Modeling the natural complexity of local tsunamis

Eric L. Geist

U.S. Geological Survey, Menlo Park, California, U.S.A.[1]

Abstract. Characterizing rupture of large, shallow subduction zone earthquakes by a uniform slip dislocation will not accurately simulate details of the local tsunami wavefield. The effects of non-planar fault structure, variations in elastic properties, and heterogeneous slip distributions on tsunami generation are reviewed. To accurately model these effects, site-specific observations (geologic structure, elastic properties, historic seismicity) and specialized tsunami source modeling techniques are needed. For past events, the local tsunami can be accurately modeled given the slip distribution derived from a seismic inversion of the earthquake. To account for heterogeneous slip in assessing future tsunami hazards, a stochastic self-similar source model is employed to produce a large number of different slip distribution patterns for an earthquake of a given seismic moment and location. Results using the stochastic source model for a $M_w = 7.8$ interplate thrust earthquake along the Cascadia subduction zone indicate that peak nearshore tsunami amplitude can vary by a factor of 2.5 or more. Tsunami hazard assessments based on only a few scenario earthquakes may not accurately account for natural variation in tsunami amplitude caused by earthquake rupture complexity.

1. Introduction

Many natural phenomena such as forest fires, high Rayleigh-number convection, and earthquake rupture exhibit dynamic complexity that is chaotic: small changes in initial conditions lead to unpredictable end states. The focus of this study is to describe how earthquake rupture complexity is imparted to the local tsunami wavefield. First, the effect of large-scale variations in fault structure and material properties in subduction zones is described. Then, the effect that fractal distributions of slip has on tsunami generation is examined. Except for the slowest earthquake ruptures, the phase velocity of tsunami waves is slow enough that explicit coupling between slip evolution along the fault plane and tsunami generation need not be considered (Geist, 1998). Therefore, the final, static slip distribution can be used to calculate the coseismic displacement field that provides the initial conditions for tsunami propagation. This slip distribution, however, is the result of a highly non-linear, chaotic process and is not deterministic for an earthquake of a particular location and magnitude. Methods such as the Andrews (1980) stochastic source model described here and more fully in Geist (submitted) are needed to account for source complexity. It is emphasized in this paper that simplified elastic dislocation methods used to simulate tsunami generation are largely insufficient to account for local tsunami amplitude variations caused by the combined effect of earthquake source complexity and inhomogeneous fault and earth structure in subduction zones.

[1]U.S. Geological Survey, Coastal and Marine Geology, 345 Middlefield Rd., MS 999, Menlo Park, CA 94025 (egeist@usgs.gov)

2. Non-Planar Fault Structure

Though tsunamigenic earthquakes occur on a number of different faults in a subduction zone (Geist, 1998), the largest tsunamis are often generated from rupture of the megathrust or interplate thrust that separates the downgoing, subducted plate from the overriding plate. The most significant source of non-planar fault structure for interplate thrust earthquakes is rupture onto steeply dipping splay faults within the accretionary prism as originally postulated by Fukao (1979) as a mechanism for generating large tsunamis associated with tsunami earthquakes. Shuto *et al.* (1995) indicate that rupture on a secondary splay fault can also result in an earlier than expected arrival time of a tsunami. Multichannel seismic data have shown that both seaward-vergent (common) and landward-vergent (rare) splay faults are present in many subduction zones (e.g., Kato, 1987; Ryan and Scholl, 1989; MacKay *et al.*, 1992).

The central question for tsunami generation is whether rupture on the interplate thrust can propagate updip onto shallow splay faults. The frictional behavior of rocks in the shallow crust is often velocity strengthening (e.g., Boatwright and Cocco, 1996) such that slip along shallow faults occurs aseismically. During a large earthquake at depth, dynamic rupture can either be arrested in the shallow part of a subduction zone (termed an "absorbing barrier") or transgress frictional stability limits, depending on the interplay between the frictional behavior of clay minerals in accretionary rocks (Vrolijk, 1990) and pore pressure (Zhang *et al.*, 1993). Though it is difficult to observe changes in fault dip using long-period surface waves (Pelayo and Wiens, 1992), Fukao (1979) presents evidence for a mechanism change during the 1963 and 1975 Kurile tsunami earthquakes. Using a static stress analysis, Jeyakumaran and Keer (1994) indicate that slip is retarded on splay faults with higher dip angles under compressional loading. More recent work on modeling dynamic rupture along a splay fault by Aochi *et al.* (2000) demonstrates that rupture progression on the splay fault depends strongly on the splay angle and the initial stress distribution.

For ruptures that do progress onto splay faults, techniques are needed to calculate the coseismic displacement field for a non-planar fault. In the past, this has been calculated by discretizing the fault into planar segments and using standard elastic dislocation expressions (Okada, 1985), by using triangular dislocation elements (Jeyakumaran *et al.*, 1992), or by using finite-element methods. Using the latter technique, Geist and Yoshioka (1996) calculate the initial tsunami wave profile for 5 different types of planar and non-planar faults that have been surveyed along the Cascadia subduction zone. They note that for a given amount of slip, rupture along steeply dipping splay faults, either within the accretionary wedge or beneath the outer continental shelf, are more likely to generate higher local run-ups than rupture solely along the interplate thrust. These scenarios described by Geist and Yoshioka (1996) were performed using uniform slip. In future studies, heterogeneous slip distributions, optimally derived from dynamic rupture simulations such as Aochi *et al.* (2000) or seismic inversion results, should be used to accurately simulate the tsunami wavefield from non-planar faults. The hypothesis of Fukao (1979) should still be seriously considered as a source for large tsunamis.

3. Variation in Elastic Properties

It has been long known that subduction zones are composed of a diversity of rock types (e.g., Peacock, 1996). The differences in rock types translate to large differences in elastic properties, posing difficulties in accurately calculating the static response to earthquake rupture. The effect that a horizontal layered earth structure has on the coseismic displacement field has been theoretically established by, for example, Savage (1998). For subduction zones that exhibit strong horizontal contrasts in elastic moduli in addition to vertical contrasts, Yoshioka *et al.* (1989) and Yoshioka and Suzuki (1999) have used finite-element methods to model displacement fields for the 1946 Nankaido earthquake.

The larger problem caused by variations of elastic moduli present in subduction zones is determining the amount of slip during rupture for a given moment according to $\mathrm{M_o} = \mu AD$, where μ is the shear modulus, A is the area of rupture, and D is the average slip. For the general case of finite rupture, with a constant rake, the total moment $\mathrm{M_o}$ is given by

$$\mathrm{M_o} = \iint_{\Sigma} \mu D d\Sigma$$

where $d\Sigma$ is an infinitesimal area element and μ and D are variable within the rupture zone (cf., Aki and Richards, 1980). In situ estimates for shear modulus have recently been made for the circum-Pacific subduction zone by Bilek and Lay (1999, 2000). By deconvolving teleseismic records to obtain point-source time functions, they note that there is a systematic decrease in rupture duration (normalized with respect to $\mathrm{M_o}$) with depth. Two end-member cases are provided that explain this observation: (1) static stress drop is constant and shear modulus increases with depth; or (2) static stress drop increases with depth and shear modulus is constant. While both effects may contribute to the depth-dependence of normalized rupture duration, many studies suggest that static stress drop is constant for earthquakes over a broad range in magnitude (e.g., Abercrombie, 1995), thus indicating that the effect is caused primarily by variations in shear modulus.

Under the assumption that static stress drop is constant, Bilek and Lay (2000) indicate that shear modulus increases by a factor of 5 between depths of 5 and 20 km. Shear modulus at shallow depths, therefore, is substantially lower and the shear modulus gradient higher than predicted by a standard earth model (Dziewonski and Anderson, 1981). Low shear modulus at shallow depths in subduction zones has important implications for tsunami generation as discussed by Geist and Bilek (2001). For a variable moment distribution derived from seismic inversions, the corresponding slip distribution will be skewed toward relatively higher slip values at shallow depth. An important caveat, however, is that the excitation of short-period seismic waves is also dependent on variations in elastic moduli such that a consistent elastic model should be used for both seismic inversions and tsunami models.

4. Slip Heterogeneity

The distribution of slip for subduction zone earthquakes has been shown to be remarkably heterogeneous from both seismic studies (e.g., Thatcher, 1990) and tsunami studies (e.g., Satake, 1993). The source of slip heterogeneity has been ascribed to both the non-linear dynamics of rupture and physical heterogeneity along the fault zone (Cochard and Madariaga, 1996; Ben-Zion and Rice, 1997). The origin of rupture complexity in subduction zones specifically has been discussed by Rundle and Kanamori (1987). Because of the low dip angle (approximately 6–30°) for shallow interplate thrust earthquakes, variations in the final (static) slip distribution are mimicked in the coseismic vertical displacement field and the initial tsunami wavefield. Slip heterogeneity for deeper earthquakes or for earthquakes along steeply dipping faults has less of an effect on the tsunami wavefield.

Geist and Dmowska (1999) demonstrate that characterizing a shallow interplate-thrust earthquake as a single, uniform-slip dislocation will underestimate the amplitude and wavenumber (frequency) content of a tsunami, in comparison to an ideal crack model or a strongly heterogeneous slip distribution. The deformation field surrounding a uniform-slip dislocation is more diffuse compared to deformation from a heterogeneous slip distribution. Freund and Barnett (1976) and Rudnicki and Wu (1995) have shown that for dip-slip faulting, a crack-like representation results in significantly higher amplitudes and shorter dominant wavelengths for vertical surface displacement profiles compared to a seismic-moment equivalent dislocation.

For assessing the tsunami potential from future earthquakes, a technique is needed to produce realistic synthetic slip distributions. A stochastic source model has been developed by Andrews (1980) and later by Herrero and Bernard (1994) to explain the characteristic ω^{-2} falloff at high frequencies in the far-field seismic displacement spectrum (Aki and Richards, 1980). These authors and others (e.g., Hanks, 1979; Huang and Turcotte, 1988) explain that the ω^{-2} falloff is caused by self-similar variations in initial stress or stress drop. The corresponding slip distribution follows a fractal scaling relationship such that for a general falloff of $\omega^{-\gamma}$ in the seismic displacement spectrum, the wavenumber spectrum for the slip distribution falls off at high wavenumbers according to $k^{-\gamma}$ (Tsai, 1997). The technique to generate a catalog of stochastic slip distributions is to first establish a site-specific characteristic source spectrum parameterized by γ. Polet and Kanamori (2000) indicate that values of γ are approximately consistent within a given region and that there does not seem to be a difference in γ between tsunami earthquakes and typical interplate thrust earthquakes. Values of γ range between 1.0 and 2.6 are based on studies by Hartzell and Heaton (1985) and Polet and Kanamori (2000). Once the spectral decay is chosen for the slip distribution, the phase is randomized to generate a large number of slip distribution patterns (Herrero and Bernard, 1994).

To demonstrate the effect of slip heterogeneity only, local tsunami amplitudes are calculated for a large number of synthetic rupture (N=100) with a fixed seismic moment and location. A shallow interplate thrust earthquake along the Cascadia subduction zone is chosen as the test case in this example (Fig. 1a). A planar rupture geometry is used according to the following parameters constrained by recent seismic surveys (Parsons *et al.*, 1998): L = 230 km, W = 60 km, strike = 350°, and dip = 9°. The corresponding moment magnitude using the shear modulus function described by Geist and Bilek (2001) is $M_w = 7.8$. Because we have no information on the characteristic spectral decay for Cascadia subduction zone events, the generic ω^{-2} model is chosen.

Coseismic vertical displacement is calculated by superimposing the displacements from individual fault elements, using Okada's (1985) point-source elastic dislocation expressions. Because a large number of synthetic earthquakes are considered, the computationally efficient linear long-wave equations are used to model tsunami propagation up to the 50 m isobath. Spatial grid size for the model is 1.3 km and time interval is 4.5 seconds. (Further details of the modeling are described in Geist, submitted.) Peak nearshore tsunami amplitude (PNTA) is recorded at the 50 m isobath for each simulation. In Fig. 1b, average and extrema values of PNTA are plotted along the Pacific Northwest coastline. For individual points along the coastline, maximum and minimum PNTA differ by a factor of 2.5 on average and as much as by a factor of 6.5. Histograms of PNTA are characterized by a central peak at most locations along the coastline, though typically at coastline locations near bathymetric promontories the PNTA distribution is more complex and a characteristic PNTA cannot be determined (Fig. 1b).

5. Summary

Because both inhomogeneous earth structure and rupture complexity have a significant effect on tsunami generation, it is necessary to have sufficient knowledge of fault geometry, elastic properties, and slip distribution to accurately model local tsunamis. To model historic tsunamis, the slip distribution can be derived from seismic inversions. To estimate future tsunamis for an earthquake of a given magnitude, a large number of slip distribution patterns need to be considered to obtain a realistic estimate of the range of possible tsunami heights. For tectonically complex areas, such as Hawaii or the Caribbean, the number of simulations for an accurate tsunami assessment needs to be expanded to consider faults with different mechanisms and depths.

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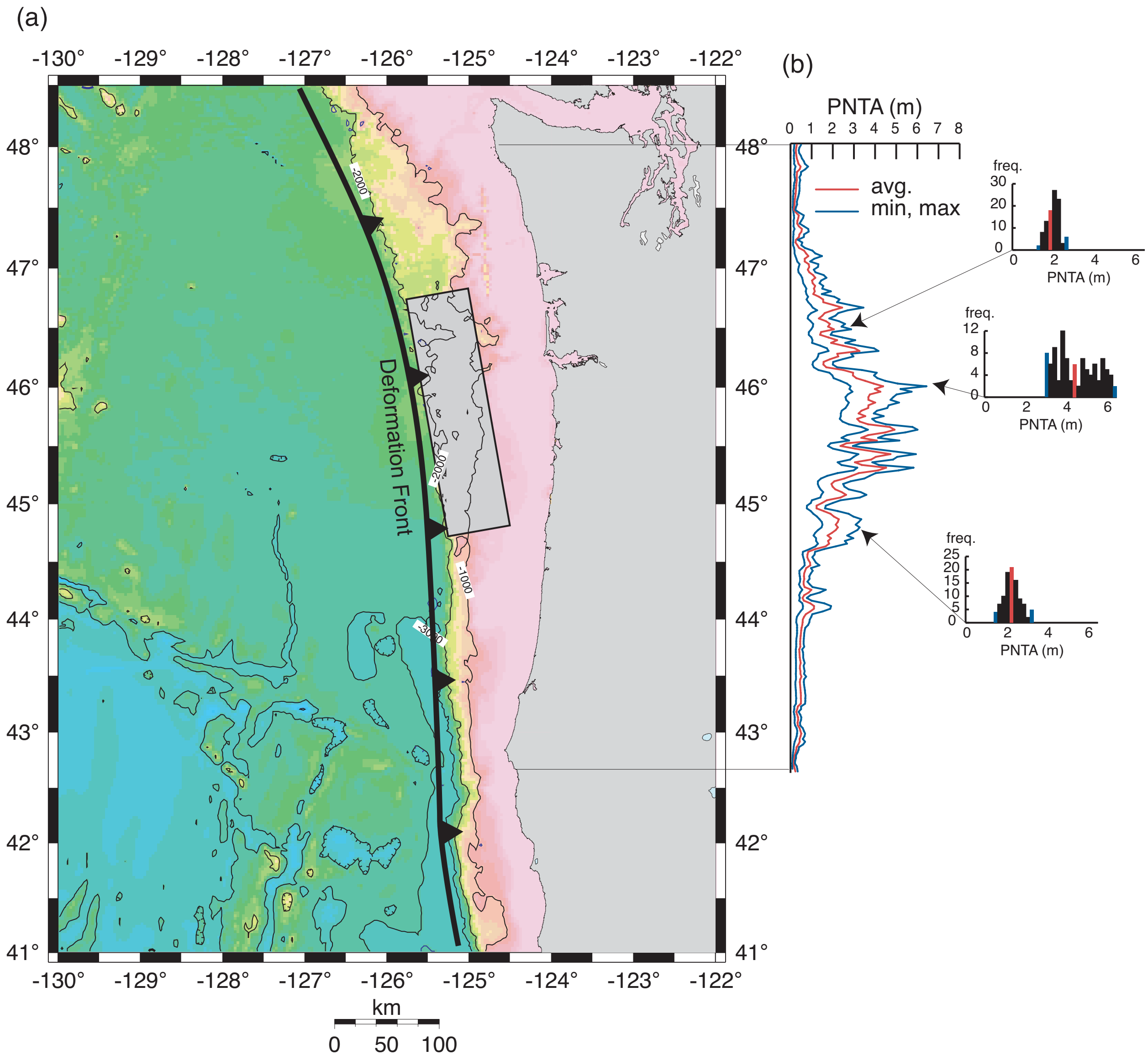

Figure 1: (a) Map of Cascadia subduction zone showing test rupture area along the interplate thrust for tsunami simulations. (b) Peak nearshore tsunami amplitude (PNTA) along the Cascadia coastline at the 50 m isobath. Average and extrema values of PNTA are shown for 100 different slip distributions generated by the stochastic source model. Each synthetic rupture has identical seismic moment ($M_w = 7.8$) and location (shown in (a)). Difference between maximum and minimum ranges between a factor of 1.2 and 6.5 (average = 2.5). Histograms at three locations demonstrate typical differences in PNTA distributions that are dependent on the local, nearshore bathymetry.

6. References

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