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Mechanisms of dispersion in a porous medium

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We study the mechanisms of dispersion in the laminar flow through the pore space of a 3–dimensional porous medium. High performance numerical flow and transport simulations of solute breakthrough at the outlet of a sand-like porous medium demonstrate significant deviations from the hydrodynamic dispersion paradigm and identify two distinct regimes. The first regime is characterized by a broad distribution of advective residence times in single pores. The second regime is determined by diffusive mass transfer into low-velocity regions in the wake of solid grains. These mechanisms are quantified systematically in the framework of a time-domain random walk, which models particle transitions over the characteristic pore length at random times given by heterogeneous advection and diffusion. Under globally advection-dominated conditions, this means Péclet numbers larger than 1, particles sample the intrapore velocities by diffusion, and the interpore velocities through advection. In order to quantify this advection mechanism, we develop a model for the statistics of the Eulerian velocity magnitude based on Poiseuille's law for flow through a single pore, and for the distribution of mean pore velocities, both of which are linked to the distribution of pore diameters. Diffusion across streamlines through immobile zones in the wake of solid grains gives rise to exponentially distributed residence times that decay on the diffusion time over the pore length. The resulting time-domain random walk approach is parameterized by the medium and flow properties and captures both pre-asymptotic regimes. It describes the physical non-equilibrium caused by a broad distribution of mass transfer time scales, both advective and diffusive, on the representative elementary volume (REV). Thus, while the REV indicates the scale at which medium properties like porosity can be uniquely defined, this does not imply that transport can be characterized by hydrodynamic dispersion.