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The moving boundary approach to modeling gravity-driven stable and unstable flow in soils

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Many field and laboratory studies in the last 40 years have found that water flow in homogeneous soil profiles may occur in preferential flow pathways rather than in a laterally uniform wetting front, as expected from classical soil physics theory and expressed by the Richards equation. The water-content distribution within such gravity-driven fingers was found to be nonmonotonic due to water accumulation behind a sharp wetting front (denoted as saturation overshoot). The unstable flow was first related to soil coarseness. However, its appearance in water-repellent soils led the authors to hypothesize that gravity-driven unstable flow formation is triggered by a non-zero contact angle between water and soil particles. Despite its widespread occurrence, a macroscopic-type model describing the nonmonotonic water distribution and sharp wetting front is still lacking. The moving boundary approach, which divides the flow domain into two well-defined subdomains with a sharp change in fluid saturation between them, is suggested to replace the classical approach of solving the Richards equation for the entire flow domain. The upper subdomain consists of water and air, whose relationship varies with space and time following the imposed boundary condition at the soil surface as calculated by the Richards equation. The lower subdomain also consists of water and air, but their relationship remains constant following the predetermined initial condition. The moving boundary between the two subdomains is the sharp wetting front, whose location is part of the solution. As such, the problem is inherently nonlinear. The wetting front's movement is controlled by the dynamic water-entry pressure of the soil, which depends on soil wettability and the front's propagation rate. A lower soil wettability, which hinders the spontaneous invasion of dry pores and increases the water-entry pressure, induces a sharp wetting front and water accumulation behind it. The wetting front starts to propagate once the pressure building up behind it exceeds the dynamic water-entry pressure. The moving boundary problem was numerically solved by COMSOL MULTIPHYSICS software, in which the Richards equation and the deformed geometry moving boundary models were coupled. The moving boundary solution was successfully verified by comparison with experimental data where saturation overshoot has been observed, and was further used to demonstrate the effect of the contact angle, soil characteristic curves and incoming flux on flow stability. To conclude, the moving boundary approach is a physically based model for solving stable and gravity-driven unstable flow in soils. It supports the conjecture that saturation overshoot, a pileup of water at the wetting front, is a prerequisite for gravity-driven fingering.