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Criticality of cascading-up and its dependence on rupture velocity

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Could rupture propagation be interpreted as a continuing cascading-up process from a tiny negligible nucleus under broad scale stress fluctuation due to the multiscale heterogeneity of fault system? From seismological observations [Ellsworth and Beroza, 1995; Uchide and Ide, 2007; Meier et al., 2016], rupture process does not seem to have a specific scale during its growth stage. However, theoretical or numerical studies for the condition of cascading-up or termination have been limited. Quantitative understanding would be possible in the same way with many previous studies for spontaneous rupture propagation on a limited scale range [e.g., Andrews, 1976; Day, 1982; Rubin and Ampuero; 2005].

To describe critical situations for cascading rupture, we examined a Mode III self-similar crack with a constant rupture velocity, propagating into the surrounding region of high fracture energy, using numerical simulation. A small fragile patch with a half-length $R^{dyn.}$ is embedded on a planer fault with homogeneous stress and friction condition (T_p: yield strength, T_e: uniform stress, μ: rigidity, D_C^{BG}: slip-weakening distance). Slip-weakening friction law is applied, and D_C inside the patch is proportional to the distance from the centre (hypocentre) as described in Eqn. 1. $D_C^{'}$ is the gradient of D_C in the small patch, and H(x) Heaviside function. ($D_C^{BG} > D_C^{'} R^{dyn.}$)

$$D_C(r) = D_C^{'} r \cdot H(R^{dyn.} - r) + D_C^{BG} \cdot H(r - R^{dyn.}) \tag{1}$$

The critical crack size $R_C^{dyn.}$ is the smallest $R^{dyn.}$ that the rupture can cascade-up to a spontaneous rupture outside the patch. $R_C^{dyn.}$ should have specific relation with fault parameters, similar to static critical crack size $R_C^{sta.}$ ($= \kappa\mu \cdot T_p D_C / T_e^2$). κ is a constant parameter which depends on geometry .

The crack growth inside the patch approximately satisfies Eqn. 2, which represents the balance of energy release and consumption of self-similar crack with constant rupture velocity [c.f. Bromberg(1999)], though exponential numbers of T_e and T_p increase with larger $D_c^{'}$.

$$\pi T_e^2/\mu = T_p D_C^{'} \cdot \frac{\sqrt{1-\gamma^2}}{[E(\sqrt{1-\gamma^2})]^2}, \gamma = V_r/V_S \tag{2}$$

(E(x): complete elliptic integral of the second kind)

It turned out by numerical simulation that the relation of $R_C^{dyn.}$ and parameters converges to the simple function below with smaller $D_C^{'}$. Exponential numbers of T_e and T_p again increase with larger $D_c^{'}$.

$$R_C^{dyn.} = R_C^{sta.} \cdot f(V_r) = \kappa\mu \cdot T_p D_C / T_e^2 \cdot f(V_r) \tag{3}$$

$f(V_r)$ is a function that monotonically decreases from 1 to about 0.5 as V_r increase from 0 to V_s in Mode III crack problem. A similar result is obtained in the three-dimension numerical simulation. Crack with small rupture velocity is more likely to be slowed and occasionally terminated by smaller fluctuations of heterogeneity, which high-speed rupture is not affected by. That may explain why most earthquakes have high rupture velocity [c.f. Yamada et al.,2005; Dreger et al.,2007; Imanishi et al, 2004; Tomic et al., 2009].