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Evolution of Particle Swarms Falling under Gravity in Fractures

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Cohesive particle swarms have been shown experimentally to exhibit enhanced sedimentation in fractures for an optimal range of fracture apertures. In this optimal range, swarms travel farther and faster than a disperse (particulate) solution. This study aims to uncover the physics underlying enhanced sedimentation. Swarm behavior at low Reynolds number in a quiescent unbounded fluid and between smooth rigid planar and rough boundaries is investigated numerically using direct-summation, particle-mesh (PM) and particle-particle particle-mesh (P3M) methods –based upon mutually interacting viscous point forces (Stokeslet fields). Wall effects are treated with a least-squares boundary singularity method, which can also model realistic, measured profiles of wall roughness. Much of the sedimentation behavior of a swarm is similar to the behavior of a homogeneous liquid drop. Sub-structural effects beyond pseudo-liquid behavior (i.e., particle-scale interactions) are approximated by the P3M method much more efficiently than with direct summation. The non-spherical initial shape instability, which occurs as the swarm is introduced into a tank below the surface of an otherwise quiescent fluid, leads to the formation of a torus. The swarm can also bifurcate, which significantly retards its sedimentation. Inhibition of breakup by the presence of the walls, within some optimal range of apertures, seems to account for the phenomenon of enhanced sedimentation.

From the simulations, if the initial swarm geometry at release is unaffected by the fracture aperture, no enhanced transport occurs. The swarm velocity as a function of aperture increases monotonically until it asymptotes to the swarm velocity in an open tank. However, if the fracture aperture affects the initial swarm geometry, the swarm velocity does not exhibit monotonic behavior. When swarms are released between two parallel smooth walls in very small apertures, the swarm is forced to reorganize and quickly deforms, which results in dramatic reduction in swarm velocity. At large apertures, the swarm evolution is similar to that of a swarm in open tank and quickly flattens into a slowly moving torus. In the optimal aperture range, the swarm maintains a cohesive unit behaving similarly to a falling sphere. Swarms falling in apertures less than or greater than the optimal aperture range, experience a level of anisotropy that considerably decreases velocities. Unraveling the physics that drives swarm behavior in fractured porous media is important for understanding particle sedimentation and contaminant spreading in the subsurface.

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References

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