Supplemental Material for

Capillary fracturing in granular media

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Experimental procedure

We begin the experiments by pouring a known volume V of glass beads with mean diameter d into a cylindrical acrylic cell of internal diameter L. Bead size distributions for several of the bead packs are shown in Fig. 1 below. To distribute the beads uniformly across the cell and homogenize the packing, we vibrate the cell by tapping on it in the horizontal direction in two rounds: first with no confinement, and then after placing an acrylic disk (the "lid" in Fig. 1, weighing 0.3 kg) on top of the beads. After tapping, the bed is a few layers thick with approximate thickness $b = V/(\pi L^2/4)$.
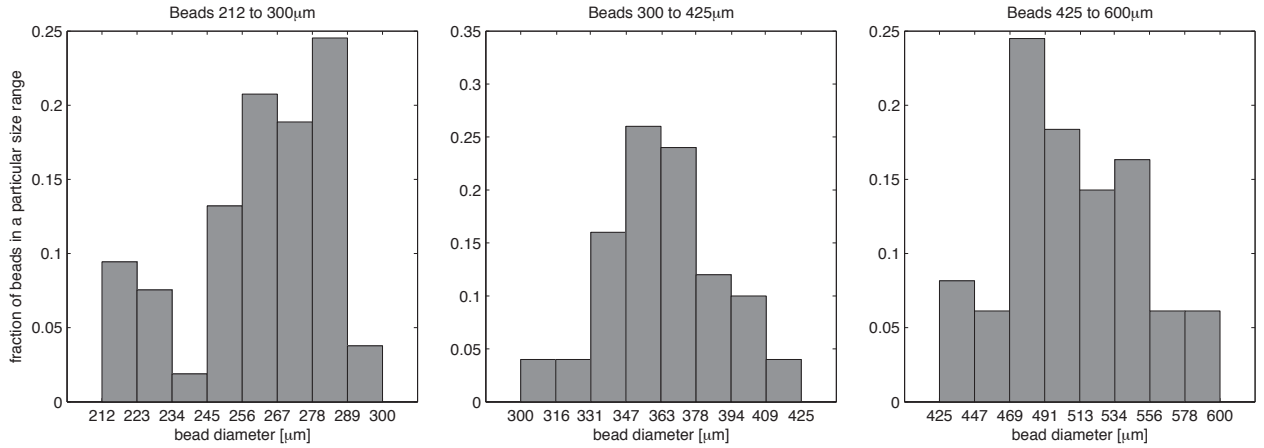

FIG. 1. Bead size distributions for three of the bead packs.

To saturate the bed, we place weights (18.5 kg total mass including the lid) on top of the lid and then inject water at a constant rate into the center of the cell. The injection occurs through a mesh-covered hole in the bottom of the cell, which is 1.6 mm in diameter (Fig. 2 below). The hole is connected to a fixed length of Tygon PVC tubing, 1.6 mm inner diameter, via a brass tube fitting, 1.2 mm inner diameter. One end of the fitting is machined to fit snugly inside the hole in the cell, and the opposite end is barbed to hold the tubing. The tubing is connected to a syringe loaded in a syringe pump. Using the pump, we inject water at a sufficiently high rate to avoid trapping of air, but at a sufficiently low rate to avoid displacing the beads. After the bed is saturated, we load the desired weight w onto the lid and inject air at a constant rate q. The initial volume of air in the tubing and the syringe is the same in all experiments. To observe the invasion pattern, we illuminate the bottom of the cell with reflected light from LED panels and take images with a digital camera. The camera is a Canon EOS 60D (18 Megapixel; maximum frame rate of 60 fps), used with a 17-55 mm, f/2.8 lens.

Creating a mechanically and hydraulically homogeneous packing—with uniform distribution of interparticle forces and pore apertures—is an extremely difficult task. We evaluate the uniformity of injection and the homogeneity of permeability by observing the invasion front of the water during the initial stage to saturate the granular pack with the wetting fluid. The air-water front is a radially symmetric, circular invasion front as shown in Fig. 3 below, indicating that injection is uniform and the permeability is homogeneous. We assume that a bed that is hydraulically homogeneous is also mechanically homogeneous. We reject experiments for which the invasion pattern during water injection is not circular.

To investigate the reproducibility of our results, we perform repeatability experiments for most of the experimental conditions. For a given condition, the invasion patterns in the experiments differ in the details—since our packing procedure does not create a perfectly homogeneous or reproducible bed—but always fall in the same regime.
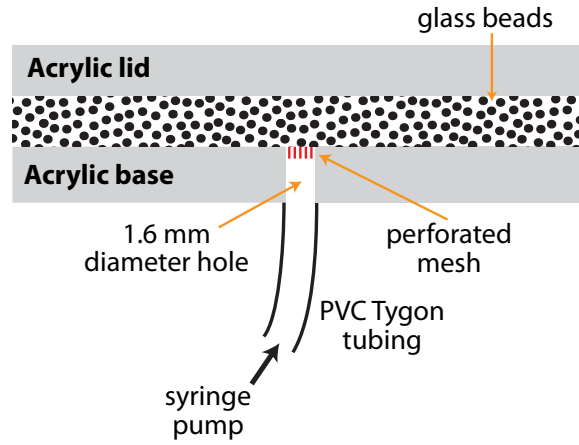
FIG. 2. Cross section of the experimental cell showing the port through which we inject fluid.
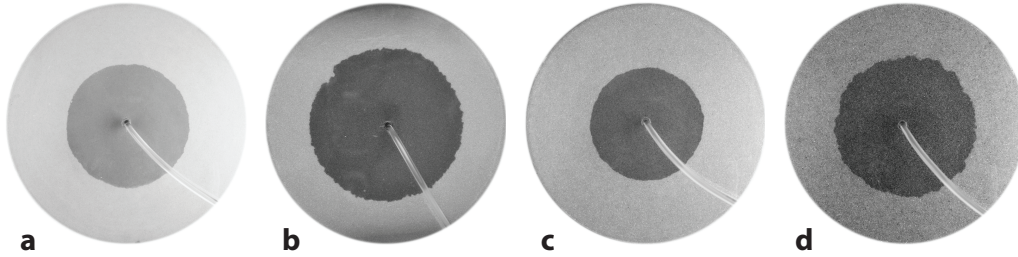

FIG. 3. Snapshots of the initial injection of water in four different experiments. The symmetry of the wetting front suggests packing homogeneity and uniform injection.

Invasion dynamics

The dynamics of the fluid-fluid displacement in the different invasion regimes are demonstrated by videos from sequences of images taken during air injection. Each image is obtained by subtracting the initial image prior to air invasion. Air shows as white, and water and beads show as black.

Video 1: Viscous fingering—continuous growth of the air invasion pattern at multiple locations simultaneously. The resulting pattern is radial and exhibits thin fingers and few trapped water clusters. The pattern appears more space-filling than in 2-D (for example a monolayer of beads) because of 3-D effects—water clusters that appear in the 2-D image to be trapped actually remain connected vertically (across layers), allowing interface growth within those regions. Experimental conditions: bead size d=360 μm, confining weight w=181 N, and injection rate q=100 mL/min. Video is in real time.

Video 2: Capillary fingering—intermittent propagation of the air-water interface, advancing at alternating locations. The final pattern is asymmetric, with thick, dense fingers and multiple trapped water clusters. As in viscous fingering, 3-D effects cause the pattern to appear more space-filling and with relatively less trapped water clusters than in 2-D media. Experimental conditions: d=360 μm, w=181 N, and q=0.1 mL/min. Video speedup of 72.

Video 3: Capillary fracturing—thin branches with long, straight segments. The pattern is asymmetric and exhibits low air saturation. Local particle displacements around the fractured region appear as a sparkly halo, due to changes in the reflected light. Experimental conditions: d=360 μm, w=3 N, and q=1 mL/min. Video speedup of 51.

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