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Avalanches in dry and saturated disordered media at fracture in shear and mixed mode scenarios

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ABSTRACT

We investigate shear and mixed mode fracture scenarios in inhomogeneous dry and fully saturated porous media with a 2D central force lattice model. For the fully saturated case we adopt the extended Biot's theory. The bars of the lattice break only under traction which is a common assumption in lattice models for rocks. The breaking process is simulated with a continuous damage model where after a partial failure event, spring elements are assigned a new failure threshold sampled from a uniform distribution. We investigate avalanche behaviour of the damaging events as well as the pressure evolution and the existence of pressure jumps linked to the breaking events in the disordered medium. In pure shear fracture the behaviour differs from that observed previously with the same model for prevailing tearing conditions. Power law distribution of the damaging events does not hold anymore and the overall behaviour is brittle without intermittent crack tip advancement. Pressure fluctuations are however observed. In a mixed mode scenario some of the features observed under prevailing tearing conditions are recovered such as the overall elasto-plastic behaviour. An estimate of the time needed for the internal rearrangements within a loading step is given.

1. Introduction

Fracturing in fluid saturated porous media is of importance in geophysics. Problems range from seismicity induced by injection of discarded fluids from hydraulic fracturing [28,12,23,10] to the role of fluids in deeper formations. Availability of water in deep formation is shown in [3,11] and some of its effects in [9]. Slow earthquakes originate from layers of the earth crust that are saturated with fluid. As pointed out by Beroza and Ide [4,5], the role of pore fluids in tremors observed e.g. in Cascadia [22] and Japan [18] is still to be worked out. In fact, Beroza and Ide [4] state "does triggered tremor occur by shear slip on the deep extension of faults, or is some other mechanism involved?"; and further "simple friction laws by themselves do not provide an explanation for this complex behaviour". Fracturing in presence of fluids may possibly shed some light on this. In problems related to fluid injection mode I fracturing (tearing) is the prevailing mechanism, but in the other problems shearing and mixed modes are important: slabs do not go down gently as rightly indicated by Nolet [17] and Obayashi et al. [19]. Our aim is to investigate these last two fracturing aspects. Pure shear fracturing of homogeneous saturated porous media is addressed with an XFEM model in [20] but otherwise to our best knowledge this particular topic has received up to date little attention. We choose a 2D central force lattice model for disordered media at mesoscopic level [16] (described in the next paragraph) because with this model and the connected statistical analyses we have already obtained insight in the behaviour of saturated media under prevailing tearing conditions.

At macroscopic level the currently used tip advancement/time step algorithms, with exception of [20,25,27,21] and to a certain extent of [14] interfere with the development of the crack and hide hence salient aspects. This is extensively discussed in [29,24]. In these models usually average values of the mechanical properties are chosen. In our aforementioned mesoscopic model for disordered media, first developed in [16] and here summarized for dry media, the stress thresholds of each element are picked randomly from a uniform distribution in the interval $(0, 1)$ MPa. The elements break only under traction. When the stress in a truss of the lattice exceeds the local threshold, the elastic modulus of the truss

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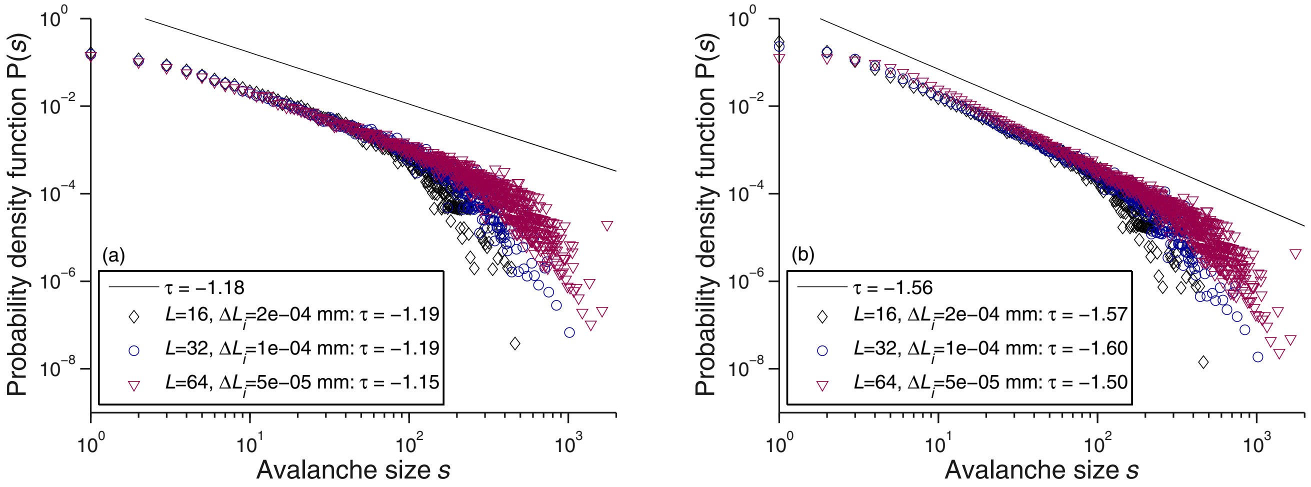

Fig. 1. $P(s)$ in the steady state (left) and in the whole simulation (right) of a dry specimen for $L = 16$ (black diamonds), $L = 32$ (blue circles) and $L = 64$ (purple downward-pointing triangles); L is the grid size, ΔL_i is the imposed displacement increment per step (scaled with system size). Damage events follow a self-organization, $P(s)$ cut-off scales with system size hence we have scale-free behaviour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

is reduced adopting a continuous damage law. At each step, the thresholds of the damaged elements are updated using a uniform distribution in the same interval as above. This updating of the thresholds corresponds to annealing disorder while keeping the initial thresholds fixed would correspond to quenched disorder. The system is then solved again with unchanged assigned loads and these steps are repeated for as many times as needed to reach an equilibrium state in which no stress threshold is exceeded in any bond. Only then the load is increased and the steps necessary to check if any and how many trusses are damaged at this stage are repeated. The process continues until the final failure of the lattice when the full crack has developed. As a consequence the fracture can develop unhindered. The dry model can be extended for saturated porous media by coupling the equilibrium equation for the medium with the continuity equation for the solid and fluid phases, following Biot's model, as done first in [16] and as will be explained in Section 2. The presence of the fluid then affects the mechanics of the lattice, while the rules adopted in the dry model for setting the trusses thresholds and applying damage still hold unmodified. The material being inherently heterogeneous, many simulations are run with the same boundary conditions but randomly varying material properties and a statistical analysis is carried out on the gathered data. This analysis usually focuses on the so-called avalanche behaviour of the specimen, i.e. the amount of failing elements per step. It is known that the probability distribution function of the recorded avalanches size in dry specimens displays power law behaviour and that the main features of self-organized criticality [2] are satisfied: external input (loading conditions) is increased at a time scale much slower than the one of the inner response of the specimen (avalanches and stress rearrangements) which keeps the overall material behaviour in a steady state (constant global stress) within a loading step.

With this model we have investigated the cases of assigned biaxial boundary tractions, pressures and flow [16]. We have investigated avalanche behaviour and the connected power laws [34,33], see Fig. 1. We have found that the existence of fluid itself does not destroy this power law behaviour except when the length scales introduced in the model through fluid flow become effective which happens when the value of the increment per step of the external loading (pressure or flow) increases above a certain threshold.

Moreover we have found the confirmation that crack tip advancement is intermittent [25,29] because it takes place only at a limited number of avalanches. The other avalanches correspond to simple damaging events of the bars or opening of holes in the domain. Further, pressure rises at each crack tip advancement in case of assigned traction and assigned pressure with jumps of the order of 0.05 MPa and 0.004 MPa respectively while it drops in case of assigned flow (hydraulic fracturing) with jumps of the order of 0.25 MPa. Pressure peaks appear also when somewhere else in the lattice, away from the crack tip, a broken bar results in an opening which corresponds to a sudden increase of the volumetric strain. This behaviour has been explained with Biot's theory as follows: if a load, pressure, or displacement boundary condition is applied suddenly (all acting on the equilibrium of the solid–liquid mixture), then the fluid takes initially almost all the induced solicitation because its immediate response is undrained and it is much less compressible than the solid skeleton. It discharges hence the solid. Then through the coupling with the fluid through the volumetric strain, the overpressures dissipate and the solid is reloaded. Hence we have a pressure rise upon rupture. Pressures and stresses evolve out of phase (partial scenario 1). On the contrary if flow is specified (acting on the continuity of the fluid) its effect is transmitted to the solid through the pressure coupling term in the effective stress. The solid is loaded and upon rupture produces a sudden increase of the volumetric strain. This in turn produces a drop in pressure. In this case stresses and pressures evolve in phase (partial scenario 2). In all three cases the intervals between two crack tip advancements are found to be irregularly distributed. This is true even for homogeneous media. Note that these are prevailing scenarios because the sudden changes of displacements would induce also some pressure drop in the first partial scenario due the volumetric strain (effect of the equilibrium of the solid–liquid mixture) and pressure rise in the second partial scenario (effect of the continuity of the fluid) due to the suddenly changing displacements in the crack; therefore the effects of both scenarios have to be superimposed (whole scenario). However we have found that the first scenario prevails in case of loading applied to the first of Biot equations (applied displacement boundary conditions, assigned pressure) and the second one in case of hydraulic loading where the flow is applied to the second of Biot's equations. This is true for prevailing mode I fracturing (tearing) while for shear fracturing the whole scenario applies as will be shown below. For mode I fracturing the partial scenarios have been confirmed also at macroscopic level with the standard Galerkin finite-element method in conjunction with adaptivity in time and space and with an XFEM model [24]. In both cases a cohesive fracture model has been adopted. A detailed comparison between macro- and mesoscopic models in case of hydraulic fracturing can be found in [15].

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