known (e.g. McGuire, 2004) and here we will only briefly describe the adaptations that are made for PTHA. Whereas in PSHA we are usually interested in the exceedance of some ground motion measure such as Peak Ground Acceleration (PGA) or Spectral Acceleration (SA), in PTHA a parameter of interest (not necessarily the only one) is the maximum tsunami height that is expected to be exceeded at sites along the coast. The statistical earthquake model behind the two methods is the same, the only difference being that in PTHA we are not concerned with earthquakes that are completely inland. The difference between the two methods lies in the part that in PSHA is referred to as attenuation relations. These relate a certain moment release on a fault (or an area) to the ground motion parameters as a function of distance. Because of the strong laterally varying nature of tsunami propagation, we have adopted a waveform excitation and propagation approach instead of trying to develop analogous tsunami attenuation relations. In fact, current developments in traditional PSHA include the replacement of the attenuation relations with ensembles of numerically generated ground motions, which is entirely analogous to the approach that we propose here.

The excitation and propagation of tsunamis in deeper water can be modeled using the shallow water wave approximation, which, for amplitudes that are significantly smaller than the water depth, are linear (Satake, 1995). We can solve the equation of motion numerically using a finite-difference method and in Figure 1 we show tsunami heights computed for the 2004 Sumatra-Andaman earthquake and 2005 Sumatra earthquake using this method. The numerical method has been validated to produce accurate tsunami heights for propagation through the oceans, although for very shallow water the amplitudes may become too large and more sophisticated non-linear methods are required to model the details of the run-up accurately. Nevertheless, the linear approach provides a very good first approximation of tsunami propagation, taking into account the effects of lateral variations in seafloor depth.

3.2 Tsunami Green's function summation

The underlying principle for this approach is the validity of the linear behaviour of tsunami waves. This enables us to deconstruct a tsunami that is generated by an earthquake into a sum of individual tsunami waveforms (Green's functions) from a set of subfaults that adequately describe the earthquake rupture. By pre-computing and storing the tsunami waveforms at points along the coast generated by each subfault for a unit slip, we can efficiently synthesize tsunami waveforms for any slip distribution by summing the individual subfault tsunami waveforms (weighted by their slip). The same principle is used in the inversion of tsunami waves for earthquake rupture (e.g. Satake, 1995). This efficiency make it feasible to use Green's function summation in lieu of attenuation relations to provide very accurate estimates of tsunami height for probabilistic calculations, where one typically needs to compute thousands of earthquake scenarios. For instance, in the example below the probabilistic tsunami heights results are based on more than ten thousand scenarios, which were computed (using the Green's functions summation) on a 30-node cluster computer.

The assumption of linearity is not valid for tsunamis where the amplitudes are comparable to the water depth. Also, the detailed bathymetry near the shoreline is important to estimate the final run-up heights. For these cases, a non-linear method is necessary to compute the run-up heights correctly. However, several authors have proposed simple corrections that can be applied to the tsunami heights that are calculated with a linear code. Our first concern will be in computing the tsunami response to a particular depth contour off the coastline (e.g. 15 m).

3.3 Source regions

In order to obtain a comprehensive overview of the tsunami hazard in our target region, we are considering tsunami sources from all along the Pacific Rim. Although in many cases this may appear redundant, since some source regions seem unlikely to pose any tsunami hazard, to the western US, we will include these anyway since the effort is primarily a computational one. Given the extensive distribution of our target region (western North America and Hawaii) it is likely that any source region affects at least part of our target region. With our deterministic based approach, conservatism in choosing sources is warranted since low hazard regions will automatically be interpreted correctly in the process.

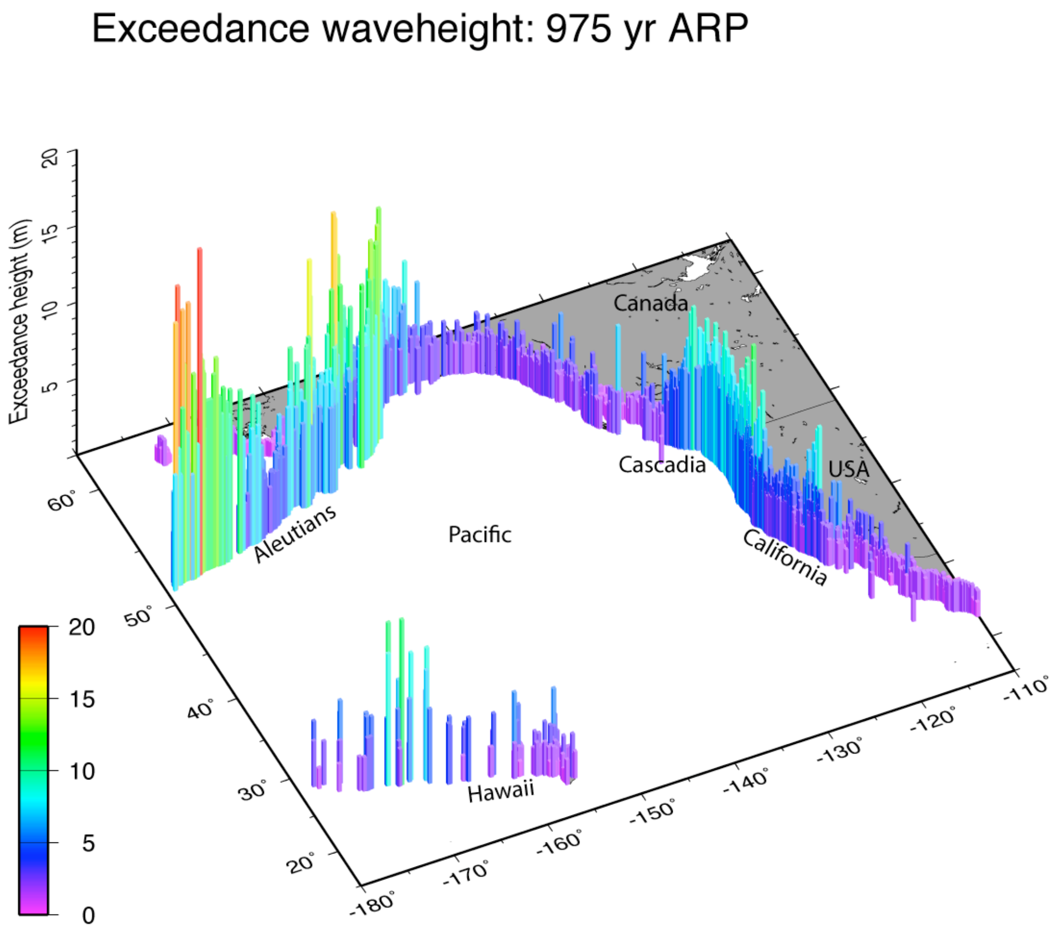

Figure 1 Hazard map for the west coast of North America and Hawaii shopwing the peak wave height exceedance levels for 975 year return period.

For any probabilistic hazard analysis, the statistical properties of the source model are essential. There have been many recent studies on the recurrence rates along the subduction zone interfaces for the circumpacific region (e.g. Gusev et al., 2005, Ikehara et al 2001, Nelson et al. 2003; Nishenko, 1985). In general, we use tectonically based recurrence rates for the source models. These can be checked against tsunami records at locations where they are available.

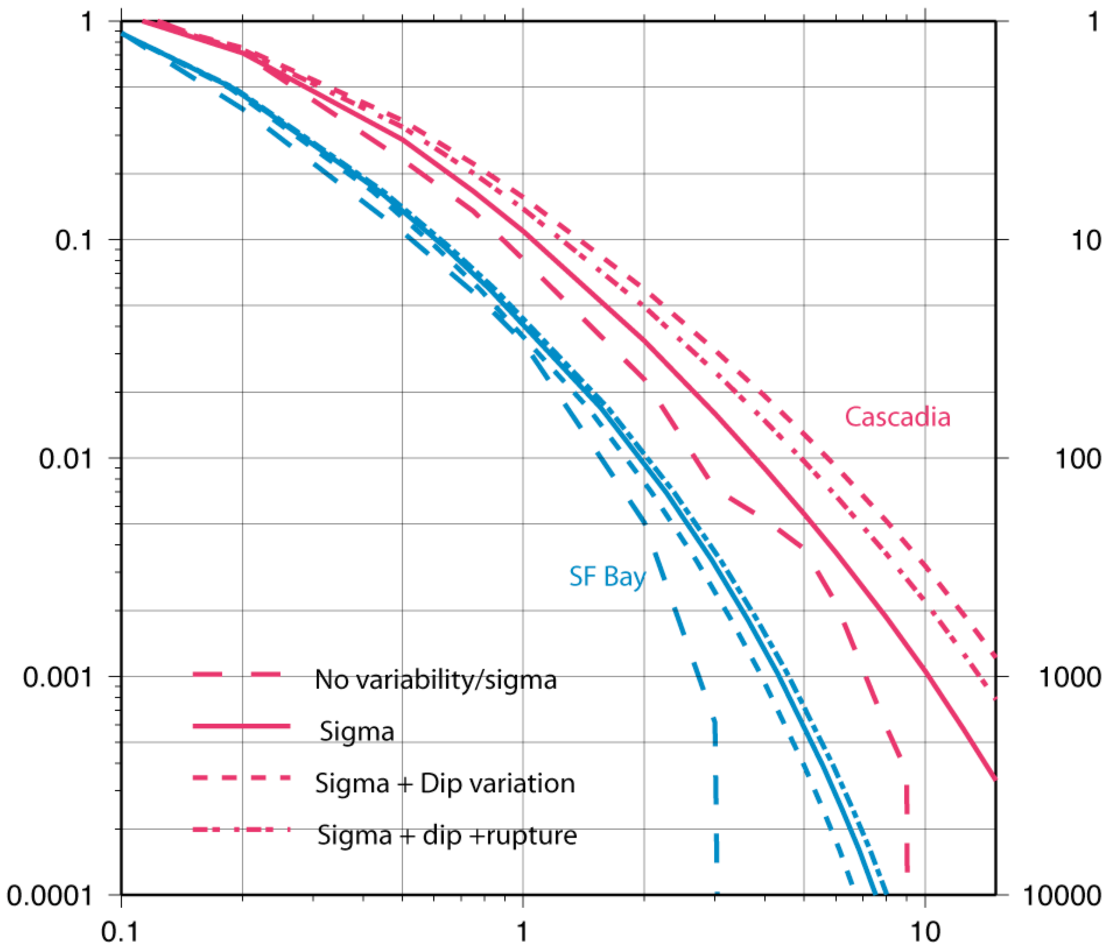

Figure 2. Waveheight hazard curves for different localities.

Based on our experience with the tsunami modeling of the 2004 Sumatra earthquake and other events, we have parameterized our rupture planes following the subduction zone model with a cut-off depth of 50 km, i.e. ruptures are not allowed to propagate deeper than 50 km. This boundary is consistent with seismic studies of interface earthquakes. The exact depth is not very important for tsunami generation, since their amplitude is predominantly dictated by shallow slip, but there is some significance to this boundary in terms of the recurrence models. The extent of shallow slip is very important, and we will include (aleatory) uncertainties in the upward extent of the rupture into our analysis.

In the present analysis, we have not included local offshore faults (apart from the Alaska and Cascadia subduction zones). Although these are predominantly strike-slip along the Norh American Pacific coast, they will contribute to the local hazard especially at longer return periods. They will be included in our final analysis.

3.4 Uncertainties in source models

A crucial element in PTHA is the estimation of the maximum magnitude, and its probability, for any source region. Due to the very short historic record for mega-thrusts and other large earthquakes in relation to their recurrence times, it is not possible to base any such constraint on directly the observed seismicity. We therefore need to resort to models that are at least partly based on earthquake mechanics, which can be as simple as magnitude/area relations but can also include physics based constraints in addition to empirical data such as earthquake locations. Uncertainties in source parameters, such as maximum earthquake and slip rate, are included using logic tree analysis. Other approaches toward PTHA often use a limited range of deterministic scenarios with associated probabilities or return periods, sometimes in combination with historical tsunami records (Berryman, 2006; Imamura et al., 2006; Geist and Parsons, 2006).

4 Results

4.1 Hazard maps

We have computed the probabilistic tsunami wave heights for the west coast of North America based on subduction zone sources around the Pacific Ocean. An example of such a map is presented in Figure 1. It shows the peak tsunami wave height that is exceeded in 975 years, a typical hazard level for engineering purposes. The wave height patterns show the expected high hazard levels in the Aleutians and Cascadia and lower levels elsewhere along the west coast.

We have plotted corresponding hazard curves for two localities along the Pacific coast in Figure 2. Here, we also show examples where aleatory uncertainties are included in the hazard curve. The include source heterogeneity, dip variability and intrinsic uncertainties in the numerical modeling.

4.2 Uniform tsunami hazard spectra

Since the hazard calculations are based on actual waveform simulations, we have the ability to compute the hazard for any tsunami waveform characteristic, not just the peak wave height. For instance, in cases where withdrawal of water is of importance, we could compute the hazard for minimum wave height. For application to ports and harbors, we suggest that spectral amplitudes are of interest because of the problem of harbor resonance. This phenomenon is well known and extensively studied in the context of storm waves but is equally important for tsunami waves that span very wide period range.

Analogous to PSHA, we can determine uniform hazard spectra as shown in Figure 3. The spectra represent the spectral amplitude that is exceeded for that particular hazard level, say 475 years, for a set of periods. Note that these spectra do not represent any single tsunami simulation, but instead for every individual period a complete probabilistic calculation. We have only plotted the response at a few periods because of time considerations, but can, and in the future will, compute more continuous uniform hazard spectra.

The spectra in Figure 3 are simple Fourier spectra, as opposed to the response spectra used in PSHA. If the response spectrum for a particular harbor is known, we can determine actual response spectra that are tailor made for that particular

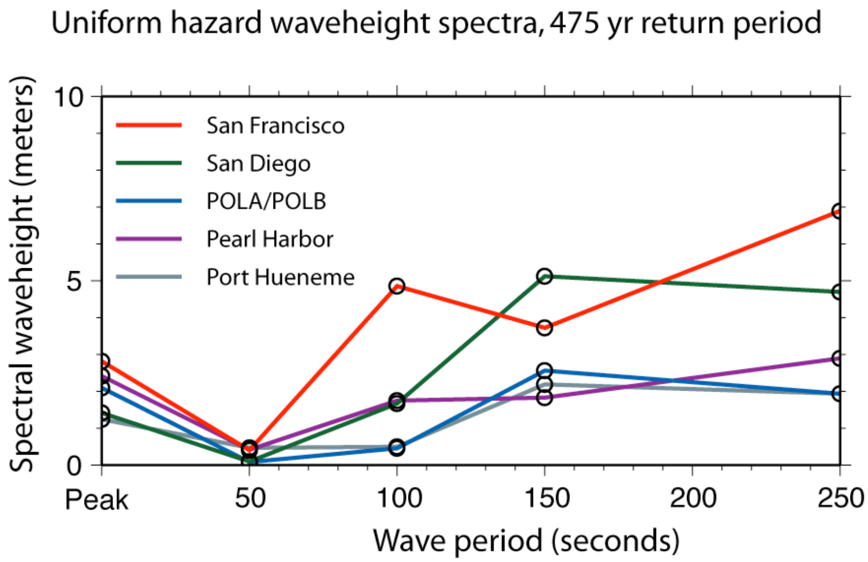

Figure 3. Uniform tsunami hazard spectra for several sites along the California coast and Hawaii.

location, including specific source characterizations, propagation effects and local response.

4.3 Disaggregation of tsunami hazard

The probabilistic peak and spectral wave heights are very useful tools in assessing the hazard posed by tsunamis. However, as mentioned before, the current approach that allows compute thousands of scenario tsunamis efficiently is not suited for detailed (non-linear) inundation studies. Disaggregation of tsunami hazard into source areas (and other relevant source parameters such as magnitude) allows identifying all the high-hazard sources that need to be studied in more detail through scenario modeling. In contrast to earlier modeling efforts, these scenarios are firmly based on a probabilistic analysis, and do not represent some poorly defined maximum credible event, but instead an event with a specific hazard level.

The disaggregation maps shown in Figure 4 illustrate how the tsunami hazard in a certain area, in this Los Angeles, stems from several distant source regions with the highest hazard from the Aleutian arc but also significant contributions from the Kurile Islands and Kamchatka as well as the Chile trench. It is clear that the subduction zone that is closest to the site, i.e. the Cascadia subduction zone, poses a very low hazard to the Los Angeles area. This is primarily due to the orientation of the subduction zone relative to the direct path to Los Angeles. The largest amplitudes for distant tsunami are registered in the direction perpendicular to the strike of the fault. In the case of Cascadia, paths to southern California are in the direction of the strike, and furthermore the coastline bends eastward, which also helps reduce the tsunami hazard from Cascadia.

5 Discussion

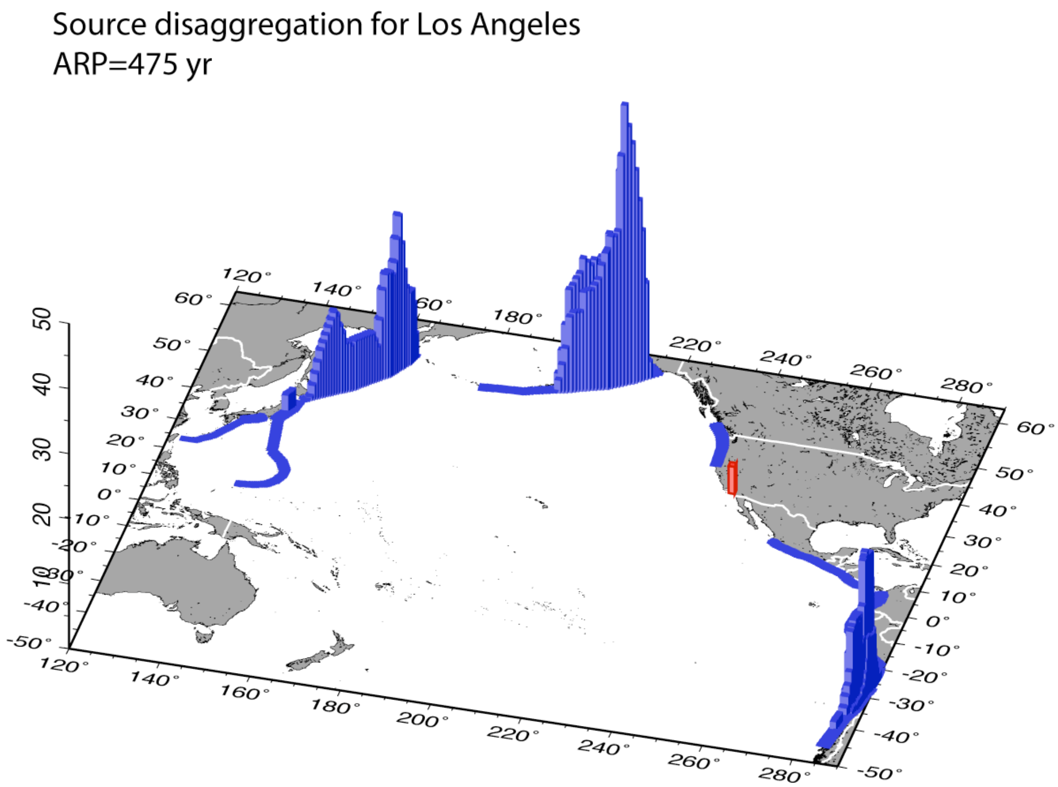

Figure 4. Source disaggregation for the tsunami hazard in the Los Angeles area for peak waveheight. The blue bars represent the relative contribution of each element towards the tsunami hazard (red bar) in the target area

The method for probabilistic tsunami hazard analysis is very versatile, and can be tailor made for very specific purposes, such as ports and harbors, while still being consistent with common practice in hazard analysis. Because of the similarities with PSHA, which is firmly established as standard practice in ground motion hazard analysis, we believe that PTHA, and our implementation in particular, can be a very useful tool in tsunami hazard mitigation for a wide range of facilities and projects. A probabilistic analysis enables us to evaluate the tsunami hazard in a more objective framework and help identify scenarios of particular concern, rather than proceeding directly with scenario modeling with arbitrary likelihoods of occurrence (e.g. Borrero et al., 2005).

Our current results show that this approach is very feasible. We have identified areas with elevated tsunami hazard, and through our spectral analysis, we can also address the hazard in relation to harbor resonance, and identify particular source areas that warrant further study. For longer recurrence times (> 1000 years), the current set of source zones needs to be augmented with local (offshore N. America) earthquake sources, which is currently ongoing, and possibly submarine landslides. These events typically have much larger return periods, and can cause local tsunamis that are more severe than distant tsunamis.

The large uncertainties that are encountered with landslide sources in particular (e.g. slide velocity, recurrence rates and dimensions) can be taken into account using the logic tree approach similar to the way uncertainties in earthquake source parameters are included.

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