Effects of stress history on earthquake timing

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Abstract

We examine theoretically and through laboratory sliding experiments the timing of earthquake failure. In particular we study the change of failure time induced by stress perturbations superimposed on a steady, background loading rate. We model the response of a simple, one-degree-of-freedom fault using a rate-state friction constitutive expression, and compare model behavior and predictions of failure time to predictions of a simple Coulomb model in which failure occurs instantaneously at a fixed threshold stress. In these calculations as well as in laboratory stick-slip sliding tests on smooth, granite surfaces, changes to the loading path cause the peak stresses and failure times to vary in ways inconsistent with simple Coulomb failure. The magnitude of the deviation from the Coulomb prediction depends strongly on when in the loading cycle the perturbation is applied and its specific form; in other words the failure criteria is time-dependent. While the Coulomb model is likely adequate under most circumstances, its correctness should be evaluated especially when calculating the effect of stress changes occurring near impending earthquake failure.

Introduction

Stress changes, *e.g.*, those due to nearby and distant earthquakes, can alter the timing of future earthquakes. Interpretation of such stress changes may be of use in probabilistic seismic hazard analysis. In other studies, the Coulomb failure condition is used to predict the effect of static stress offsets on earthquake timing. The Coulomb condition amounts to a fixed stress threshold, reached due to tectonic loading and the static stress change. However, many field and laboratory observations are inconsistent with a constant failure stress threshold (*e.g.*, Omori aftershock decay sequences, which suggest a time-dependent failure condition, and remotely triggered seismicity). Direct verification of failure models in the Earth is difficult because quantities on which failure may depend, such as stress and inelastic strain, cannot be measured at nucleation depths and others, such as recurrence time, are poorly known. However, stick-slip 'earthquakes' induced on laboratory 'faults' provide data from numerous repeating events responding to a variety of known loading histories. Moreover, the laboratory permits measurement of fault slip, stresses, and material rheologic properties at resolutions not possible in the Earth.

We have studied the effects of loading history via experiments of stick-slip on smooth granite surfaces, and interpret results in the context of Coulomb-failure and rate-and-state frictional models. Under constant normal stress and steadily increasing shear stress ('tectonic' loading) repeated stick-slip cycles occur with nearly constant cycle time (recurrence interval). The nearly constant peak shear stresses before failure corroborates time-predictable earthquake models. In general, changes to the loading path cause the peak stresses and failure times to vary in ways consistent with simple Coulomb failure, which predicts that a step increase in static stress (*e.g.*, from a nearby earthquake) will hasten the failure time by the ratio of the step amplitude to loading rate, and that a transient stress perturbation (*e.g.*, due to seismic waves) should have no effect on the failure time unless it is large enough to cause instantaneous failure. However, we observe that a sufficiently large stress step causes failure to occur early, with decreased peak stress. We also observe that a sufficiently large stress transient causes delayed failure, with increased peak stress. The magnitude of the deviation from the Coulomb prediction depends strongly on when in the loading cycle the perturbation is applied and its specific form; thus the failure criteria is time-dependent. The Coulomb model also requires all slip to occur instantaneously at the time of failure; our observations show precursory slip both just prior to failure and concurrent with the onsets of sufficiently large perturbations.

Our experimental observations are well fit using a friction constitutive equation proposed by Ruina (1983 [1]) in which state (inherent frictional resistance) evolves with slip. Since the slip rate is a highly non-linear function of stress, the timing and magnitude of stress changes directly impact peak stress and failure time. In this model the fault strengthens only when slipping, like materials that strain-harden. A rapid increase in load causes a rapid rise in frictional stress (and thus in slip and slip rate), which changes the path toward failure and can cause failure to occur earlier or later, and at lower or higher stress levels, respectively. If the increase is followed by a decrease (as in a boxcar or sinusoidal transient), the stress drop causes slip rate to decrease by an amount much greater than the increase, leading to delayed failure at higher stress. This asymmetry results from the logarithmic dependence of frictional stress on slip rate (Gomberg et al., 1997 [2], 1998 [3]).

Differences between the predictions of the Coulomb model and the more complex and realistic rate-and-state model are not immediately intuitive, and depend strongly on the loading situation of interest. Only in certain circumstances (most notably very late and very early in the earthquake loading cycle) are those differences likely to be large enough to invalidate the Coulomb model, given levels of uncertainty in earthquake cycle times, strain rates and other field observables. However, the relationships between frictional failure and the load path that precedes it are easily explored through numerical modeling, using constitutive models vetted in the laboratory and tested in the field.

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