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Micromechanics of Dense-Phase Sand-Fluid Flow and Transport in Fractures

Ingrid TOMAC[a,1] and Brian YAMASHIRO[a]
[a]*University of California, San Diego*

Abstract. The research presented in this paper is on settling and flow and transport of sand particles in hydraulic fractures. During hydraulic fracturing of georeservoirs for geothermal and hydrocarbon extraction, small particulate material is introduced into newly formed fractures. Although the granules keep the fractures open under in-situ pressures, the best practices to transport proppant into reservoir fractures have not yet been developed. This paper contributes to better fundamental understanding of dense- and dilute-phase flow and transport of particulate slurries in fractures. From the micromechanical perspective, understanding the spatio-temporal flow and transport of particles into realistic fractures poses a significant challenge. Discrete Element Method is coupled with computational fluid dynamics for numerical modeling, and particle agglomerations on flow and transport, as well as, settling and deposition of particles on inclined fracture bottoms was studied.

Keywords. Micromechanics, proppant flow and transport, geothermal energy, hydraulic fracturing, granular mechanics.

1. Extended abstract

This paper shows new insights into dense- and dilute-phase flow and transport of small particles through rock fractures in georeservoirs. Sand and other small particulate material called proppant serves for propping hydraulic fractures in georeservoirs for long term geothermal fluid circulation or hydrocarbon extractions [1]. From the micromechanical perspective, understanding the flow and transport of particles into rough, wavy and branching fractures poses a significant challenge. Specifically, it has not yet been well understood if a theory can be proposed which will unify various regimes of slurry flows and transports for predicting the proppant placement outcome and therefore to be included in large-scale hydraulic fracturing simulators. This paper presents a fraction of results of experimental, theoretical and numerical ongoing studies at University of California San Diego. The results presented focus on micromechanics of dense-phase sand-fluid flow and transport in smooth and rough inclined narrow fractures, using numerical technique which couples the Discrete Element Method and computational fluid dynamics in two- and three-dimensional models.

Discrete Element Method (DEM) solves the motion and the interaction of a system of discrete particles using explicit finite differences [2]. For solid-fluid multi-phase flow and transport, DEM is coupled with computational fluid dynamics (DEM-CFD). The DEM defines the system of particles that are represented by finite spherical or discs

[1] Ingrid Tomac, Structural Engineering Department, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0085, USA; E-mail: itomac@ucsd.edu.

particles and walls in two- and three- dimensional Particulate Flow Code [3]. The calculation cycle in DEM is a time-stepping algorithm that consists of the repeated application of the Law of Motion to each particle, a Force-displacement Law to each contact, and a constant updating of wall positions. Lubrication force is introduced at the contact between particles using elasto-hydrodynamic theory to improve the simulation of submerged particle collision behavior in DEM-CFD models with introducing realistic non-linear behavior at particle contacts for dense-phase fluid flows. The lubrication force acts as a thin layer of viscous fluid between two particle surfaces before the contact acts as a cushion that slows down the initial particles velocities and decreases the kinetic energy of the particles. If the particle slows down enough to near zero, the particles may stick next to each other, get trapped with the fluid and move along the fracture as a agglomerate [4-8]. The effect of fluid lubrication on particle settling and agglomeration in narrow rough fracture is studied numerically, as shown in Figure 1. Sand particles form clusters and agglomerates, slow down or speed up and influence the fluid motion around them.

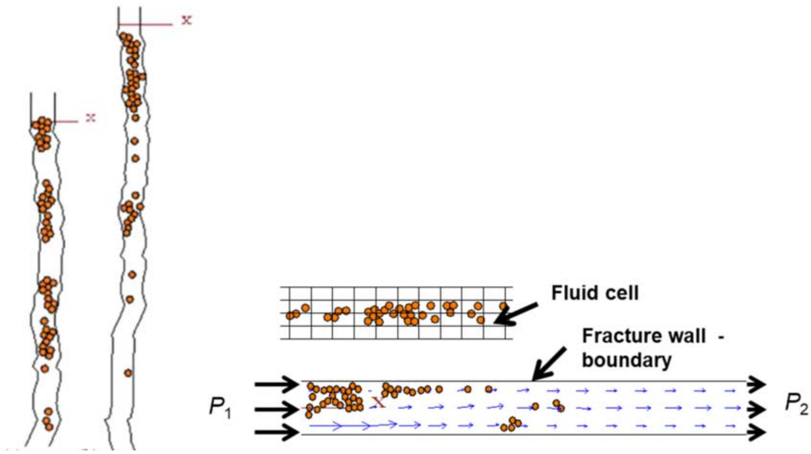

Figure 1. Fluid lubrication effect on proppant agglomeration in DEM-CFD model.

Three-dimensional settling of different concentrations is studied with three-dimensional DEM-CFD code. The Rouse number is a non-dimensional number in fluid dynamics which is used to define a concentration profile of suspended sediment and which also determines how sediment will be transported in a flowing fluid. Therefore, varying particle distribution along the fracture height represents realistic heterogeneous initial particle distribution that evolves during experienced turbulence near wellbore, as shown in Figure 2. Results of studying settling rates of particles distributions with different initial Rouse numbers during flow and transport in horizontal and inclined fractures are shown. In upper and lower sections of heterogeneous concentration profiles, settling rates are similar in profiles with Rouse numbers of 0.8 and 0.5 for locations with similar initial concentrations. On the contrary, the concentration layers located at mid-profiles show notable settling rate difference with Rouse numbers of 0.8 and 0.5, as shown in Figure 3. Increased asymmetric upward vs. downward acting particle-particle collisions for mid-profile layers appears to occur due to differing in profile concentration transition rates.

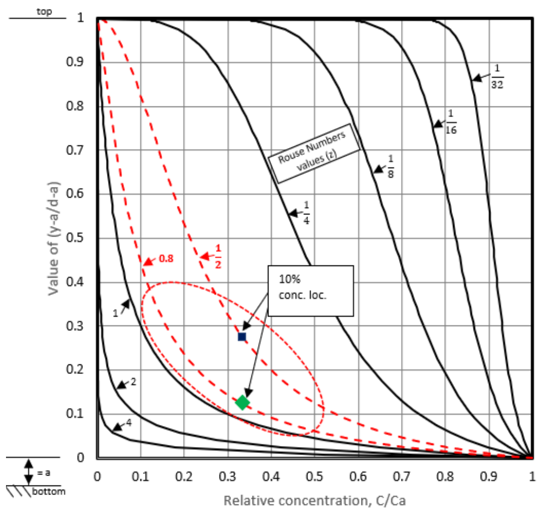

Figure 2. Concentration distribution diagram with indication of 10% concentration value locations on profile curves for Rouse number values of 0.8 and 0.5.

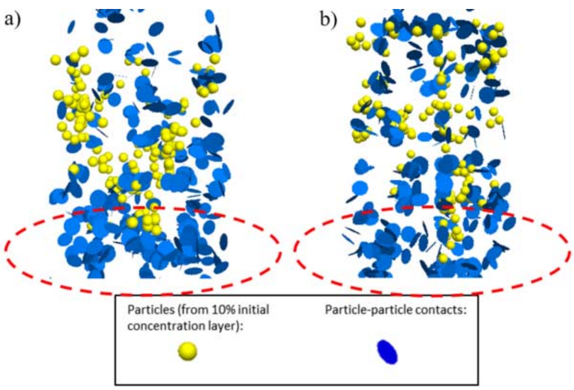

Figure 3. Particle-particle collisions at time=0.14 sec. for a) 10% initial concentration layer for Rouse number = 0.8, b) 10% initial concentration layer for Rouse number value of 0.5. Circled regions showing greater amount of particle to particle contacts for the higher Rouse number of 0.8 as compared to that in the 0.5 Rouse number profile at bottom of layer.

Effect of enhanced sediment deposition rates is studied on flow and transport in inclined fractures. The rate at which solid particles sediment under the action of gravity can be greatly enhanced if the walls of a settling vessel are inclined rather than oriented vertically. This phenomenon, often referred to as "The Boycott Effect", plays an increasingly important role in a variety of separation processes because, in principle, the sedimentation rate can be enhanced by several orders of magnitude if the vessel is inclined. In the proppant flow and transport simulations, reduced deposition velocity is also observed normal to inclined fracture bottom, with increased variance from horizontal inclination. The observed results are similar to the Boycott effect, but with added influence of proppant tangential flow velocity and particle concentrations. Similarity in relative deposition rates, as compared to respective horizontal deposition rate, is also observed as shown in Figure 4.

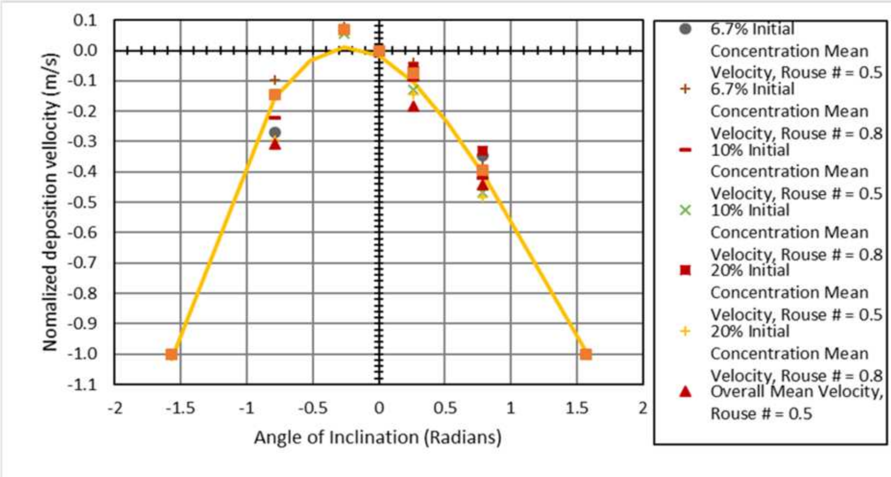

Figure 4. Deposition velocities as normalized by the deposition velocity for 0 radians (i.e. 0 degree) horizontal inclination for particle concentration profiles developed with Rouse number values of 0.8 and 0.5.

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