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PERMEABILITY EVOLUTION IN A FRACTURED ROCK MASS IN RESPONSE TO FLUID INJECTION

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PERMEABILITY EVOLUTION IN A FRACTURED ROCK MASS IN RESPONSE TO FLUID INJECTION

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ABSTRACT: Large-scale carbon capture and sequestration (CCS) projects involving annual injections of millions of tons of CO2 are a key infrastructural element needed to substantially reduce greenhouse gas emissions. The large rate and volume of injection will induce pressure and stress gradients within the formation that could activate existing fractures and faults, or drive new fractures through the caprock. We will present results of an ongoing investigation to identify conditions that will activate existing fractures/faults or make new fractures within the caprock using the Livermore Distinct Element Code (LDEC). LDEC is a multiphysics code, developed at LLNL, capable of simulating dynamic fracture of rock masses under a range of conditions. We will present several demonstrations of LDEC functionality and applications of LDEC to CO_2 injection scenarios including injection into an extensively fractured rock-mass. These examples highlight the advantages of explicitly including the geomechanical response of each interface within the rock-mass.

1. INTRODUCTION

LDEC was originally developed by Morris et al. [1] as a distinct element (DEM) code to simulate the response of jointed geologic media to dynamic loading. Cundall and Hart [2] review a number of numerical techniques that have been developed to simulate the behavior of discontinuous systems using DEMs. The DEM is naturally suited to simulating such systems because it can explicitly accommodate the blocky nature of natural rock masses. For example, Figure 1 shows a jointed medium, typical of the early applications of LDEC. LDEC was later extended to include Finite Element-Discrete Element transition [3], including an extension to include a nodal cohesive element formulation, which allows the study of fracture problems in the continuum-discontinuum setting with reduced mesh dependence [4]. Additionally, LDEC supports fully-coupled fluid flow using both Smooth Particle Hydrodynamics (SPH) and unstructured fracture flow mesh methods.

This paper will consider the application of LDEC to activation of fracture networks during CCS.

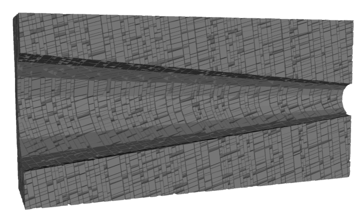

Fig. 1. An example of an LDEC geomechanical computational domain: A cavity in coal. The model includes non-persistent and randomized joint sets. LDEC was designed to calculate the evolving mechanical properties of such structures as they fail under different loading conditions.

2. STUDY OF PERMEABILITY CHANGE DUE TO JOINT ACTIVATION DURING INJECTION

Before considering direct simulation of an entire fracture network using LDEC, it is useful to consider an analysis of individual fractures. This analysis considers fractures of all orientations in isolation and highlights those orientations that will be activated by elevated pore pressure.

We consider the following in situ stress state:

$$\sigma_{east} = \sigma_{overburden} = 40\text{MPa} \quad (1)$$
$$\sigma_{north} = 0.6\,\sigma_{overburden} = 24\text{MPa} \quad (2)$$

and a hydrostatic pore pressure of 15MPa. Figure 2 shows the coefficient of friction required for stability of fractures of all orientations experiencing these stress conditions.

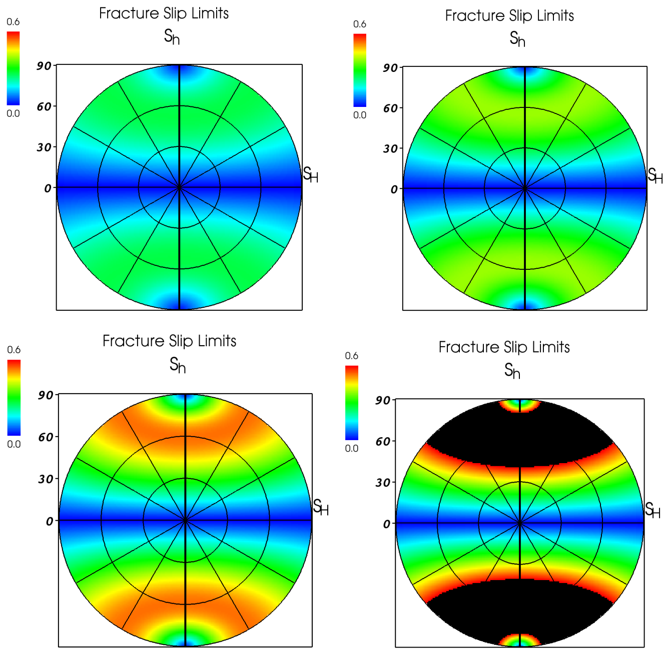

Fig. 2. Plots of friction coefficient for fractures of all orientations with a pore pressure perturbation of 0 MPa, 10 MPa, 15 MPa and 20 MPa.. Blue corresponds to a coefficient of friction of 0.0 and 0.6 respectively. Orientations requiring larger frictions coefficients are presumed to fail in shear and are shown in black.

The results indicate that shear failure of the fractures is observed at approximately 16 MPa of increase pore pressure.

3. APPLICATION OF LDEC TO INJECTION INTO AN EXTENSIVELY FRACTURED RESERVOIR

In this section we present results of a direct simulation of an entire fracture network using the LDEC code. In contract with the previous section, the LDEC analysis includes interaction between the fractures as they fail and stress is redistributed throughout the network. We consider injection into an extensively fractured region bounded above and below by intact rock. In this section we consider the extensively fractured domain shown in Figure 2 which cannot be practically meshed into a conforming finite element mesh. Consequently, for this application we employed the deformable polyhedral block implementation in LDEC which permits the explicit inclusion of each fracture surface. Although LDEC has been demonstrated on geomechanical problems including tens of millions of fractures [5], this small demonstration problem only considered 13 thousand fractures.

The in-situ stress state was assumed to be anisotropic with:

$$\sigma_{east} = \sigma_{overburden} \tag{1}$$

$$\sigma_{north} = 0.6\ \sigma_{overburden} \tag{2}$$

LDEC was used to simulate the response of the fractured region to a point injection source centered within the fractured region (Figure 3).

As the pore-pressure is increased, stress is redistributed throughout the rock mass, inducing shear failure on many fractures. Figure 4 shows the distribution of responses within the fractured portion of the domain. The simulation predicts that fractures of all orientations will be activated. However, as one would expect, a larger proportion of fractures initially experiencing shear stress are activated. Such simulations can be used to predict the evolving anisotropic permeability field due to complex interactions between the in-situ stress, fracture distribution and pore pressure fields within a heavily fractured rock-mass.

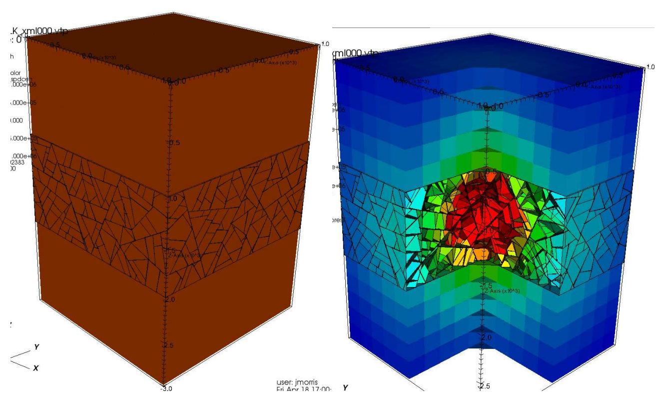

Fig. 3. This geometry of this small demonstration problem has 13 thousand, variably oriented fractures within the fractured region (left). The imposed pore pressure distribution (right) corresponds to a point injection source.

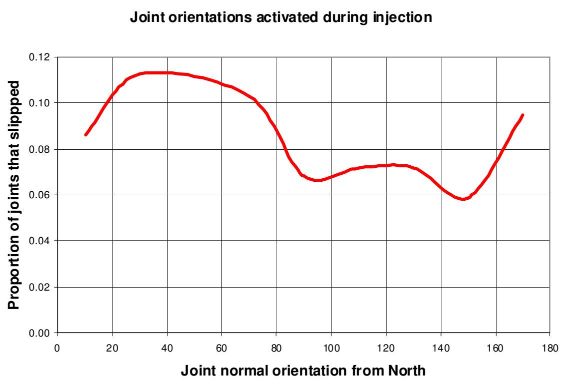

Fig. 4. The proportion of joints of each orientation relative to North that have failed. Joints of all orientations fail, but predominantly those initially experiencing shear stress.

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REFERENCES

1. Morris, J.P., L.A. Glenn, and S.C. Blair (2002) The distinct element method - application to structures in jointed rock. In *Lecture Notes in Computational Science and Engineering: Meshfree Methods*, 291-306.
2. Cundall, P.A. and R.D. Hart (1992) Numerical modeling of discontinua. *Engineering Computations*, **9**: 101-113.
3. Morris, J.P., et al. (2006) Simulations of fracture and fragmentation of geologic materials using combined FEM/DEM analysis. *International Journal of Impact Engineering*, **33**: 463-473.
4. Block, G., et al. (2007) Simulations of dynamic crack propagation in brittle materials using nodal cohesive forces and continuum damage mechanics in the distinct element code LDEC. *International Journal of Fracture*, **144**: 131-147.
5. Morris, J.P., et al. (2004) Simulations of underground structures subjected to dynamic loading using the distinct element method. *Engineering Computations*, **21**: 348-408.