2021 SCEC Report

Investigating the effects of absolute friction level on shallow fault dynamics

PI: David D. Oglesby, Department of Earth and Planetary Sciences, University of California, Riverside
Co-PI: Christodoulos Kyriakopoulos, University of Memphis

Amount Awarded: $19000 (UCR)

Proposal Category: B (Integration and Theory)

Related SCEC Science Priorities

- **4a.** Determine the relative roles of fault geometry, heterogeneous frictional resistance, crustal material heterogeneities, intrinsic attenuation, near-surface nonlinearities and ground surface topography in controlling ground motions.
- **1e.** Evaluate how the stress transfer among fault segments depends on time, at which levels it can be approximated by quasi-static and dynamic elastic mechanisms, and to what degree inelastic processes contribute to stress evolution.
- **2e** Describe how fault complexity and inelastic deformation interact to determine the probability of rupture propagation through structural complexities, and determine how model-based hypotheses about these interactions can be tested by the observations of accumulated slip and paleoseismic chronologies.

Background and Motivation

Earthquakes that rupture up to the Earth's surface pose significant threats to populations in Southern California and beyond. Unfortunately, modeling the dynamics of a shallow fault can be more challenging than modeling their more deeply buried counterparts. For the former case, one must consider the asymmetry between the hanging wall and footwall, and a half-space mechanical model is needed instead of a full-space model. The analytical solution of a half-space model is usually harder to obtain than a full space model; therefore, most early theoretical source models adopted a full-space condition (e.g., Eshelby, 1957; Brune, 1970; Madariaga, 1976; Das and Aki, 1977). As numerical methods rapidly developed, simulating a fault rupture in half-space is no longer as difficult, and now it has become a common practice to include the traction-free earth surface (the free surface) in earthquake simulations (e.g. Oglesby et al., 1998; Zhang and Chen, 2006; Ma and Beroza, 2008; Hok and Fukuyama, 2011; Kozdon and Dunham, 2013; Kyriakopoulos et al., 2017; Ulloa and Lozos, 2018; Harris et al., 2018; Ulrich et al., 2019; Wollherr et al., 2019; Wang et al., 2019). These models have shown, among other conclusions, that when symmetry with respect to the free surface is broken, thrust fault slip and ground motion can be amplified with respect to otherwise-equivalent normal faults, and hanging wall motion is typically larger than footwall motion. However, our quantitative understanding on how the free surface affects earthquake rupture is still incomplete. At present, many researchers still heavily rely on the relations and intuitions obtained in full space models to design experiments and interpret the results.

Recent numerical studies have implied that an analysis based on intuition from full space models might lead to misleading conclusions when applied to interpret a half space model result. For example, it is well known that in a full space with a symmetric fault, the level of absolute stress and friction has no effect on earthquake dynamics; it is the drop in stress that matters (e.g., Eshelby, 1957; Kostrov, 1974; Das and Aki, 1977). However, Scala et al. (2018) show that the absolute friction level could control the dynamic rupture behavior for a shallow-buried thrust fault model, where there is feedback between normal and shear stresses (e.g., Brune 1996, Nielsen, 1998, Oglesby et al., 1998, Gabuchian et al., 2014). These numerical and laboratory results highlight the need for further quantitative investigations of the free surface interaction with dynamic rupture. In our SCEC funded research from 2021, we carry out a parameter study to accomplish this goal. In particular, we help to explain the role of absolute friction level in affecting rupture behaviors, particularly in the shallow part of the crust where the Earth's free surface may have a controlling role.

Methods and Results

Our goal is to construct 2D Finite Element dynamic rupture models (Barall, 2009) at different levels of initial stress and frictional coefficient, but otherwise identical. We hold the relative fault strength and the static stress drop (as estimated prior to the earthquake) constant between the models:

We perform dynamic rupture simulations of a thrust fault with identical settings but with two adjustable parameters (see cartoon model in Figure 1 and parameters in Table 1): 1. Burial depth (H=0 km [surface rupturing], 9 km, or 120 km); 2. Absolute friction coefficient coupled with stress level (high and low). All models have the same expected shear stress drop of 1.83 MPa and the same relative fault strength $S = \frac{\mu_{static}\sigma_{normal}-\sigma_0}{\sigma_0-\mu_{sliding}\sigma_{normal}}$ of 2.68, where "expected" means calculated under the assumption that the normal stress σ_{normal} stays unchanged from its initial value (such as would be expected for a deeply buried fault).

Table 1. Physical and Computational Parameters

Common Parameters

V_P	6000 m/s
V_S	3464 m/s
ρ	2670 kg/m^2
S	2.685
$\Delta\sigma$	1.8312 MPa
d_0	0.6 m
Triangular grid size	200 m

High Friction+Stress Parameters

τ_0	15 MPa
σ_n	24 MPa
μ_{static}	0.8299
$\mu_{sliding}$	0.5487

Low Friction+Stress Parameters

τ_0	3.1808 MPa
σ_n	13.496 MPa
μ_{static}	0.6
$\mu_{sliding}$	0.1

The resulting fault slips are shown in Figure 2. Our results imply that when the thrust fault is buried deeply, the absolute friction and stress level have no influence on the final slip as long as the stress drop and S are the same, as expected from full-space models from before. However, as the thrust fault approaches the free surface, the high absolute friction/stress models have larger slip than the otherwise equivalent lower friction/lower stress models.

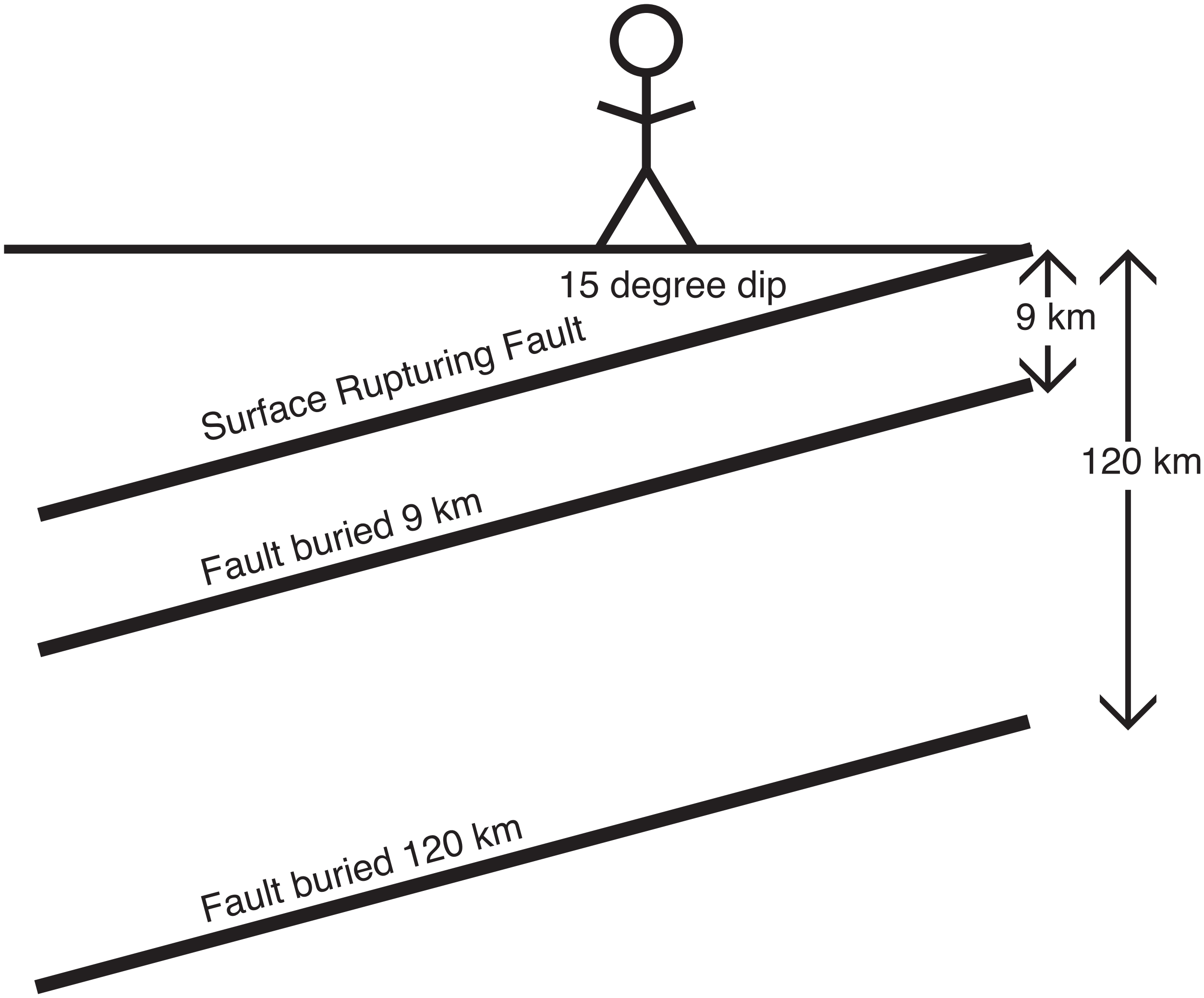

Figure 1. Fault geometries tested, each under the effects of either low stress/low friction or high stress/high friction.

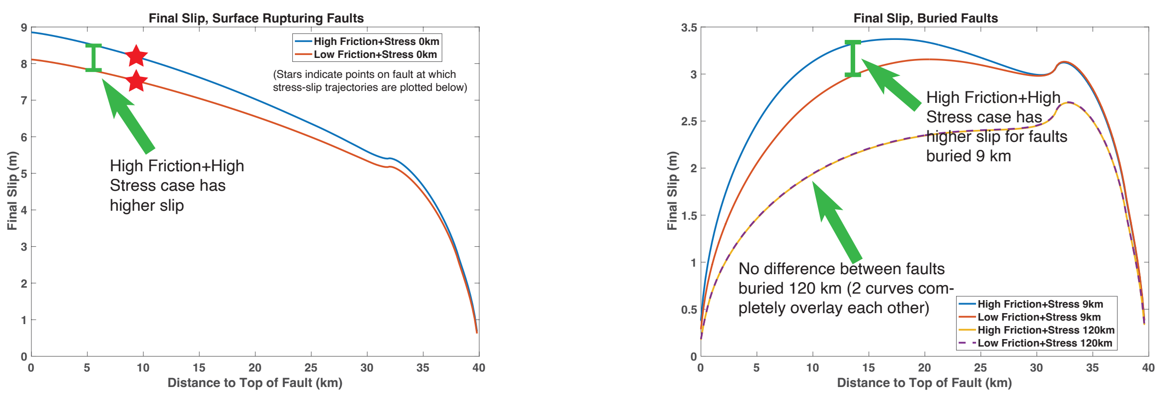

Figure 2. (left panel) Slip for faults that intersect the surface. High friction and high stress drop produce higher fault slip even with the same estimated stress drop and S. (right panel) Slip for faults buried 9 km and 120 km. Faults

buried only 9 km from the free surface also exhibit higher slip in the high friction/high stress case, but faults buried 120 km have no difference between the two cases of stress and friction.

We find that the depth-dependent effect of absolute fault stress and friction is related to the differences in stress drop between the different models. As shown in Figure 3, surface-rupturing faults with high friction and absolute stress have higher static stress drops than faults with lower friction and absolute stress. Shallow buried faults also display this effect to a somewhat lesser degree, and deeply buried faults do not display this effect.

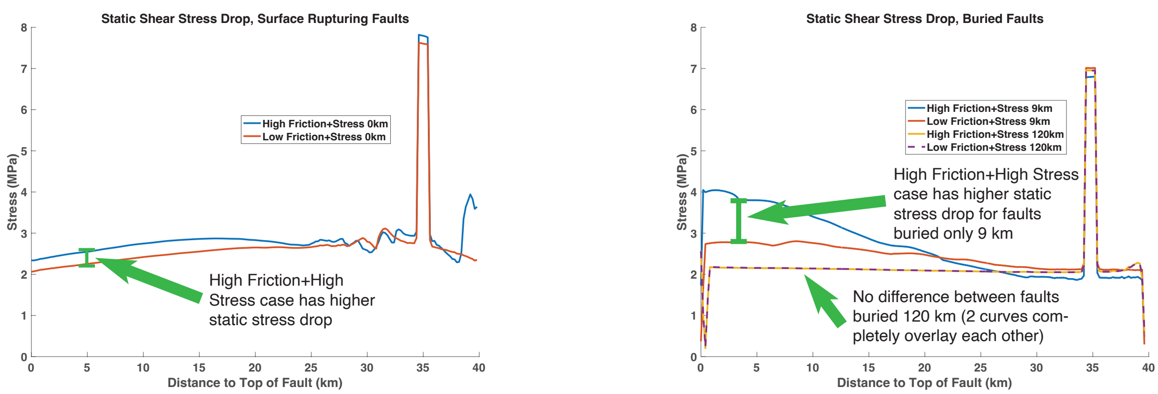

Figure 3. (left panel) final static stress drop along dip for surface-rupturing faults. (right panel) final static stress drop along dip for buried faults. Faults that approach the surface have higher static stress drop in cases with high friction and stress compared to otherwise equivalent cases with low friction and stress. Deeply buried faults do not show this effect.

The reason for the depth-dependent nature of the effect of absolute friction and stress lies in the feedback between slip, normal stress, and shear stress. Figure 4 shows the perturbations of normal stress and shear stress for surface-rupturing faults, in both the high friction/high stress case and the low friction/low stress case. Both faults experience perturbations in normal stress, but in the case high-friction/high stress case, a higher coefficient of friction means that there is a greater perturbation in shear stress (due to the normal stress perturbation being multiplied by a larger number) compared to the low-friction/low stress case. Thus, there is a higher stress drop in the high friction/high stress case, which in turn induces more slip, which feeds back into yet more normal and shear stress perturbation. For deeply buried faults, there is no normal stress perturbation, so the previously described effect does not exist; high friction/high stress and low friction/low stress models give identical results.

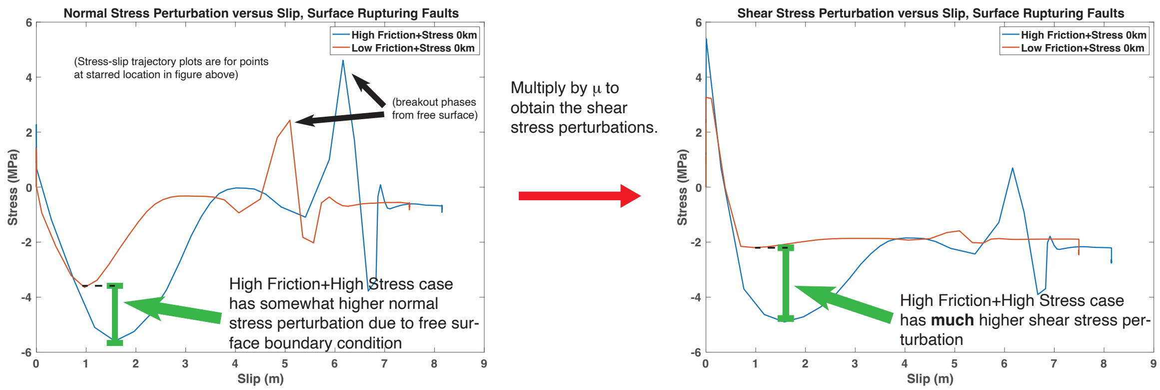

Figure 4. (left panel) normal stress perturbation as a function of slip for surface-rupturing faults. Note that there is slightly more normal stress perturbation in the high-friction/high stress case. (right panel) shear stress perturbation for same models as in left panel. Multiplying the normal stress perturbation by a higher coefficient of friction gives a larger shear stress perturbation, resulting in more slip for the high-friction/high stress model.

Our results imply that even if the normal stress perturbation in a thrust fault is a small percentage of the ambient stress, a high frictional coefficient may render it an important effect in determining the dynamics of the system. This effect may also have implications for other fault systems in which normal stress perturbations feed back into shear stress perturbations, such as stepovers, bends, and branches.

References

Barall, M., 2009. A grid-doubling finite-element technique for calculating dynamic three-dimensional spontaneous rupture on an earthquake fault. *Geophysical Journal International*, *178*(2), pp.845-859.

Brune, J.N., 1970. Tectonic stress and the spectra of seismic shear waves from earthquakes. *Journal of geophysical research*, *75*(26), pp.4997-5009.

Brune, J.N., 1996. Particle motions in a physical model of shallow angle thrust faulting. *Proceedings of the Indian Academy of Sciences-Earth and Planetary Sciences*, *105*(2), p.197.

Das, S. and Aki, K., 1977. A numerical study of two-dimensional spontaneous rupture propagation. *Geophysical journal international*, *50*(3), pp.643-668.

Dunham, E.M., Belanger, D., Cong, L. and Kozdon, J.E., 2011. Earthquake ruptures with strongly rate-weakening friction and off-fault plasticity, Part 1: Planar faults. *Bulletin of the Seismological Society of America*, 101(5), pp.2296-2307.

Dunham, E.M., Belanger, D., Cong, L. and Kozdon, J.E., 2011. Earthquake ruptures with strongly rate-weakening friction and off-fault plasticity, Part 2: Nonplanar faults. *Bulletin of the Seismological Society of America*, *101*(5), pp.2308-2322.

Eshelby, J.D., 1957. The determination of the elastic field of an ellipsoidal inclusion, and related problems. *Proceedings of the royal society of London. Series A. Mathematical and physical sciences*, *241*(1226), pp.376-396.

Gabuchian, V., Rosakis, A.J., Lapusta, N. and Oglesby, D.D., 2014. Experimental investigation of strong ground motion due to thrust fault earthquakes. *Journal of Geophysical Research: Solid Earth*, *119*(2), pp.1316-1336.

Harris, R.A., Barall, M., Archuleta, R., Dunham, E., Aagaard, B., Ampuero, J.P., Bhat, H., Cruz-Atienza, V., Dalguer, L., Dawson, P. and Day, S., 2009. The SCEC/USGS dynamic earthquake rupture code verification exercise. *Seismological Research Letters*, *80*(1), pp.119-126.

Harris, R.A., Barall, M., Andrews, D.J., Duan, B., Ma, S., Dunham, E.M., Gabriel, A.A., Kaneko, Y., Kase, Y., Aagaard, B.T. and Oglesby, D.D., 2011. Verifying a computational method for predicting extreme ground motion. *Seismological Research Letters*, *82*(5), pp.638-644.

Harris, R.A., Barall, M., Aagaard, B., Ma, S., Roten, D., Olsen, K., Duan, B., Liu, D., Luo, B., Bai, K. and Ampuero, J.P., 2018. A suite of exercises for verifying dynamic earthquake rupture codes. *Seismological Research Letters*, *89*(3), pp.1146-1162.

Hok, S. and Fukuyama, E., 2011. A new BIEM for rupture dynamics in half-space and its application to the 2008 Iwate-Miyagi Nairiku earthquake. *Geophysical Journal International*, *184*(1), pp.301-324.

Kostrov, V.V., 1974. Seismic moment and energy of earthquakes, and seismic flow of rock. *Izv. Acad. Sci. USSR Phys. Solid Earth, Engl. Transl.*, *1*, pp.23-44.

Kozdon, J.E. and Dunham, E.M., 2013. Rupture to the Trench: Dynamic Rupture Simulations of the 11 March 2011 Tohoku EarthquakeRupture to the Trench: Dynamic Rupture Simulations of the 11 March 2011 Tohoku Earthquake. *Bulletin of the Seismological Society of America*, *103*(2B), pp.1275-1289.

Kyriakopoulos, C., Oglesby, D.D., Funning, G.J. and Ryan, K.J., 2017. Dynamic rupture modeling of the M7. 2 2010 El Mayor-Cucapah earthquake: Comparison with a geodetic model. *Journal of Geophysical Research: Solid Earth*, *122*(12), pp.10-263.

Ma, S. and Beroza, G.C., 2008. Rupture dynamics on a bimaterial interface for dipping faults. *Bulletin of the Seismological Society of America*, *98*(4), pp.1642-1658.

Madariaga, R., 1976. Dynamics of an expanding circular fault. *Bulletin of the Seismological Society of America*, *66*(3), pp.639-666.

Nielsen, S., 1988. Free surface effects on the propagation of dynamic rupture. *Geophysical Research Letters,* 25, pp. 125-128.

Oglesby, D.D., Archuleta, R.J. and Nielsen, S.B., 1998. Earthquakes on dipping faults: the effects of broken symmetry. *Science*, *280*(5366), pp.1055-1059.

Okada, Y., 1992. Internal deformation due to shear and tensile faults in a half-space. *Bulletin of the seismological society of America*, *82*(2), pp.1018-1040.

Scala, A., Festa, G., Vilotte, J.P., Lorito, S. and Romano, F., 2019. Wave interaction of reverse-fault rupture with free surface: Numerical analysis of the dynamic effects and fault opening induced by symmetry breaking. *Journal of Geophysical Research: Solid Earth*, *124*(2), pp.1743-1758.

Ulloa, S. and Lozos, J.C., 2018. Surface Displacement and Ground Motion from Dynamic Rupture Models of Thrust Faults with Variable Dip Angles and Burial Depths. *Bulletin of the Seismological Society of America*

Ulrich, T., Gabriel, A.A., Ampuero, J.P. and Xu, W., 2019. Dynamic viability of the 2016 Mw 7.8 Kaikōura earthquake cascade on weak crustal faults. *Nature communications*, *10*(1), pp.1-16.

Wang, Y., Day, S.M. and Denolle, M.A., 2019. Geometric controls on pulse-like rupture in a dynamic model of the 2015 Gorkha earthquake. *Journal of Geophysical Research: Solid Earth*, *124*(2), pp.1544-1568.

Wollherr, S., Gabriel, A.A. and Mai, P.M., 2019. Landers 1992 “reloaded”: Integrative dynamic earthquake rupture modeling. *Journal of Geophysical Research: Solid Earth*, *124*(7), pp.6666-6702.

Wu, B., Oglesby, D. D., Kyriakopoulos, C., and Ryan, K. J. (2020, 08). How do inertia, free surface interaction, and absolute friction coefficient level affect the final slip amplitude in a theoretical thrust fault rupture model? . Poster Presentation at 2020 SCEC Annual Meeting. SCEC Contribution 10721

Zhang, H. and Chen, X., 2006. Dynamic rupture on a planar fault in three-dimensional half space—I. Theory. *Geophysical Journal International*, *164*(3), pp.633-652.