An Active Fracture Model for Unsaturated Flow and Transport

Research Objectives

Fracture/matrix (F/M) interaction is a key factor affecting flow and transport in unsaturated fractured rocks. In classic continuum approaches (Warren and Root, 1963), it is assumed that flow occurs through all the connected fractures and is uniformly distributed over the entire fracture area, which generally gives a relatively large F/M interaction. However, fractures seem to have limited interaction with the surrounding matrix at Yucca Mountain, Nevada, as suggested by geochemical nonequilibrium between the perched water (resulting mainly from fracture flow) and pore water in the rock matrix.

Because of the importance of the F/M interaction and related issues, there is a critical need to develop new approaches to accurately consider the interaction reduction inferred from field data at the Yucca Mountain site. Motivated by this consideration, we have developed an active fracture model based on the hypothesis that not all connected fractures actively conduct water in unsaturated fractured rocks.

Approach

Physically, the F/M interaction reduction can result from three mechanisms. First, because of gravitational instability and a heterogeneous aperture distribution, water flow through an unsaturated fracture is likely to be channelized, which can considerably reduce the F/M interface area. Second, fracture coating can reduce imbibition into the matrix, significantly in some cases. Third, because of the combination of the large nonlinearity involved in an unsaturated system and heterogeneities of fracture structure at different scales, significant fingering flow can occur even in a well-connected fracture network. In other words, only a portion of fractures in a connected network contribute to water flow, while other fractures are simply by-passed. For large-scale flow and transport, the third mechanism is the most important. The portion of the connected fractures that actively conduct water are defined as active fractures.

It is important to note differences between the active fracture model and the conventional, capillary equilibrium-based, fracture water distribution model. The latter assumes that liquid water

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occupies fractures with small apertures first and then fractures with relatively large apertures as water potential increases. In contrast, the active fracture model presumes gravity-dominated, non-equilibrium, preferential liquid water flow in fractures. The

water distribution is not controlled by the capillarity.

The fraction of active fractures in a connected fracture network, f_a , should be determined by flow and transport conditions and fractured rock properties. An expression for f_a must satisfy the following conditions: (1) all connected fractures are active if the system is fully liquid saturated; (2) all fractures are inactive if the system is at residual saturation; and (3) f_a should be related to water flux in fractures. Based on these considerations, we express f_a as a power function of effective water saturation in connected fractures, S_e ,

$$f_a = S_e^\gamma$$

where γ is a positive constant depending on properties of the corresponding fracture network and can be considered as a measure of the "activity" of connected fractures.

A generalized version of van Genuchten capillary pressure and relative permeability relations for the fracture continuum were developed based on the above equation for f_a and the following considerations: (1) van Genuchten relations are assumed to be valid for active fractures; (2) inactive fractures are filtered out from the fracture continuum in describing flow and transport in fractures; and (3) the apparent F/M interface area reduction factor (R) results not only from the actual interface area reduction, but also from the difference between active fracture

spacing and fracture spacing, determined from the geometry of the corresponding fracture network. Note that the derived relation for the F/M interface area reduction factor is used as an additional constitutive relation. Figure 1 shows the factor as a function of the effective water saturation.

Results

An inverse modeling approach was used to determine the "activities" of connected fracture networks, characterized by the γ factor, for the Topopah Spring welded (TSW) unit of Yucca Mountain by matching currently available matrix water saturation and potential data

Figure 1. The fracture-matrix interface area reduction factor (R) curves for $\gamma = 0, 0.5$ and 0.9 .

from several deep boreholes (e.g., Figure 2). The ITOUGH2 code was used for the inversion.

The estimated γ values are about 0.43, indicating that about 18-27% of connected fractures are active in the TSw unit under ambient conditions. This relatively high percentage is consistent with various field observations, including the relatively uniform matrix saturation and in-situ water potential values measured for most of the units. Furthermore, calcite coatings, signatures of water flow history in fractures, were found in about 10% of the fractures within the welded units.

Tracer transport simulations were also performed to check the consistency of the model with geochemical data. The calculated 50% tracer concentration breakthrough times of fracture continuum at the bottom of the TSw unit are between 3,500 and 5,000 years, and are generally in agreement with the perched water age data.

Significance of Findings

Fingering flow in a fracture network is a common flow mechanism in an unsaturated fracture-matrix system. This makes it

necessary to formulate the fracture water flow differently from water flow in unsaturated porous media. This study introduced a new model to incorporate fingering flow at a fracture network scale into the dual continuum approach. The simulation results based on the new model are generally in agreement with the field observations at the Yucca Mountain site.

Related Publications

Liu, H.H., C. Doughty, and G.S. Bodvarsson, An active fracture model for unsaturated flow and transport in fractured rocks, *Water Resour. Res.*, 34(10), pp. 2633-2646, 1998.

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Figure 2. Comparison between simulated matrix water saturation profile corresponding to Borehole SD-7 and measured data.