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# Topological Control on Flow and Transport in Unsaturated Porous Media from Temporally Resolved 3D X-ray Computed Micro-tomography

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The unsaturated zone, including soil and vadose zone, controls the exchange of water, heat, and chemical substances between the soil surface and aquifers. It also hosts several processes involved in the transfer of nutrients, playing a key role in the availability of life-sustaining resources. Anthropogenic actions, such as agriculture, urban waste management, and industrial activities, add substances to the soil that might compromise the quality of fresh groundwater resources. Being able to predict the fate of such substances in the subsurface through an assessment of flow and transport processes is essential for mitigating their negative effects and for designing more effective remediation measures. We analyze flow and transport processes in unsaturated media at pore-scale using high spatio-temporal resolution X-ray computed micro-tomography (synchrotron). 3D transport experiments through a synthetic sand-like porous medium using a contrast solution were performed at different saturation degrees. Experimental data allowed the reconstruction of the plume's advancing front and the tracking of its deformation over time, i.e., variation in the surface area of the 50% concentration plane. Results indicate an enhancement of the solute front deformation at lower saturation degrees and at larger flow rates, showcasing the role of the system's heterogeneity in shaping solute dispersion. This is explained by a better connectivity of the system at lower saturation degrees, expressed through more negative Euler characteristic values, which highlights the better performance of the system at connecting initially separated parcels of fluid through the formation of preferential paths and a larger number of stagnation zones. To also link the observed solute front deformation rates with the hydrodynamics in the pore space, the average helicity density in the pore space was computed. Lower saturation degrees resulted in a larger helicity density, indicating a more heterogeneous flow field characterized by larger tortuosity and more complex streamlines, which explains the observed stronger solute front deformation at lower saturation degrees. Implications of these results on transport were assessed via estimation of the Okubo-Weiss parameter, which indicated a stronger control of both shearing and vorticity on solute plume deformation at lower saturation, potentially hinting at an enhancement of mixing rates. These findings represent a major step towards understanding the control of saturation on the hydrodynamic landscape within the pore space and on the deformation rate of solute plumes and fronts, both essential to understand mixing dynamics in unsaturated porous media.

## Participation

In-Person

## References

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