The Lattice Solid Model: towards a realistic simulation model for earthquake micro-physics and the development of a virtual laboratory for the earthquake cycle

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Abstract

A realistic numerical simulation model for all physical processes underlying the earthquake phenomenon on HPC's would provide a powerful tool to study fault behavior and earthquake nucleation. The microphysical particle-based Lattice Solid Model (LSM) currently being developed at QUAKES provides a basis on which to construct such a model. Presently, the model simulates stress transfer, seismic waves, fracture, friction, heat and gouge dynamics. Simulations show numerous features compatible with laboratory and field studies including shear localization, low-strength faults compatible with the Heat-Flow Constraint, slip pulses on faults, Gutenburg-Richter power law statistics and cycles of seismic activity exhibiting accelerating energy release prior to large events. Ultimately, when fully developed, it is envisaged that the LSM will be capable of simulating all physical processes underlying earthquakes including lubrication and dynamics of fluids, phase transformations, and chemical effects as well as all observable signals including strain, seismic, electric and magnetic. Increased computational capacity, a model refinement process involving feedback with laboratory and field observations, and integration with macroscopic simulation models would provide the means to study the earthquake cycle, and hence, to develop earthquake hazard quantification and forecasting methodology that best uses the incomplete recorded and incoming data. Recent LSM simulation results of patterns of accelerating energy release prior to large events suggest that earthquake statistics can evolve in a predictable way. These results demonstrate the potential utility of realistic numerical simulation models as a means to probe the earthquake cycle, and provide encouragement that earthquake forecasting is feasible, at least under certain conditions.

Introduction

Earthquakes involve physical processes occurring over a wide range of space and time scales (Figure 1) making it seem unlikely that simulation of these processes in a single approach could be practical. The processes include fracture of heterogeneous solids, granular dynamics, friction between rough brittle rock surfaces, solid-fluid dynamics and lubrication, phase transformations such as mineralogical or solid-liquid, stress accumulation, finite-strain elastic or plastic deformation, elastic stress transfer via seismic wave propagation, seismic wave radiation from the crustal zone of interest, heat conduction and mechano-thermal feedback processes. Assuming it is possible to describe both the inter-fault region and faults by specific constitutive relations, the problem can be solved using classical continuum-mechanics-based direct approaches such as finite-differences, finite-elements, pseudo-spectral and spectral-elements. However, while the inter-fault region is well approximated as an elastic solid, the fault constitutive relation is only partially accessible by direct observations. This necessitates extrapolations based on laboratory observations or indirect inferences based on compatibility between scaling relations derived from macroscopic simulation studies and field data (e.g. Shaw, 1999[12]). A numerical model capable of simulating processes at the micro-scale and meso-scale covering the nucleation processes zone of Figure 1 would help bridge this crucial gap in knowledge.

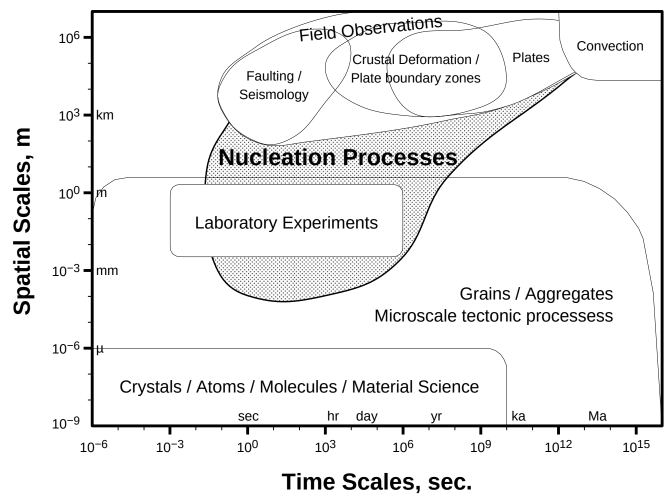

Figure 6: Space and time scales relevant to the earthquake cycle. Physical processes occurring at the microscopic scale (Grains/Aggregates Micro-tectonic processes) control earthquake generation. This domain is only partially accessible by direct observations. The meso-scale where earthquake nucleation processes occur is difficult to access with direct observations and lies between the microscopic and macroscopic realms (note: boundaries on the plot should be considered as fuzzy rather than sharp). *From The ACES Proposal, Mora, Matsu'ura, Minster and Yin, 1997.*

The lattice solid model

A Lattice Solid Model (LSM) having the elements needed to simulate the physical processes underlying earthquakes was initially proposed in 1992 (Mora, 1992[4]). The model was motivated by molecular dynamics and consisted of a system of particles whose interactions were to be specified such that they represented the basic units of the system being simulated. For example, at the micro to meso-scale, interactions should be specified corresponding to those between cemented or touching rock grains. The particle discretization of matter makes it tractable to simulate the essential complex phenomena underlying fault dynamics such as fracture of heterogeneous solids and friction between rough brittle surfaces. In the initial LSM, solid material was discretized in 2D as particles bonded by elastic brittle bonds. Even with such simple interactions, a variety of phenomena relevant to earthquakes were observed including mode II fracture (Mora and Place, 1993[5]), slick-slip behavior and occurrence of rupture as a slip-pulse (Mora and Place, 1994[6]).

In the most recent version of the LSM (Place and Mora, 1999[10]), pieces of material are discretized as groupings of bonded particles arranged into a regular triangular lattice, thus yielding isotropic elastic behavior for each piece of material. These pieces of material are used to represent rock grains or blocks. Bonded particles undergo linear elastic and repulsive forces depending on the inter-particle separation. Different pieces of material interact with one another if they come into contact through the frictional and repulsive forces that occur between their surface particles. An approach involving the resolution of a nonlinear system allows all dynamical and static frictional forces to be precisely calculated at each time step of the numerical integration algorithm. An artificial viscous force proportional to particle velocity is applied to avoid the buildup of kinetic energy in the closed system that may modify system dynamics (Mora and Place, 1994[6]). This mimics the effect of seismic wave radiation to outside a given crustal fault region. The LSM is similar to the particle based Distinct Element Method (DEM) of Cundall and Strack (1979[2]) but the independent roots have led to a vastly different computational approach. Comparisons between the two methods (Place and Mora, 1999[10]) demonstrate that under the given LSM assumptions of stopping slip exactly between static surface particles, the LSM is more precise and efficient than the DEM method.

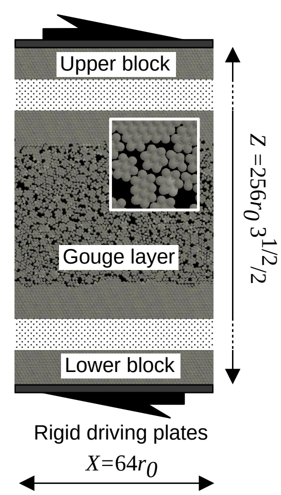

Figure 2: A typical numerical experimental setup involving a gouge layer being sheared showing how the current version of the LSM is composed of particles arranged into a triangular lattice that make up grains and blocks of solid material.

A series of recent papers have involved simulation of complex fault zones with and without fault gouge. These have demonstrated that a 2D model fault zone yields results that are compatible with the observations surrounding the long-standing Heat Flow Paradox (Mora and Place, 1998[7]) including stress drops, heat flow and fault weakness. The underlying weak fault mechanism in the model was rolling and jostling of fault gouge grains which allowed macroscopic slip to occur with minimal slip between grain surfaces. Subsequent numerical experiments (Mora and Place, 1999[8], Place and Mora, 1999[9]) involving a wide weak solid band that was allowed to evolve into a fault gouge layer showed that after a sufficient time, the gouge layer self-organizes into a weak state in which slip occurs on a narrow band (Figure 3). These results also suggested that internal gouge grain stresses might be low enough for the rolling-jostling slip mechanism to be viable in real faults. The long time required for self-organization into the weak layer offers a possible explanation for why weak gouge layers have yet to be observed in the laboratory. The numerical results suggest that fault friction may undergo an evolution effect raising questions about universal application of a single "friction law" in macroscopic domain numerical simulation studies of earthquakes. Detailed numerical studies demonstrate the LSM is capable of reproducing many features observed in the laboratory including Reidel shears and shear localization phenomena, and that the seismic efficiency of model faults with gouge is low, and is compatible with field estimates within the uncertainties (Place and Mora, 1999[9]).

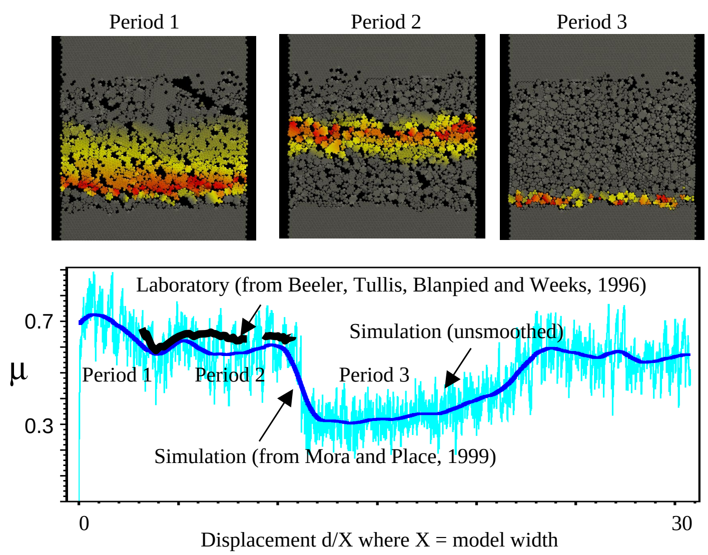

Figure 3: **Top:** Snapshots showing how shear strain in a fault gouge layer localizes into a narrow band. The lighter grey depicts the zone of active shear. **Bottom:** Fault friction in the numerical experiment compared to that of a long displacement laboratory experiment (note: the horizontal scale of the laboratory derived curve is not the same as the simulation result).

Extensions to the model currently in progress

Realistic micro-scale geometry

The current LSM has a regularity at the micro-scale imposed by the triangular lattice structure used to discretize matter. This regular micro-scale surface roughness may potentially lead to unrealistic behavior. Work is currently in progress which aims to extend the LSM to allow more realistic geometries to be modeled (Weatherley, Place and Mora, 1998[13]). The approach being adopted is to allow grains of arbitrary surface shape to be specified. This will be achieved by retaining the triangular lattice structure internally in grains, but allowing the grain surfaces to be described by a parametric curve. This extension will also allow specification of more realistic gouge grain geometries in fault zone behavior studies, and more realistic fault geometries in interacting fault system studies.

Thermal effects and thermo-mechanical coupling

As most elastic and frictional properties of solids are temperature dependent, heat must have a major influence on fault dynamics. Extensions to the LSM are currently in progress to incorporate thermal expansion and temperature dependent friction coefficients (Abe, Mora and Place, 1998[1]). Heat flow is modeled in the LSM and can be shown to obey the diffusion equation. Initial tests validate the heat transport solution and demonstrate that temperature increase during a dynamic slip event is compatible with that expected for slip on a real fault. Preliminary results suggest that earthquake nucleation and dynamics is substantially influenced by thermal effects.

Phase transformations

Several phase transformations may have a profound effect in fault dynamics. These include melting, mineralogical phase transformations (e.g. coesite such as proposed by Sornette to explain the Heat Flow Paradox) and structural such as the olivine-spinel phase transformation proposed by Green et al. as an explanation for the mechanics of deep earthquakes. The olivine-spinel transformation has been chosen as a starting point for incorporation of phase transformation effects into the LSM in a multi-disciplinary project with Material Science researchers (Pat Kelly and John Drennan of The University of Queensland). From the geophysical perspective, an ability to model the dynamical feedback effects of the olivine-spinel transformation may lead to an understanding of deep earthquakes. From the material science perspective, this ability would be helpful in understanding the behavior of yet to be synthesized novel new materials such as transformation toughened engineering ceramics. Preliminary results show that the olivine-spinel phase transformation affects the dynamics of rupture and has a weakening effect on the rupture surface (Keane et al, 1998[4]).

Simulations of interacting faults

The nature of the LSM makes it well adapted for simulating complex evolving micro-scale geometries such as those present in a real fault zone. Systems that do not have any substantial geometrical evolution effect such as systems of pre-existing faults can be more efficiently modeled using macroscopic modeling methods. Nonetheless, the LSM can be used for this purpose, and offers an alternative approach.

Two interacting faults

Results for a system of two interacting faults specified in the LSM show periods of seismic activity which alternate between the two faults (Zeng, Mora and Place, 1998[14]). This result is compatible with other simulation results for two interacting faults such as those of Knopoff, and demonstrates the time dependence of the earthquake hazard. An understanding of how to distinguish when an inactive fault is about to re-activate would be invaluable for earthquake hazard quantification and forecasting applications. The numerical results also show cases of dynamic triggering of fault slip by waves generated during the rupture of another fault.

Many interacting faults: accelerating energy release in simulated earthquake cycles

Recent LSM simulations of long earthquake sequences are generated in a model representing an evolving fracture zone of the Earth's crust subjected to shear. Cycles of seismic activity are observed in which the rate of seismic energy release of simulated earthquakes accelerates in the lead-up to the largest events. The simulated data generally fits a power law time to failure function adding support for the critical earthquake hypothesis discussed in various theoretical works by authors including Sornette, Sammis, Saleur and Huang, and observational studies (Jaumé and Sykes, 1999[1]). During a cycle in the LSM simulations, the cumulative number of events with energy above a given value is well described by a Gutenburg-Richter power law frequency-size distribution with an exponent similar to the global average for earthquake data. The exponent is initially high and becomes low in the latter part of the cycle prior to when the large earthquakes occur, in accord with observations noted by Jaumé and Sykes (1999)[1]. The new simulation results indicate that in systems comparable to the model fault system, earthquake statistics can be expected to evolve in a predictable way. At least under such conditions, earthquake hazard forecasting would be viable. The results provide encouragement that the LSM and other physical based models for interacting faults can be used to understand the conditions when earthquake hazard forecasting may be feasible, and can provide a test-bed to develop earthquake forecasting methodology.

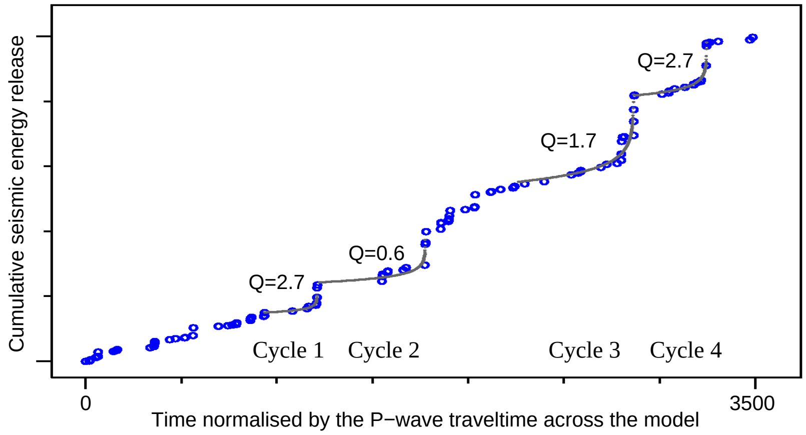

Figure 4: Cumulative seismic energy release in a simulated earthquake cycle. The light grey curves are best fit power law time to failure curves. The power law fit quality factor Q is calculated as the least squares error of a linear fit divided by that of a power law fit. Q is generally greater than 1 indicating a good fit of the power law time to failure curve.

Conclusion

The Lattice Solid Model is a particle based approach with the elements to allow the physical processes underlying earthquake generation to be simulated, and thus provides an important bridge to help understand the micro- and meso-scales which are only partially accessible by direct observation. Results so far demonstrate the utility of this model to probe fault behavior and the earthquake cycle, and provide encouragement that earthquake forecasting is feasible, at least under certain conditions.

Acknowledgments

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