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RAPID TSUNAMI MODELS AND EARTHQUAKE SOURCE PARAMETERS: FAR-FIELD AND LOCAL APPLICATIONS

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ABSTRACT

Rapid tsunami models have recently been developed to forecast far-field tsunami amplitudes from initial earthquake information (magnitude and hypocenter). Earthquake source parameters that directly affect tsunami generation as used in rapid tsunami models are examined, with particular attention to local versus far-field application of those models. First, validity of the assumption that the focal mechanism and type of faulting for tsunamigenic earthquakes is similar in a given region can be evaluated by measuring the seismic consistency of past events. Second, the assumption that slip occurs uniformly over an area of rupture will most often underestimate the amplitude and leading-wave steepness of the local tsunami. Third, sometimes large magnitude earthquakes will exhibit a high degree of spatial heterogeneity such that tsunami sources will be composed of distinct sub-events that can cause constructive and destructive interference in the wavefield away from the source. Using a stochastic source model, it is demonstrated that local tsunami amplitudes vary by as much as a factor of two or more, depending on the local bathymetry. If other earthquake source parameters such as focal depth or shear modulus are varied in addition to the slip distribution patterns, even greater uncertainty in local tsunami amplitude is expected for earthquakes of similar magnitude. Because of the short amount of time available to issue local warnings and because of the high degree of uncertainty associated with local, model-based forecasts as suggested by this study, direct wave height observations and a strong public education and preparedness program are critical for those regions near suspected tsunami sources.

KEYWORDS: Tsunami Warning, Stochastic Source Model, Tsunami Generation, Earthquake Source Parameters, Monte Carlo Analysis

INTRODUCTION

In contrast to tsunami warning systems designed for far-field tsunamis, designing warning systems for local tsunamis is difficult for two primary reasons. First, the time lapse between the arrival of earthquake waves at local seismograph stations and the impact of the tsunami is often very short. As observed with the 1993 Hokkaido-Oki tsunami, the first tsunami waves can arrive in as little as 3-5 minutes after the earthquake (Shuto, 1995; Tatehata, 1997). The second challenge in designing local tsunami warning systems is that, unlike distant tsunamis, there often is no direct confirmation of the size of a tsunami until the tsunami reaches the local shoreline and is recorded on tide gauge stations. Ocean-bottom pressure sensors and cables designed primarily for validation of trans-oceanic tsunamis, however, can provide confirmation of local tsunamis if the source is located near an open-ocean instrument (Okada, 1995; Iwasaki et al., 1997; González et al., 1998; Hirata et al., 2002).

Presently, seismic information such as magnitude and hypocenter is used to trigger the warning system, such as in Japan (Uchiike and Hosono, 1995). To improve the accuracy of short-term tsunami forecasts, other indirect ways of determining the tsunami potential from seismologic information alone have been proposed, including the variable period mantle magnitude M_m (Talandier and Okal, 1989; Schindelé et al., 1995), *T*-waves (Okal and Talandier, 1986; Walker et al., 1992), high-frequency energy characteristics, M_{wp} (Tsuboi et al., 1995; Tsuboi, 2000) and other seismic discriminants (Newman and Okal, 1998; Okal and Newman, 2001). The focus of this study is on another type of tool to improve tsunami forecasts: rapid numerical modeling of tsunami generation and propagation to determine the amplitude of tsunamis. Once the earthquake source parameters are determined for a given region, the coseismic displacement field of each source provides initial conditions for tsunami propagation models based on the shallow-water wave equations (Satake, 2002; Mader, 2004). I discuss aspects of tsunami generation that should be considered in developing these models, as well as how details of earthquake rupture might affect local tsunami forecasts in particular.

RAPID TSUNAMI MODELING

In general, two different approaches to rapid tsunami modeling have been discussed: (1) real-time modeling for given finite-fault source parameters of the earthquake (Curtis and Mader, 1987; Imamura et al., 1991; Shuto et al., 1991) and (2) pre-computed database of models for different earthquake scenarios (Tatehata, 1997; Titov et al., 1999; Koike et al., 2003; Titov et al., 2005). The first approach relies on inferences from seismologic data or empirical scaling relationships to adequately construct a finite fault source for computing tsunami generation. Recent advances in real-time seismology have had an important impact on mitigating earthquakes hazards (Kanamori et al., 1997) as well as on providing crucial information such as scalar seismic moment M_0 (Okal and Talandier, 1986; Schindelé et al., 1995; Tsuboi et al., 1995; Tsuboi, 2000) and moment tensor M_{ij} (Pasyanos et al., 1996) that can be used to better determine the tsunamigenic potential of an earthquake. The scalar moment defined as

$$M_0 = \mu\bar{\delta}A \qquad (1)$$

provides an important constraint to determine the dimensions of the rupture area (A) and the average amount of slip ($\bar{\delta}$), for an assumed shear modulus (μ). Furthermore, Ward (1982) noted that the M_{rr} and $M_{r\theta}$ components of the moment tensor (using the equatorial spherical coordinate system r, θ, ϕ) strongly influence far-field tsunami excitation, although it is difficult to resolve $M_{r\theta}$ and $M_{r\phi}$ components for shallow thrust event using only long-period surface wave data (Michael and Geller, 1984). It is also difficult to obtain direct and rapid information of the rupture area and slip from seismic observations. Izutani and Hirasawa (1987a, 1987b) proposed a method to determine the length of rupture and direction of rupture from the observed directivity on near-field seismograms and accelerograms. Rupture width and slip can then be estimated using empirical scaling relationships (Imamura et al., 1991; Shuto et al., 1991). The accuracy of this approach depends on the spatial and azimuthal coverage of seismic stations, as well as uncertainty associated with the scaling relationships.

The second approach is to pre-compute tsunami propagation for a large number of earthquake locations and magnitudes. The database of near-shore tsunami amplitudes can then be rapidly searched and interpolated for a given earthquake location and magnitude to estimate tsunami amplitude in real-time. Tatehata (1997) pre-computes tsunami amplitude solutions for specific magnitudes, whereas Titov et al. (1999, 2005) and Wei et al. (2003) construct “unit sources” that can be combined to encompass an earthquake of a certain magnitude and location. This approach assumes that all tsunamigenic earthquakes will mainly occur along the same fault: an assumption that is most likely valid for subduction zone earthquakes distant from plate triple junctions. Titov et al. (1999, 2005) demonstrate that for a given fault type (e.g., thrust earthquakes) moderate changes in the rake and dip angles have small effect on far-field tsunami amplitudes, in comparison to other source parameters.

EARTHQUAKE PARAMETERS THAT AFFECT RAPID TSUNAMI MODELS

Analysis of historic seismicity (e.g., Engdahl and Villaseñor, 2002) can greatly aid in constructing and validating the source parameters for rapid tsunami models. The overall geometry (dip and strike) of major tsunamigenic faults can be determined by examining cross-sections of past seismicity that have been relocated using regional velocity structures (e.g., Engdahl and Gubbins, 1987; DeShon et al., 2003). Other earthquake source parameters such as orientation of slip vector involve analysis of past focal mechanisms and moment tensor inversions, which may involve difficulties for the most common tsunamigenic earthquakes: shallow-dipping subduction zone thrust events (Michael and Geller, 1984).

1. Variation in Focal Mechanism

Variation in focal mechanisms for the purpose of generating pre-computed tsunami databases can be investigated by measuring the seismic consistency of past events and constructing ternary graphs. Composite moment tensors M_{sum} for a given region are calculated by summing the individual tensor components for earthquakes in a given region and are related to the strain tensor (ε) (Frohlich and Apperson, 1992). Seismic consistency $\left(C_s\right)$ is defined by Frohlich and Apperson (1992) as the ratio of the scalar moment of a composite tensor to the sum of the scalar moments for each event:

$$C_s = \frac{M_{0(sum)}}{\sum\limits_k M_{0(k)}} \tag{2}$$

A region with mechanisms that are all similar will have a seismic consistency close to 1. If, for example, one event is much larger than all other events in a region, then C_s may be a less accurate measure of mechanism similarity. For this reason, one may also display mechanisms on a ternary graph (Frohlich, 1992) to qualitatively analyze mechanism similarity. Geist and Scholl (1994) used these techniques to analyze mechanisms at the junction of the Kamchatka and Aleutian subduction zones. They demonstrated that while the seismic consistency of the region as a whole is low (C_s = 0.68), zones of similar mechanisms that have a high C_s can be delimited and composite mechanisms determined. Therefore, in complex tectonic regions, mechanism zonation for tsunamigenic earthquakes can be used to more accurately construct pre-computed tsunami databases.

2. Non-uniform Slip Distribution

In constructing tsunami models for shallow earthquakes, it is also important to note the effect that slip distribution has on the coseismic vertical displacement field. Geist and Dmowska (1999) demonstrated that dip-directed variations in slip will have a significant effect on coseismic vertical displacement, and hence, the initial tsunami wave profile. Particularly for shallow dipping subduction zone earthquakes, assuming uniform slip in the dip direction will underestimate the amplitude and leading wave steepness of the local tsunami. The most accurate representation of the tsunami source is provided by the slip distribution determined from detailed inverse modeling of geodetic measurements, and seismic and tsunami waveforms performed after the event has occurred. Since these analyses cannot yet be accurately performed in real time, simplifying assumptions of the source must be made. Geist and Dmowska (1999) proposed that a crack representation of earthquake rupture provides better accuracy of coseismic seafloor deformation in near-real time than a dislocation (uniform slip) representation. For the crack representation, the slip distribution is given by the static stress drop of the earthquake. Amplitude of the vertical displacement profile ($u_z(x, z=0)$) is dependent on the gradient of slip in the dip direction (δ_s'), expressed in two-dimensions by Freund and Barnett (1976) as

$$u_z(x,0) = \int_a^b U_z(x,s)\,\delta_\xi'(s)\,ds \tag{3}$$

where a and b represent the updip and downdip distances along a coordinate axis s in the plane of the fault (see Geist and Dmowska (1999) for details). The exact profile of the generated tsunami depends on how slip is assumed to taper near the crack tips. In each case, the amplitude of the initial tsunami is greater than a tsunami from a seismic-moment equivalent dislocation (uniform slip) representation. Moreover, whereas deformation is concentrated near the rupture edges for dislocations, deformation is concentrated near the center of cracks, resulting in greater leading-wave steepness for a tsunami derived from a crack representation.

The fact that there are singularities in the deformation field near dislocation edges is often overlooked in tsunami modeling. For either dislocations or cracks, deformation is physically manifested by anelastic processes near the rupture edges. The region that is affected by the non-physical component of deformation caused by the singularity is spatially limited, such that for most earthquakes, surface displacement is accurately represented by elastic dislocation (e.g., Okada, 1985). For shallow imbedded ruptures, however, the dislocation edge is near the seafloor and the component of deformation from the singularity appears as a spike in the vertical displacement profile or as a sharp ridge in map view. The artifact is particularly apparent for faults of shallow-moderate dip. If this artifact is left unchecked in tsunami propagation models, dispersion will be accentuated (Carrier, 1971). Tsunami generation models should, in fact, attenuate these short-wavelength displacements through the water column according to the tsunami Green's functions that basically act as a $1/\cosh(kh)$ low-pass filter of the vertical coseismic displacement field, where k is the wavenumber and h is the water depth (Kajiura, 1963). Seafloor displacement from a crack representation is more likely to provide numerically well-behaved initial conditions for tsunamis generated by shallow earthquakes.

3. Surface Rupture

For earthquake ruptures that break through to the seafloor, the zero stress-intensity condition at the updip edge results in an inherently different slip distribution profile, with the average and maximum slip twice that for an equivalent rupture (Knopoff, 1958; Boore and Dunbar, 1977; Shimazaki, 1986). Thus, the observation that for a given seismic moment, tsunami earthquakes are associated with higher amounts of slip in comparison to other subduction zone earthquakes is most likely explained by the fact that tsunami earthquakes rupture to the surface (Kanamori and Kikuchi, 1993; Geist and Dmowska, 1999). Because seafloor displacement is dependent on the integrated gradient of slip (Equation (3)), the increase in average slip does not translate to an identical increase in vertical displacement (Geist and Dmowska, 1999). With respect to rapid tsunami models, the important point is that the circumstance of surface rupture inherently changes the distribution of slip and the coseismic displacement field.

4. Effects of Earthquake Sub-Events

There is a remarkable diversity of observed source time functions or slip distribution patterns for major subduction zone earthquakes as determined from seismic inversions (Thatcher, 1990), with many earthquakes occurring as the composite of sub-events or asperities (e.g., Lay et al., 1982; Tanioka and Ruff, 1997). If the sub-events are spatially distinct, they will often act as separate, but virtually simultaneous, tsunami sources. As the local tsunami propagates toward shallow water, along-strike variations in slip will largely be preserved, owing to focusing and refraction effects (Geist, 1999). Different tsunami phases from the sub-events may constructively interfere at discrete locations along the local coastline that would not be predicted from a uniform slip model. For example, a seismic inversion by Ihmlé (1996) using long-period surface waves from the 1992 Nicaragua tsunami earthquake revealed two distinct regions of slip. Each of these regions acted as a separate but simultaneous tsunami source, with the arrivals constructively interfering at nearshore water depths broadside from the gap between the slip patches (Geist and Dmowska, 1999). Furthermore, there was a concentration of slip near the updip edge of rupture, suggesting, in accordance with the hypothesis of Kanamori and Kikuchi (1993), that rupture extended all of the way to the seafloor. If one were to use a slip model in which uniform slip spans the dip dimension of rupture, the derived tsunami would have significantly different amplitude, period, and leading wave steepness characteristics (Geist, 2002). These wave characteristics have a direct influence on the local run-up process (Tadepalli and Synolakis, 1994, 1996). These effects are gradually smoothed out as the tsunami propagates into the open ocean, although sub-events are still discernable from far-field records (Johnson, 1999).

STOCHASTIC SOURCE MODEL

The variability of local tsunami run-up for an earthquake with a given magnitude presents challenges in the design of local tsunami warning systems. The origin of this variability is, primarily, spatial variations in earthquake source parameters and their effects on the local tsunami wavefield. To determine whether local, rapid tsunami models can be implemented based on initial seismic parameters (e.g., magnitude and hypocenter), a stochastic source model is used to measure the variability of nearshore tsunami amplitude related solely to different slip distribution patterns. The self-similar stochastic model (Andrews, 1980; Herrero and Bernard, 1994) is consistent with the ω^{-2} falloff observed in the source spectrum of most earthquakes, as well as with the b-value of aftershocks (Hanks, 1979; Frankel, 1991). An example of different synthetic slip distribution patterns calculated using the stochastic source model is shown in Figure 1. A Monte Carlo simulation can then be performed for a large number of slip distributions in which the seismic moment and location are held constant. For each synthetic slip distribution, the coseismic vertical displacement and tsunami wave propagation are calculated (Figure 2). The average and extreme values for nearshore tsunami amplitude or tsunami run-up can then be determined from the synthetic earthquake catalog. For test cases of earthquake rupture along the Mexico and Cascadia subduction zones, nearshore tsunami amplitude can vary by a factor of 2 or more, solely from the effects of different slip distribution patterns (Geist, 2002, 2005).

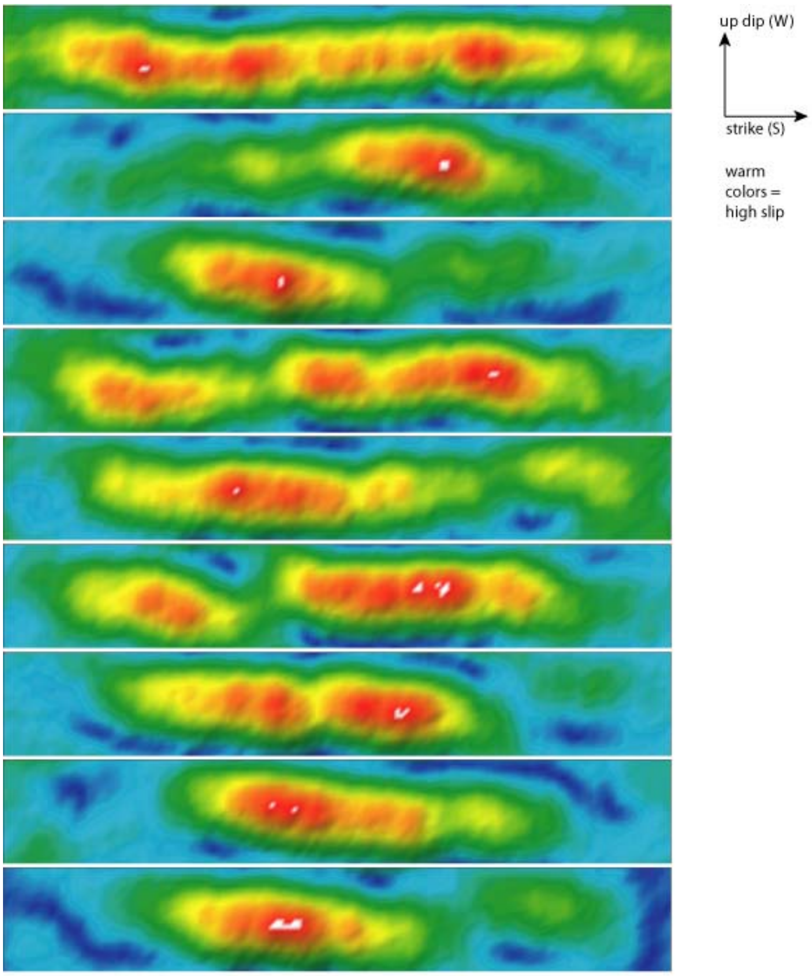

Fig. 1 Example of synthetic slip distributions for a $M \sim 9$ earthquake calculated using the stochastic source model

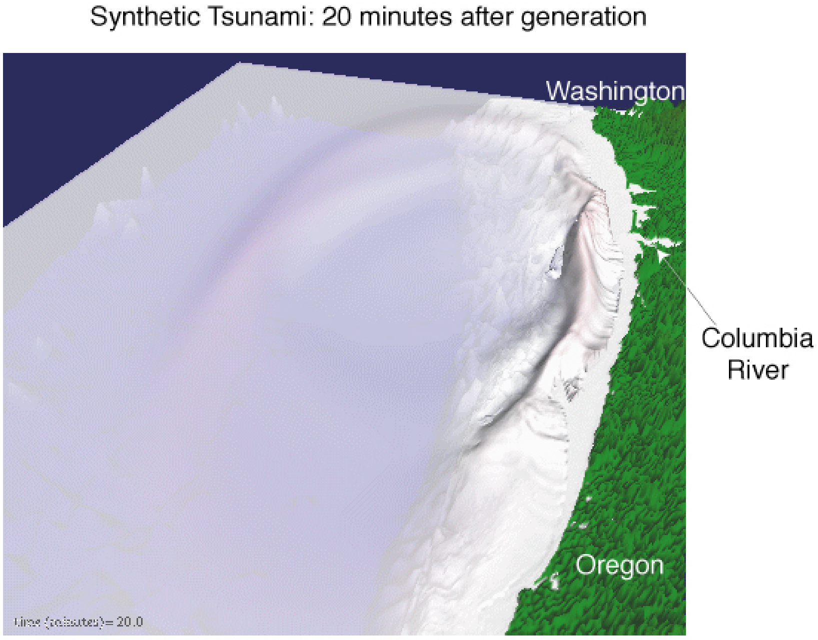

Fig. 2 Tsunami wavefield 20 minutes after generation for a hypothetical earthquake along the Cascadia subduction zone (synthetic slip distribution calculated from stochastic source model; horizontal and vertical scales for the topography and waves vary in the figure)

If other source parameters such as focal depth and shear modulus are allowed to vary, a much larger variation of local tsunami amplitude is realized for earthquakes of identical moment magnitude (Geist and Bilek, 2001; Geist, 2005). As an example, in Figure 3 we perform a Monte Carlo analysis to determine the natural variability of local, nearshore tsunami amplitudes caused by the combined influence of focal depth and variations in slip distribution. A depth-variable shear modulus function (Bilek and Lay, 1999) is used in calculating slip from the constant seismic moment ($M = 7.1$). The earthquake source parameters then are used as initial conditions for tsunami propagation models to compute nearshore tsunami amplitudes. Because this test involves small tsunamigenic earthquakes, large variations in tsunami amplitudes are observed. Low tsunami amplitudes are associated with earthquakes located at depth in the subduction zone and beneath shallow water depths or near the coast. Large tsunami amplitudes are associated with shallow focal depth earthquakes near the trench and in deep water, resulting in greater amplification due to shoaling.

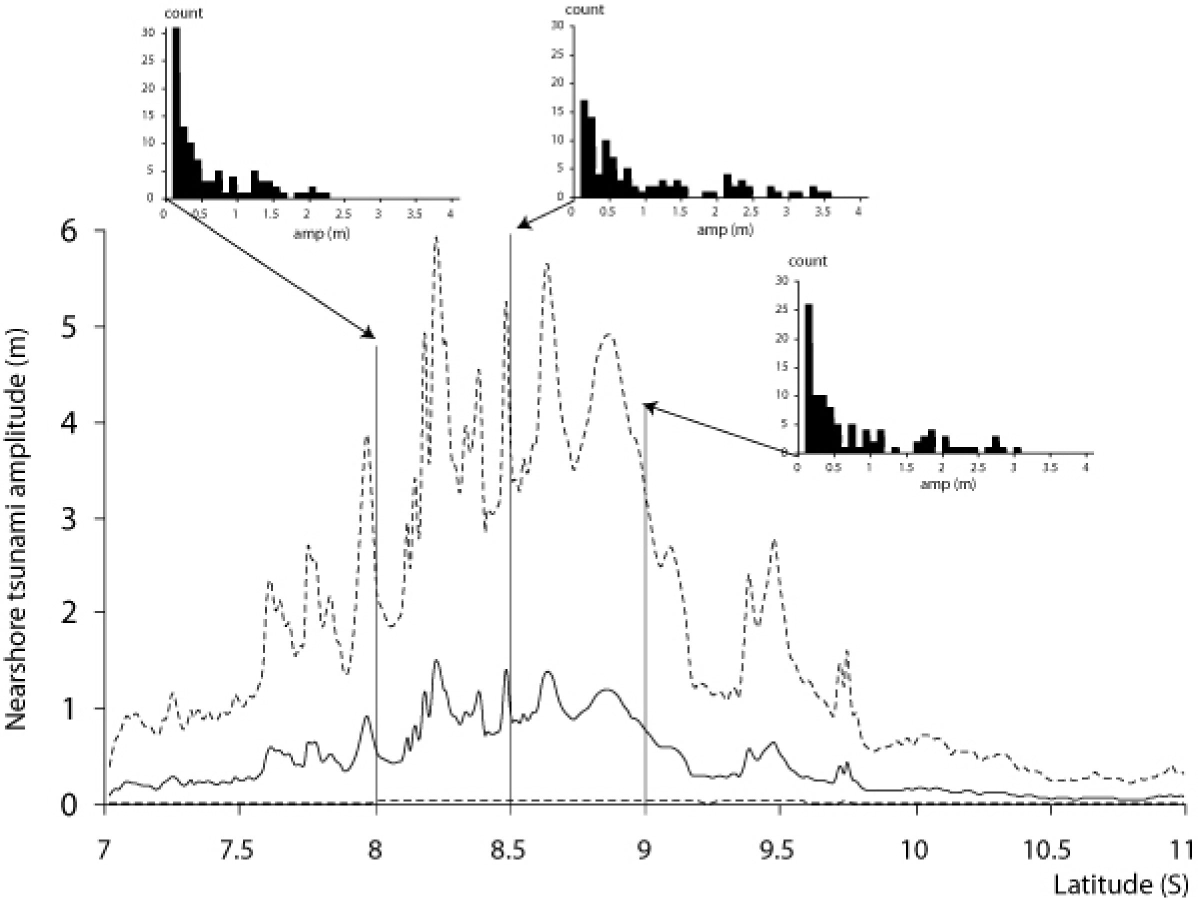

Fig. 3 Monte Carlo analysis to determine combined effect of changes in slip distribution and focal depth on peak nearshore tsunami amplitudes for small tsunamigenic earthquakes (one hundred $M = 7.1$ earthquakes with random focal depth and slip distributions from the stochastic source model were each used as initial conditions for local tsunami propagation; histograms at three locations show typical distributions of peak nearshore tsunami amplitudes; example is from the Peru subduction zone near the source region of the 1996 Peru tsunami earthquake (Geist and Bilek, 2000))

The frictional stability conditions for these near-trench earthquakes do not typically support spontaneous earthquake rupture. The exception, however, is the occurrence of tsunami earthquakes that may occur under unique frictional conditions (Bilek and Lay, 2002). This analysis suggests that rapid tsunami models for small tsunamigenic earthquakes are critically dependent on accurate focal depths derived from seismic waveforms (e.g., Sipkin, 2000). In contrast, large tsunamigenic earthquakes ($M > 8$) frequently occur at depth in the seismogenic zone (Das and Scholz, 1983) and rupture the entire width of the fault (Scholz, 1990), resulting in less variability in nearshore tsunami amplitudes (as measured by the coefficient of variation), than tsunamis from smaller earthquakes.

SUMMARY

Rapid tsunami models have the potential to forecast the amplitude of tsunami waves in near real time. Accurate forecasts, however, depend on accurate estimates of earthquake source parameters, especially precise location, hypocentral depth, and focal mechanism. In developing a database of pre-computed solutions, it is necessary to examine the consistency of focal mechanisms in a source region. Tsunami generation should also include a realistic distribution of slip throughout the rupture zone. The pre-computed method of rapid tsunami modeling based on source specifications using available geologic and geophysical information can greatly aid far-field warning guidance, as discussed by Titov et al. (1999, 2005).

In contrast, application of rapid tsunami models for local tsunami warnings is considerably more difficult, because of the short travel time from source to shore and the larger effect that earthquake rupture parameters have on the local tsunami wavefield. A synthetic catalog of slip distributions calculated from the stochastic source model can be used to estimate the variability of local tsunami amplitudes caused by earthquake source complexity and focal depth. Results of a Monte Carlo analysis presented here indicate a large uncertainty in local tsunami amplitudes if the focal depth and slip distribution are not well known, especially for smaller magnitude tsunamigenic earthquakes. It may be possible in the future to have rapid estimates of slip distribution from inverse modeling of seismic and geodetic information to aid in the development of local, rapid tsunami models. Until then, local tsunami warnings need to rely on direct wave height observations and an effective public education and preparedness program, in combination with initial location and magnitude information of the causative earthquake.

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