Summary of Session 1.1: Modelling the micro-physics underlying earthquake nucleation processes and rupture

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Objectives

Modelling microscopic properties of rock allows simulation of non-linear and complex macroscopic behaviour. Rather than specifying a "true" representation of rock at a microscopic scale, models use empirical properties at a mesoscopic scale such that the correct macroscopic behaviour is simulated. The objectives of the session "Modelling the micro-physics underlying earthquake nucleation processes and rupture" were: (1) to explore properties that can be modelled at the grain scale, (2) to explore macroscopic behaviour that can be reproduced by such models and (3) to gain insight from micro/meso-scopic changes to predict macroscopic failure.

Plenary

Plenary papers:
David Place, QUAKES, Modelling rock grain interactions at a meso-scale to study the micro and macro-physics of rocks: simplicity vs. complexity.
Yilong Bai, LNM, Damage Localization as Possible Mechanism Underlying Earthquake.

Modelling rock grain interactions: questions

Different properties such as elasticity, roughness induced friction, thermal effects and phase transitions can be modelled at a grain scale. However, emergent properties of a model can be used to specify the material properties. For instance rather than specifying a roughness at the grain scale, an assemblage of smaller grains can be used. What are the properties that need to be modelled at the grain scale? What properties can be simulated without excessive computational cost? What is the impact in the macroscopic behaviour of not modelling a given property?

Modelling the rupture process: questions

In the process of fracture, grains of rock can break down until a lower scale is reached, which may be microns or molecules. Cracks and complex structures are present on many scales. The disorder present at a microscopic scale can be significant at a larger scale. How can the evolution of micro damage such as micro cracks be used to predict macroscopic failure? What intrinsic factors in solids govern macroscopic failure?

Outcomes

Modelling rock grain interactions

Particle based models are applied to the study of the physics of rock and earthquakes and to the study of geophysical phenomena occurring at various scales. Because using a microscopic representation of rock (e.g. using molecules for instance) will be too costly, a mesoscopic representation of rock is used. Different properties can be modelled at the particle scale such as radial or shear elasticity, friction, fracture and thermal effects. A mesoscopic approach would consist of modelling these properties at the particle scale, whereas a microscopic approach would consist of simulating these properties by using a larger number of particles. A microscopic approach has the main advantage of limiting the number of input parameters while obtaining a greater complexity. For instance, in the Lattice Solid Model, shear elasticity and rotational dynamics are simulated at the grain scale (grains of model rock are composed of several particles) rather than modelled at the particle scale (Place and Mora [5]). Numerical experiments show that similar results can be obtained with both approaches. However, the computational needs can be enormous when using a microscopic approach, in which case a more mesoscopic approach should be used.

Calibration

Because models are often based on empirical definitions, they need to be calibrated such that a given process is correctly simulated. In order to check that the correct physics is modelled, laboratory experiments are reproduced and compared with numerical simulations. In a numerical experiment aimed at studying the damage process in a rock specimen (Peng et al., [4]), damage localisation or cracks were observed at the tip of a pre-existing crack when the specimen was subjected to bi-axial compression. As in all numerical experiments, even if the simulation can effectively reproduce results from laboratory experiments, no confirmation can be given to the validity of the results. This is because all the input parameters of the simulation cannot be calculated from observations or laboratory experiments. For instance, the damping process, introduced in order to overcome problems arising from using a closed system cannot be calibrated according to observations or laboratory experiments. Furthermore, when using complex interactions between particles of model rock, additional input parameters must be evaluated to simulate the correct physics (eg. shear elasticity and bending elasticity for instance). This is a difficult step since all quantities in laboratory experiments cannot be known. Hence, the calibration is achieved by matching macroscopic quantities of the simulations with observations or laboratory experiments. The distribution of discontinuities in rock can be an important factor in fracture processes (c.f. also Ke et al.[3]) and are difficult to quantify using laboratory experiments. Hence, the introduction of discontinuities into the model rock according to the rock specimen using in the laboratory experiment cannot be achieved from direct observation.

Damage localisation

In modelling rupture processes, the evolution of micro-damage can be described through a dynamic function (Bai et al., [2]). From this dynamic function, a condition for damage localisation is evaluated that specifies the instant of rupture. During numerical experiments, the condition for damage localisation is evaluated and gives an alarm before failure of the material. Results shows that the condition can be used to predict failure and to provide a proper warning.

The evolution of micro-damage is controlled by the distribution of pre-existing micro-cracks. Damage localization or failure occurs far from equilibrium and is driven by the nonlinear evolution of micro-damages. Using an Evolution Induced Catastrophe model (Ke et al., [3]), it was found that minor mesoscopic changes can eventually induce macroscopic failure of materials. This is called trans-scale sensitivity. However, dissipation present in real rock has the contrary effect of trans-scale sensitivity. If minor mesoscopic changes can affect the macroscopic behavior, dissipation will tend to attenuate mesoscopic changes such that only the overall evolution of the mesoscopic structure can affect the macroscopic behaviour.

Pore fluid and solid interactions

Earthquakes involve processes such as plastic deformation and rupture but also more complex processes such as pore fluid and solid interactions and thermal expansion. Pore fluid and solid interactions can be simulated with a particle based model using a hybrid modelling approach (H. Sakaguchi and H. Mühlhaus, [6]). To model pore fluid and solid interaction, a grid is constructed that connects the centers of mass of all grains of rock. With this grid, fluid flow is calculated using Darcy's law. From the solid deformations, the pressure inside each grid cell is calculated, from which the force exerted on grains is computed. The forces exerted by the fluid pressure are incorporated in the time integration used by the particle based model. Using this model, numerical experiments can reproduce behaviour observed in laboratory experiments such as quasi static fracture processes. Pore fluid and solid interactions are found to be an important factor in rupture processes, where development of fractures are mainly caused by the increasing pressure inside cracks. However, dynamic processes linked to fluid flow cannot be simulated using this kind of modelling. A possible approach to model these dynamic process would be to couple a lattice gas model with a particle based model.

Thermal expansion

Thermal expansion is modelled by changing the size of particles according to the the temperature of the media (Abe et al., 1998[1]). Due to the intrinsic friction of particles, rubbing particles against one another will generate heat which causes particles to expand. In numerical experiments consisting of two blocks with rough surfaces pushed against one another at a constant rate, heat is generated on the fault surfaces during synthetic earthquakes events (Abe et al., 1998[1]). Heat dissipates throughout the entire lattice according to the diffusivity of the rock being model. The effect of thermal expansion was to delay large events and to increase the number of small or precursor events. The diffusivity (i.e. the rate of diffusion of the heat throughout the lattice) is scale dependent and effectively sets the scale of the numerical experiment. To obtain results similar to field observations, the same scale must be used which is not feasible due to computer limitations. Blocks of model rock are pushed at a constant velocity which is much higher by many orders of magnitude than the steady movement of tectonic plates. Hence, large synthetic earthquake events are too frequent to allow the blocks to dissipate the heat from previous earthquakes. Furthermore, if the diffusivity is increased to compensate for the high loading rate, then, the effect of thermal expansion on nucleation processes would be altered since most of the heat generated would be dissipated immediately after the nucleation.

Conclusions and perspectives

The trans-scale sensitivity found in rupture processes shows that fractures or damage localisation involves many scales, with minor microscopic changes affecting the macroscopic behavior. However, macroscopic failure can be predicted from the evolution of micro-damage. Particle-based models with only simple interactions at the particle scale allow the simulation of complex and non-linear processes. Because of the computational requirements due to the broad range of scales involved in earthquake processes, large scale simulations using simple particle interactions are not feasible. Hence, more complex interactions such as friction, rotational dynamics, thermal expansion, torque, bending, and pore fluid flow are modelled at the particle or grain scale. As the complexity of particle interactions increases, the calibration of the model becomes more difficult and simulation requires more input from laboratory experiments.

References

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