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Parallelized fully-coupled multi-scale Smoothed Particle Hydrodynamics model for gravity-driven infiltration processes in the vadose zone of fractured and porous-fractured media

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Flow in unsaturated porous media is commonly described by the volume-averaged effective Richards equation. Originally developed for soil systems, the Richards equation has also been applied to model flow in fractured systems, when the fracture density is sufficiently high (or fracture apertures are rather low) and the existence of an REV is likely. Given the complexity of gravity-driven flows, many discrete flow and transport processes, e.g. fingering, preferential flow pathway formation, meandering, and erratic flow mode dynamics (droplets, rivulets) are not taken into account in the effective model. In the past, we proposed a fracture-scale model, where the Navier-Stokes equation is discretized with the pairwise-force smoothed particle hydrodynamics (PF-SPH). Our model can efficiently simulate flow through fractures or fracture networks and recover all relevant flow dynamics including the effects of free surfaces and surface tension. However, in fractured systems the porous matrix represents an important storage compartment and influences flow dynamics within the highly permeable fractures. Here, we present a new multi-scale PF-SPH model for fracture flow with matrix infiltration, which describes flow in a porous matrix with the Richards equation and free-surface flows in the fracture with the Navier-Stokes equations. Inflow dynamic from the fracture into the porous matrix is realized by an efficient particle removal algorithm and a virtual water redistribution formulation, which exactly preserve mass and momentum. The model validation is carried out via comparison to a FEM model (COMSOL) for the Richards based flow dynamics and small-scale laboratory experiments to cover more complex cases of free-surface flow dynamics on porous surfaces, where matrix infiltration influences the bulk outflow behavior and onset of preferential flows.