Wedge Mechanics and Tsunamigenic Seafloor Deformation

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Elastic bulging of the seafloor is recognized as the primary cause of tsunami generation in great subduction earthquakes, but many other factors, such as splay faulting, pervasive permanent deformation, and induced submarine landslide, also contribute to enhancing coseismic seafloor displacement. For coseismic seafloor deformation to generate large tsunami waves, the spatial requirement is that the wavelength of the deformation must be large as compared to water depth, and the temporal requirement is that the deformation must take place in seconds to minutes. The first-order characteristics of tsunamigenic seafloor deformation are well described by static or dynamic models of a fault embedded in an elastic material. More detailed study of the deformation requires considering the mechanics of a wedge-shaped body above a thrust fault.

When applied to subduction zones, the classical theory of a critically tapered Coulomb wedge is meant to describe long-term processes averaged over numerous earthquake cycles. In order to study the mechanics of submarine wedges in individual great earthquake cycles, we expand the classical theory and devise the theory of dynamic Coulomb wedge. Building on the Coulomb-plasticity of the classical theory, we assume an elastic – perfectly Coulomb-plastic rheology and derive exact stress solutions for stable and critical wedges. The new theory postulates that the actively deforming, most seaward part of an accretionary prism (the outer or frontal wedge) overlies the updip velocity-strengthening part of the subduction fault, and the less deformed inner wedge overlies the velocity-weakening part (the seismogenic zone). During a great earthquake, friction along the updip segment suddenly and briefly increases (strengthening), and thus the outer wedge is pushed into a compressively critical state, with an increase in stress and pore fluid pressure. After the earthquake, the outer wedge relaxes and returns to a stable state. The inner wedge generally stays in the stable regime throughout earthquake cycles, acting as an apparent backstop and providing a stable environment for the formation of forearc basins.

The theory explains observations such as the tendency of great earthquake ruptures to occur beneath the inner wedge that hosts forearc basins, the structural contrast between outer and inner wedges, and post-seismic deformation of the outer wedge. It also provides a conceptual framework for the study of coseismic seafloor deformation. For example, the sudden, coseismic compression of the outer wedge accompanied by fluid pressure increase provides a favourable condition for splay faulting. Parts of the aseismic updip fault segment beneath the outer wedge may coseismically slip at a fast enough rate to enhance the magnitude and wavelength of tsunamigenic seafloor uplift. Where ultimate coseismic fault strength is controlled by the strength of the (bottom part of the) wedge material, such as at margins dominated by subduction erosion, wedge strength may control the updip limit of the megathrust seismogenic zone. We are currently using the dynamic wedge theory to modify the dislocation model widely used in modeling tsunamigenic seafloor deformation.