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The Dynamics of Elongated Earthquake Ruptures

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The largest earthquakes propagate laterally after saturating the fault's seismogenic width and reach large length-to-width ratios L/W. Smaller earthquakes may also develop elongated ruptures due to confinement by heterogeneities of initial stresses or material properties. The energetics of such elongated pulse-like ruptures is radically different from that of conventional circular crack models, but a synoptic understanding of their dynamics is still missing. Here we combine computational and analytical modeling of long ruptures in 3D and 2.5D (width-averaged) to develop a theoretical relation between the evolution of rupture speed and the spatial distribution of fault stress, fracture energy and rupture width. We then use this theory to gain insight on the dynamics of large earthquakes and fault heterogeneity.

We find that the evolution of elongated ruptures is well described by the following rupture-tip-equation-of-motion:

$$\left(W/v_s^2/\left(1-G_c/G_0\right)\right)\dot{v}_r = A\alpha_s^P,$$

where G_c/G_0 is the ratio of fracture energy to static energy release rate, v_s the S wave speed, v_r the rupture speed, $\dot{v}_r = dv_r/dt$ the rupture acceleration, $\alpha_s = \sqrt{1-\left(v_r/v_s\right)^2}$, and $A = \pi$ and $P = 3$ for rupture acceleration and $A = 1.2\pi$ and $P = 2.6$ for rupture deceleration. If G_c is exactly balanced by G_0, the rupture can in principle propagate steadily at any speed. The steady energy release rate is $G_0 \approx \Delta\tau^2 W/\pi\mu$, where $\Delta\tau$ is the stress drop (smoothed along-strike over a length scale smaller than W) and μ the shear modulus. When $G_c \neq G_0$, rupture acquires an inertial effect: the rupture-tip-equation-of-motion depends explicitly on rupture acceleration. This inertial effect does not exist in the classical theory of dynamic rupture in 2D unbounded media, but emerges in bounded media or, as shown here, as a consequence of the finite rupture width. Assuming a constant energy ratio G_c/G_0, integrating the rupture-tip-equation-of-motion yields a relation between rupture speed and propagation length ΔL: $\pi\left(1-G_c/G_0\right)\Delta L/W = \Delta\alpha_s^{-1}$ for acceleration and $0.72\pi\left(1-G_c/G_0\right)\Delta L/W = \Delta\alpha_s^{-0.6}$ for deceleration. These relations then allow to determine if a given fault barrier can stop an ongoing earthquake.

More generally, this work provides theoretical relations between earthquake source properties (final magnitude, moment rate function, radiated energy) and the heterogeneities of stress and strength along the fault. We will illustrate how these relations can be used to extract statistical constraints on fault heterogeneity from databases of source time functions of past earthquakes. They can also be used as physics-based constraints on finite-fault source inversion, and to examine the connection between rupture segmentation and seismogenic width. We will also report on possible extensions of the theory to supershear ruptures, to gain insight into recent strike-slip events such as the 2018 Mw 7.5 Palu earthquake.