PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2018
SGP-TR-213

Experimental Evaluation of Turbulent Flow and Proppant Transport in a Narrow Fracture

Ingrid Tomac[1] and Daniel M. Tartakovsky[2]

[1]University of California, San Diego, Department of Structural Engineering, 9500 Gilman Drive #0085, La Jolla, CA 92093-0085

[2]Stanford University, Department of Energy Resources Engineering, 367 Panama St., Stanford, CA 94035

[1]itomac@ucsd.edu, [2]tartakovsky@stanford.edu

Keywords: proppant, geothermal, reservoirs

ABSTRACT

We present results of an experimental investigation of turbulent flow of proppant and fluid slurries in narrow smooth fractures. Proppant is a small granular material, which is introduced into hydraulic fractures to keep them open for a long-term geo-reservoir function. Proppants are used in geothermal reservoirs wherein permeability enhancement relies on tensile fracture propagation, and shearing of existing fractures is not a dominant mechanism. Such georeservoirs occur in sandstone geological formations or on the boundary between sedimentary and igneous rock masses. Our laboratory experiments are performed using Plexiglas and 3D printed narrow fracture zones. A progressive cavity pump injects proppants mixed with carrying fluids in varied volumetric concentrations at varied flow rates. Several different proppants are used. Our results indicate that turbulence is a decisive factor in progression of the slurry into a fracture system. However, turbulent motion of dense particle phase slurries is not yet well understood. Smaller particles respond well to higher flow rates and are carried over the bed of proppant in turbulent swirls. Therefore, the slurry consisting of smaller sand particles does not form a large proppant bed and is transported further into the fracture system. Fracture aperture, fluid viscosity, and flow rates are also evaluated against turbulent slurry motions.

1. INTRODUCTION

Proppant flow and transport occurs in rock fracture systems during hydraulic fracturing of georeservoirs. Proppant role is to keep the fractures open for a long-term geothermal fluid circulation. Proppants are small, hard and durable granular materials, which withstand in-situ reservoir pressures and prop a fracture open. Some geothermal reservoirs maintain the required long-term permeability through self-propping of sheared rough fractures, but a majority of fracture systems requires the introduction of proppants. Although many researchers investigated, both experimentally and theoretically, proppant flow and transport, placement of proppant into long, rough, narrow and wavy fractures is not yet completely understood. The process of placing proppant in a fracture occurs in several phases. First, a low viscosity fluid (prepad), which meets requirements for easy fracture initiation and propagation of a fracture tip, is injected from a borehole into the rock formation. Second, a higher viscosity fluid that caries proppant is injected into the fracture. As a result, a propped hydraulic fracture is formed in the rock formation. There are several types of proppant available today, and their characteristics depend on application and reservoir characteristics, such as depth, temperature and rock type. Typically, natural sands and synthetic ceramic proppants are used for lower-pressure (10/20 mesh, 20/40 mesh) and deeper reservoirs, respectively. The fracturing treatment requires a schedule and a design of parameters, such as proppant's mesh size and shape, proppant's type and concentration, properties of the proppant-carrying fluid, pressure rate, slurry velocity, and fracturing treatment schedule. Ideal design and procedures would be optimal for both the fracturing process and the final propping of fractures in hot dry rock reservoirs (Economides et al., 2000).

Multiple laboratory and site investigations of pertinent phenomena, such as near-wellbore tortuosity, effect of fracture wall roughness on proppant placement and flow in a fracture, influence of proppant concentration and fluid viscosity on slurry flow and proppant settling in a fracture, are insightful but cannot be readily incorporated into the contemporary hydraulic fracturing models. Experimental, theoretical, and numerical studies of proppant flow in hydraulic fractures provide rough guidelines. For example, laboratory measurements in slot-flow models yielded the minimum fluid viscosity for successful proppant transport (Goel et al., 2002; Goel and Shah, 2001). Studies of the ratio of particle diameter to the slot cell width provided estimates of the particle retardation velocities and clogging of proppant (Barree and Conway, 1995; Novotny, 1977; Patankar et al., 2002; Sharma and Gadde, n.d.): when a proppant flows in a narrow channel, fluid velocity is different from proppant velocity, and some amount of the velocity retardation is present. Experimental observations of interactions between proppant particles in the flow revealed that hydrodynamic forces dominate at low proppant concentrations, while inter-particle interactions become a dominant factor at higher concentrations (Shah, 1982). Experiments in a vertical-slot flow demonstrated that proppant particles follow erratic paths, but do not scratch or touch the slot walls (Sievert et al., 1981). Proppant particles-bridging occurs when the annular flow-channel diameter is 3-6 times the value of particle diameter (Sievert et al., 1981). Screen-out, which causes premature end of a fracturing effort, can be caused by proppant clogging near the wellbore and occurs suddenly and without warning (Barree and Conway, 1995a). Proppant packs, which exhibit significant grain-to-grain contact, usually lead to clogging and screen-out events. A proppant pack forms within a fracture and can grow in any directions, with the fluid flowing on either side of the proppant pack (Daneshy, 2005). The laboratory studies (Novotny, 1977) of proppant concentration and bridging effects on proppant flow, as well as corresponding numerical simulations (Daneshy, 1978), provide some practical guidelines for avoiding particle bridging, such as that the diameter of the fracture needs to be at least 2-3 times larger than the particle diameter. Particle agglomerations occur as a result of fluid lubrication forces in a constrained flow and transport of dense slurries (Luo and Tomac, 2018, 2017, 2016; Tomac and Luo, 2016).

Fundamental qualitative and quantitative theories for estimating whether the particle-fluid coupling is dilute or dense are given in the literature (Crowe et al., 2011). The prediction of the slurry particle-fluid coupling is based on the comparison between the average response time of particles to the fluid drag and particle collisions. In a dilute flow regime, particles do not collide frequently and fluid drag forces dominate their motion. On the other hand, since the elapsed time between particle collisions decreases at high particle concentrations, particle collisions significantly impact the slurry flow field. To conclude, for collision- and contact-dominated flows, both particle and fluid motions and their interactions need to be modeled in order to account for the effect of particle collisions. A major objective of this study is to better understand the role of fracture walls, particle concentrations and type and fluid properties on the regime of proppant flow and transport in a narrow fracture and to investigate the role of turbulence.

2. EXPERIMENTAL PROPPANT FLOW AND TRANSPORT SETUP

Our experimental setup is located at the Structural Engineering Department at the University of California, San Diego. It consists of a progressive cavity pump with flow rate controlled with variable frequency drive, which are run by a 3-phase 1HP motor. Proppant is pumped into a narrow acrylic-aluminum slot 2 mm wide, 51 cm high and 150 cm long. The slot is initially filled with water, to mimic a low viscosity fluid present in reservoir fractures prior to proppant slurry arrivals. Proppants used are silica sands, and for carrying fluid Newtonian fluids are used which are water and glycerol-water mixture. Figure 1 shows the experimental setup with the narrow slot experiment. Videos of experiments were taken with 2 high-speed cameras with up to 1000 fps capability. The experiment was illuminated with 3 extra lamps to add more light. Captured videos were analyzed using an open-source particle image velocity software (PIV) called GEO-PIV and specially developed for studying geotechnical materials including sand (Take, 2015).

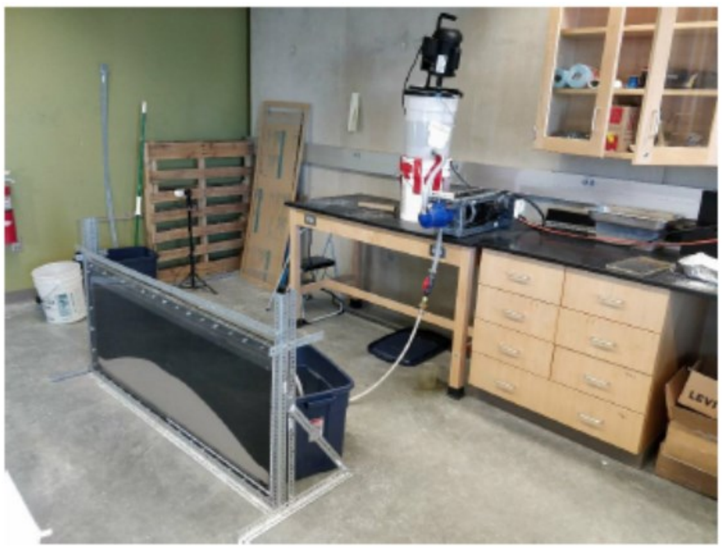


Figure 1: The experimental setup consisting of buckets for proppant mixing with motorized mixer, a motorized progressive cavity pump and acrylic-aluminum narrow fracture cell.

A particle image velocimetry (PIV)-analysis was carried out using GeoPIV. GeoPIV is a PIV software via MATLAB that was specifically developed for soils is shown in Fig. 2 by White and Take (2002). Most PIV-algorithms generally struggle with granular flows due to yield obscure or diffuse pictures, but White and Take made a PIV method with improved precision for this application. First, the user must select mesh size and location using an accessory script to obtain a mesh file. Areas without particulate flow are masked out to avoid wild vectors and reduce computation time. A launch file is prepared with a small set of input values including set of two pictures and PIV search zone. In theory, the only downside of a large PIV search zone is the computation time. However, it was discovered that a large interrogation area increased the number of number of wild vectors, because of noise in the pitch-black parts of the picture. Alternatively, a very large search zones cause a manifold increased number of chances for the GeoPIV to mistake a random set of pixels in picture n+1 for the original set. Instead, the interrogation width is set to the maximum expected displacement. The displacement is easily obtained through visual investigation of the pictures. The search zone is set to 30 pixels, which is about 50% higher than the estimated maximum displacement for any experiment based on visual observations.

The GeoPIV retrieves displacement vectors, and the velocity is calculated since the framerate is a constant at 120 frames per second. The inch-bar placed on the bottom of the experimental setup serves for calculation of the relationship between distances and pixels. Since the goal is to investigate flow with particle-particle interactions, a small measurement array size is preferred. 30x30 pixel was found to have an acceptable performance and level of detail. Smaller interrogation areas were useful in select small areas of flow but generally did not perform well for the entire picture. Results from any frame n and n+1 was found to be generally consistent based on a random set of PIV-analyses within a short time-interval from the same video.

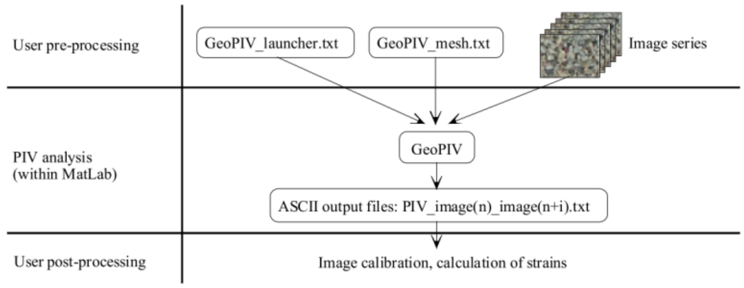


Figure 2: The GeoPIV method (White and Take, 2002).

3. EXPERIMENTAL RESULTS

The chosen experimental results are presented here for the evaluation of turbulent slurry flow and transport in a narrow smooth fracture. The experiments are conducted with silica sand sieved to 20/40, 40/70 and 60/100 sieve sizes, corresponding to coarse, medium and fine sands. The information about the experimental input data is given in Table 1. The particle Reynolds number (Re_s) is calculated for the average particle size of used selected sands. The particle Reynolds number serves as an indicator of slurry being held in a suspension during sediment transport. For $Re_s < 10^{-6}$, particles can be conveyed by Brownian molecular movement and are kept in suspension without any turbulence, as so called *colloidal dispersions*. However, it is not viable to use such small particles for proppants. As the Re_s increases in the region between $10^{-6} < Re_s < 0.1$, particles can be easily held in suspension by hydraulic forces, and this tendency is supported by a low density and by a non-spherical particle shape. Only little turbulence is needed to keep those particles homogeneously suspended, so liquid velocity can be low in this *homogeneous flow regime*. If the $0.1 < Re_s < 2$, some turbulence and velocity is needed to keep particles in a suspension, but in the case of horizontal flow, completely uniform solid distribution cannot be reached. A certain degree of segregation will occur. This type of suspension can exist at economically-feasible velocities and is called *pseudo-homogeneous flow regime*. The Re_s is defined as

$$\mathrm{Re}_s = \frac{\rho v_S D}{\mu} \tag{1}$$

where ρ is the fluid density, v_s is the particle terminal settling velocity or Stokes's velocity, D is the particle diameter and μ is the fluid dynamic viscosity for Newtonian fluids. The Rouse number dictates the mode of sediment transport and it is the ratio of particle settling velocity to the shear velocity. Rouse number defines rate of fall versus strength of turbulence acting to suspended particles. To evaluate the sediment transport, we also calculate the Rouse number ,

$$Rouse\# = \frac{v_S}{ku} \tag{2}$$

where v_s is the particle terminal settling velocity or Stokes's velocity, u is the slurry shear velocity, and $k = 0.4$ is Von Karman's constant. Depending on the Rouse# > 2.5, the bedload forms, 1.2 < Rouse# < 2.5 particles are 50% suspended, 0.8 < Rouse# < 1.2 particles are 100% suspended, and Rouse# < 0.8 wash load occurs. The average slurry approximate horizontal velocity measured with PIV method is about 0.28-0.33 m/s for cases of Sand 2 and Sand 3. Sand 1 exhibited dominantly settling behavior forming a triangular pile. Fluid approximate Ref is reported here. Ref is calculated based on the mean slurry velocity and the height of the moving fluid zone in the fracture perpendicular to the fracture width recorded from the experiments. The retardation velocity of the particles is not possible to record now, so the Re_f describes an approximate slurry motion:

$$\mathrm{Re}_f = \frac{\rho_f u D_h}{\mu_f} \tag{3}$$

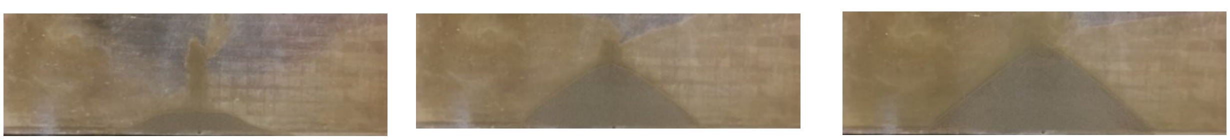
$$D_h = \frac{2wh}{w+h} \tag{4}$$

where ρ_f is the fluid density, μ_f is the fluid dynamic viscosity, u is the slurry shear velocity, w is the fracture width and h is the height of the slurry flow region. PIV measured slurry velocity vectors enable qualitative and quantitative analyses of proppant slurry flow and transport in a 2-mm wide vertical fracture. The obtained information is then compared with theoretical prediction indices for general sediment transport in wide channels. The interest of this research is to evaluate importance and need of turbulence for more successful procedures of placing proppant further into a narrow fracture. Another goal is to investigate if and how the general sediment transport theories can be applied in a case of flow and transport in a narrow fracture.

Table 1. Parameters for experiments in a narrow smooth slot

	Mesh size	Average particle diameter (mm)	Particle Re_s (-)	Fluid Re_f (-)	Particle settling velocity (m/s)	Rouse number (-)
Sand 1	20/40	0.66	271.5	-	0.4114	3.4
Sand 2 - in water	40/70	0.3	25.5	1280	0.085	0.71
Sand 2 in glycerol-water	40/70	0.3	1.14	200	0.0164	0.31
Sand 3	60/100	0.2	7.5	1094	0.0377	0.13

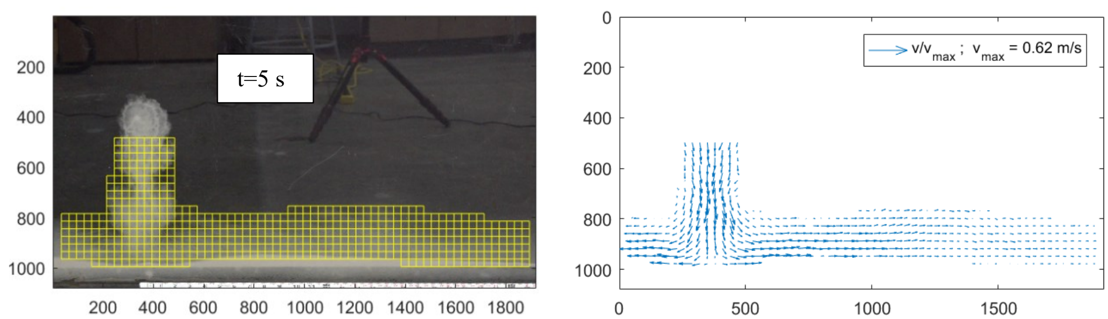
Fig. 3 shows experimental analysis for Sand 1, which is coarse sand injected into the 2-mm wide fracture through the hole in the middle. The sand forms bed without significant proppant transport, which can be seen by observing the angle of repose. Transport of particles occurs only partially by rolling down the sand dune. The dune spread is not significant, which is in accordance with very large Re_s. Figs. 4 and 5 show results of injection of medium Sand 2 40/70 and fine Sand 3 60/100 sand into the same 2-mm wide fracture, under slightly higher flow rates and initial volumetric concentration than the coarse sand. The corresponding Res for Sand 2 and 3 are shown in Table 1. According to the sediment transport indices, both sands would need turbulent motion of the fluid to be transported into the fracture. What is observed in experiments is that the dune spread increases significantly as the Res decreases, which is expected, but the significant degree of segregation is also present. For Res smaller than 2, the sediment transport is pseudo-homogeneous. The case of Sand 2 in glycerol-water fluid would fit into this category, but the observed experimental results only partially agree. Fig. 6 shows that slurry falls vertically down from the injection point, and then some portion of the slurry gets carried away from the injection point. It is evident that the dune is most spread in the case of Sand 2 in higher viscosity fluid, but the suspension can't be characterized as pseudo-homogeneous in a narrow fracture. If the Rouse# is evaluated towards the experimental data, it can be seen that in all cases particles are expected to either be suspended in a fluid or slurry behaves as a wash load. However, it can be seen in Figs. 3 to 6, that slurry exhibit predominately settling motions after being injected into the fracture, with a certain degree of re-suspension and partial wash load characteristics after the injection point becomes closer to the rising dune, increasing the horizontal velocity in a smaller available fracture height in Fig. 6.



(a) t = 15s (b) t = 45s (c) t = 75s

Figure 3: Experimental analyses for Sand 1 20/40 mesh in water, 2-mm fracture aperture and 37% of volumetric sand concentration (*d* = 0.6 mm, µ = 0.001 Pa·s, *q* = 33 ml/s, c_v = 37%).

Figs. 7, 8 and 9 show the development of dune, characterizing the dune angle with distance from the injection point. In all the experimental cases the injection point was in the middle of the bi-wing fracture. The dune is generally symmetric in all the cases, so only one side is shown in the graphs. The dune form is however different for three different sands injected in a water slurry. Injection of coarse sand produced very steep triangle dune without further transport of particles except for some minor rolling down the dune. When the average sand particle size decreases, as well as Re_s, dune spreads out in a different geometry. For the medium sand, the dune has S shape and significant resuspension and upslope motion of particles occurs. For the fine sand, particles are transported further in a fracture in a horizontal direction suspended over the bed, and form very mild almost horizontal slope.



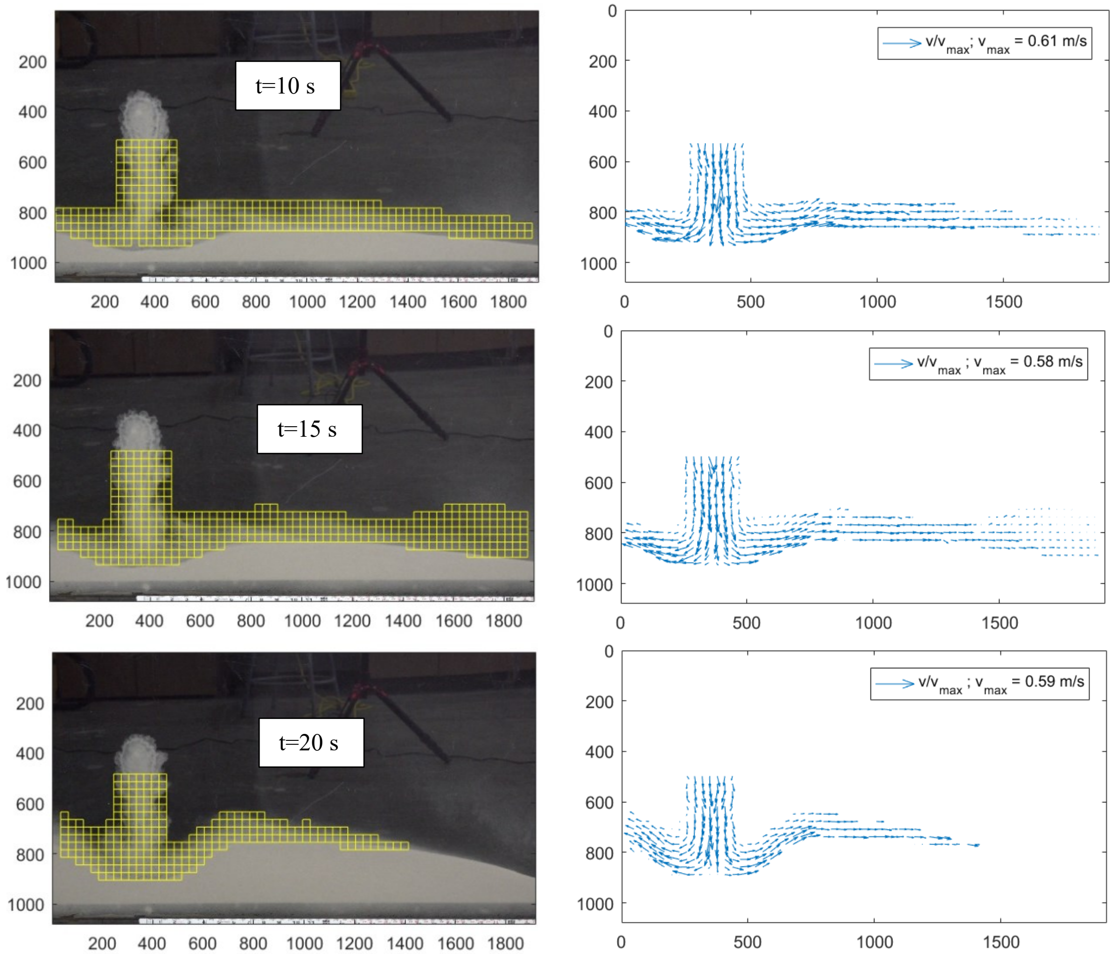
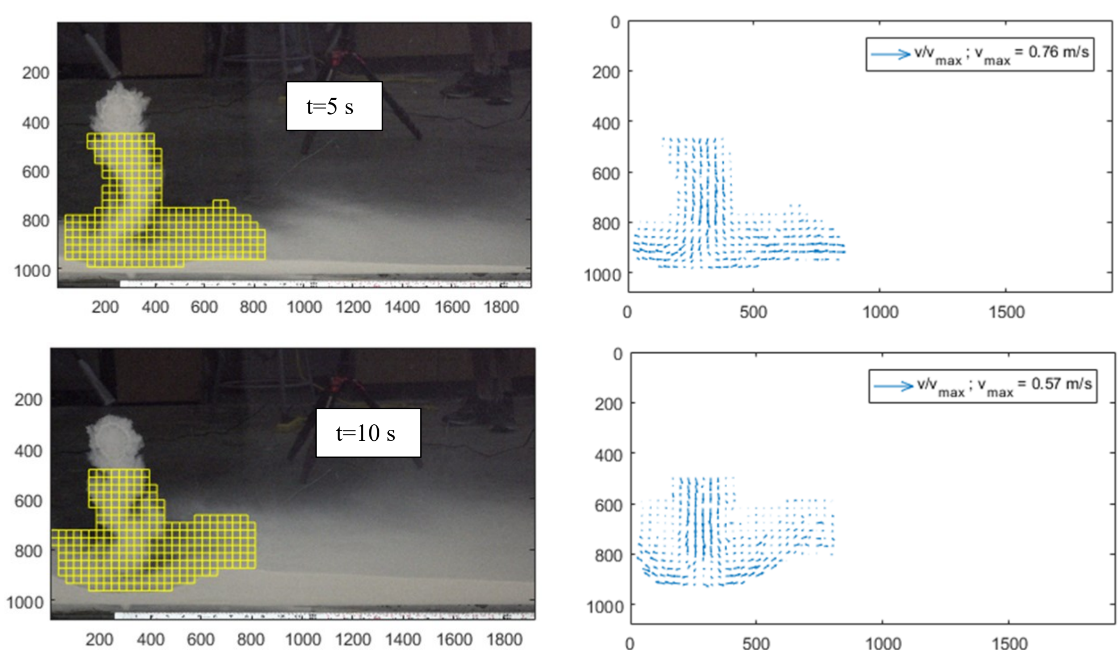


Figure 4: Experimental analyses for Sand 2 40/70 mesh in water, 2mm fracture aperture and 59 % of volumetric sand concentration (d = 0.3 mm, μ = 0.001 Pa·s, q = 80 ml/s, c_v = 59 %).



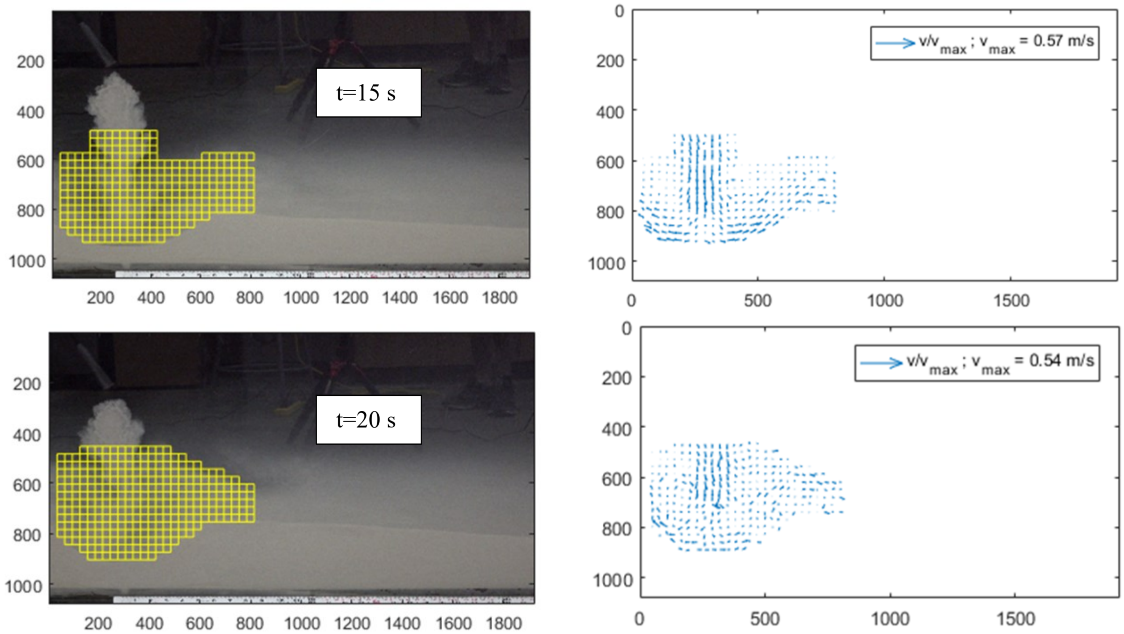
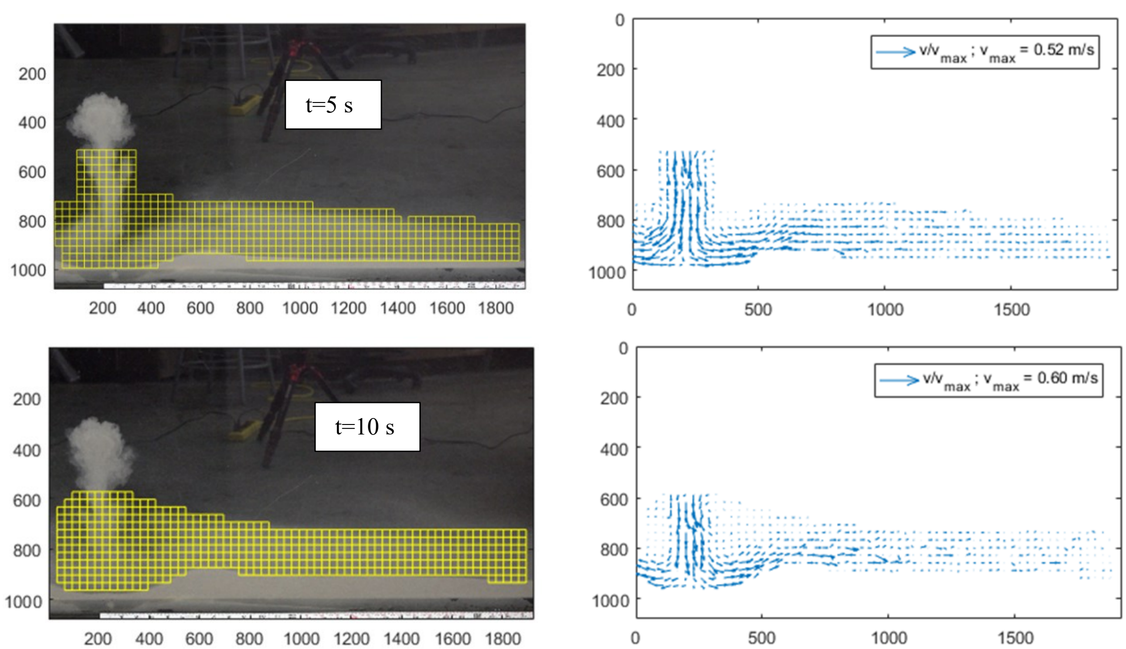


Figure 5: Experimental analyses for Sand 3 60/100 mesh in water, 2mm fracture aperture and 59 % of volumetric sand concentration (*d* = 0.2 mm, μ = 0.001 Pa·s, *q* = 80 ml/s, c_v = 59 %).



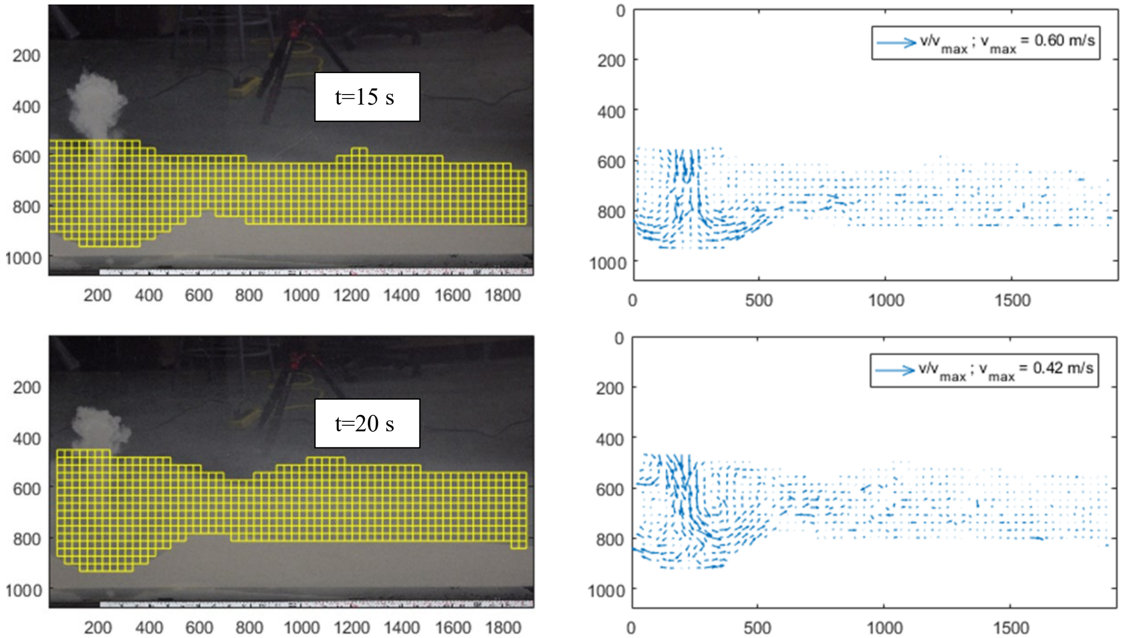


Figure 6: Experimental analyses for Sand 2 40/70 mesh in water-glycerol mixture, 2mm fracture aperture and 59 % of volumetric sand concentration (d = 0.2 mm, μ = 0.005 Pa·s, q = 80 ml/s, c_v = 59 %).

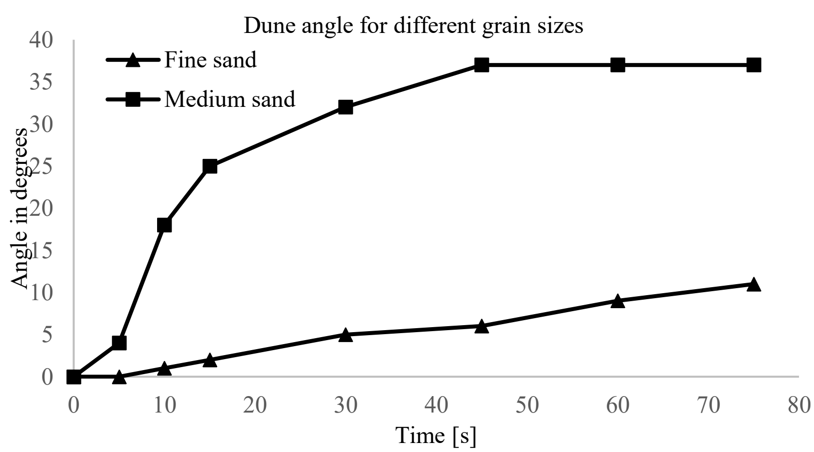


Figure 7: Dune angle at different injection periods for fine and medium sand.

Figure 8: Dune angle at different injection periods for Sand 2 40/70 mesh in water, 2mm fracture aperture and 59 % of volumetric sand concentration.

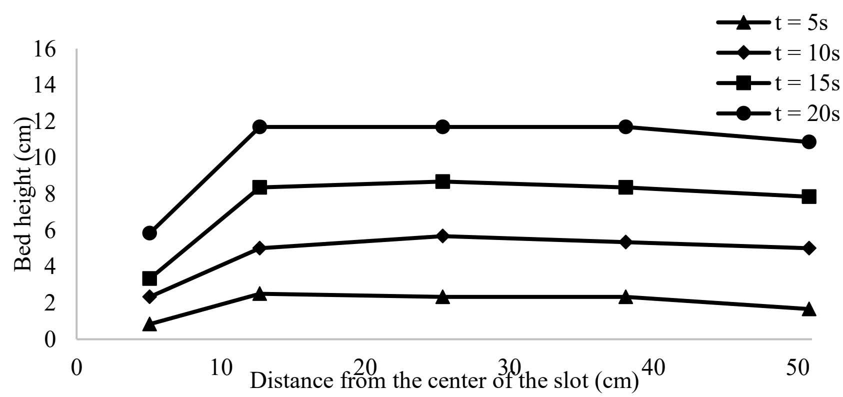


Figure 9: Dune angle at different injection periods for Sand 3 60/100 mesh in water, 2mm fracture aperture and 59 % of volumetric sand concentration (d = 0.2 mm, μ = 0.001 Pa·s, q = 80 ml/s, c_v = 59 %).

2. CONCLUSIONS

This paper presents experimental results of proppant injection in a 2-mm narrow fracture formed of aluminum and acrylic walls. The fracture is approximately 70 cm high and 150 cm wide. The injection point is located in the middle of the length and height, to model a small bi-wing fracture. Coarse, medium and fine sand are used to form a high-density slurry with water and water-glycerol mix. Flow and transport of the slurry in a fracture was recorded and videos were analyzed using GeoPIV particle image velocimetry method. Basic indices, which are typically used for evaluation of sediment transport in wider spaces like rivers and lakes, are calculated. The goal of this research is to evaluate validity of standard sediment transport indices for dense slurries flow and transport in narrow fractures. The results show only partial agreement, which means that the general trends were met, but the quantitative agreement was not achieved. Particularly, the smaller the sand average grains are, as well as, the higher the fluid dynamic viscosity, more transport is achieved down the fracture length accompanied with the less steep dune. More slurry suspension was also observed with smaller particle sizes and higher fluid velocities. Particle Reynolds numbers characterize the modeled flow experiments as settling or quasi-homogeneous flowing slurries, which was also observed in experiments. Rouse numbers indicate that complete slurry will bee transported as a wash load, which was only partially observed for fine sand and medium sand in glycerol-water mixture. Both used indices do not incorporate injected concentration of particles, particle-particle interactions, or the effect of narrow fracture walls with particle-wall interaction forces.

ACKNOWLEDGEMENT

Financial support provided by the U.S. National Science Foundation, Division of Civil, Mechanical and Manufacturing Innovation under grant NSF CMMI 1563614 is gratefully acknowledged. The opinions expressed in this paper are those of the authors and not the NSF. We would like to acknowledge contributions of undergraduate students Kasey Lee, Tobin K Lee, Arthur Ferreria dos Santos Netto, Andre Niquini and Thomas Hum and graduate students Natalia Syulyukina and Daniel Fjaestad who helped in preparing and executing laboratory experiments.

REFERENCES

Barree R.D., and Conway M.W.: Experimental and Numerical Modeling of Convective Proppant Transport (includes associated papers 31036 and 31068), *J Pet Technol,* **47**, (1995), 216–22.

Crowe C., Schwarzkopf J., Sommerfeld M., Tsuji Y.: Multiphase flows with droplets and particles, (2011).

Daneshy A.A.: Numerical solution of sand transport in hydraulic fracturing, *J Pet Technol*, 30, (1978), 132–40.

Economides M.J., Nolte K.G., and Ahmed U.: Reservoir stimulation, Wiley, (2000).

Goel N, and Shah S.: A Rheological Criterion for Fracturing Fluids to Transport Proppant during a Stimulation Treatment. *Pap SPE* (2001), 71663.

Goel N., Shah S.N., and Grady B.P.: Correlating viscoelastic measurements of fracturing fluid to particles suspension and solids transport, *J Pet Sci Eng*, **35**, (2002), 59–81.

Luo L., Tomac I.: Particle Image Velocimetry (PIV) Analysis of Particle Settling in Narrow Fracture Experiments, *Geotech Test J* , **41**, (2018), 20170136. doi:10.1520/GTJ20170136.

Luo L., Tomac I.: Experimental Investigation of Particle Agglomeration Effects on Slurry Settling in Viscous Fluid, *Transp Porous Media*, (2017), 1-20.

Luo L., Tomac I.: Particle image velocimetry analysis of proppant settling in a narrow slot, *50th US Rock Mech. / Geomech. Symp*., **vol. 4**, (2016).

Novotny E.J., Proppant transport, SPE *Annual Fall Technical Conference and Exhibition*, ***SPE-6813-MS,*** (1977).

Patankar N.A., Joseph D.D., Wang J., Barree R.D., Conway M., and Asadi M.: Power law correlations for sediment transport in pressure driven channel flows. *Int J Multiph Flow*, **28**, (2002),1269–92.

Shah S.: Proppant settling correlations for non-Newtonian fluids under static and dynamic conditions. *Old SPE J*, 22, (1982), 164–70.

Sharma M., and Gadde P.: The Impact of Proppant Retardation on Propped Fracture Lengths, *SPE Annual Technical Conference and Exhibition*, **SPE-97106-MS**, 2005.

Sievert J., Wahl H., Clark P., and Harkin M.: Prop Transport in a Large Vertical Model, *SPE/DOE Paper*, **9865**, (1981)

Take W.: Thirty-Sixth Canadian Geotechnical Colloquium: Advances in visualization of geotechnical processes through digital image correlation 1, *Can Geotech J*, **52**, (2015), 1199-1220.

Tomac I., Luo L.: Experimental study of proppant particle-particle interaction micromechanics during flow and transport in the fracture, *Energy Geotech. - Proc. 1st Int. Conf. Energy Geotech. ICEGT 2016*, (2016).

White D., and Take W.: GeoPIV: Particle Image Velocimetry (PIV) software for use in geotechnical testing, *Technical Report CUED/D-SOILS/TR322*, (2002), 1 - 15.