Frequency Dependence of Radiation Patterns and Directivity Effects in Ground Motion from Earthquakes on Rough Faults

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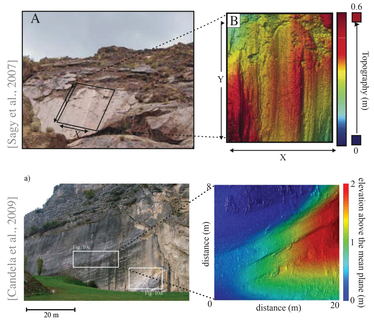
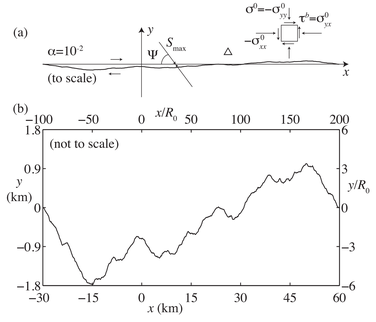
Abstract

We study ground motion from spontaneously propagating ruptures on rough faults (idealized as self-similar surfaces with local slope perturbations of order 10^{-3} to 10^{-2}). These two-dimensional plane strain models assume a uniform, isotropic medium, such that all complexity in the source process and resulting incoherent high frequency ground motion emerges naturally as ruptures interact with stress perturbations induced by slip on the nonplanar faults. Synthetic seismograms feature an ω^{-2} displacement spectrum. The focus of this research is to understand far-field ground motion from our models. Primarily unilateral earthquake rupture propagation causes a pronounced directivity effect, where ground motion in the direction of propagation is of larger amplitude than that in the opposite direction. Observations suggest that directivity effects are generally only present at frequencies less than about 1 Hz, and that at higher frequencies, the directivity effect vanishes and the far-field radiation pattern changes from the usual double-couple pattern to an isotropic one. The differences between high and low frequency ground motion have been alternatively explained as either a source effect (with the source losing coherence at short wavelengths) or a path effect (with high frequency waves being preferentially scattered by crustal heterogeneities). In this work we isolate the contribution of source effects to the frequency dependence of far-field ground motion. We construct an approximate three-dimensional source model by projecting the source onto a high-aspect-ratio fault under the assumption that the rupture process and nonplanar fault topography are everywhere the same across the smaller dimension. We then calculate far-field body wave seismograms and Fourier spectra using the representation theorem. The radiation pattern transitions from a clear double couple pattern with strong directivity effects at low frequencies to a more isotropic pattern with diminished, but not absent directivity effects at high frequencies.

Simulation Model

Self-Similar Fractal Fault Surfaces



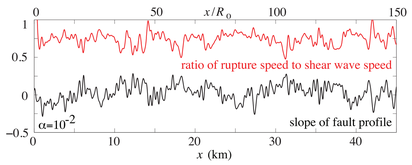


▲ Faults have self-similar fractal surfaces with amplitude-to-wavelength ratio of roughness, α, varying from 10^{-2} (immature faults) to 10^{-3} (mature faults); α is independent of scale of observation. Slip on rough faults generates stress heterogeneities that lead to irregular rupture propagation.

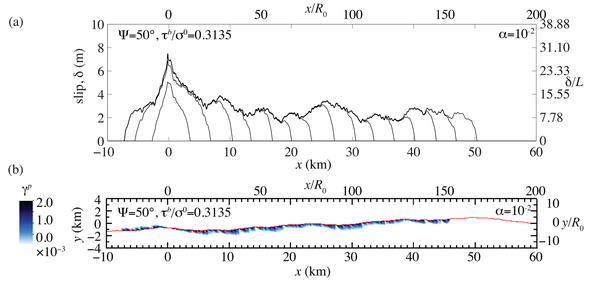
▲ We use a randomly synthesized self-similar fault surface of $\alpha = 10^{-2}$, with roughness at wavelengths down to about 300 m. Initial stresses are spatially uniform. Synthetic seismograms calculated at triangle in (a).

Dynamic Ruptures

We model dynamic ruptures using strongly rate-weakening fault friction (in a rate-and-state framework) and off-fault plasticity (Drucker-Prager model). Background stresses are sufficiently low that ruptures occur as slip pulses.



▲ Variability in rupture propagation speed, which is correlated to local fault geometry, helps excite incoherent high frequency waves.

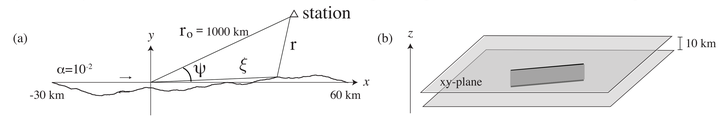


▲ Synthesized earthquake generates realistic levels of high frequency waves. Compare with 1992 Landers earthquake records. (a) Near-field seismograms and (b) Fourier spectra both show similarity.

◀ Roughness introduces slip heterogeneity and decreases total slip by introducing additional resistance to slip. (a) Snapshots of fault slip process and (b) plastic strain showing amplitude modulation by roughness.

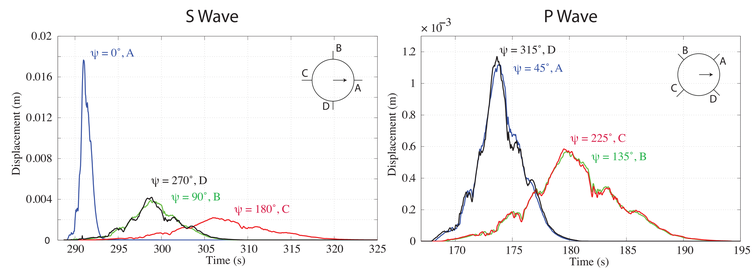
Far-field Ground Motion

To obtain far-field ground motion, we use the representation theorem. We first Fourier transform in time the slip velocity each grid point of the fault. Introducing a spatially varying phase factor representing the lag time of wave arrival from each fault point at the far-field station and integrating over the fault gives the displacement spectrum as a function of frequency (see expression in Frequency Dependency column). Inverse Fourier transforming then gives us the far-field seismogram.

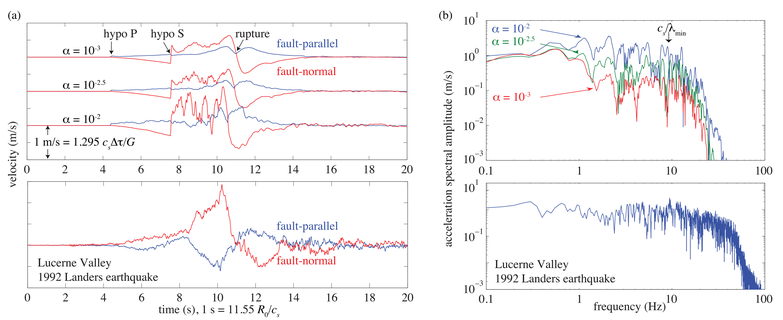


▲ ψ is the angle between the station and x-axis. We use 1000 km as the distance to the station which is considerably far compared to fault length of less than100 km.

▲ Two-dimensional fault is simply elongated along z-axis to obtain fault surface, assuming that nonplanar topography is same everywhere across the smaller dimension.



▲ Calculated seismograms show clear directivity effect and double-couple radiation pattern. Note that two stations in equivalent positions when rotating with respect to x-axis show difference because the fault is asymmetrically nonplanar.



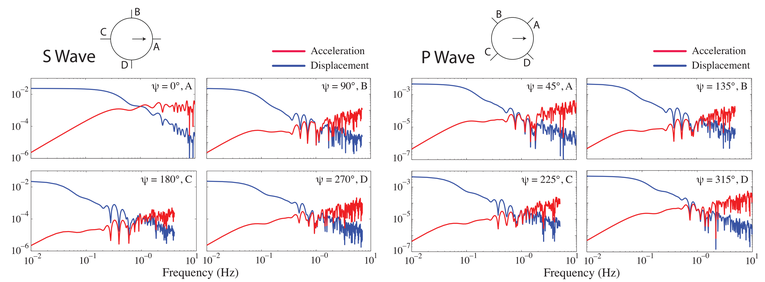
Frequency Dependency

Fourier Spectra

In order to provide the smoother profile, Gaussian window is applied in the initial step. Only the part consistent regardless of the characteristics of window is taken into consideration.

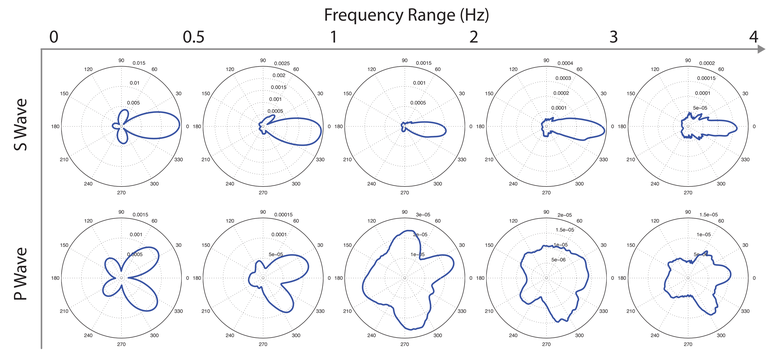
$$\hat{u}^w(\psi,\omega) = \frac{R^w_{ijk}GW}{4\pi\rho r_o c_w^3}\int_F e^{i\omega\frac{r}{c_w}}[T_j(\xi)N_k(\xi)+T_k(\xi)N_j(\xi)]\hat{V}(\xi,\omega)d\xi$$

Wave type · Radiation pattern · Fault width · Phase factor for lag time · Tangent vector
Displacement · Station distance · Fault curve · Normal vector · Slip velocity · Fault point from origin



▲ S-wave displacement spectrum in forward direction displays ω^{-2} decay.

Radiation Patterns



▲ Starting from a clear double-couple pattern at low frequencies, radiation pattern becomes more isotropic at higher frequencies because local radiation pattern of each point on fault varies on rough faults. Directivity effects become weaker, but do not disappear entirely.

Conclusions

- Isotropic radiation pattern at high frequencies can be partially attributed to source effects.
- However, the reason for diminished, but not absent directivity effects remains unclear. Some of possible explanations:
  - It becomes entirely isotropic only in partner with heterogeneous materials and scattering effects.
  - Current model has limitations including the simplistic projection of two-dimensional fault curve to three-dimensional surface.
  - Standard representations of source heterogeneity (spatially variable initial stress or friction parameters on flat faults) cannot capture fluctuations in local radiation pattern on rough faults that causes radiation pattern to become more isotropic at high frequencies.