Uncovering the Mysteries of Tsunami Generation and Anomalous Seismic Radiation in the Shallow Subduction Zone

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40-Year Puzzles About Tsunami Earthquakes

Identified by Hiroo Kanamori in 1972

- Large tsunamis
- Depletion in high-frequency radiation
- Slow rupture velocity and long rupture duration
- Possibly small stress drop and slip velocity
- Low energy-to-moment ratio
- Occur in a frictionally stable (velocity-strengthening) or conditionally stable regime
Characteristics of Large Tsunamigenic Earthquakes

- Weak high-frequency radiation
- Slow rupture velocity (long rupture duration)
- Strong tsunami generation

Lay et al. (2012)
Mechanism for Slow Rupture Propagation: Sediments and Fault Morphology

- Presence of sediments gives rise to slow rupture velocity.
- Horst-and-graben structure on the plate interface allows the rupture to reach the trench.
- Fault roughness causes large fracture energy.

One inconsistency:
Fault roughness tends to generate more high-frequency radiation.
Dynamic Rupture Simulations in a Low-Velocity Fault Zone

Sediments in the fault zone:

- Promote pulse-like rupture.
- Do not always decrease rupture velocity, and can instead lead to supershear rupture.

More high-frequency radiation!

Harris and Day (1997)
Mechanism for Tsunami Generation:
Large Shallow Slip

- Nearly horizontal displacement
- Inefficient to generate tsunami

\[ \text{uplift} \approx \text{slip} \times \sin(\text{dip}) \]

Shallow fault dip → large slip

Lay et al. (2012)
Slip Models Using Tsunami Data

Sumatra

Fujii et al. (2007)

Tohoku

Fujii et al. (2011)
Tohoku Slip Models Using Teleseismic or GPS Data

Lay et al. (2012) Ide et al. (2011)
Critical Taper (Coulomb Wedge) Theory

“The overall mechanics of fold-and-thrust belts and accretionary wedges along compressive plate boundaries is considered to be analogous to that of a wedge of soil or snow in front of a moving bulldozer… The critical taper is the shape for which the wedge is on the verge of failure under horizontal compression everywhere, including the basal decollement.”

Davis et al. (1983)
Fault Geometry and Stress Conditions

Depth-dependent effective stresses:

\[ \sigma_3 = \sigma_{zz} = -(1 - \lambda) \rho gz \]
\[ \sigma_1 = \sigma_{xx} = 3.7469 \sigma_{zz} \]

\[ \mu_0 = \frac{\tau}{\sigma_N} = 0.58 \]

\[ \rho = 2670 \text{ kg/m}^3 \]
\[ \alpha = 6000 \text{ m/s} \]
\[ \beta = 3464 \text{ m/s} \]
Mohr-Coulomb Failure Criterion

\[ \tan \varphi = 0.7095 \]

\[ CF = 0.99 \]

\[ C = 0.017 \sigma_{zz} \]

\[ \tan \varphi = 0.7095 \]

Closeness-to-Failure (CF)

\[ CF = \frac{R}{c \cos \varphi - \sigma_m \sin \varphi} \]

Sub-critical wedge
Slip-Weakening Friction

\[ \mu_s = 0.6 \quad \mu_0 = 0.58 \]
\[ \mu_d = 0.57 \quad D_c = 0.2 \text{ m} \]
\[ S = \frac{\mu_s - \mu_0}{\mu_0 - \mu_d} = 2 \]

The fault is also close to failure.

No velocity-strengthening friction is used.

Ida (1972)
Pore Pressure Change in Undrained Condition

\[ \Delta p = B \left( \frac{1 + \nu_u}{3} \right) (\Delta \sigma_{xx} + \Delta \sigma_{zz}) \]

- \( B \): Skempton’s coefficient
- \( \nu_u \): undrained Poisson’s ratio

We use \( B = 0.3 \) everywhere in the wedge.
Rupture Movie (Hydrostatic)
Time-Distance Plots of Slip Velocity and Slip Distribution (Red)

Elastic

Large rupture velocity
Large slip near the trench

Inelastic

Slow rupture velocity
Small slip near the trench
Time Histories at 25 km and 65 km Down Dip

- More gradual stress change
- Smoother slip velocity
- Less high-frequency radiation
Moment Rate Time Functions and Spectra

Less high-frequency radiation!
16 August 2005 Miyagi-oki
$M_o = 0.9 \times 10^{20} \text{ Nm (} M_w = 7.2\text{)}$
Depth 36 km

centroid time 9.7 s

9 March 2011 Tohoku-oki
$M_o = 1.9 \times 10^{20} \text{ Nm (} M_w = 7.5\text{)}$
Depth 14 km

centroid time 14.3 s

Lay et al. (2012)
Moment-Scaled Radiated Energy

Moment contributor

Seismic potency density off the fault

$M_{\text{off}} = 3.22 \times 10^{15} \text{ N}$
$(M_{\text{off}}/M_{\text{on}} = 0.19)$

Density of net work done off the fault ($\text{J/m}^3$)

$W_{\text{off}} = -2.44 \times 10^{11} \text{ J/m}$
$(W_{\text{off}}/W_{\text{on}} = -0.46)$

Elastic

$M: 2.52 \times 10^{16} \text{ N}$
$E_R: 6.12 \times 10^{11} \text{ J/m}$
$E_R/M: 2.43 \times 10^{-5}$

Inelastic

$M: 1.99 \times 10^{16} \text{ N}$
$E_R: 2.91 \times 10^{11} \text{ J/m}$
$E_R/M: 1.46 \times 10^{-5}$
Another Look at Subduction Zone Fault Geometry

- Larger seafloor uplift
- Shallower fault dip
- Smaller confining pressure
- Easier to fail
- Less high-frequency radiation
Coseismic Displacements for the 1964 Alaska Earthquake
Conclusions

Extensive Coulomb failure in the wedge provides a unifying interpretation to nearly all anomalous features of shallow subduction earthquakes, including:

- Slow rupture velocity
- Efficient tsunami generation
- Deficiency in high-frequency radiation
- Low energy-to-moment ratio