A 3D Virtual Earth Simulator for Earthquake Micro-physics: LSMearth.

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Abstract

The particle-based Lattice Solid Model (LSM) was developed to provide a basis to study the physics of rocks and the non-linear dynamics of earthquakes. In previous work, intact material was modelled as particles bonded together by elastic-brittle links in a regular 2D triangular lattice and the model was applied to the study of fault zone evolution. A new modular and flexible LSM approach has been developed that allows different microphysics to be easily added and removed at the grain scale to enable the effect of different microphysics on macroscopic behaviour to be studied. The model is extended to allow three-dimensional simulations to be performed and particles of different sizes to be specified. The new model provides a basis to investigate nucleation, rupture and slip pulse propagation in complex fault zones without the previous model limitation of a regular low-level surface geometry.

Introduction

With advances in numerical simulation methodology and High Performance Computing, development of new tool for understanding the physics of earthquakes is made possible: numerical simulation models for the complete earthquake process. This is a scientific challenge because of the range of scales involved and number of physical processes that control fault dynamics: fracture of heterogeneous discontinuous solids, granular dynamics, friction between rough brittle rock surfaces, solid-fluid dynamics, lubrication, phase transformations (mineralogical, structural, melting, etc.), stress accumulation, elastic stress transfer via elastic wave propagation, finite strain, plastic deformation, heat conduction and thermo-mechanical feedback mechanisms.

The particle-based Lattice Solid Model (LSM) was developed to provide a basis to study the physics of rocks and the non-linear dynamics of earthquakes (Mora and Place, 1993[8]; 1994[9]; 1998[10]; Place and Mora, 1999[11]). The model is similar to the Discrete Element Method (DEM) proposed by Cundall and Strack (1979[2]) for modelling granular assemblies but was motivated by a desire to simulate earthquake processes.

Unlike laboratory experiments and field studies, numerical experiments allow all quantities to be measured at any scale resolved by the model. Hence, they provide a means to study the processes underlying earthquake phenomena, emergent behaviour such as space-time patterns for long seismicity sequences or localisation phenomena, and the impact of different potentially important microphysics on fault behaviour. For this to be achievable, the model is being refined such that features (e.g., microphysics, different computational algorithms) can easily be added or removed. With the use of an advanced scripting interface, various numerical simulations can be easily setup to study the effect of microphysics on fault behaviour. The approach provide a virtual laboratory where numerical experiments can easily be setup and all measurable quantities visualised.

To increase the scale of numerical experiments and allow multi simulation, the particle-based model is being coupled with two macroscopic approaches: GeoFEM (developed at the Research Organisation for Information Science and Technology, RIST) and Element-Free Galerkin Method (Hazama and Okuda, 2000). The resulting hybrid model (developed during collaboration between RIST and QUAKES; Iizuka et al, 2000[7]; Hazama et al., 2000[5]) will allow simulation of a fault system at a macroscopic scale while modelling phenomena in a fault zone occurring at a microscopic scale.

The lattice solid model

The LSM consists of a lattice of interacting particles and was motivated by short range molecular dynamics concepts. In the model, particles represent grains of rock (or building blocks of grains) and interactions are specified accordingly. This approach enables the non-linear behaviour of discontinuous solids such as rocks to be simulated with relative simplicity.

In the simplest form of the LSM, particles in solid regions are arranged in a two-dimensional triangular lattice and linked with specified behaviour. For instance, particles can be linked by bonds that have elastic behaviour and can break if the separation exceeds a given threshold.

A viscosity is introduced in order to damp reflected waves from the edges of the lattice. The viscous forces are proportional to the particle velocities. The viscosity chosen is frequency independent and does not fundamentally alter the dynamics of the system if carefully chosen (Mora and Place, 1994[9]).

In addition, a frictional force is applied to unbonded particles that come into contact. The frictional force opposes the direction of slip and its magnitude is no greater than the dynamical frictional force given by

$$F_{ij}^F = \mu|\mathbf{F}_{ij}|, \tag{1}$$

where μ is the coefficient of friction and $\mathbf{F}_{ij}$ is the normal force between particle i and j (cf. Place and Mora, 1999[11]).

The numerical integration is based on a modified velocity Verlat scheme where particle velocities and positions are updated according to the new estimate of forces exerted on particles. The integration approach (Place and Mora, 1999[11]) accurately captures discontinuities such has bond breaking or the transition between static and dynamic frictional contact.

LSMearth

Distinct element and particle models are widely use to simulate fracturing processes (Donzé et al., 1994[3]), earthquake dynamics (Mora and Place, 1994[9]) and pore fluid and solid interaction (Sakaguchi and Mülhaus, 2000[12]). Those models use the same basic principles of short range interactions and differ mainly in the numerical integration scheme or the properties modelled at the grain scale. The lattice solid model has been extended to allow different properties to be modelled at the grain scale such that these properties can be switched on or off in order to study their impact in the macroscopic behaviour. Different algorithms can be specified such a LSM type friction or Cundall type friction to study their effect on macroscopic behaviour. The programming method used is oriented object, which allows different properties to be easily merged. For instance, if one extension allows different particle shapes and sizes to be simulated and another extension allows the effect of intrinsic surface roughness (friction) at the particle scale to be simulated, both properties can be merged requiring a minimum reprogramming effort.

An advanced scripting interface is used to initialise and specify numerical experiment. Scripts consist of "C" like program with are interpreted at run time and allow the setup of different kind of simulations without modification of the program. In the scripts, all parameters of the model can be modified and measurable quantities can be extracted while the simulation is running. This enables implementations of various type of dynamic loading and extraction of the desired data into files. Figure 1 shows a snapshot of the LSMearth user-interface which allows the visualisation of any quantities during the simulation.

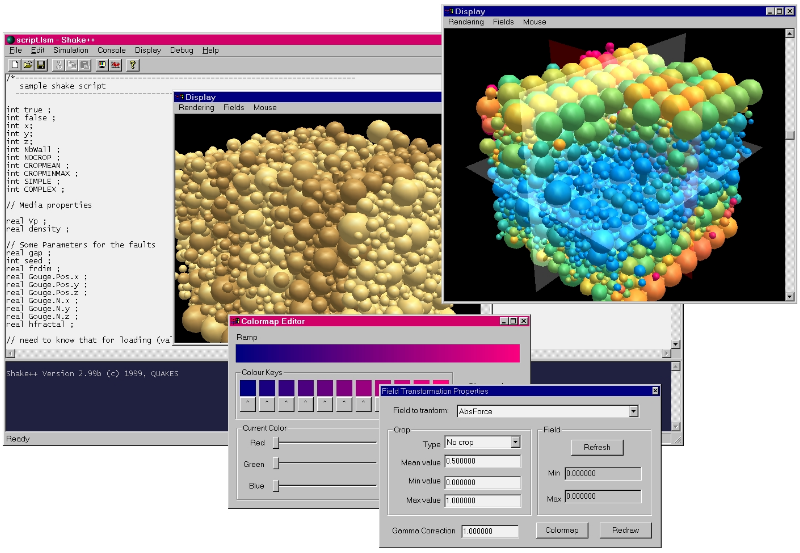

Figure 1: Snapshot of the LSMearth user interface

Modelling the physics of rocks

A set of 2D numerical bi-axial compression experiments was performed to illustrate simulation of fracturing behaviour using the random lattice. In previous work, similar numerical experiments were performed using a regular triangular lattice (Mora and Place, 1993[8]). Due to the geometry of the lattice, fracturing tended to occur along shear bands oriented at an angle of 60 degrees following the principal axis of the triangular lattice. Numerical experiments of biaxial compression using a random lattice illustrate that the new approach is capable of simulating typical rock fracture behaviour using only simple radial interactions between particles. Using simple particle interaction, the model can be calibrated with laboratory experiments of rock fracture (cf. Figure 2). However, not all macroscopic parameters can be matched with laboratory results so more complex particle interactions may be required. With the capability of easily adding new features in the model such as rotational dynamics, microscopic breakage through bending, fluid and thermal effects, the model can be more easily calibrated against laboratory observations and provides a means to simulate complex phenomena such as localisation processes, and to study the dynamics of complex systems such as fault zones.

With the ability to add new micro-physics, the model has also been refined by incorporating various friction laws such as rate and- state friction (Abe, et al., 2000[1]) and healing effects (Fujii, 2000[4]) in collaborative research with USGS (Jim Dieterich) and Tokyo University (Yoshihiro Hujii and Mitsuhiro Matsu'ura). This demonstrates that the new approach can be easily applied to various geophysical problems without a time consuming

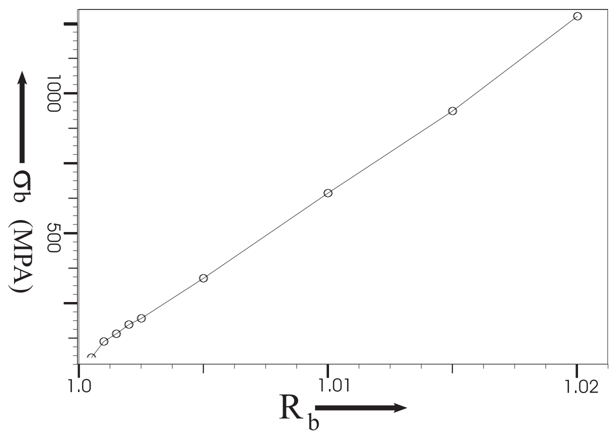

Figure 2: Macroscopic stress (σ_b) versus microscopic breaking criterion R_b for uniaxial compression experiments.

re-programming effort. Furthermore, with the advance-scripting interface, the studies of LURR with the lattice solid model (Wang et al., 2000[13]) were made possible without any re-programming effort.

Multi-scale simulation

Particle-based models enable the simulation of physical processes occurring at a microscopic scale. With particles representing grains of rock of sizes ranging from a few microns to meters, a large number of particles is required to simulate phenomena occurring at the fault scale such as interaction of faults in a fault system. Because of the enormous computational needs, alternative approaches must be developed to enable simulation of macroscopic phenomena.

The interface being developed between the microscopic software system developed at QUAKES (LSMearth), and a finite-element based macroscopic software system developed at RIST - GeoFEM will enable simulation of processes occurring at the microscopic scale using the particle-based model (LSMearth) and simulation of processes occurring at the macroscopic scale, such as plastic deformation and wave propagation, using the finite-element method (GeoFEM). Using this approach, the effect of microscopic phenomena on the macroscopic behaviour of a large-scale fault system can be studied. This hybrid method will also extend the resolution of numerical experiments of fault zone behaviour by allowing more efficient simulation of those parts of models well approximated as a continuum such as elastic regions outside the gouge zone (Iizuka et al., 2000[7]).

In addition, using the same interface, the Lattice Solid Model has been coupled with an Element-Free Galerkin Method (Hazama and Okuda, 2000[6]; Hazama et al., 2000[5]). The Element-Free Galerkin Method can use an elasto-static formulation to simulate deformation in a solid. This formulation is currently used in the coupling of the two models. In the future, the dynamic formulation will be used in the coupling as in the LSMearth-GeoFEM coupling. Using the Element-Free method, in the dynamic case, no remeshing is required in order to interface with the particle-based model.

Conclusion

The particle based lattice solid model (LSM) provides a framework to simulate and study the micro-dynamics of fault zones and rocks. The new modular and flexible LSM approach allows different microphysics to be easily added and removed at the grain-scale. This enables the effect of different microphysics on macroscopic behaviour to be studied. The approach provide a virtual laboratory where numerical experiments can easily be setup and all measurable quantities visualised. The interfaces GeoFEM-LSMearth and EFG-LSMearth will enable multi-scale simulations of the dynamics of earthquakes to be performed.

Acknowledgments

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References

[1] Abe, S., Mora, P. and Place, D., *Simulation of the Influence of Rate and State Dependent Friction on the Macroscopic Behaviour of Complex Fault Zones with the Lattice Solid Model,* 2nd ACES Workshop, Japan (2000).

[2] Cundall, P.A. and Strack, O.D.L., *A discrete numerical model for granular assemblies*, Géotechnique, **29**, 47-65 (1979).

[3] Doné, F., Mora, P. and Magnier, S.A., *Numerical simulation of faults and shear zones,* Geophys. J. Int., **116**, 46-54 (1994).

[4] Pers. communication during collaborative work, Brisbane, 2000.

[5] Hazama O., Place D., Okuda H., *LSMEarth - EFG Coupling: an Alternative Numerical Approach for Multi-scale Simulations,* 2nd ACES Workshop, Japan (2000).

[6] Osamu Hazama O. and Okuda H., *Element-Free Implementation in Two-Dimensional Elasto-Plastic Analysis*, 5th U.S. National Congress on Computational Mechanics Book of Abstract, p.312, 1999

[7] Iizuka M., Place D., Hazama O., *LSMearth and GeoFEM Coupling Analysis,* 2nd ACES Workshop, Japan (2000).

[8] Mora, P. and Place, D., *The lattice solid model for the nonlinear dynamics of earthquakes,* Int. J. Mod. Phys. C, **4**, 1059-1074 (1993).

[9] Mora, P. and Place, D., *Simulation of the Frictional Stick-slip Instability,* PAGEOPH, **143**, 61-87 (1994).

[10] Mora, P. and Place, D., *Numerical simulation of earthquake faults with gouge: towards a comprehensive explanation of the heat flow paradox*, J. Geophys. Res., **103**, 21,067-21,089 (1998).

[11] Place, D. and Mora, P., *The lattice solid model: incorporation of intrinsic friction,*J. Int. Comp. Phys., **150**, 332-372 (1999).

[12] Sakaguchi H. and Muhlaus, H. *Hybrid Modelling of Coupled Pore Fluid-Solid Deformation Problems*, PAGEOPH, **157**, in press (2000).

[13] Wang, Y., Mora, P., Place, D. and Yin X.C., *Simulation of Load-Unload Response Ratio in the Lattice Solid Model*, 2nd ACES Workshop, Japan (2000).