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Partitioning dynamics of gravity-driven preferential flow in unsaturated fractures: Laboratory study and three-dimensional smoothed particle hydrodynamics simulations

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Fractures and fracture networks have a high potential to contribute to the formation of preferential flow paths, and thus control important catchment-scale parameters, such as aquifer vulnerability, mass arrival times and dispersion dynamics. Particularly, the unsaturated zone of fractured porous aquifers exhibits highly space- and time-variant coupling of phase saturation and flow (transport) dynamics and remains an extremely challenging aspect of vadose zone research. Non-Darcian and highly non-linear unsaturated flow modes, strongly deviate from the classical laminar and low Capillary number flow regimes and therefore most volume-effective approaches fails to capture important flow and transport characteristics.

Here we study unsaturated gravity-driven free-surface flows on a synthetic surface intersected by a horizontal fracture and demonstrate the importance of flow modes (droplet; rivulet) on the partitioning behavior at the fracture intersection. We present (1) laboratory experiments, (2) three-dimensional smoothed particle hydrodynamics (SPH) simulations using a heavily parallelized code, and (3) an analytical solution. The flow-rate-dependent mode switching from droplets to rivulets is reproduced by the SPH model, and the transition ranges agree with the laboratory experiments. We show that flow modes heavily influence the bypass behavior. Flows favoring the formation of droplets exhibit a much stronger bypass capacity compared to rivulet flows, where nearly the whole fluid mass is initially stored within the horizontal fracture. This behavior is demonstrated for a multi-inlet laboratory setup where the inlet-specific flow rate is chosen so that either a droplet or rivulet flow persists. The effect of fluid buffering within the horizontal fracture is presented in terms of dimensionless fracture inflow so that characteristic scaling regimes can be recovered. For both cases (rivulets and droplets), the flow within the horizontal fracture transitions into a Washburn regime until a critical threshold is reached and the bypass efficiency increases. For rivulet flows, the initial filling of the horizontal fracture is described by classical plug flow. Meanwhile, for droplet flows, a size-dependent partitioning behavior is observed, and the filling of the fracture takes longer. For the case of rivulet flow, we provide an analytical solution that demonstrates the existence of classical Washburn flow within the horizontal fracture.