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Capillary Fracturing in Granular Media

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We study the displacement of immiscible fluids in deformable, noncohesive granular media. Experimentally, we inject air into a thin bed of water-saturated glass beads and observe the invasion morphology. The control parameters are the injection rate, the bead size, and the confining stress. We identify three invasion regimes: capillary fingering, viscous fingering, and “capillary fracturing.” Where capillary forces overcome frictional resistance and induce the opening of conduits. We derive two dimensionless numbers that govern the transition among the different regimes: a modified capillary number and a fracturing number. The experiments and analysis predict the emergence of fracturing in fine-grained media under low confining stress, a phenomenon that likely plays a fundamental role in many natural processes such as primary oil migration, methane venting from lake sediments, and the formation of desiccation cracks.

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The invasion of one fluid into a porous medium filled with another fluid occurs in many natural and industrial processes. These processes include gas venting, hydrocarbon recovery, geologic CO₂ sequestration, and soil wetting and drying. Pore-scale disorder, hydrodynamic instabilities, and mechanical deformation of the pore geometry result in complex displacement patterns. Understanding the emergent patterns is both scientifically fascinating and technologically important [1].

Fluid-fluid displacements in rigid porous media have been studied in depth. While fundamental questions remain, previous studies have provided a basic understanding of the different displacement regimes, including compact displacement, capillary fingering, and viscous fingering, through laboratory experiments and computer simulations [2–11]. These regimes depend on the flow velocity, the degree of pore-scale disorder, and the interfacial tension and viscosity contrast between the fluids.

In a deformable medium such as a granular bed, fluid flow can displace the particles and affect the pore geometry, which in turn can affect the flow. This interplay between the displacements of the fluids and the particles leads to a variety of patterns, including desiccation cracks [12], granular fingers [13], labyrinth structures [14], stick-slip bubbles [15], open channels [16,17], and fractures [15,18–22].

While fracturing during gas invasion in liquid-saturated media has been observed in several experiments [15,18–22] and simulations [23], the underlying mechanisms and controlling parameters behind the morphodynamics of gas invasion in liquid-filled deformable granular media remain poorly understood. Holtzman and Juanes [24] developed a model that predicts the transitions among capillary fingering, viscous fingering, and fracturing. The authors used pore-scale simulations and scaling analysis to show that fracturing caused by elastic deformation of particles is the dominant mode of invasion for fine, soft particles under low confining stress. In this Letter, we study fracturing in a system of rigid particles. We show that frictional sliding, rather than elastic deformation, is the key mechanism controlling fracturing. We provide experimental evidence for three displacement regimes—capillary fingering, viscous fingering, and capillary fracturing—and derive two dimensionless groups that govern the transitions among these regimes.

We inject air into a thin bed of water-saturated glass beads packed in a cylindrical cell. We prepare each granular bed by pouring beads into the cell and then vibrating it to increase the packing homogeneity [25]. There are three control parameters: the mean particle diameter, \( d \), the air injection rate, \( q \), and the confining weight, \( w \). The confinement is applied by weights placed on a rigid disk that rests on top of the beads. To allow fluids (but not the particles) to leave the cell, the disk is made slightly smaller than the interior of the cell (inner diameter \( L \)).

The experiments exhibit three displacement regimes: viscous fingering, capillary fingering, and capillary fracturing. We identify the regimes based on the qualitative characteristics of the invasion pattern, as has been done previously [2,4,7,18,24]. In viscous fingering, the air-water interface grows continuously and at several locations simultaneously. The resulting pattern is radial and exhibits thin fingers and few trapped water clusters. The pattern appears more space-filling than in two-dimensional experiments.
Video 1 in the Supplemental Material [25]. In capillary fracturing, the patterns are typically not radially symmetric, as which in turn is controlled by the distribution of pore throat sizes, a function of the degree of pore-scale disorder [24]. For instance, for a uniform aperture distribution, $r \in [1 - \lambda, 1 + \lambda]$, we get $\chi(\lambda) = \lambda/(1 - \lambda^2)$.

The transition from viscous to capillary fingering occurs when $\delta p_v \sim \delta p_c$, and is therefore controlled by the following "modified capillary number," $Ca = \delta p_v/\delta p_c$:
We compare this force with the frictional resistance force, evaluated from the limiting value at sliding, $\Delta f_r \sim \mu f_{r,0} \sim \mu w(L/d)^2$, where $\mu$ is the coefficient of friction. The resulting force ratio is then

$$\frac{\Delta f_e}{\Delta f_r} = \frac{\lambda E^{2/3} L^{4/3}}{\mu w^{2/3}}.$$  

For our experimental system, with $E = 70$ GPa, $\mu = 0.3$ [30], $L = 0.2$ m, $\lambda = 0.75$, and $w = 3–181$ N, the elastic resistance is 5–6 orders of magnitude higher than frictional resistance, suggesting that pore opening occurs by overcoming friction. Elasticity would play an important role in fracturing only for much softer beads and much larger confining stresses.

We predict the emergence of fracturing through a dimensionless parameter we call the “fracturing number,” $N_f$, that measures the system deformability as the ratio of the pressure force that drives fracturing, $\Delta f_p$, and the resisting force, $\Delta f_r$. The driving force is the product of the local pressure difference at the front tip, $\Delta p$, and the area over which it acts, $\Delta p \sim d^2$. The pressure difference is the sum of the capillary pressure, $\gamma/d$, and the local viscous pressure drop, $\nabla p_v d \sim \eta u/d$. Thus, $\Delta f_p = \gamma d + \eta u d = \gamma d(1 + Ca)$, and

$$N_f = \frac{\gamma L^2}{\mu w d}(1 + Ca).$$  

This scaling suggests that, for a given fluid pair, particle material, and system size, the transition from fingering to fracturing occurs at $w \sim d^{-1}$. This is consistent with our observations [Fig. 3(b)]. While the scaling accounts for the effects of both the capillary pressure and the local viscous pressure drop, the capillary pressure is the dominant cause of fracturing in our experiments (with $\eta = 10^{-3}$ Pa s, $\gamma = 0.07$ N/m, $q \leq 100$ mL/min, and therefore $Ca \ll 1$). As a result, the observed transition does not depend on the flow rate [Fig. 3(c)].
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The scaling analyses allow us to collapse our data from a three-parameter dimensional phase space \((q, w, d)\) into a two-parameter dimensionless space \((Ca^*, N_f)\). For \(N_f \gtrsim 1\), fracturing is the dominant mode of invasion. For \(N_f \ll 1\), the medium is essentially rigid (negligible particle rearrangements), and the transition from capillary to viscous fingering occurs at \(Ca^* = 1\) (Fig. 4).

These results demonstrate and rationalize the crossover among three regimes of drainage in granular media: capillary fingering, viscous fingering, and capillary fracturing. They show that the crossover between capillary fingering and viscous fingering can be characterized by a modified capillary number, \(Ca^*\). Our results demonstrate the emergence of capillary fracturing, in which capillary forces dilate pore throats by exceeding the internal frictional resistance of the medium. The scaling of the fracturing number [Eq. (3)] suggests that, in granular systems with rigid solid particles, capillary fracturing tends to occur when the particle size falls below a critical value, \(d_c \sim \gamma L^2/\mu v\). This provides a rationale to observations of capillary-induced fracturing in a variety of natural systems, such as drying in granular media \([12,20]\), gas venting in lake sediments \([19,31]\), and hydrate veins in the ocean floor \([32]\). In all of these settings, the formation of fractures provides open conduits that allow fast exchange of elements, which are likely critical to the water, carbon, and energy budgets in the biosphere.

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FIG. 4 (color online). Phase diagram of drainage in granular media, showing three invasion regimes: viscous fingering (VF), capillary fingering (CF), and fracturing (FR). The tendency to fracture is characterized by the “fracturing number” \(N_f\); drainage is dominated by fracturing in systems with \(N_f \gg 1\). At lower \(N_f\) values, the type of fingering depends on the modified capillary number, \(Ca^*\).

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