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Investigating the Role of Hydromechanical Coupling in Shallow, Fractured Rock Aquifers

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Abstract

Aquifers hosted in fractured crystalline rocks are generally characterized by low porosity and strongly heterogeneous and anisotropic flow paths, with flow and transport dominated by discrete fracture sets. In general, zones of high hydraulic conductivity correlate with zones of high fracture intensity and fracture connectivity. Fractured rock hydraulic conductivity,

however, is not only a function of spatial fracture distributions, but also displays dynamic variability due to changes in fracture aperture with changes in effective stress, such as those due to groundwater pumping and seasonal variations in water level. Some studies suggest hydromechanical coupling plays a minimal role in hydraulic conductivity alteration at shallow depths, whereas other studies attribute hydraulic conductivity alteration directly to hydromechanical coupling, thus raising a fundamental science question: what is the role of hydromechanical coupling in shallow fractured rock aquifers?

This study investigates the role of hydromechanical coupling in shallow fractured rock aquifers from 3 perspectives. First, a sensitivity study presents the results of analytical and numerical modeling to determine what key hydromechanical parameters are important in the shallow crust under realistic stress states. Results suggest that hydraulic conductivity alteration is dominated by fracture normal closure, with shear dilation playing a minimal role, and that shallow dipping fractures are likely to have the highest hydraulic conductivity relative to steeply dipping fractures due to compressional deviatoric stress states. These results suggest that depth-dependent hydraulic conductivity trends observed in nature may be due in part to hydromechanical phenomena, and thus fractured rock characterization should include hydromechanical characterization.

Study two presents the results of an aquifer-scale fractured rock characterization at Gates Pond, Berlin, MA in which hydromechanical variables are constrained in the field and coupled with structural and hydraulic characterization, including stress-tests, long-term water level monitoring, isotope analysis and earth tide analysis, to provide insight into the mechanical properties of the aquifer. Results of this study reveal an interesting field setting in which the mechanical properties of the aquifer are homogeneous throughout the study area, but the aquifer is compartmentalized by foliation parallel fractures that restrict hydraulic connection between wells that are placed perpendicular to foliation. Gates Pond also displays a hydraulic conductivity trend in which Foliation Parallel Fractures (FPF) have a decreasing transmissivity with increasing depth, and tectonic fractures display a decrease in transmissivity with increasing dip. Such observations suggest a conceptual model in which FPFs dominate flow in the shallow subsurface, with transmissivity decreasing with depth, where Tectonic fracture become the dominate flowing set. These results are consistent with the results of analytical and numerical modeling predictions from Chapter 1.

Lastly, the third study presents results of a regional scale correlation of critically stressed fractures and fracture transmissivity in the Nashoba terrane, eastern Massachusetts. Whereas Chapter 1 suggests that fracture transmissivity is strongly modified by fracture normal closure, which is supported by field observations in Chapter 2, many workers suggest that flowing fractures are those that are critically stressed, and are thus strongly modified by shear dilation. This study addresses the role of shear dilation by identifying critically stressed fractures at a regional scale and correlating resolved stresses on transmissive fractures to fracture transmissivity. Fracture characteristics, transmissivity and borehole breakouts are characterized for 17 wells from throughout the Nashoba terrane. Critically stressed fractures are identified using inferred stress states, and correlation of critically stressed fractures to fracture transmissivity is investigated. Results suggest that transmissivity is weakly correlated to the ratio of shear to normal stress, and that ratio is strongly correlated to fracture dip. A conceptual model is proposed in which shallow dipping fractures are more likely to be critically stressed, such as FPFs in the shallow subsurface; however, high transmissivity fractures need not be critically stressed. Thus, it is concluded from observations in this dissertation that fractures in the shallow crust are most sensitive to fracture normal closure, although shear dilation may enhance transmissivity. The complex interaction between normal closure and shear dilation results in shallow dipping fractures being the most transmissive in the shallow subsurface, with tectonic fractures becoming more important with increasing depth. Each of the 3 studies presents a unique contribution to the study of hydromechanical coupling in fractured rock aquifers, with each study supporting the hypothesis that hydromechanical coupling may alter hydraulic conductivity of fractures in the shallow subsurface, contributing to observed depth-dependent hydraulic conductivity trends, variable hydraulic conductivity as a function of fracture dip, and dynamic permeability. Results of these studies show

that hydromechanical coupling affects hydraulic conductivity of fractures in the shallow crust, and should therefore be incorporated into fractured rock aquifer characterization in conjunction with standard structural and hydrogeologic characterization.

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