Stick-slip and Earthquake Mechanics

Background. Earthquakes within the shallow crust and lithosphere are understood as an instability of frictional sliding. In a descriptive sense, instability refers to the jerky motion by which slip occurs (called stick-slip sliding), in contrast to slow, continuous sliding, which is referred to as stable sliding. Instability also refers to the dynamic motion (i.e., accelerations and inertia are important) that occurs during stick slip when a stationary portion of the sliding surface accelerates.

Instability is the result of an interaction between a frictional surface (or volume if the slipping region has finite thickness, such as in a fault zone) and its elastic surroundings. Two things are required for instability: (1) that frictional resistance decrease in some way (for example with increasing slip or slip velocity), and (2) that friction decrease more rapidly with displacement than the elastic force applied by the surroundings.

Elastic stresses are stored in Earth’s crust as elastic strains, which derive from plate tectonic motions or other mechanisms. In our laboratory experiment the elastic stresses are provided by simple coil springs. The slider block is small enough to slip as a rigid unit and the entire surface accelerates and slips simultaneously. On an earthquake fault the rupture area is bounded and dynamic accelerations are associated with rupture growth and propagation. Acceleration of material on each side of the fault produces seismic waves.

We have a simple laboratory analog for earthquake motion. The sketches below show the basic set up. A mass $m$ is pulled by a spring of constant $k$. The applied (spring) force is $F_a$ and the resisting frictional force is $F_r$. We can denote spring extension as the difference $x - x'$, where $x'$ is the position of the slider block. Thus $F_a = k (x - x')$ if $x$ is measured relative to the initial spring length when $F_a = 0$ and $x' = 0$. The plot on the right shows the relevant forces and displacements. It is analogous to the stress-strain plots made for rock deformation. The experiment is valuable because we can study some of the factors that control the transition from stable to unstable sliding. In the case of unstable sliding, we can also study some additional details of the mechanics of slip.

Friction experiment. The block starts at rest and the spring force is zero. As the spring stretches, force increases in proportion to displacement $x$. For a simple case, the block displacement, $x'$, is zero until $F$ reaches a critical value, which is typically called static friction and noted $\mu_s$. Up until this point, everything is in static equilibrium. The block is at rest and $F_r = F_a$. Thus, there are no net forces available to accelerate the block. At point B, the sketch below shows a case in which the frictional resistance, $F_r$ (bold line starting near B) is exceeded and decreases rapidly as slip begins. We consider a case in which friction decreases very rapidly (the physics of this is discussed on the next page, but for now we can just assume that it does). However, the spring force can only drop as fast as the spring constant allows. Thus, $F_a$ must fall along the line of slope $-k$ between points B and C. The situation $F_r < F_a$ indicates a force imbalance, which leads to acceleration and transfer of potential energy to kinetic energy. The energy release is given by the integral $F \, dx$ and is the area between the two lines. The block accelerates until the spring force falls below the frictional resistance and then deceleration occurs until the block comes to rest at point C.

From the point of view of frictional stabil weakening frictional behavior. An important que:

Weakening Law* indicates one possible explanation of the physics of frictional weakening. In this case,
the coefficient of friction during sliding is lower than the coefficient of static friction. Point B then
represents the point at which sliding begins, and frictional strength breaks down over slip L. The slope of
the weakening \((\mu_s - \mu_d)/L\) is therefore a critical term, since it sets the critical spring stiffness for which
sliding will be stable or unstable. If we multiply the friction coefficients by a normal force or stress, we
can define a critical stiffness: \(k_c = N(\mu_s - \mu_d)/L\), where \(N\) is the normal force at the base of the slider block.
Springs of stiffness \(k > k_c\) should result in stable sliding, whereas those of stiffness \(k < k_c\) should produce
unstable sliding. The slip weakening friction law is more accurate than simpler laws, such as a ‘\textit{static-
dynamic}’ friction law in which friction simply drops instantaneously from \(\mu_s\) to \(\mu_d\) upon initiation of
sliding. For a static-dynamic friction law, unstable sliding would occur for all stiffnesses. However, it is
observed experimentally that for sufficiently stiff springs sliding can be stable. A slip weakening law
friction law, coupled with elastic interaction can be used to predict the transition from stable to unstable
sliding.

Modern theories of rock friction recognize that the transition from static to dynamic friction does not occur
instantaneously but rather over some critical slip distance. This distance represents a memory that friction
retains of its prior state --e.g. time of stationary contact or surface properties. In addition, the difference
between static and dynamic friction is seen as a specific case of a more general velocity dependence of
friction (see lower sketch). In the context of this theory, frictional weakening occurs via velocity
weakening (friction decreases as slip velocity increases).
Stick-slip and Earthquake Mechanics; The Deliverables

Note: My assumption is that you will work together, as 1, 2 or perhaps 3 groups. That’s part of the reason we’re using 10 springs. Make sure that you get to measure at least one spring – but then share your data. Everyone should have their own report, with all details in it, but you are welcome/encouraged to share the data that you collect as a group.

The experimental apparatus consists of a slider (rock), which may be pulled over a rough rock surface via an electric motor. The motor is equipped with a variac (dimmer switch!), which may be used to vary the loading rate. At a given slip rate, the slider may undergo stick-slip sliding if the stiffness of the loading spring is sufficiently low. We can vary the loading stiffness by using springs in series with the string.

1. [5] Measure the stiffnesses of the 10 springs supplied using at least three masses per spring (what is the 10th spring?). Give the masses, length changes and resulting stiffnesses for each spring in units of N/m. Note 1 N = 0.2248 lbs. Make any notes necessary to understand what you’ve done.

1.1 [5] Start with the 3.375 kg block. Wash each surface of the block and keep track of which surface you’re using. Make notes about what you’re doing here and include them in your report.

Begin by pulling the block with springs of varying stiffness at a given velocity. A good suggestion would be to start with the max slip velocity. Make sure that your springs are compliant enough to observe stick slip and stiff enough to observe stable sliding. Make any notes necessary to understand what you’ve done.

2) You should observe both stick slip and stable sliding.

2.1 [5] Based on your observations sketch the force displacement relation for stick slip and stable sliding.

2.2 [10] Measure the average slip distance for each spring and plot this slip distance versus stiffness. Plot the independent variable on the x-axis of your plots. Give a brief description of the significance of this slope, what is the theoretical value for this slope.

3) Because stick-slip is possible we know that the rock’s frictional behavior must include some form of slip or velocity weakening. Using the various springs provided determine the rock’s friction response at the point of instability (i.e., determine the slope of its force displacement relation). This value will correspond to the critical stiffness discussed above.

3.1 [10] Give your value for the critical stiffness in units of N/m. Explain your reasoning for choosing this value and briefly discuss the uncertainty in your estimate. If you assume a value for the difference between 'static' and 'dynamic' friction, you can use your estimate of critical stiffness to provide an estimate of the slip weakening distance. How does this value compare to other measurements and estimates from the literature?

4 [10] Dampen the surface of your block and use a much lower pulling velocity than above; repeat step 2. Briefly, in a few sentences, explain any differences you observe.

5 [10] Coat the surface of the blocks with talcum powder and repeat numbers 2 and 3. Briefly, in a few sentences, explain any differences you observe.

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