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Can flow velocity distribution at a pore-scale be quantified by a celerity-saturation curve?

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The macroscopic subsurface hydrological behaviour, such as surface water infiltration, volumetric water flow in a hillslope, groundwater pressure propagation, or tracer transport, are intimately related with the variability of microscopic flow velocity in the soil porous medium. The subsurface flow equations, expressed by a continuum approach, conceptualize the uniform flow in a representative elementary volume (REV), in which the volumetric flow velocity and average pore velocity are two common variables of water flow velocity. Even though a combination of the continuity equation with Darcian flow velocity is able to quantify the volumetric flow, such a continuum approach is unable to represent the variability of flow velocity at pore-scale. As result of the homogeneity assumption in the subsurface flow equations, the pore-scale heterogeneity cannot be fully represented.

Celerity describes the speed of a perturbation-induced propagation of flow or pressure wave. The physical meaning of celerity differs in saturated and unsaturated condition, and such difference can lead to confusion. Specifically, for saturated flow, the celerity indicates pressure transmission, while, for unsaturated flow, the celerity transmits a disturbance through water flow. If a soil is in an equilibrium state (steady condition), even a 'tiny disturbance' of water actuates both water flow and pressure propagation following the path of minimum resistance. Under a perturbation analysis, the celerity, therefore, represents the maximum pore water velocity among all the water-filled pores that contribute to the water flow. Consequently, the relationship between celerity and effective soil saturation reveals a distribution of pore water velocities.

A theoretical study was performed to analyse and quantify the hydraulic behaviour of natural soils with a special emphasis on the difference between pore water flow velocity and pressure propagation. The Mualem-Van Genuchten and Brooks-Corey constitutive relationships were used to describe the non-linear hydraulic conductivity of the soils. The analysis manifests that under full saturated conditions, a small fraction of the pores (with larger size and lower tortuosity) can conduct a large amount of volumetric water flow, while, under near-saturated condition, the celerity can be significantly larger than the Darcian velocity or average pore water velocity. If the soil saturation is below a certain threshold, pore water velocity and its variability are rather small. Solute transport in a variable saturated soil is controlled by both process of diffusion (driven by concentration gradient) and convection (related with distribution of flow velocities). Therefore, a variable pore water velocity induces a bimodal behaviour of the mass transport that is often observed in tracer experiments. We will present the results of our analysis and focus on pore water velocities derived from celerity – effective saturation plots and discuss whether this could be considered as a universal phenomenon in the subsurface flow system.