9. Discussion: Resolvable Issues Through Future Research

9.1 Tsunami Earthquakes

Although not included as part of this study, it is important to note the possibility of tsunami earthquakes (Kanamori, 1972; Kanamori and Kikuchi, 1993; Polet and Kanamori, 2000). These earthquakes typically rupture the shallowest part of the interplate thrust near the trench and characteristically have a slow rupture velocity. Although we know of subduction zones where they have occurred (Aleutian, Kuril, Japan, Peru, Nicaragua), it is unclear how ubiquitous they are or whether or not their downdip rupture extent overlaps with that of typical subduction zone earthquakes. It is especially difficult to assign average return times for these earthquakes, though a minimum return time can be estimated from the characteristic amount of slip during a tsunami earthquake and the relative plate convergence velocity.

One possible scenario for tsunami earthquakes for the Cascadia Subduction Zone is that they occur by rupture on a shallow splay fault near the deformation front (Geist and Yoshioka, 1996; Priest *et al.*, 1997; Satake *et al.*, 2003). The possibility of rupture propagation onto splay faults is an area of active research (for example, Kame *et al.*, 2003). For now, it is difficult to quantify how likely this scenario is.

9.2 Smaller Cascadia Subduction Zone Earthquakes

Inclusion of earthquakes that have a magnitude smaller than the idealized characteristic earthquake magnitude will likely affect the results of the probabilistic calculations. Much of the recent paleoseismic research suggests that not all of the subduction zone earthquakes preceeding the 1700 event ruptured the entire length of the subduction zone. However, we have neither sufficient information for the paleoseismic record nor information from recorded seismicity to determine what the distribution of earthquake magnitudes is for Cascadia. One of the main questions we addressed during the beginning of this study was “Do we model earthquakes of $M < 9$ and alternative rupture models in addition to characteristic $M = 9$ earthquakes?” Depending on the exact form of the frequency-magnitude distribution, the inclusion of smaller earthquakes will tend to increase the tsunami hazard for the 0.01 yr^{-1} recurrence rate and decrease the tsunami hazard for the 0.002 yr^{-1} rate (Geist and Parsons,

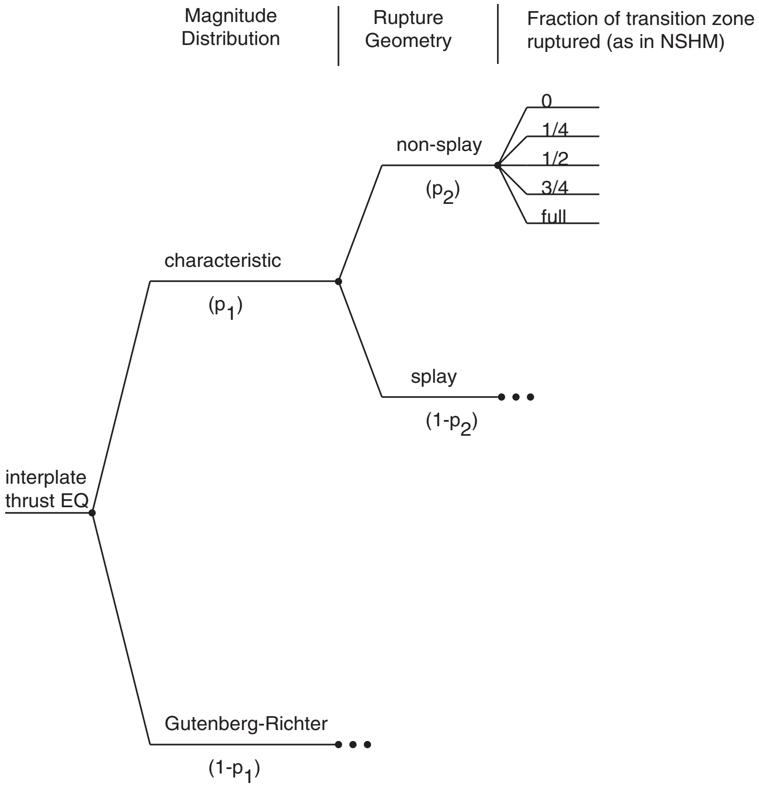

Figure 33: Sample logic tree to include the effects of epistemic uncertainties for local subduction zone earthquakes. The ellipses indicate replication of the branches from the top level.

2005). It is important to emphasize, however, that it is currently quite difficult to get reliable recurrence rates for the smaller Cascadia earthquakes from paleoseismic studies to build such a distribution, thus adding a significant amount of uncertainty to the calculations. Instead, we have focused on sources of uncertainty that we can quantify with some degree of confidence: influence of tides (Appendix E) and natural variability in slip distribution.

9.3 Other Sources of Epistemic Uncertainty

In any probabilistic study, the distinction between epistemic and aleatory uncertainties is made because they are handled in different ways in the probability calculations. Epistemic uncertainties are typically incorporated using logic trees, whereas aleatory uncertainties, such as the tidal stage at tsunami arrival and slip distribution at the source, are handled through direct integration in the rate calculations (Appendix E). Variation in parameters such as rupture width and whether or not splay faults are ruptured also has a demonstrated effect on local tsunami runup (Priest *et al.*, 1997). A sample logic tree that includes many of the sources of epistemic uncertainty is given in Fig. 33. As displayed, this would involve a total of 20 branches. The total number of model runs would be dependent on both the number of branches and the sample size for the G-R distribution branch—in any case, the number would be excessive. Even just considering the characteristic distribution branch, if 12 model runs are needed to capture the uncertainty from slip distribution patterns, then a total of 10 × 12 = 120 model runs would be needed according to the scheme above. Clearly, some judicious choices need to be made to reduce this computational load. As possible options for future studies, one can reduce the number of branches (for example, just considering two rupture widths) or randomly sample the different branches of a more complete logic tree.

10. Recommendations

This pilot study was motivated by the previous finding (Chowdhury *et al.*, 2005) that the current methodology for including tsunami information on Federal Insurance Rate Maps is inadequate, because it does not include advances of the last few decades in tsunami science and tsunami hazard assessment. The study has integrated advances of the last few decades in the scientific understanding, tools, and methods available for geophysical and tsunami hazard assessment to develop a Probabilistic Tsunami Hazard Assessment (PTHA) methodology, and has applied this methodology to the community of Seaside, Oregon. The resulting products, including 100- and 500-yr tsunami hazard maps and a comprehensive GIS database, represent a major advance in tsunami hazard assessment methodology.

The PTHA must now be applied to other Cascadia Subduction Zone communities, and refined and adapted to other tsunami regimes as part of a formal FEMA/NOAA/USGS partnership in a systematic, cost-effective, national effort to upgrade the FEMA series of Federal Insurance Rate Maps. To this end, we make the following recommendations:

10.1 Scientific/Technical Recommendations

- Include all reasonable epistemic and aleatory sources of uncertainty in each Probabilistic Tsunami Hazard Assessment, using the best available science.
- Utilize tsunami hydrodynamic models that meet NOAA standards, to ensure consistency of Federal agency products.
- Test all earthquake and tsunami models by extensive field studies to gather and exploit all possible paleogeography and paleotsunami data, historical tsunami measurements, eyewitness reports, and other types of field observations.
- Develop and maintain a comprehensive GIS database of all field data, model results, and a comprehensive site- and source-specific tsunami/earthquake bibliography for the region as an essential and invaluable analysis and product development tool.
- Publish a report for each PTHA project that documents procedures, data sources, and results, that includes a bibliography, and that is reviewed for consistency with FEMA standards.
- Publish PTHA results either as a separate Federal Insurance Rate Map, or include PTHA information as separate, tsunami-specific items on FIRMs. In either case, include: (a) the 100-year and 500-year events, (b) tsunami-

specific V-zones, (c) measurements available for the worst case historical and/or paleo-tsunami events, and (d) the "Credible Worst-Case Scenario" event.

10.2 Policy/Programmatic Recommendations

- Establish a formal FEMA/NOAA/USGS partnership to address national needs for tsunami hazard assessment products in a federally consistent and cost-effective manner.
- Apply PTHA to additional Cascadia Subduction Zone communities as NOAA inundation models are completed.
- Conduct pilot studies to adapt PTHA to other tsunami regimes in the Pacific, Caribbean, Atlantic, and Gulf, using a preliminary assessment of uncertainty.
- Apply PTHA to additional Pacific, Caribbean, Atlantic, and Gulf communities as the corresponding pilot studies and NOAA inundation models are completed.
- Establish a systematic maintenance and improvement program to integrate scientific and technical advances into the PTHA methodology.

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