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A new method to estimate location and slip of simulated rock failure events

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ABSTRACT

At the laboratory scale, identifying and locating acoustic emissions (AEs) is a common method for short term prediction of failure in geomaterials. Above average AE typically precedes the failure process and is easily measured. At larger scales, increase in micro-seismic activity sometimes precedes large earthquakes (e.g. Tohoku, L'Aquilla, oceanic transforms), and can be used to assess seismic risk.

The goal of this work is to develop a methodology and numerical algorithms for extracting a measurable quantity analogous to AE arising from the solution of equations governing rock deformation. Since there is no physical property to quantify AE derivable from the governing equations, an appropriate rock-mechanical analog needs to be found.

In this work, we identify a general behavior of the AE generation process preceding rock failure. This behavior includes arbitrary localization of low magnitude events during pre-failure stage, followed by increase in number and amplitude, and finally localization around the incipient failure plane during macroscopic failure. We propose deviatoric strain rate as the numerical analog that mimics this behavior, and develop two different algorithms designed to detect rapid increases in deviatoric strain using moving averages.

The numerical model solves a fully poro-elasto-plastic continuum model and is coupled to a two-phase flow model. We test our model by comparing simulation results with experimental data of drained compression and of fluid injection experiments. We find for both cases that occurrence and amplitude of our AE analog mimic the observed general behavior of the AE generation process.

Our technique can be extended to modeling at the field scale, possibly providing a mechanistic basis for seismic hazard assessment from seismicity that occasionally precedes large earthquakes.

1. Introduction

Understanding failure and rupture processes in geomaterials is one of the primary goals in earth sciences and engineering. Stimulated seismicity has many applications in enhanced geothermal systems and the extraction of hydrocarbons from tight shales, while natural seismicity has long been studied to try to understand the earthquake process and behaviors indicative of impending failure in a large event. A variety of studies at the field scale focused on the interaction between fluid (and fluid pressure) propagation and location of seismic events (e.g. Baisch et al., 2010; McClure and Horne, 2010), and on laboratory scale with acoustic emissions (AEs) acting as laboratory scale equivalent for seismic events (e.g. Mayr et al., 2011; Stanchits et al., 2011). Acoustic emissions and seismic events have similar source mechanisms, but a different range of frequencies (Cai et al., 2007; Mogi, 1967), while both often precede and accompany plastic deformation and changes of mechanical properties. Observations of seismic and acoustic events are utilized as a predictor of rock failure and rock burst (e.g. Lockner, 1993; Pettitt et al., 2002). Modern laboratory techniques allow the detection and location of acoustic emissions at very high rates and accuracy, with the rate of recorded signals increasing from hundreds to thousands of events per second over the last few years (e.g. Amitrano, 2003; Stanchits et al., 2011). Acoustic emission analysis is performed on a wide range of materials, including metals (e.g. Aggelis et al., 2011; Farrelly et al., 2004; Huang et al., 1998; Marfo et al., 2013; Oh and Han, 2012; Sind et al., 2012), ceramics (e.g. Aggelis et al., 2013; Drozdov, 2013, 2014; Maillet et al., 2014; Mei et al., 2013; Yonezu and Chen, 2014), polymers (e.g. Berdowski et al., 2013; Boominathan et al., 2014; Burks and Kumosa, 2014; Fu et al., 2014; Hamdi et al., 2013; Njuohvic et al., 2014; Sause et al., 2013), and concrete (e.g. ElBatanouny et al., 2014; Elfergani et al., 2013; Hu et al., 2013; Itturrioz et al., 2013; Kawasaki et al., 2013; Kencanawati et al., 2013; Ohno et al., 2014; Shahidan et al., 2013; Zhu et al., 2010).

AE cannot be derived directly from physical properties in numerical simulations, so analogs are needed. Some theoretical approaches exist for discrete element modeling (DEM). In discrete element models the material is represented by discrete bonded particles that interact with each other. Exceeding the bond strength is used as the AE analog (e.g. Hazzard and Young, 2002, 2004; Hazzard et al., 2002; Kun et al.,

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2014). However, DEM are computationally expensive, and have no inherent length scale necessary to quantitatively compare with observations, thus limiting their utility.

Continuum formulation of the underlying mechanics has the advantage that most of the parameters can be obtained from experimental data, however, an appropriate AE analog must still be found. Some methods have been proposed to characterize AE in continuum mechanical models, such as the evolution of a damage function acting on the elastic properties of the rock material (e.g. Amitrano, 2003; Amitrano et al., 1999; Fang and Harrison, 2002; Lyakhovsky et al., 1997; Tang, 1997; Tang and Kaiser, 1998; Wang et al., 2012). For simple fluid–rock interactions, an event is registered if the pore pressure exceeds some predefined critical value (e.g. (Parotidis et al., 2003, 2005)), while for simple plastic models an event is registered by reaching the yielding point in a numerical grid cell (e.g. Baisch et al., 2010; McClure and Horne, 2010). However, in more advanced rheological models that include frictional hardening, cohesion softening and damage effects, the yield function is insufficient because it does not reproduce important characteristics of AEs.

In this paper we propose the deviatoric strain rate as an indicator of local failure, and as an analog of acoustic emissions. The deviatoric strain measures distortion with no volumetric change, thus identifying shear movement. Any rapid shear movement is commonly referred to as slip, and in the plastic regime, it indicates fracture generation or growth. This is the mechanistic source for acoustic emissions, so a natural link between deviatoric strain and acoustic emissions is proposed. In addition, since deviatoric strain is a common rock-mechanical value that can be easily calculated, no new ad-hoc rock-mechanical parameter needs to be introduced. Besides shear movement, acoustic emissions can also be generated by tensile or collapse events (Zhang et al., 1998). In this work we focus on shear events because they are the most common type of failure events in the experiments we study, especially close to macroscopic failure. As AEs mostly have a mixed type of failure source, a clear separation between source types is difficult.

We use a continuum mechanical model that includes poro-elasto-plasticity, frictional hardening, cohesion softening and damage effects, and solve the governing equations using a finite difference approximation. The results of the numerical simulation are analyzed and compared with experimental data for dry compression and high pressure fluid injection in a sandstone sample. We identify location, evolution and amplitude of AEs, and show very good comparison with experimental data.

2. Rheological model and fluid flow

2.1. The poro-elasto-plastic model

Elastodynamic equations in their velocity–stress form describe the elastic response of a rock skeleton in two dimensions

$$\frac{\partial V_x}{\partial t} = \frac{1}{\rho}\left(\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y}\right) \tag{1}$$

$$\frac{\partial V_y}{\partial t} = \frac{1}{\rho}\left(\frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{xy}}{\partial x}\right) \tag{2}$$

$$\frac{\partial \sigma_{xx}}{\partial t} = (\lambda + 2\mu)\frac{\partial V_x}{\partial x} + \lambda\frac{\partial V_y}{\partial y} \tag{3}$$

$$\frac{\partial \sigma_{yy}}{\partial t} = \lambda\frac{\partial V_x}{\partial x} + (\lambda + 2\mu)\frac{\partial V_y}{\partial y} \tag{4}$$

$$\frac{\partial \tau_{xy}}{\partial t} = \mu\left(\frac{\partial V_x}{\partial y} + \frac{\partial V_y}{\partial x}\right) \tag{5}$$

with μ and λ as Lamé constants, ρ as density, V_x and V_y as velocities and σ_{xx}, σ_{yy}, and τ_{xy} as components of the stress tensor.

In saturated porous rock, where pores form a connected network, deformation is controlled by the Terzaghi effective stress with pore pressure P (positive for compression).

$$\sigma_{ij}^{eff} = \sigma_{ij} - P\delta_{ij}. \tag{6}$$

Plastic deformation of rocks is modeled using Mohr–Coulomb criteria

$$F = \tau - \left(\sigma_m + \frac{C^*}{\tan(\varphi^0)}\right) \cdot \sin(\varphi^*) \tag{7}$$

where F is the yield function, C^* is mobilized cohesion, φ^* is mobilized internal frictional angle, φ^0 is maximal internal frictional angle, τ is second invariant of the deviatoric stress and σ_m is mean stress.

Cohesion and internal friction angle are mobilized in terms of a cohesion weakening and frictional strengthening model dependent on effective plastic strain $\overline{\epsilon}_p$ (Hajiabdolmajid et al., 2002). Mobilized values for friction angle, cohesion and dilatancy angle are calculated following Vermeer and de Borst (1984) and are dependent on effective plastic stress.

Plastic strain rates are given by

$$\dot{\epsilon}_{ij}^{pl} = 0 \text{ for } F < 0 \text{ or } F = 0 \text{ and } \dot{F} < 0 \tag{8}$$

$$\dot{\epsilon}_{ij}^{pl} = \lambda^p \frac{\partial q}{\partial \sigma_{ij}} \text{ for } F = 0 \text{ and } \dot{F} = 0. \tag{9}$$

with λ^p as the plastic multiplier and q as the flow rule.

Effective plastic strain $\overline{\epsilon}_p$ follows from there

$$\overline{\epsilon}_p = \sqrt{\frac{2}{3}\dot{\epsilon}_{pl}^{\,T} \cdot M \cdot \dot{\epsilon}_{pl}} \tag{10}$$

where $\dot{\epsilon}_{pl}$ is the plastic strain rate written as a vector with three components. The first and second components are normal and the third component is shear direction. M is a diagonal weighting matrix which weights shear component half of normal component (Abbo, 1997).

We use non-associative plastic flow rules (Vermeer and de Borst, 1984)

$$q = \tau - \sigma_m \cdot \sin(\psi^*) \tag{11}$$

where ψ^* is the mobilized dilatancy angle (Vermeer and de Borst, 1984).

Degradation of elastic properties dependent on a damage operator D is described by

$$E^d = (1 - D)E^0 \tag{12}$$

where E is the elasticity tensor in damaged E^d and undamaged E^0 state. The evolution of D is modeled following the method described in Peerlings et al. (1998).

2.2. Two phase flow

Fluid flow is considered as an isothermal water–gas immiscible mixture with no phase transitions and is modeled using Richards approximation. In the context of water intrusion in an unsaturated regime the air reservoir is infinite, so air pressure is the zero reference (Richards, 1931). Darcy velocity in a multiphase environment can be generalized for any phase $\alpha = w, a$

$$v_\alpha = \frac{-k_\alpha k_0}{\mu_\alpha}\nabla P_\alpha \tag{13}$$