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A unified variational eigen-erosion framework for interacting brittle fractures and compaction bands in fluid-infiltrating porous media

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Highlights

- A unified variational framework is introduced for both cracks and compaction band (anti-cracks).
- Projection model is used to capture the difference between mechanical and hydraulic apertures and cure mesh dependence.
- The proposed model is applicable for simulating borehole breakout and hydraulic fracture.

Abstract

The onset and propagation of the cracks and compaction bands, and the interactions between them in the host matrix, are important for numerous engineering applications, such as hydraulic fracture and CO2 storage. While crack may become flow conduit that leads to leakage, formation of compaction band often accompanies significant porosity reduction that prevents fluid to flow through. The objective of this paper is to present a new unified framework that predicts both the onset, propagation and interactions among cracks and compaction bands via an eigen-deformation approach. By extending the generalized Griffith's theory, we formulate a unified nonlocal scheme that is capable to predict the fluid-driven fracture and compression-driven anti-crack growth while incorporating the cubic law to replicate the induced anisotropic permeability changes triggered by crack and anti-crack growth. A set of numerical experiments are used to demonstrate the robustness and efficiency of the proposed model.

Keywords: Compaction band; Eigen-erosion; Porous media; Hydraulic fracture; Anti-crack; Hydraulic aperture

1. Introduction

Crack growth in fluid-infiltrating porous media has important implications on many engineering applications and activities. The onset, nucleation, branching and coalescence of cracks may dictate the success of geological disposals of carbon dioxide, hydraulic fracture operation, geothermal energy extraction, storage of nuclear waste underground and tunneling. In the cases where the void space of the porous media is filled with fluid, the propagation of fracture may also lead to significant increase in effective permeability and induced anisotropy in the hydraulic responses of the porous media [1–3]. Perhaps a less well-known fact to the general public is that porous media may also form compaction band. As shown in Fig. 1, a compaction band is a narrow zone in which large porosity reduction is observed in an otherwise intact host matrix [4–7].

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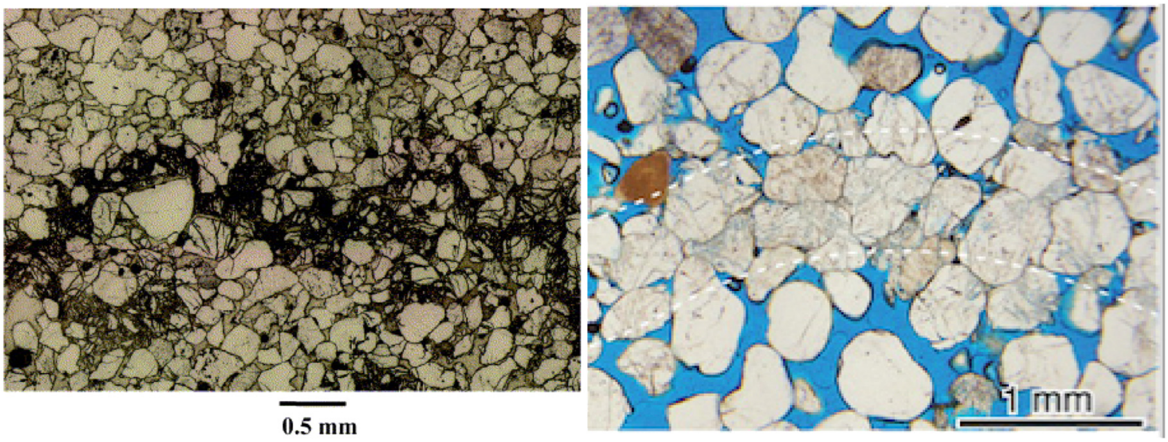

Fig. 1. (Left) SEM image of a laboratory-reproduced compaction band in Bentheim sandstone reported in [8]. (Right) SEM image of a field compaction band in Navajo Sandstone found in Buckskin Gulch site, Utah as reported in [9].
Source: Figure reproduced from [8,9].

Due to the highly localized porosity reduction, pure and shear-enhanced compaction bands may lead to several orders of permeability reduction [8,9,7,10,11]. Depending on the mineralogy, porosity, grain size, loading conditions and other environmental factors, compaction band and fractures may coexist in a hydro-geological system. The interactions between them in the host matrix may profoundly alter the mechanical and hydraulic characteristics. For instance, in a series of papers [12,13,5,14], Haimson and co-workers have generated a collection of experimental evidence to support that borehole breakouts, the elongations of borehole cross-section resulting from preferential rock failure, is related to the propagation of both the fracture and compaction band. Their experimental data also indicate that the compaction band, which advances orthogonally to the maximum compressive stress, can be regarded as a Mode I anti-crack in the LEFM framework [15]. Related findings can also be found in the laboratory tests, such as [16, 17], in which notched specimen is used to study the initiation and propagation of compaction band and measure the two fracture energies related respectively to fracture and compaction bands, as shown in Fig. 2.

These experimental findings are further validated in another series of theoretical and experimental studies (e.g. [18,15,19,20]) performed on the Aztec Sandstone found in the Valley of Fire, Nevada. The researchers have found that the normal contractional strain across the compaction band is nearly constant, which implies a constant driving stress along the compaction bands with negligibly small processing zone. These results are consistent with the LEFM anti-crack interpretation based on Griffith's theory. First pointed out by Sternlof et al. [15], the anti-crack theory on compaction band explains the initiation and propagation of compaction bands as the consequence of Griffith-type grain-scale flaw collapses due to weak grains, irregular pores or other causes. This similarity with Griffith's theory on brittle fracture provides an opportunity for us to derive a unified variational framework in which the propagation of both cracks and anti-cracks is viewed as the competition between the surface energy and the restitution of bulk energy during crack or compaction band growth [21,22].

It should be noted that the anti-crack theory is not the only one accepted theoretical framework to interpret the onset of compaction band. In particular, bifurcation analysis has also been widely used to predict the onset of the compaction band at the continuum scale [23–25]. As pointed out in [17], the drawback of this approach is that it is difficult to apply bifurcation analysis to predict compaction band patterns on heterogeneous material or to explain the various geometrical features such as the wiggly patterns recently found in [26].

While there are many discrete modeling approaches proposed in to simulate compaction band and fractures with either DEM or lattice–spring network (e.g. [27,28,26,29]), the applicability of these models are limited to interpretation of micro-scale mechanism in the laboratory under fully drained condition. This limitation is likely related to (1) the prohibitive computational cost to simulate grain-scale processes at the field scale, (2) the difficulty to calibrate material parameters for grain crushing and fragmentation process, and (3) the difficult to properly introduce the hydro-mechanical effect in the grain scale with a 2D DEM and lattice–spring model.

On the other hand, there are significant progresses made in the development of numerical approaches for simulating the propagation of fluid-driven fracture at the macroscopic continuum scale. For instance, cohesive zone interface