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Partitioning of preferential flows in fracture networks: Smoothed Particle Dynamics simulations and analytical modeling of infiltration dynamics

Jannes Kordilla¹, Marco Dentz², and Alexandre Tartakovsky³

¹University of Göttingen, Dept. Applied Geology, Germany

²Institute of Environmental Assessment and Water Research (IDAEA), Spanish National Research Council (CSIC), Barcelona, Spain

³Pacific Northwest National Laboratory, Computational Mathematics Group, USA

Recharge estimation in fractured-porous aquifers is an essential tool for proper water management and assessment of vulnerability. As opposed to diffuse infiltration, often encountered in consolidated and unconsolidated porous media, the infiltration dynamics in the unsaturated zone of fractured-porous media and karst aquifers often exhibit a rapid, gravity-driven flow component along preferential flow paths such as fractures, fracture networks, faults and fault zones. The partitioning into two hydraulically contrasting domains commonly leads to a breakdown of classical volume-effective flow equations employed in many FD or FEM modeling approaches which only consider the capillarity of the medium. Even in the presence of a porous matrix, preferential pathways along fractures have been shown to sustain flow percolation under equilibrium and non-equilibrium conditions. In order to properly capture the flow physics, various components have to be considered such as static and dynamic contact angles, surface tension, free-surface (multi-phase) interface dynamics, dynamic switching of flow modes (between droplets, rivulets, films) and associated formation of singularities in the case of merging or snapping flow. Here we study the process of vertical infiltration and partitioning at a single fracture intersection into a horizontal and vertical flow component. Via parallelized Smoothed Particle Hydrodynamics simulations we demonstrate how flow is first channeled into the horizontal fracture and then transitions into a Washburn-type inflow when pressure conditions are met and a connection to the next vertical flow path is established. We further proceed to capture this process with an analytical approach and finally demonstrate how to obtain a process-based transfer function to upscale this process to arbitrary fracture geometries and fracture cascades.