

Simulation of the Influence of Rate and State Dependent Friction on the Macroscopic Behavior of Complex Fault Zones with the Lattice Solid Model

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Abstract

In order to understand the earthquake nucleation process, we need to understand the effective frictional behavior of faults with complex geometry and fault gouge zones. One important aspect of this is the interaction between the friction law governing the behavior of the fault on microscopic level and the resulting macroscopic behavior of the fault zone. Numerical simulations offer a possibility to investigate the behavior of faults on many different scales and thus provide a means to gain insight into fault zone dynamics on scales which are not accessible to laboratory experiments. The numerical experiments performed to investigate the influence of the rate and state friction on the dynamics of faults. These are designed to be similar to laboratory experiments by Dieterich and Kilgore [4] in which a slide-hold-slide cycle was performed between two blocks of material and the resulting peak friction was plotted vs. holding time. Simulations with a flat fault without a fault gouge have been performed to verify the implementation. These have shown close agreement with comparable laboratory experiments. The simulations which have been performed with faults containing a fault gouge show a large dependence on the structure of the fault gouge. Simulations with a gouge in which the movement mainly takes place by grain rotation show a highly variable response to the holding event without a visible trend. Simulations with a gouge consisting of irrotational grains, however, show the expected increase in macroscopic friction. Preliminary results from those simulations also suggest that the macroscopic critical displacement D_c is dependent on the roughness of the fault surfaces.

Introduction

The lattice solid model (Mora and Place 1994 [5], Mora and Place 1998 [6]), is a particle based model to study the simulation of the dynamics of earthquakes and faulting. Different kinds of microphysics have been included in the model (Place and Mora 1999[7], Abe, Mora and Place 2000[1]) in order to investigate the influence of different physical processes on the dynamics of earthquakes. The model consists of a lattice of particles which are interacting through a brittle-elastic potential function and an intrinsic friction between particles. Rate and state dependent friction has been implemented on a microscopic scale by tracking the contact time and velocity for each frictional interaction between particles and computing the rate and state variables from those.

Theory

The coefficient of friction of a material can be described by the product of the shear strength of contacts S and the inverse of contact normal stress P (Dieterich 1979 [3], Ruina 1983 [8])

$$\mu = SP \quad . \quad (1)$$

The inverse of contact normal stress P can be computed from two constant material dependent parameters P_1 and P_2 and the state variable Θ as

$$P = P_1 + P_2 \ln \left(\frac{\Theta}{\Theta^*} + 1 \right) \quad , \quad (2)$$

and the shear strength of contacts can be computed from the material parameters S_1 and S_2 and the contact velocity V using

$$S = S_1 + S_2 \ln \left(\frac{V}{V^*} + 1 \right) \quad . \quad (3)$$

The parameters Θ^* and V^* are normalizing constants. Ignoring higher order terms and inserting Eqns. (2) and (3) in Eq. (1) we obtain

$$\mu = S_1 P_1 + S_2 P_1 \ln \left(\frac{V}{V^*} + 1 \right) + S_1 P_2 \ln \left(\frac{\Theta}{\Theta^*} + 1 \right) \quad , \quad (4)$$

which is equivalent to the friction law

$$\mu = \mu_0 + A \ln \left(\frac{V}{V^*} + 1 \right) + B \ln \left(\frac{\Theta}{\Theta^*} + 1 \right) \quad , \quad (5)$$

presented by Dieterich and Kilgore (1994) [4] where the constants can be computed as

$$\mu_0 = S_1 P_1 \quad (6)$$

$$A = S_2 P_1 \quad (7)$$

$$B = S_1 P_2 \quad . \quad (8)$$

The evolution of the state variable Θ at constant normal stress can be described by the law

$$\frac{d\Theta}{dt} = 1 - \frac{\Theta V}{D_c} \quad , \quad (9)$$

proposed by Ruina (1983) [8] where D_c is the characteristic slip distance required to stabilize friction after a change in sliding conditions. Assuming that D_c is proportional to the displacement required to completely change the population of contacts (Dieterich and Kilgore 1994 [4]), we can calculate an approximate value for D_c from the contact area a and thus from the normal force F_n and the inverse of contact normal stress P by the following equation:

$$D_c = \sqrt{a} = \sqrt{F_n P} \quad . \quad (10)$$

Implementation

The rate and state dependent friction is implemented in the Lattice Solid Model on a microscopic level. For each frictional contact between particles, the parameters P, S, Θ, D_c and μ are computed at each time step. The velocity V depends on μ due to the calculation of

the dynamic behavior of the particles involved in the contact, but μ depends on S (Equation (1)) and thus on the velocity (Eq. (3)). The inverse of contact normal stress P depends on Θ , but Θ depends on D_c (Eq. (10)) which depends on P (Eq. (2)). Thus an iterative approach to the computation of the friction is necessary. This is implemented as a pair of nested loops in which the dependence between V and μ is treated in the outer loop and P and Θ in the inner loop (Table 1). Tests have shown that those iterations are necessary to ensure the stability of the algorithm but the iteration counts both for the inner and outer loop are relatively low, i.e. between 2 and 5 iterations.

<pre> For all particles iterate { $V = V(\mu, \dots)$ for each particle compute $\mu = \mu(V, \dots)$ iterate { $P = P(\Theta, \dots)$ $D_c = D_c(P, \dots)$ $\Theta = \Theta(D_c, \dots)$ } until converged $S = S(V, \dots)$ $\mu = \mu(P, S)$ } until converged </pre>
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Table 1: Algorithm for the computation of rate and state dependent friction

Results

Simulations with a flat fault without a gouge layer have been performed to verify the implementation. The model used consisted of a 2D-lattice of 2528 circular particles with random sizes between 0.1 and 1.0 arranged in two elastic blocks with a fault between them which is flat to the resolution possible with this range of particle sizes. At the fault line, the particles have been fit to a straight line to minimize fault roughness. To investigate the macroscopic frictional behavior, the model was sheared in a direction parallel to the fault with a constant velocity. After the model reached a steady state, the state variable Θ was increased by a given amount for all particle interactions which is equivalent to holding the fault without movement for a specified time. The difference between the resulting macroscopic friction of the model and the macroscopic friction of a model without the state increase was then plotted for 10 events each for increases in the state variable of 10, 100, 1000, 3000, 10000, 30000 and 100000 (Figure 1). The peak values of these differences are then plotted over the increase in the state variable which is equivalent to the holding time (Figure 2). The results show good agreement with the log-linear relation obtained in the laboratory experiments by Dieterich and Kilgore (1994) [4].

Further simulations have been performed with a model with a rough fault which contained a fault gouge consisting of 32 rounded grains. The radii of these grains were distributed according to a power law with an exponent of 1.58. Each of the grains consisted of multiple circular particles bonded together and arranged to approximate a round grain. The small size of the model means that the evolution of the macroscopic friction in the individual simulation runs is mainly determined by the geometric microstructure of the fault. The results (Figure 3) show that the complex dynamics of fault gouge yields a varied response to an increase in

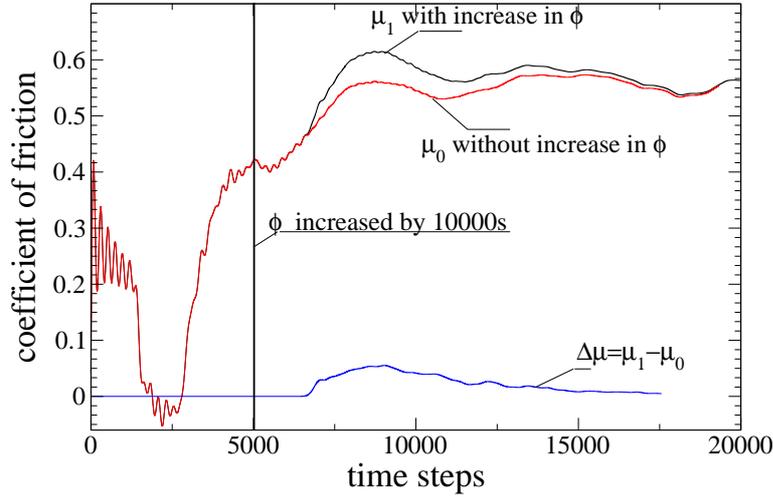


Figure 1: Evolution of the macroscopic friction in the model with bare surfaces with and without an increase in Θ .

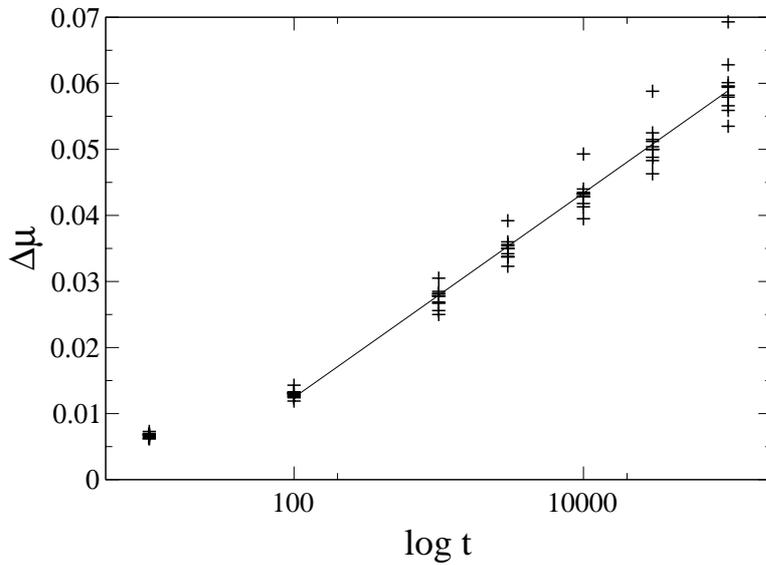


Figure 2: Increase in friction vs. holding time in a bare surface model.

the state variable without showing any visible trend. It is believed that this is mainly due to the dominance of grain rotation over sliding caused by the very round grains.

The gouge used in a second set of simulations consisted of irrotational single particle grains, thus avoiding the problem of particle rotation dominating the fault movement. The total omission of grain rotation, however, leads to a higher average macroscopic friction of the fault. Because of the small size of the models, containing between 100 and 150 gouge grains, the raw data contain a significant amount of noise. Thus, multiple slide-hold-slide cycles have been simulated for each model and the results have been averaged to improve the signal to noise ratio. So far the results of two simulations are available. The first model contained a gouge consisting of 102 irrotational particles with radii ranging from 0.2 to 1.0 and flat fault surfaces. The second model contained a gouge with 150 particles with radii between 0.2 and 1.5 and a rough fault surfaces. Both models showed the expected increase in macroscopic friction after the holding event followed by a decrease to the level of friction before the holding event (Figures 4 and 5).

The value of the critical displacement D_c obtained by fitting an exponential curve to the decrease in friction is different for the two models. The value of ≈ 0.06 obtained for the model with a flat fault surface is identical with the value for bare surfaces. However, the value of ≈ 0.35 obtained for the model with the rough fault surface is significantly larger. This

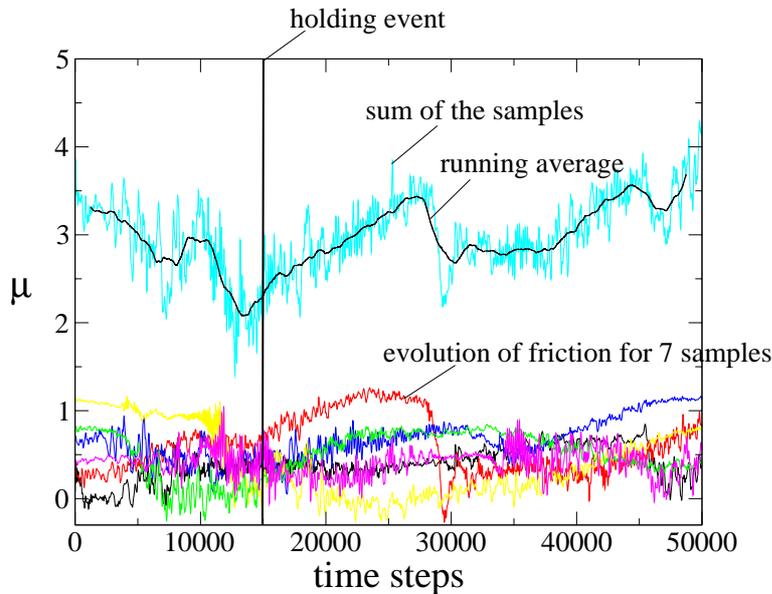


Figure 3: Evolution of macroscopic friction for several slide-hold-slide cycles in a model with fault gouge consisting of multi particle grains.

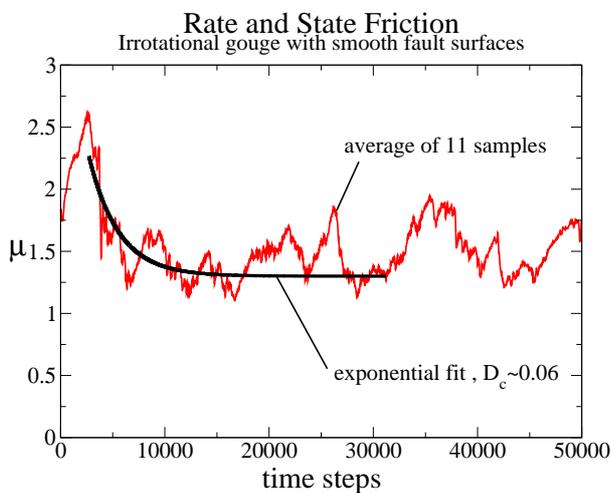


Figure 4: Evolution of macroscopic friction averaged over several slide-hold-slide cycles in a model with flat fault surfaces and a fault gouge consisting of irrotational grains.

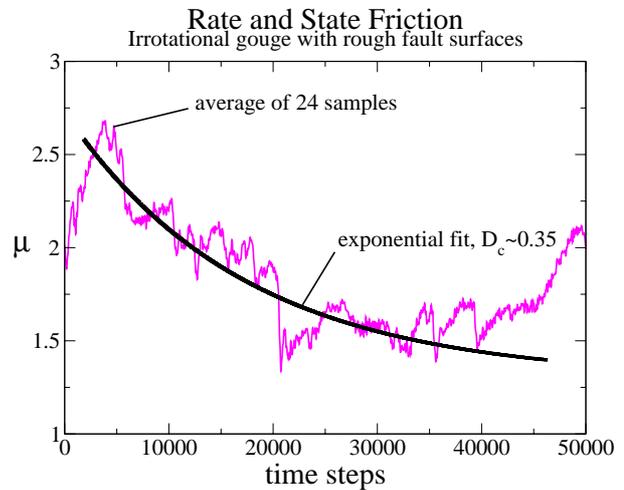


Figure 5: Evolution of macroscopic friction averaged over several slide-hold-slide cycles in a model with rough fault surfaces and a fault gouge consisting of irrotational grains.

increase of D_c with fault surface roughness would be consistent with results from laboratory experiments by Biegel et.al [2] but there is not yet enough data to confirm it.

Conclusion

By introducing rate and state dependent friction into the Lattice Solid Model on a microscopic level, it has been possible to produce simulation results which were in close agreement with the results from comparable laboratory experiments for friction between bare surfaces. The simulations of a model including a fault gouge have shown a high degree of complexity in the response of the system to changes of the frictional state, in particular in gouge configuration where movement is dominated by grain rotation. Simulations of a model with a gouge consisting of irrotational grains have shown the expected macroscopic response. Preliminary data from those simulations suggest an increase in the macroscopic critical displacement D_c

for models with rough fault surfaces. This result, however, needs to be confirmed by more data from subsequent simulations.

Acknowledgments

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