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Impact of Stress on Anomalous Transport in Fractured Rock

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ABSTRACT

We investigate the effects of geologic (tectonic) stress on flow and tracer transport through natural fracture networks. The fracture network is extracted from the geological map of an actual rock outcrop, and we model the impact of stress on aperture field, flow field and tracer transport properties. We observe that anomalous transport emerges in response to confining stress on the fracture network, and show that the stress state is a powerful determinant of transport behavior. An anisotropic stress state can induce preferential flow paths through shear dilation, and an increase in geologic stress can also increase aperture heterogeneity that induces late-time tailing of particle breakthrough curves. Our results point to a heretofore unrecognized link between geomechanics and anomalous transport in natural fractured media.

1. Introduction

Fluid flow and transport in fractured rock controls many natural and engineered processes in the subsurface, including hydrocarbon production from fractured reservoir and the fate of radionuclides during geologic nuclear waste storage in crystalline rock. However, characterizing flow and transport through fractured media is challenging due to the high uncertainty and large heterogeneity associated with fractured rock properties. In addition to these "static" challenges, geologic fractures are always under significant overburden and tectonic stresses, and changes in the stress state can lead to changes in the fracture's ability to conduct fluids. While in-situ stress has been shown to impact fluid flow through fractures in a fundamental way, the impact of in-situ stress on transport through fractured rock remains poorly understood. The link between anomalous (non-Fickian) transport and in-situ stress has been shown, only recently, at the level of a single rough fracture [1].

Here, we investigate the impact of geologic (tectonic) stress on flow and tracer transport through natural fracture networks. We model geomechanical effects in 2D fractured rock by means of a finite-discrete element method (FEMDEM) [2], which can capture the deformation of matrix blocks, reactivation of pre-existing fractures, and propagation of new cracks, subjected to the applied stress field. We apply the model to a fracture network extracted from the geological map of an actual rock outcrop to obtain the aperture field at different stress conditions. We then simulate fluid flow and particle transport through the stressed fracture networks.

2. Method

2.1 Fracture Network

The fracture network used in this research is based on the outcrop map of a limestone bed located on the southern margin of the Bristol Channel Basin, UK. This fractured limestone (10 cm thick) is sandwiched between impervious shales and the vertically dipping fractures are layer bound (not extending into the neighboring shales). The fracture network exhibits a hierarchical, ladder pattern consisting of two major sets. The E-W striking set that formed in an early stage contains "through-going" (or persistent) fractures. The N-S striking set that developed later consists of short fractures abutting those of the E-W set.

2.2 Geomechanical Modeling

The numerical method used for geomechanical modeling of fractured rocks is the combined finite-discrete element method (FEMDEM) [3]. The FEMDEM model that accommodates the finite strain elasticity coupled with a smeared crack model is able to capture the complex behavior of fractured rocks involving deformation, displacement, rotation, interaction, fracturing and fragmentation [4]. The FEMDEM model represents a two-dimensional (2D) fractured rock using a fully discontinuous mesh of three-noded triangular finite elements, which are connected by four-noded joint elements. There are two types of joint elements: unbroken

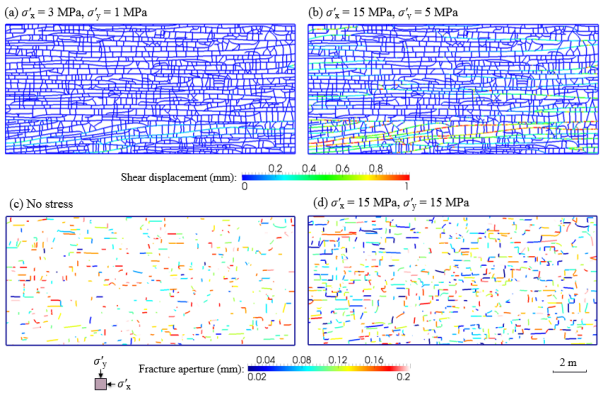

Fig. 1 The results of geomechanical simulation show that the stress state is a powerful determinant of fracture geometry: (a)(b) An anisotropic stress state can induce preferential flow paths through shear displacement and dilation; (c)(d) An increase in geologic stress increases aperture heterogeneity that induces late-time tailing of particle breakthrough curves.

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joint elements inside the matrix and broken joint elements along fractures [5]. The joint elements (either broken or unbroken) are created and embedded between the edges of triangular element pairs.

To model the deformation of fractures associated with intrinsic roughness in response to various normal and/or shear loading conditions, an empirical joint constitutive model (JCM) has been implemented into the FEMDEM framework [5]. The aperture values are obtained by combing the effects of mesoscopic opening (induced by fracture network deformation and resolved in the FEMDEM) and microscopic closure (controlled by fracture roughness and captured by the JCM) (Fig .1).

2.3 Flow and Transport Modeling

Steady state flow through a natural fracture network is modeled by assuming local cubic law in fracture segments. Imposing flux conservation at each intersection node leads to a linear system of equations, which is solved for the hydraulic heads at the nodes. We study a uniform flow setting characterized by constant mean flow in the positive x-direction parallel to the principal set of factures. No-flow conditions are imposed at the top and bottom boundaries of the domain, and fixed hydraulic head at the left and right boundaries.

Once the fluxes at the links have been determined, we simulate transport of a passive tracer by particle tracking [6]. Particles are injected along a line at the inlet with flux-weighted injection. Injected particles are advected with the flow velocity between nodes. At the fracture intersections, we apply a complete mixing rule. Complete mixing assumes that Péclet numbers at the nodes are small enough that particles are well mixed within the node. Thus, the link through which the particle exits a node is chosen randomly with flux-weighted probability.

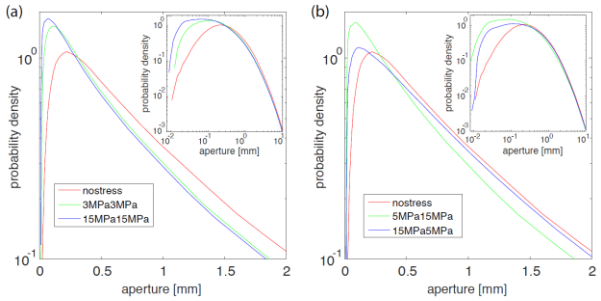

Fig. 2 Aperture probability density functions. (a) For isotropic stress states, the increase in the magnitude of stress increases the probability of small aperture values. (b) For anisotropic stress states, higher stress along horizontal fractures causes large aperture values and increase in the magnitude of stress increases the probability of small aperture values (inset)

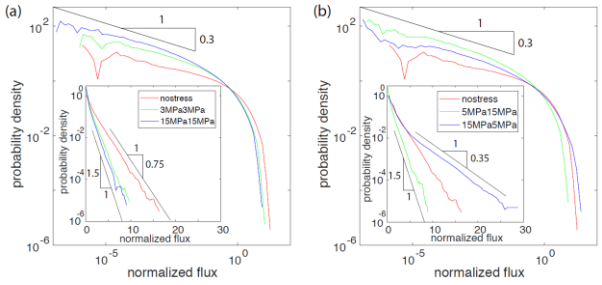

Fig. 3 Eulerian flux probability density functions. (a) For isotropic stress states, increase in the magnitude of stress increases the probability of small flux values. (b) For anisotropic stress states, higher stress along mean flow direction causes large flux values (inset) and increase in the magnitude of stress increases the probability of small flux values.

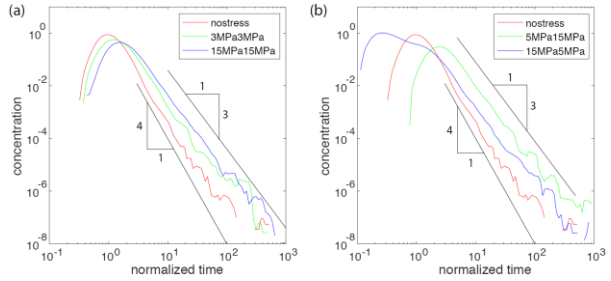

Fig. 4 Particle breakthrough curves. (a) For isotropic stress states, increase in the magnitude of stress delays particle arrival time and increases the late-time tailing. (b) For anisotropic stress states, higher stress along horizontal fractures causes anomalous early arrival of tracers and increase in the magnitude of stress increases the late-time tailing.

3. Results and Discussion

We perform geomechanical, flow and transport modeling on the actual outcrop of Bristol fracture field.

We first present probability density functions of aperture (Fig. 2) and Eulerian velocity (Fig. 3). Increase in stress state leads to higher probability of having small aperture values and anisotropic stress state can cause preferential flow paths via shear dilation

We finally show how the geologic stress state controls tracer breakthrough curves (Fig. 4). Increase in stress state causes late-time tailing and the anisotropic stress condition can cause anomalous early arrival of tracers.

4. Concluding Remarks

This study shows how the interplay between fracture geometrical properties (aperture distribution and network geometry) and geologic stress state can be a powerful determinant of transport behavior geometry behavior: (1) An anisotropic stress state can result in the formation of preferential flow paths under the effect of shear dilation, and leads to anomalously early arrival of tracers; (2) An increase in geologic stress increases small aperture heterogeneity that induces late-time tailing of particle breakthrough curves.

In this study, we investigated the particle transport and the impact of the geologic stress for a 2D layered natural fracture system. These findings should be further studied for different types of fracture networks and eventually extended to 3D fracture networks.

References

[1] P. K. Kang, S. Brown, R. Juanes, *Earth and Planetary Science Letters*, (2016), 454, 46-54.

[2] Q. Lei, J. P. Latham, C. F. Tsang, *Computers and Geotechnics*, (2017), 85, 151-176.
[3] A. Munjiza, The combined finite-discrete element method, *John Wiley & Sons*, (2004).
[4] Q. Lei, J. P. Latham, J. Xiang, C. F. Tsang, P. Lang, L. Guo, *International Journal of Rock Mechanics and Mining Sciences*, (2014), 70, 507-523.

[5] Q. Lei, J. P. Latham, J. Xiang, *Rock Mechanics and Rock Engineering*, (2016), 49(12), 4799-4816.
[6] P. K. Kang, M. Dentz, T. Le Borgne, S. Lee, R. Juanes, *Advances in Water Resources,* (2017), 106, 80-94