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PARTICLE SWARMS IN VARIABLE APERTURE FRACTURES

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Abstract. Experiments were performed to determine the effect of a rough walled fracture on the evolution and maintenance of particle swarms, i.e. coherent collections of colloidal size particles. Of particular interest is the response of a swarm to sudden changes in confinement and drag caused by variations in fracture aperture. Two different rough fracture geometries were used and are compared to smooth-walled converging and diverging synthetic fractures. The variation in aperture along a swarms transport path exerted a strong influence swarm evolution and, in many cases, enhanced swarm stability and velocity. Converging apertures tend to decelerate a swarm because of increasing confinement and drag from the fracture surfaces, while diverging apertures resulted in the acceleration of a swarm. As long as an unrestricted flow path exists, swarms will maintain their cohesion, even if a fracture contains obstacles to swarm flow (asperities). However, if the aperture of the flow path is too small, swarms will bifurcate around an obstacle and produce smaller sub-swarms that will continue on separate paths.

1. Introduction. The transport of nano- and micro-scale particles through subsurface rock formations and fluids results from a variety of natural and industrial processes. Particles may be deliberately introduced (sensors, sequestration, proppants, etc.) into the subsurface or accidentally through unintended pathways (manufacturing and farming runoff, industrial contaminants, mine tailings, etc.). Particle swarms can occur when small liquid drops containing thousands to millions of nano- to micron-size particles are released over time from leaks or seepages into fractured rock.

Studies have shown that particle swarm behavior differs from that for a single particle. A swarm consists typically of a dilute suspension ($0.4 - 4\%$ by weight) of nano or micro-meter size particles. A swarm falls under gravity in an unconfined fluid with a velocity faster than the settling speed of any individual particle in the swarm [1, 5, 3, 2]. This enables more rapid transport of particles than if the particles were released as a dispersion. From previous research, Adachi et al. [1] showed numerically and experimentally that the formation of a swarm was robust against the viscosity and density of the fluids and the particle size. Adachi et al.[1] found experimentally that a swarm forms when the swarm velocity is more than 16 times larger than the settling velocity of an individual particle. Roughly, the length scale that controls swarming is the particle size.

Other studies have examined theoretically, computationally and experimentally the formation of swarms[4, 1, 5, 3] leading to modified forms of discrete particle approaches. These studies have shown that swarms evolve as they fall. Swarm break-up occurs as particles leak-off the swarm, and the rate of leakage depends on the swarm shape[4]. All of these previous studies have examined the formation and evolution of swarms[4, 1, 5, 3] in quiescent fluids in beakers, water-cylinders, water-tanks, etc., i.e. in unconfined fluids.

Recently, [2] examined, experimentally, the effect of fracture aperture on the maintenance of swarms, i.e. how does a swarm evolve in a constrained geometry. They released swarms in uniform aperture fractures composed of 4 m in diameter glass beads. They observed that there is a range of optimal fracture aperture to swarm diameter ratio, B, (B = 1 to 10) which suppresses bifurcation or breakdown of a swarm. This suppression is attributed to forces from the walls that keep the swarm from expanding and help maintain the swarms mass distribution. Below this optimal range, drag forces from the wall dominate and constrain the expansion of the swarm to one direction. An ellipsoidal torus results in a mass distribution that leads to bifurcations. Above the optimal range, the swarm is not confined by the fracture walls and is free to expand uniformly in all directions. This leads to multiple bifurcations after the swarm has fallen only a short distance.

In this study, we examine, experimentally, the transport of particles swarms in fluid-filled fractures with variable apertures. We find that swarm velocity varies as apertures converge and diverge along the transport path through a fracture.

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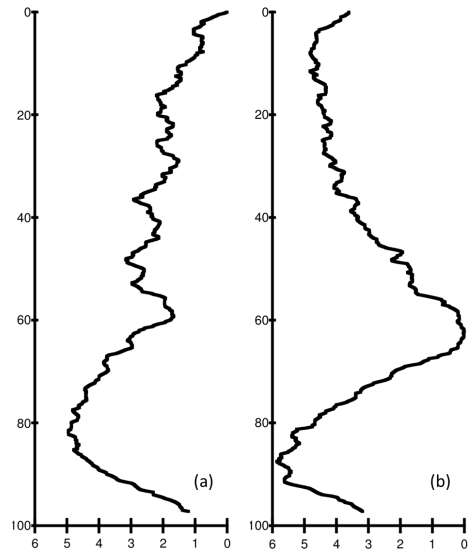

FIG. 1. *Diagrams of (a) Fracture 1 and (b) Fracture 2 highlighting the differences in asperity variation along the swarms path. The smooth wall is represented by the vertical axis.*

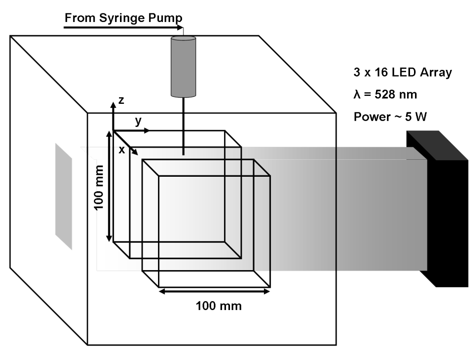

FIG. 2. *A sketch of the experimental setup.*

2. Experimental Methods. To simulate a rough fracture, acrylic casts were made of an induced fracture in Austin Chalk. Two fractures were created from the acrylic casts. Fracture 1 consisted of one fracture surface paired with a smooth block of Lucite of equal dimensions, i.e. the fracture consisted of one rough wall and one smooth wall (Fig. 1a). Fracture 2 was composed of the other fracture surface and a smooth block of acrylic (Fig. 1b). The blocks (one rough and one smooth) were mounted on an optical rail to control the distance between the surfaces and hence control the aperture. Both blocks were then submerged in water until the top faces were 5 cm below the surface (Fig. 2) to minimize the influence of evaporative convection cells on the swarms behavior.

In addition to the rough fractures, two smooth-walled variable aperture fractures were also used. Both fractures were constructed out of two acrylic blocks of Lucite with smooth walls that were mounted in the same experimental setup as the rough walled fracture. These fractures were termed converging (Fig. 3a) and diverging (Fig. 3b). A range of fracture apertures were investigated. Here aperture is defined as the separation between the parallel portions of the fracture i.e. the minimum separation distance.

Laser profilometry was used to characterize the surface roughness of each fracture. The profilometry system consists of (1) a fixed laser to measure the height of a surface, (2) a sample holder

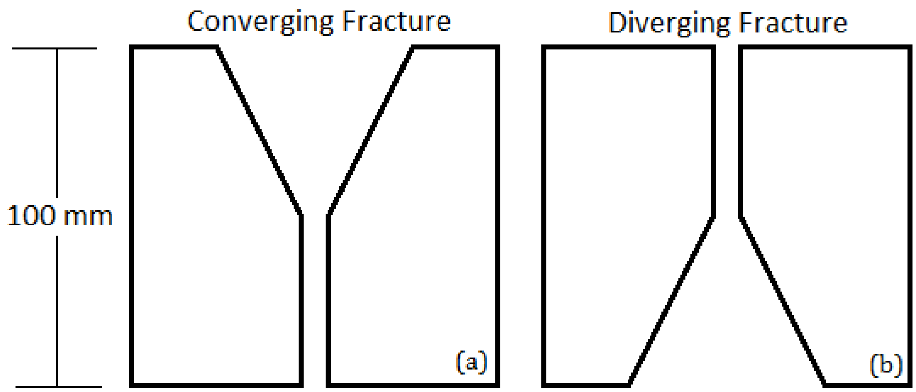

FIG. 3. *Diagrams of the (a) converging and (b) diverging aperture fractures. Aperture is defined as the distance between the parallel regions*

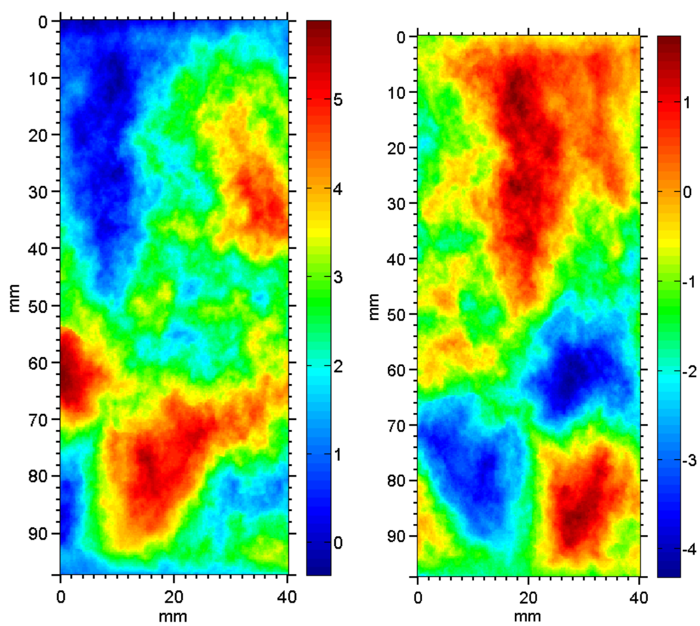

FIG. 4. *Asperity contour maps of the two fracture surfaces used in the experiments obtained using laser profilometry. The image on the left is Fracture 1, the right is Fracture 2. The color bar represents asperity height in millimeters.*

mounted on a movable platform, and (3) custom Labview code that collects the data from the laser and controls the motion of the sample holder. This setup is able to measure height variations up to 9.969 mm in increments of 0.5 m. The laser beam has a circular profile with a diameter of 120 m.

Fractures 1 and 2 were profiled using this technique. Roughness measurements were taken over the entire fracture surface in 0.25 mm increments along two orthogonal axes. Color contour maps based on the surface roughness measurements are shown in Fig. 4a. The black vertical lines (20 mm in Fracture 1, 28 mm in Fracture 2) represent the location of the scan line shown in Fig. 1. Additionally, this line indicates the path that a swarm would take if the fracture were not rough based on the swarms release point.

Swarms were composed of fluorescent polystyrene beads (3m in diameter) in a 1% solution by mass with water. Swarms (5L volume) were delivered into the fracture via a pump-driven

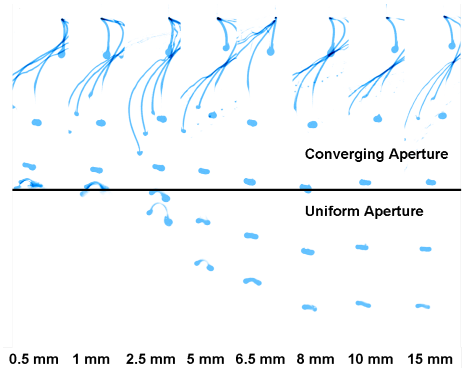

FIG. 5. *Composite image showing how swarms travelled through various apertures in a converging fracture. The horizontal line marks the transition between the converging to the uniform aperture regions.*

hypodermic needle. The tip of the needle was placed 5 mm below the top face of the blocks to eliminate any transition from unconfined fluid to fracture confined fluid. Released swarms fell under gravity and were imaged at 5 frames per second using a CCD camera.

2.1. Results. Particle swarms respond differently to converging and diverging apertures. In a converging fracture (Fig. 3a), the swarm is released in the portion of the fracture with the largest apertures. The initial evolution of a swarm occurred mainly in this unconfined region, i.e. apertures greater than 10 mm. As the blocks were moved apart or closer together, the swarm behavior in the converging portion of the fracture was very similar for all apertures (Fig. 5). Upon reaching the confined parallel region, swarms in large apertures ($>$ 5 mm) were mostly unchanged and unaffected by the walls (Fig. 5, Fig. 7), recreating the open tank swarm behavior. This is in sharp contrast to swarms evolving in uniform aperture fractures where the presence of parallel walls greatly impacted swarm evolution [2]. However, in small fracture apertures (aperture ¡ swarm diameter), once the swarm reached the confining portion of the fracture, it would bifurcate and transport was halted (Fig. 5, Fig. 7). The swarms would not enter the parallel portion of the fracture. When the swarm diameter was nearly equal to the aperture (2.5 mm aperture, Fig. 5) swarms would enter the parallel region but with a reduced speed.

In a diverging fracture (Fig. 3b), swarms were initially confined by the uniform aperture portion of the fracture. Swarms in the parallel portion of the fracture followed the usual pattern of evolution, beginning as a sphere and evolving into a torus (Fig. 6a). However, upon entering the diverging portion of the fracture, a swarm would rotate rather than bifurcate (Fig. 6b). The torus that normally destabilizes and bifurcates (see Fig. 5) instead expanded perpendicular to the fracture plane (Fig. 6c). This sudden shift in geometry coincided with an increase in swarm velocity (Fig. 7). The rough fracture samples were used to determine the effect of a variable fracture aperture on swarm evolution. From the experiments on converging and diverging apertures, swarms were observed to decelerate or accelerate, respectively, in response to changes in apertures. Our goal was to determine if swarm velocity would vary along a variable aperture fracture.

Because of the variable aperture, Fractures 1 and 2 contained asperity peaks (i.e., like mountain ridges) and troughs (i.e. like valleys) that affected swarm behavior in different ways. Upon reaching an asperity peak, a swarm would either avoid it and continue with an altered transport path (Fig. 8a, depth 70 mm) or it would bifurcate around the peak and decelerate (Fig. 8b, see depth 70 mm).

The behavior of swarms in Fracture 1 was not strongly controlled by the roughness of the fracture. While swarm velocity did vary with position (Fig. 9), there does not appear to be a strong correlation between fracture features and swarm velocity. The exception to this is the deceleration that occurs as a swarm approached the asperity maxima centered on a depth of 75 mm. Swarms that approached this fracture feature would begin to decelerate. This deceleration began at depths of 55 mm and continued until the swarm passed the obstruction, i.e. the deceleration would occur

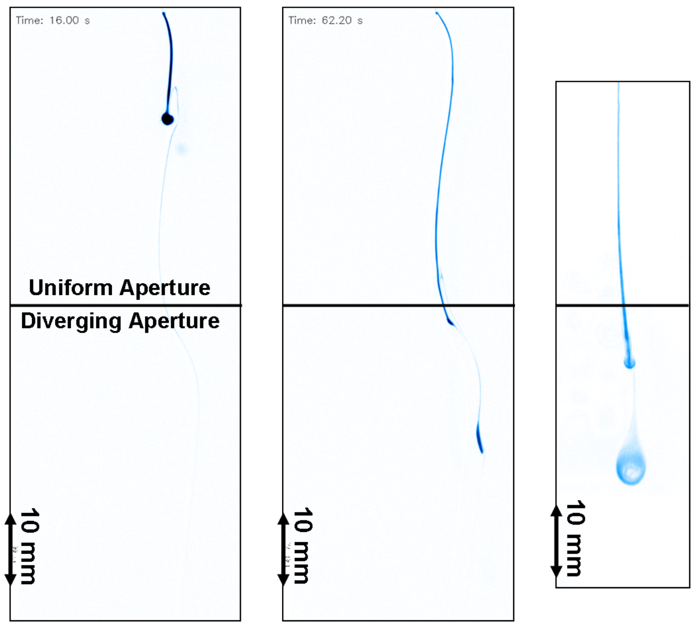

FIG. 6. *Swarms in the diverging fracture would begin (a) as a normal sphere/torus but (b) upon reaching the diverging portion of the fracture would rotate (b). A side view of b is shown in (c). The horizontal line marks the transition from a uniform aperture to a diverging aperture region.*

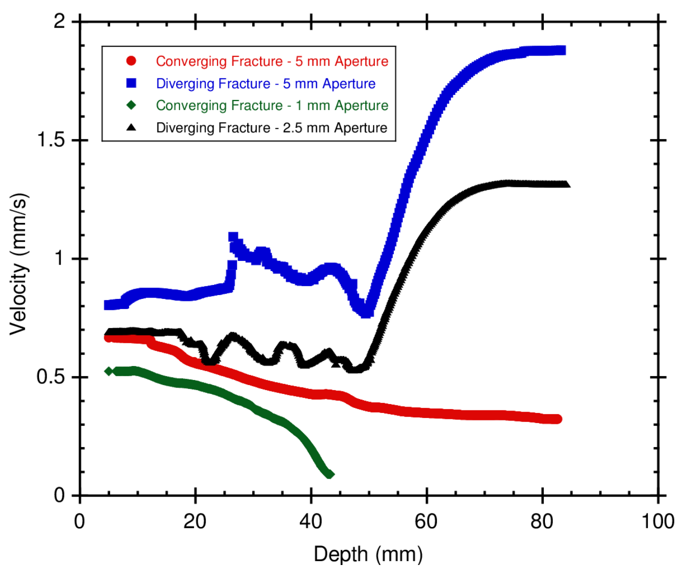

FIG. 7. *Swarm velocity vs. depth in the converging and diverging fractures.*

prior to reaching the obstacle.

In Fracture 2, swarm behavior was strongly controlled by variations in asperity height (Fig. 10). Swarms would experience regions of accelerations and decelerations that were consistent across all tested apertures. These variations can be linked to certain fracture features. Swarm accelerations beginning at depths of 30 mm correlate to a large decrease in asperity height. The swarm decelerations beginning at depths of 55 mm correspond to the large increase in asperity that occurs at the same depth. The final acceleration beginning at depths of 70 mm is caused by swarms avoiding the

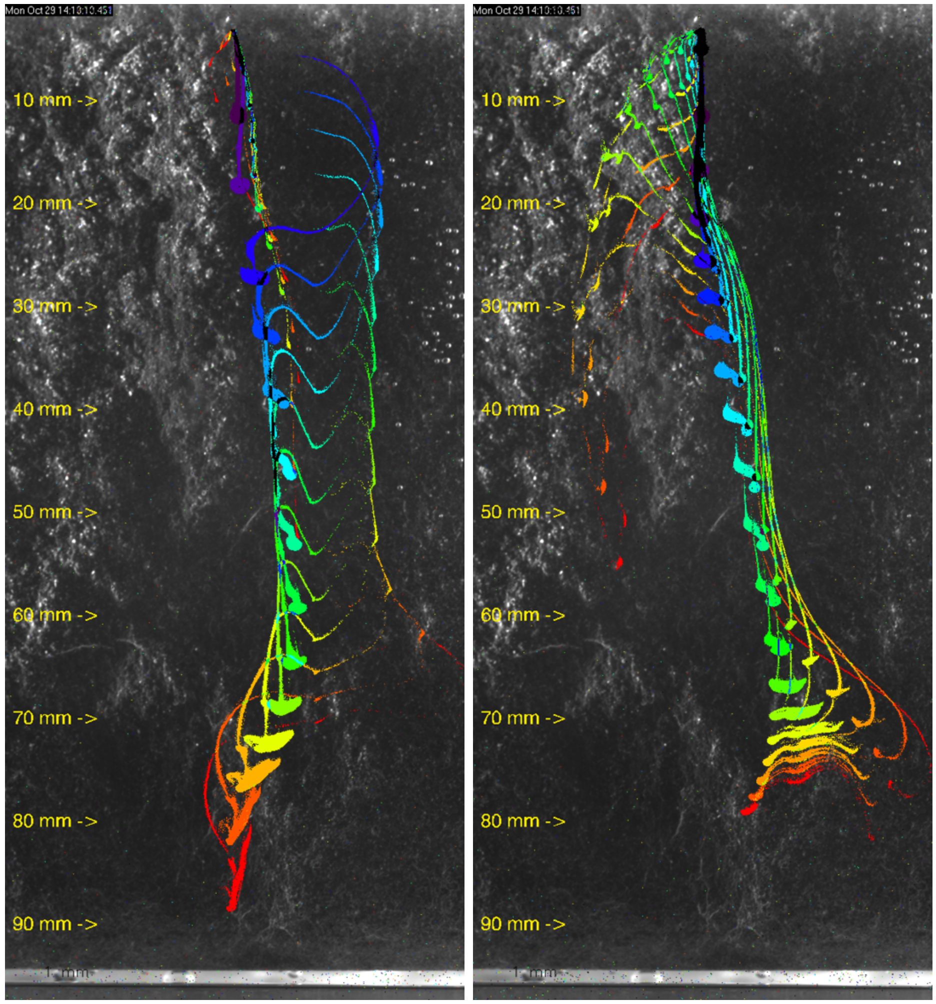

Fig. 8. *Composite image showing how swarms travel through a rough fracture. Each Step (represented by differing color) is 18 seconds apart. Fracture 2 was used with a 1 mm aperture.*

large asperity maximum (80 mm depth) as shown in Fig. 8a.

Unlike Fracture 1, the locations of these accelerations and decelerations are consistent across the fracture apertures. Swarms decelerate through confined regions as observed for uniform fractures with small apertures [2] (Boomsma & Pyrak-Nolte, 2012). Swarms accelerate in unconfined regions (similar to that observed for the diverging fracture, Fig. 7) and decelerate as they approach asperity peaks. Most swarms avoided the asperity peak and changed from a horizontally oriented shape to one that is vertically oriented (Fig. 8a, Fig. 6b), i.e. similar to the rotation observed for swarms in the diverging aperture fracture. This change in swarm geometry and the resulting unconstrained vertical path resulted in the accelerations that are seen in Fig. 10 at depths of 70 mm.

In both rough fractures, the influence of the walls decreased with increasing fracture apertures. i.e. behaved as if released in an open tank. At larger apertures, swarms always had an unrestricted flow path because the swarms were able to travel over fracture features as well. Variations in asperity height influenced swarm behavior less at large apertures than small apertures.

Both Fracture 1 and Fracture 2 had large asperity peaks at depths of 80 mm. However, swarm responses to these peaks were quite different. There were two distinct swarm responses to asperity peaks along their path of travel, avoidance (Fig. 8a) and bifurcation (Fig. 8b). Though

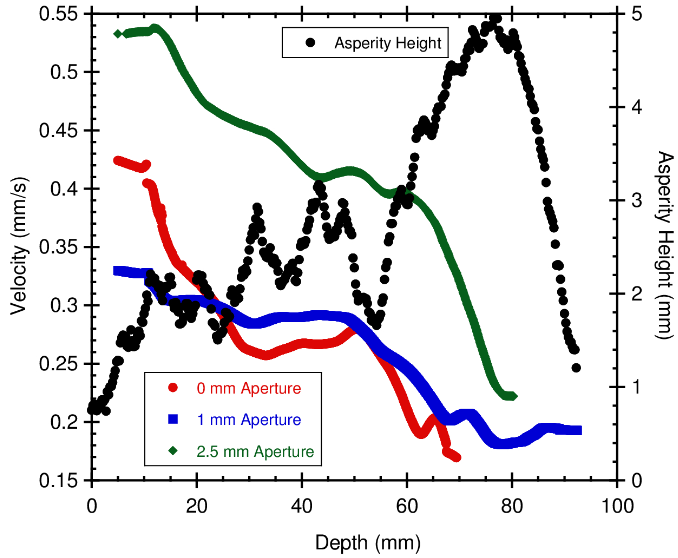

FIG. 9. *Swarm velocity vs. depth for various apertures in Fracture 1. The average asperity height as a function of depth is also shown.*

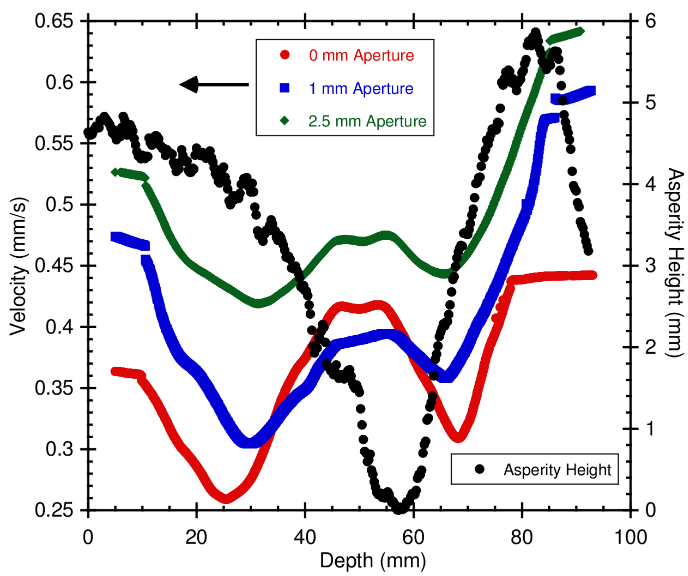

FIG. 10. *Swarm velocity vs. depth for various apertures in Fracture 2. Average asperity height as a function of depth is also shown.*

both responses were observed to occur in both fractures, bifurcation was more prevalent in Fracture 1 while avoidance was more frequent in Fracture 2. This is primarily related to the relative sizes of these peaks. The peak in Fracture 1 is approximately twice the size of the corresponding peak in Fracture 2 (Fig. 4a).

The asperity peaks in Fractures 1 & 2 resulted in narrow fracture apertures much like in the converging fracture. However, unlike the converging fracture, the narrowing of Fractures 1 & 2 was not uniform across the entire fracture. This enabled swarms to avoid the asperity peaks (Fig. 4a). In Fracture 1 the horizontal size of the asperity peak is quite large ($\sim$ 30 mm), extending nearly the entire width of the pictured portion of the fracture (Fig. 4a). While certain portions of the peak are lower than others, in general swarms are unlikely to avoid this peak and have a high probability of bifurcating. The asperity peak in Fracture 2 is much smaller (~ 18 mm, Fig. 4b). As a result swarms in Fracture 2 were able to avoid the asperity peak more readily.

It should be noted that in all of the investigated fractures, swarms traveled much faster than the settling velocity for disperse or isolated particles. The Stokes law settling velocity for the beads used in our experiments is 2.4×10^{-4} mm/s. Swarms traveled at least 1000x faster than a single particle, except in the cases where swarms were approaching asperity peaks. This highlights the great advantage that swarms have over dispersed delivery methods.

3. Conclusion. Swarm evolution is affected by the fracture aperture topology. In a converging aperture, swarms are not strongly influenced by the fracture because the swarms are released in fracture apertures above the optimal range observed by [2] Boomsma & Pyrak-Nolte (2012). Swarms in the converging region are evolving under similar conditions (i.e. mostly unconfined) across all fracture apertures. Furthermore, by the time a swarm reaches the uniform aperture regime it has already become slightly unstable and is in the preliminary stages of bifurcation.

In the diverging fracture, the sudden decrease in the level of confinement led to swarms changing their shapes and accelerating. At very small fracture apertures ($B < 1$), swarms that had already bifurcated in the uniform portion of the fracture would re-form into the long skinny swarms shown in Fig. 6b. This enabled the swarms to regain their cohesion and enhanced their transport.

For swarms in the variable aperture rough fractures, a swarms response to obstructions was very similar to their responses to a converging aperture. A swarm that approaches a region where the aperture perpendicular to the fracture plane is constrained (asperity peaks or aperture minimum) decelerates greatly and begins to bifurcate. However, unlike in the converging fracture where the constraint is uniform along the entire fracture plane, in a rough fracture the constraint is non-uniform and there is often an open or large aperture path that swarms are able to follow. Rather than completely halting their descent as in the converging fracture (Fig. 5) swarms were instead able to bifurcate around the obstruction and continue (Fig. 8b). In the case of Fracture 2, the obstruction was small enough that swarms did not need to bifurcate in order to avoid it and changed their shape, elongating and accelerating (Fig. 8a).

Swarms in rough fracture 2 tended to change shape and accelerate when they entered an open portion of the fracture. This is similar to the behavior seen in the diverging fracture. There are likely two effects occurring. One is the natural tendency of a swarm to change shape when encountering a decreasing level of confinement as seen in the diverging fracture (Fig. 6). The other is the rough fractures non-uniform confinement along the fracture plane. Asperity peaks will impact swarm evolution even when the swarm is not directly approaching them and this influence is capable of causing a change in shape.

The degree to which swarms respond to a rough fracture depends on the specific distribution of the fracture asperities. Paradoxically, the relatively stable confinement observed for Fracture 1 influenced swarm motion in an inconsistent manner, while the highly varied confinement seen in Fracture 2 resulted in far more predictable influences. The relatively subtle influence of Fracture 1 was overwhelmed by the variations between individual swarms.

Depending on the morphology, rough fractures either enhance or limit swarm stability. As long as an unrestricted flow path exists, swarms will maintain their cohesion, even if a fracture contains obstacles to swarm flow (asperity peaks). However, if the aperture of the flow path is too small, swarms will bifurcate around an obstacle and the resulting smaller sub-swarms will continue on separate paths. This has important implications for the use of swarms as delivery methods for targeting locations in fractured rocks. Swarms are robust and will maintain cohesion for as long as a sufficient flow path exists.

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REFERENCES

[1] S. Kiriyama Adachi, K. and N. Yoshioka, *The behavior of a swarm of particles moving in a viscous fluid*, Chem. Eng. Sci., 33 (1978), pp. 115–121.

[2] E. Boomsma and L.J. Pyrak-Nolte, *Particle swarms in confining fractures*, in In Proceedings of the 46th US Rock Mechanics/Geomechanics Symposium, vol. 12-350.

[3] L. Kleiser Bosse, T. and C. Hartel, *Numerical simulation of finite reynolds number suspension drops settling under gravity.*, Phys. of Fluids, 17:037101 (2005).

[4] M. Nicolas Metzger, B. and E. Guazzelli, *Falling clouds of particles in viscous fluids*, J. Fluid Mech., 580 (2007), pp. 283–301.

[5] J.M. Nitsche and G.K. Batchelor, *Break-up of a falling drop containing dispersed particles*, J. Fluid Mech., 340 (1997), pp. 161–175.