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Effects of Finite Matrix Diffusion and Kinetic Sorption on Solute Transport in a Network of Fractures

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Understanding of fluid flow and solute transport processes in naturally fractured rocks is critical to successful applications including waste disposal, environmental remediation, petroleum exploitation, and geothermal energy extraction. For crystalline rocks with tight matrix such as granite, flow and transport processes occur primarily within interconnected fracture network. However, advective transport of solute tends to be impeded by mass transfer into the rock matrix as well as by the kinetic sorption onto fracture surfaces and granular grains in the matrix. In this study, a direct time-domain particle tracking (DTDPT) algorithm is applied to specifically study these two retention processes. This DTDPT algorithm is developed by first solving, in the Laplace domain, the advection-dispersion equation (ADE) for a single fracture system. Transport processes considered in the ADE include advection, hydrodynamic dispersion, matrix diffusion, and kinetic sorption in the fracture as well as in the matrix. In particular, to reflect the field observation that matrix diffusion is usually limited to a finite domain in the vicinity of a fracture, the extent of matrix diffusion is taken into account by defining an average penetration depth into the matrix. Two memory functions, in the fracture and in the matrix, representing the combined effect of retention processes can be defined from the solution to this ADE. Subsequently, solute transport in the discrete fracture network (DFN) is solved by the time-domain particle tracking method in which particle travel time is directly sampled from the travel time CDF derived from the memory functions. Simulation results in a single fracture system indicate that, as the extent of matrix diffusion is decreased, solute mass flux in the matrix becomes significant after the advection front has passed. As a result, solute in the matrix diffuses back to the fracture and creates a second peak in the breakthrough curve (BTC). The arrival of the second peak is delayed as the extent of matrix diffusion is increased. Furthermore, a third peak may be formed as the rate of kinetic sorption is reduced. This DTDPT algorithm is applied to a hypothetical DFN. The effect of finite matrix diffusion on transport is stronger in DFN than in the single fracture system. Increasing the extent of matrix diffusion not only greatly delays the peak arrival time but also alters the BTC shape such that the double-peak may evolve to a single one. For the DFN case, the rate of sorption in the fracture has virtually no effect on solute transport. This can be understood as, in the fracture, advection tends to overwhelm other processes. On the contrary, sorption rate in the matrix tremendously affects transport characteristics in DFN. A slight change of this rate can result in a significant shape change of the resulting BTC. If the rock matrix was weathered by antecedent water-rock interactions, the altered rock matrix next to a fracture may pre-define the penetration depth of matrix diffusion. Hence, in comparison to solute invasion into intact matrix, the presence of altered rock matrix may significantly change transport characteristics for subsequent solute invasion into the rock. Furthermore, such invasion can be complicated by kinetic sorption in the matrix. Therefore, a proper consideration of retention processes in the matrix is needed to obtain a comprehensive and reasonable understanding of the underlying transport characteristics in naturally fractured rocks.

Keywords : Discrete fracture network, time-domain particle tracking, retention process, finite matrix diffusion, kinetic sorption