Earthquake Statistics Using Discrete Element Models

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Spectrum of Fault Slip Behaviors
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1. Introduction

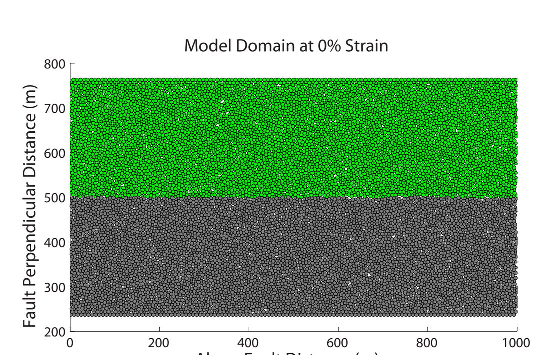
Discrete Element Method (DEM) simulations have been used to analyze the frictional properties and deformation along faults, including the effects of fault gouge [e.g. Morgan, 1999; Morgan and Boettcher, 1999], grain shape and gouge evolution [Guo and Morgan, 2004, 2006], rate and state friction [Abe et al., 2002; Morgan, 2004] and 3-dimensional effects [Abe and Mair, 2005]. However, the behavior of fault slip in this type of model has not been explored in detail. For example; are earthquakes produced? Do they follow well known laws, such as Omori and Gutenberg-Richter laws? Do parameters such as slip distance, rupture size, and stress drop agree with observations from earthquake catalogs? Are other slip behaviors (e.g. slow slip) evident? We probe these questions in a series of simple model experiments.

2. Model Set-up

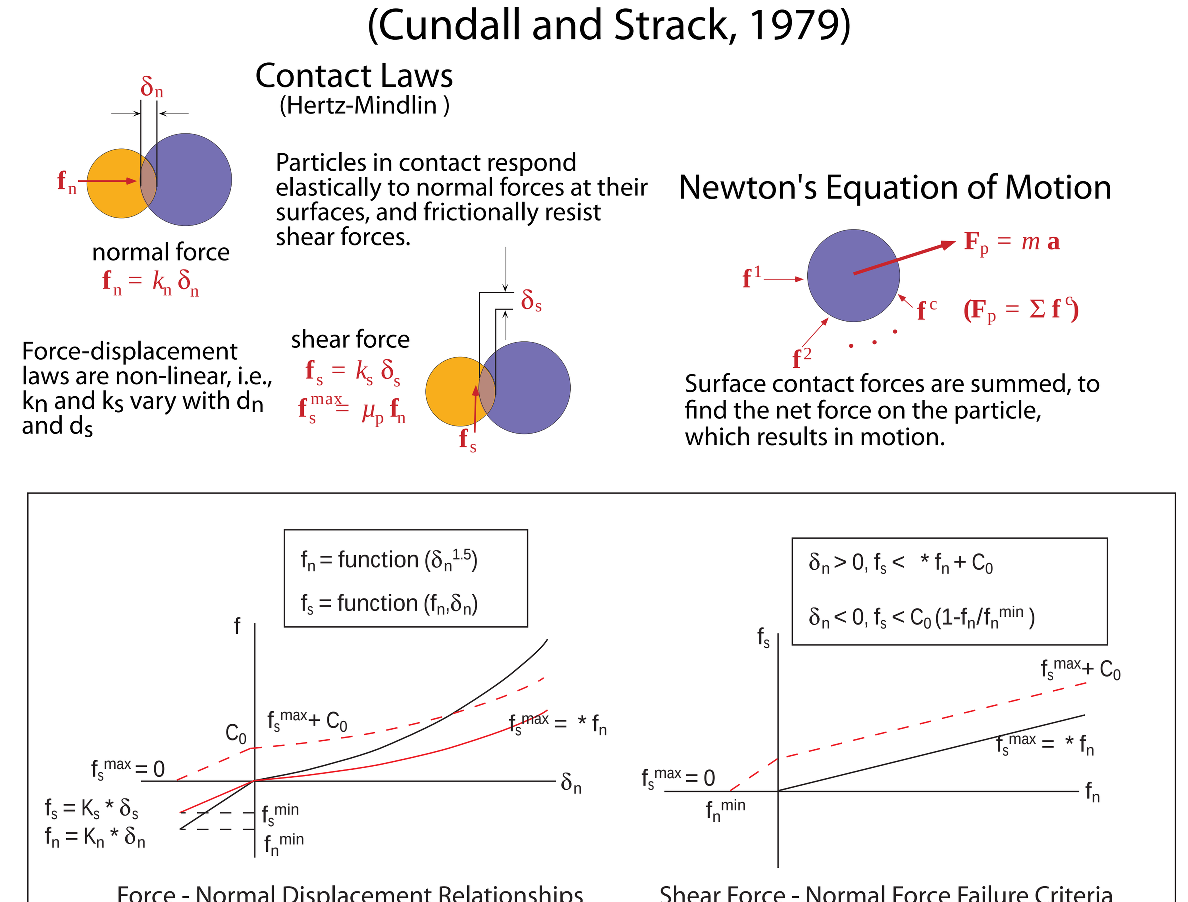
1 km x 0.5 km of particles are consolidated at 100 MPa confining pressure. Two "blocks" are formed from the consolidated material, by bonding the particles within each block. The fault is the unbonded contact between the two blocks. Right lateral shear is applied to the outer edge of each block at a total rate of 0.3m/s.

We analyze the particles near the fault to extract earthquake like slip events, and examine the behavior of the system. Due to DEM dynamics the topography of the fault interface evolves over large strains and particles can break from the wall materials and become "gouge". The experiments here occur during relatively young fault evolution, and relatively small strains (~4%).

The complete model is shown (right), where the balls are colored according the material block that they belong too (each block has the same material properties).



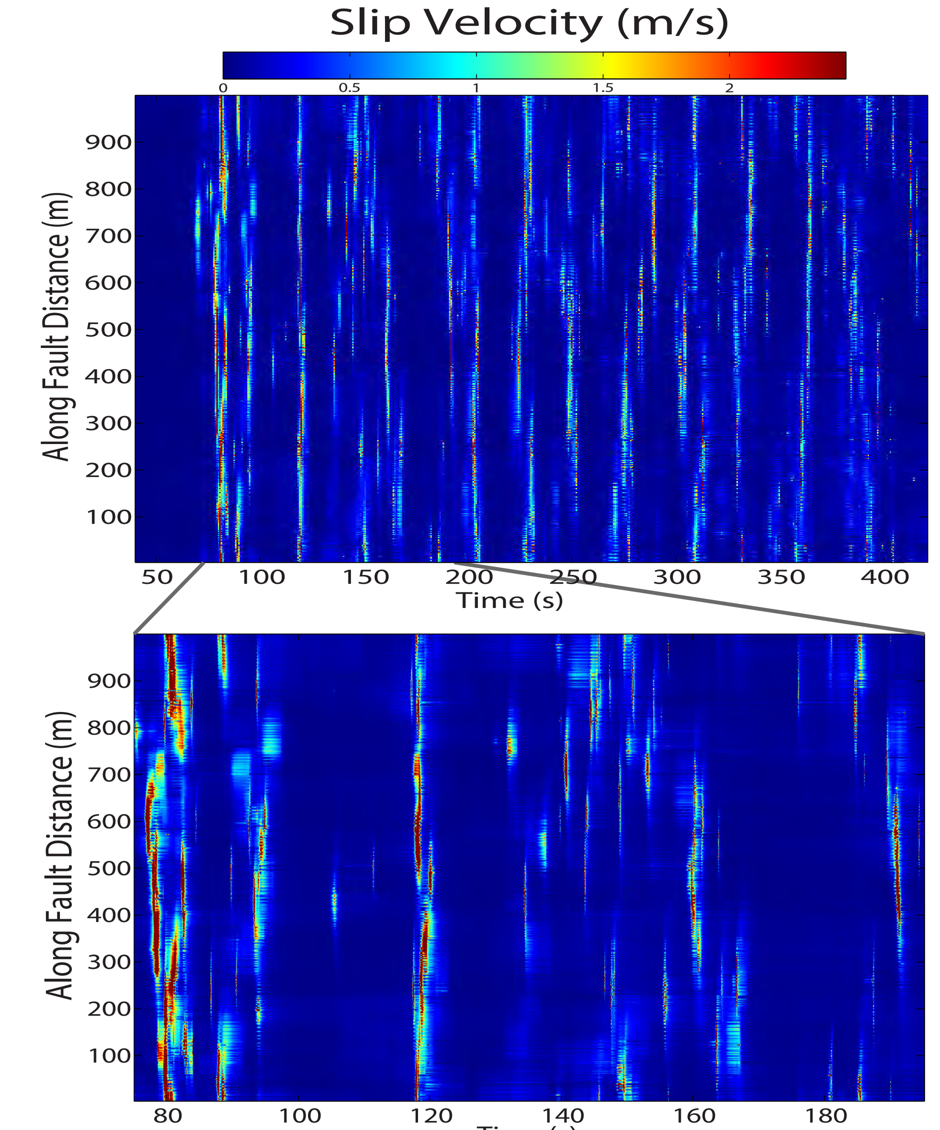
DISCRETE ELEMENT METHOD
(Cundall and Strack, 1979)



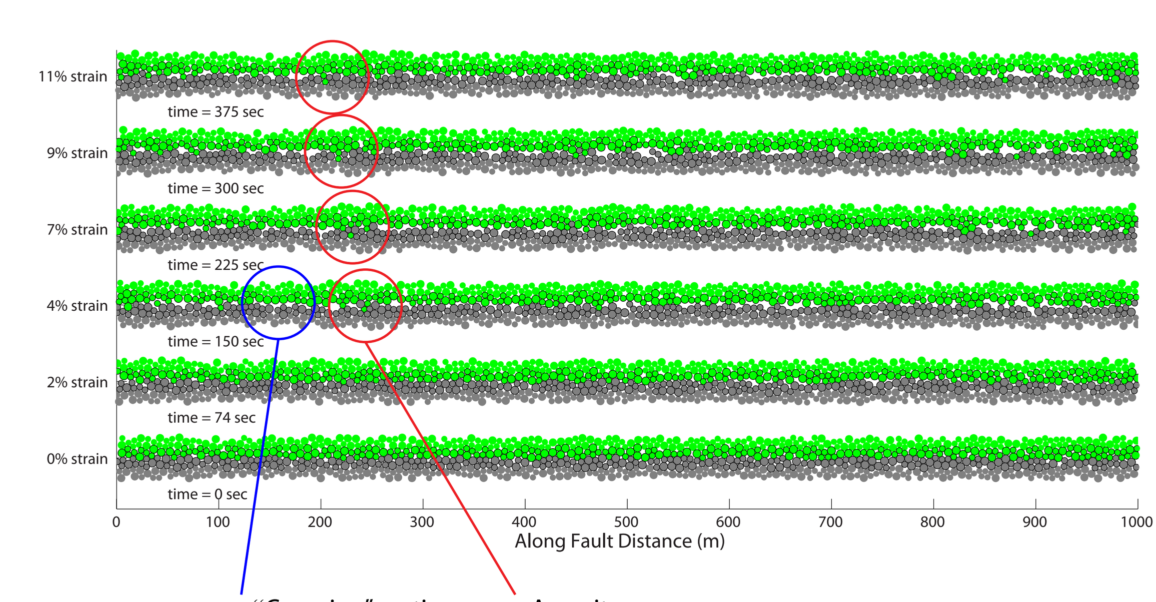
3. "Earthquake" Determination

Earthquake-like slip periodically occurs on segments of the fault interface. Slip that exceeds a threshold velocity (~2.5 m/s) is considered an earthquake and is examined for scaling relationships. Particles that exceed the slip threshold are considered part of an earthquake only when neighboring particles are also slipping (single particle motion is not an earthquake), and the event ends when all neighboring particles fall below the threshold.

The amount of slip during an event is determined by smoothing the particle displacements that are close to the fault plane and taking the difference between the smoothed displacements of the upper material from the lower material.



The slip velocity is used to select earthquakes, shown here as red regions in a time-space plot. The longer time window (top) shows the long term event characteristics, while the blow-up (bottom) shows the time period used for analyzing slip behavior. This example is from the medium-friction experiment (shown in boxes 4 and 5).

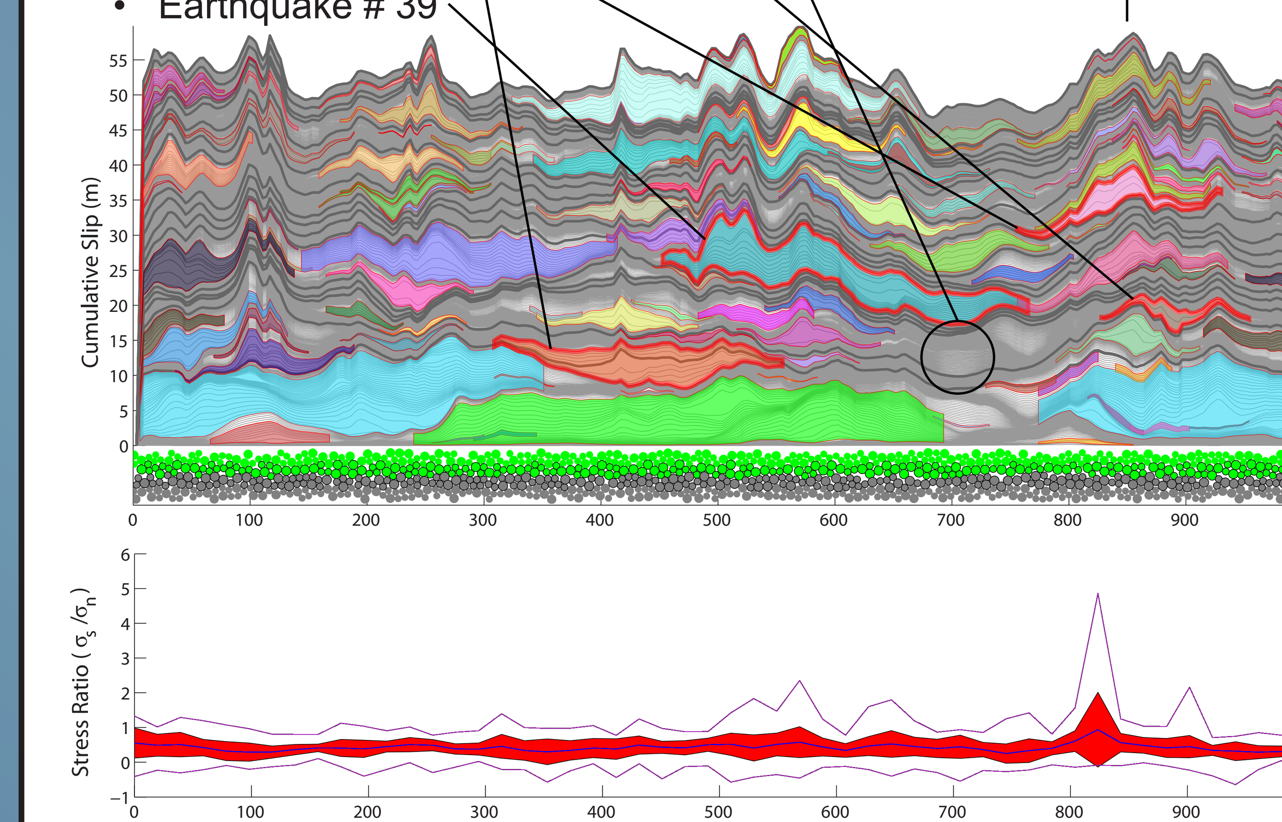


The discrete element method allows for the topography of the fault to evolve through the simulation. This evolution affects the contact distribution across the fault. Asperities remain active for extended periods of time (several earthquake cycles at least). The example given above shows the fault evolution over ~350 seconds (~10% strain) and corresponds to the medium-friction experiment shown above. We analyze earthquakes over a period of ~150 sec (shown at right).

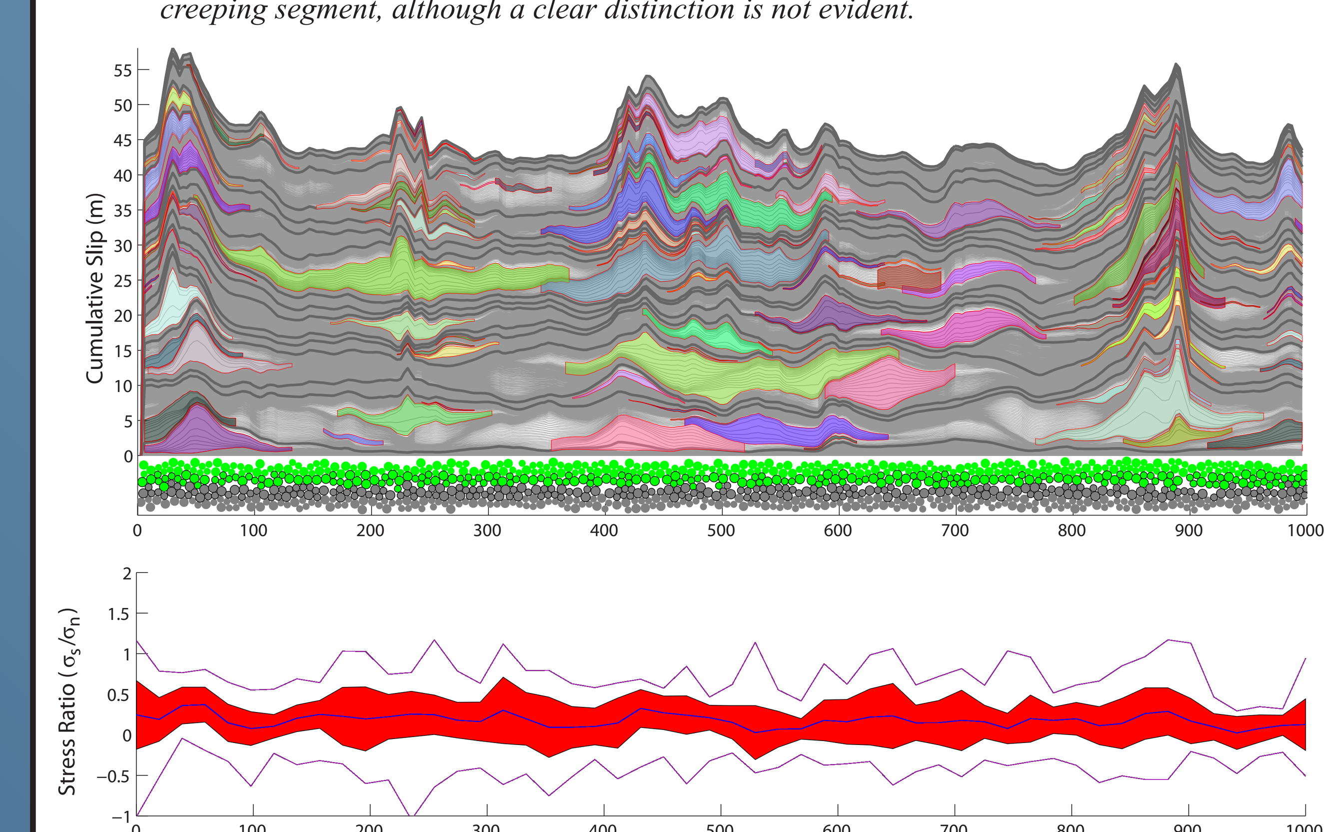
4. Distribution of Slip Events

Earthquake slip events occur predominantly at "asperities" although slip events do occur at all locations along the fault. Creep-like slip also occurs on portions of the fault and at various rates.

- Large earthquakes associated with initial rupture of the fault.
- Repeated quakes at large asperities.
- Various slow slip behaviors.
- Earthquake # 30
- Earthquake # 16
- Earthquake # 53
- Earthquake # 39

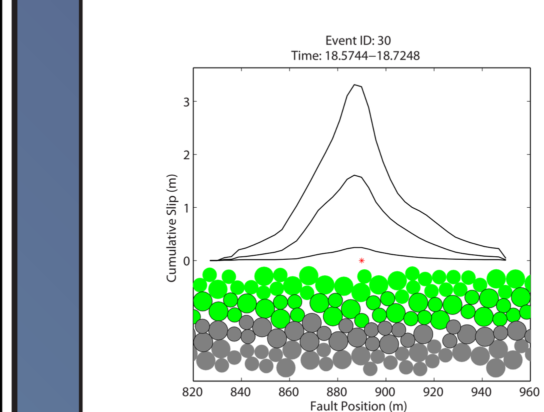


The cumulative slip for two experiments are shown, medium-friction (above) and low-friction (below). The x-axis is the location on the fault, and the y-axis is the cumulative slip. Each line represents a time increment and shows the cumulative slip at that time, the dark gray contours are every 100 time-steps (7.5 s). Slip events identified as earthquakes are colored. The mean stress ratio (shear divided by normal), its standard deviation, and the min and max values are also plotted. It is expected that the stress ratio would have a different standard deviation depending on whether the fault segment is an "asperity" or a creeping segment, although a clear distinction is not evident.

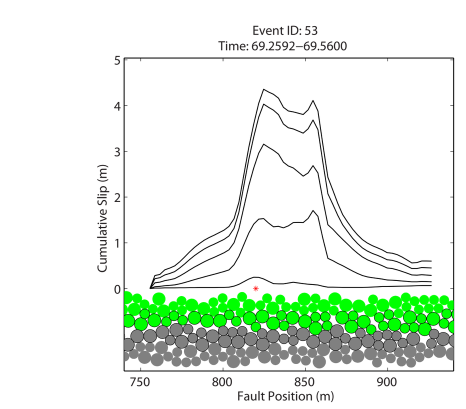


5. Example Earthquakes

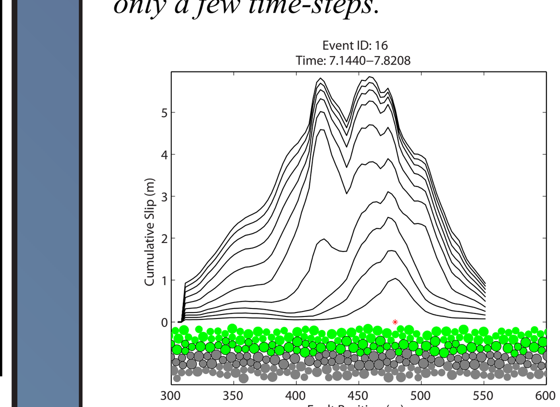
The earthquakes that are produced occur at various sizes, rupture durations and vary from simple to complicated in the rupture evolution. Below are a few examples of typical types of rupture that we observe. The examples are taken from the medium-friction experiment and show the cumulative slip during the event. Each contour is the slip accumulated at that time-step (= 0.075 s) since the beginning of the event.



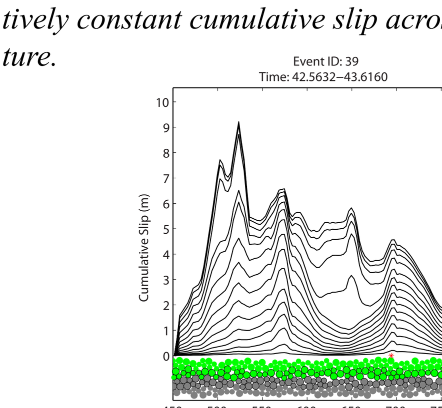
Standard small event appearance. Some quakes have two peaks; they generally last only a few time-steps.



A plateau in cumulative slip indicates the main rupture region. Many events finish with a relatively constant cumulative slip across the rupture.



More complex ruptures generally involve rupture of multiple segments, usually caused by slip accumulation on neighboring regions.



This example shows a quake that begins at the epicenter (red star) with relative slow rupture speed which then triggers two separate patches to fail.

6. Statistical Comparison

In order to compare the events produced in the model to real earthquakes, we first examine some basic scaling relationships. The relationships below are for three models where the fault friction is changed from "high" to "low". It is important to note that in the model we do not prescribe the on fault friction, instead we set the interparticle friction acting across the fault. The actual fault friction is the result of the bulk behavior of the particles. In the middle plots the constant stress drop lines assume a circular rupture patch.