EARTHQUAKE RUPTURES ON ROUGH FAULTS

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Summary. Natural fault surfaces exhibit roughness at all scales, with root-mean-square height fluctuations of order 10^{-3} to 10^{-2} times the profile length. We study earthquake rupture propagation on such faults, using strongly rate-weakening fault friction and off-fault plasticity. Inelastic deformation bounds stresses to reasonable values and prevents fault opening. Stress perturbations induced by slip on rough faults cause irregular rupture propagation and the production of incoherent high-frequency ground motion.

Keywords: earthquakes, faults, friction, roughness.

1 INTRODUCTION

While frequently idealized as infinitesimally thin planar surfaces, natural faults exhibit a variety of geometrical complexities. In this study, we focus on one ubiquitous type of complexity, fault roughness, and explore how deviations from planarity influence the earthquake rupture process. Roughness is observed at all scales using a variety of techniques (laser profilometers from $\sim$10 μm to $\sim$10 cm, ground-based LiDAR from $\sim$0.1 m to $\sim$100 m, and mapping of surface traces at the largest scales) [1, 2, 3]. Studies that combined data across the full range of scales suggest that fault surfaces are self-similar. Specifically, one-dimensional profiles along the surface (with zero mean), $y = h(x)$, are characterized by a power spectral density of the form $P_h(k) = (2\pi)^3\alpha^2 k^{-3}$, for wavenumber k and amplitude-to-wavelength ratio α. The root-mean-square (rms) roughness between wavenumbers $k_{\min}$ and $k_{\max}$ is dominated by the largest wavelengths; for a profile of length L, which has roughness at all wavelengths less than L:

$$h_{rms}(k_{\min} = 2\pi/L, k_{\max} \to \infty) = \alpha L. \tag{1}$$

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It is thus evident that the rms deviations from planarity scale with the profile length. Alternatively, if the profile is decomposed into Fourier modes, the amplitude of each sinusoidal component increases with wavelength in a manner that satisfies equation (1).

Faults are smoother in the direction of slip ($\alpha \sim 10^{-3} - 10^{-2}$, with the smaller values being more appropriate for mature faults) than in the slip-perpendicular direction ($\alpha \sim 10^{-2}$). In this study, we focus solely on roughness in the direction of slip, and consider only roughness wavelengths that are much larger than the characteristic amount of slip in a single earthquake (an assumption required for our analytic and numeric analyses). An example of a synthetically generated self-similar fault is shown in Figure 1.

Slip on nonplanar faults perturbs the local stress field and increases the resistance to slip [4, 5]. Insight into these effects can be obtained using boundary perturbation techniques to develop approximate solutions to quasi-static linear elasticity problems. In contrast to the rms roughness, the rms stress perturbations are dominated by the shortest wavelengths of roughness. For slip of magnitude Δ across a fault with constant friction coefficient, the rms normal stress perturbation is [6]

$$\sigma_{rms}(k_{\min} \to 0, k_{\max} = 2\pi/\lambda_{\min}) = 2\pi^2 \alpha \frac{G}{1-\nu} \frac{\Delta}{\lambda_{\min}}, \quad (2)$$

where G is shear modulus, and ν is Poisson's ratio. For reasonable parameters, the normal stress perturbation predicted by this analysis will exceed the background compressive effective stress levels on faults at seismogenic depths, implying that the walls of the fault should open. That seems unlikely, as such large stress perturbations will almost certainly be prevented by inelastic deformation within damage zones surrounding the fault.

2 NUMERICAL MODEL

To investigate the effects of roughness in more detail, we model rupture propagation on nonplanar faults in an infinite, homogeneous medium under conditions of plane strain. The fault is a synthetically generated band-limited self-similar profile, as shown

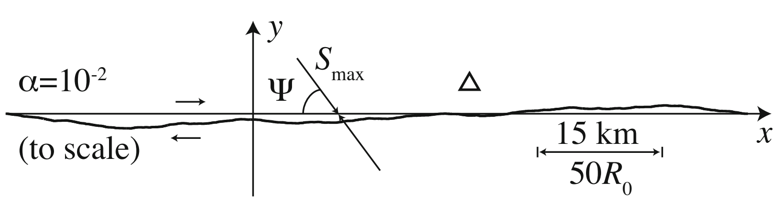

Fig. 1. Band-limited self-similar fault profile, $y = h(x)$, with amplitude-to-wavelength ratio $\alpha = 10^{-2}$. Synthetic seismograms are calculated at station marked with triangle in (a). The maximum principal prestress, $S_{\max}$, is inclined at angle Ψ to $y = 0$. Fault strength drops over a distance of $\sim R_0$ (a length scale emerging from friction and elasticity); $R_0 = 300$ m is used in dimensional scales. Roughness is present at wavelengths $\lambda \geq \lambda_{\min} = 1.25 R_0$ ($= 375$ m) in this example.

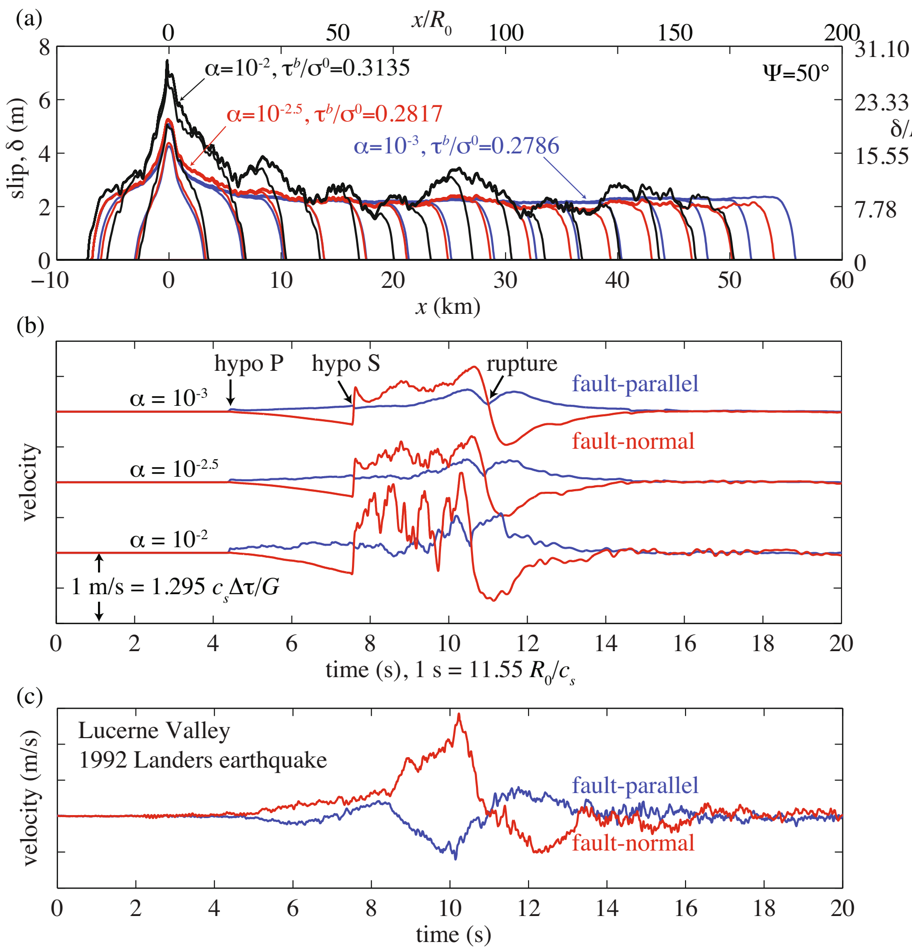

Fig. 2. (a) Profiles of slip for $\Psi = 50°$, illustrating the increase in slip heterogeneity, as the amplitude-to-wavelength ratio of roughness, α, is increased. For all the cases, the background stress, τ^b, is just slightly above that required for self-sustaining propagation; while this value of τ^b increases with α, the average amount of slip remains roughly constant. (b) Synthetic velocity seismograms at station shown in Figure 1 for several values of α. Hypocentral P- and S-wave arrivals are marked; the two-sided fault-normal pulse occurs when the rupture passes the station. (c) The Lucerne Valley record from the 1992 M_w 7.3 Landers earthquake (2 km from the fault).

in Figure 1, with a lower wavelength cutoff introduced to ensure numerical resolution of all roughness features. The medium is modeled as a Drucker–Prager elastic–viscoplastic solid without cohesion. Plasticity prevents the development of unreasonably large stress perturbations, and, at least for the specific model employed in this study, completely eliminates fault opening. The fault is governed by a rate-and-state friction law featuring a strongly velocity-weakening steady-state response. (For further description, see [7, 6].) We use a summation-by-parts finite difference method on block-structured meshes; irregular geometries are handled using a coordinate transformation technique. The method is provably stable and accurate (convergence tests demonstrate that solutions presented here have about 1% error) [8].

One consequence of strongly rate-weakening friction is the existence of self-healing slip pulse ruptures for a limited range of background stress conditions (and multiple lines of reasoning suggest that natural faults operate under such conditions); we focus exclusively on this part of parameter space. Roughness introduces heterogeneity in the slip distribution (Figure 2a) and causes rapid accelerations and decelerations of the rupture front; both processes generate incoherent high-frequency seismic waves (Figure 2b). Synthetic seismograms from our simulations bear close resemblance to data from actual events (Figure 2c), suggesting that fault roughness might be responsible for incoherent high-frequency ground motion from earthquakes.

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