Photoelastic Shear Flow

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MCEN 5151: Flow Visualization
Assignment: Team Second

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See the full video here: `https://youtu.be/dfg5uKgaH7I?si=1wJwfO3Fa9Iiu0q9`

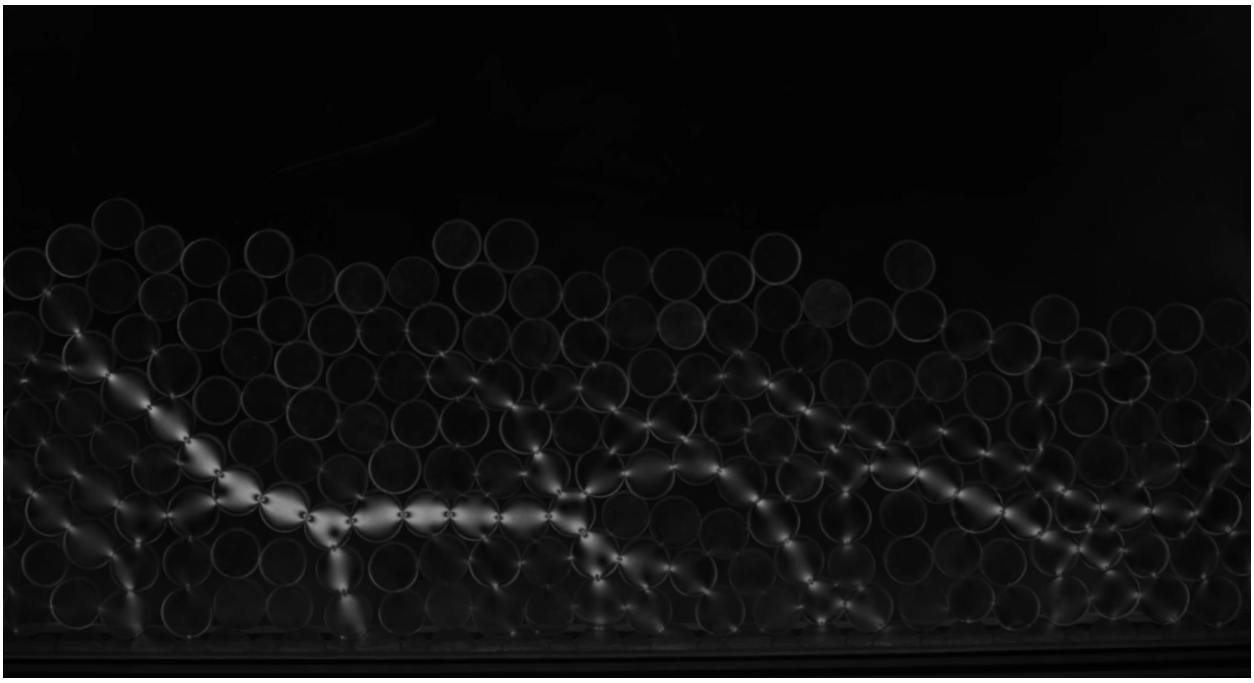


Figure 1: Photoelastic particles flowing down a chute. The fringe pattern on each particle corresponds to the magnitude and direction of force it is experiencing.

Context and Purpose

This video was made for the MCEN 5151 – Flow Visualization *Team Second* assignment, with help from my teammates Alex and Will. Dense granular flows are unique in that they can behave as a solid or liquid depending on the conditions. The most widely used continuum description of this behavior is the $\mu(I)$ rheology. My aim was to capture the internal stresses within a flowing granular material. In a granular material, load is not uniform. Instead, some particles bear most of the load while others don't experience any. These force networks are rapidly evolving in fast flows and are important to be able to measure. In ordinary opaque materials, forces are hidden,

but photoelastic materials allow us to visualize and quantify force networks in granular materials (Majmudar and Behringer, 2005; Daniels et al., 2017).

I chose this flow because it connects to granular physics, which my lab specializes in. I also built a new light panel for this experiment and wanted to practice using it and collecting high-speed data. The video shows how a granular shear flow (ex. an avalanche) carries load while flowing rapidly. Dense flows like this occur in landslides, snow avalanches, debris flows, and in chutes used to transport grain, pharmaceuticals, and mining materials (GDR MiDi, 2004).

I captured this video at 6,000 fps using a Phantom V2012 high-speed camera. While my deliverable is the video linked above, I also find the still image (Figure 1) of the bright force network visually appealing and other-worldly.

Flow Apparatus and Physics

Photoelastic disks (diameter $d = 21 \pm 1$ mm, thickness $h_t = 6$ mm) cast from Clear Flex™ 50 (CF50) polyurethane were confined between two acrylic walls, forming a quasi-2D avalanche flow. This experimental apparatus was developed by Thomas and Vriend (2019). The chute is tilted at $\theta = 20°$ below horizontal. A few hundred particles were loaded into a hopper above the chute and released, creating a gravity-driven flow down the incline. The base of the chute was an alternating mixture of large ($d = 20$ mm) and small ($d = 10$ mm) particles, cut in half and glued to the base. Figure 2 shows a schematic of the setup.

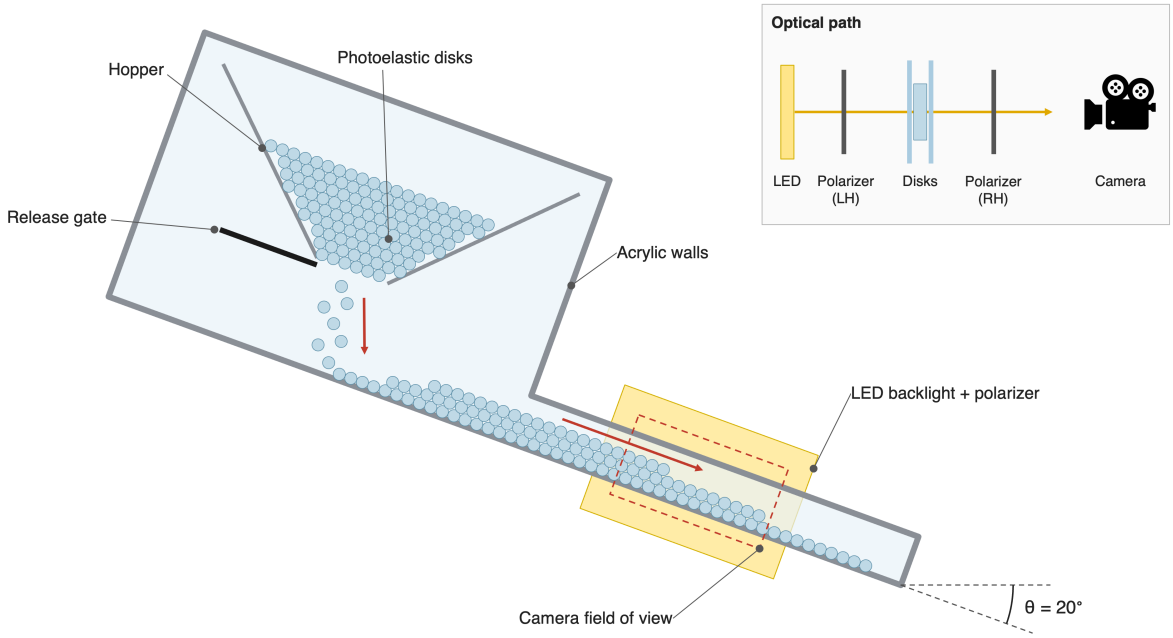


Figure 2: Schematic of the photoelastic avalanche chute.

Local Rheology

For rigid particles in a shear flow, the system is described by the dimensionless inertial number I:

$$I = \frac{\dot{\gamma} d}{\sqrt{P/\rho}} \tag{1}$$

where d is grain diameter, $\dot{\gamma}$ is the shear rate, P is pressure, and ρ is particle density (GDR MiDi, 2004; McMillan, 2026). Jop et al. (2006) proposed the following constitutive relation for dense granular shear flow:

$$\mu(I) = \mu_s + \frac{\mu_\infty - \mu_s}{I_0/I + 1} \tag{2}$$

where I_0 is a constant, μ_∞ is the friction at high I, and μ_s is the critical coefficient of friction at zero shear. The $\mu(I)$ local rheology is applicable across a large range of I, but there are a number of limitations where it fails to explain counter-intuitive phenomena caused by non-local effects.

Using this same system, McMillan (2026) quantitatively resolved the system using the open-source Photoelastic Grain Solver (PeGS) code and plotted the friction ratio μ as a function of the inertial number I, and compared it to the $\mu(I)$ proposed by Jop et al. (2006). The results are shown in Figure 3. The collapse isn't perfect (likely due to non-local effects), but there is a clear relationship between μ and I.

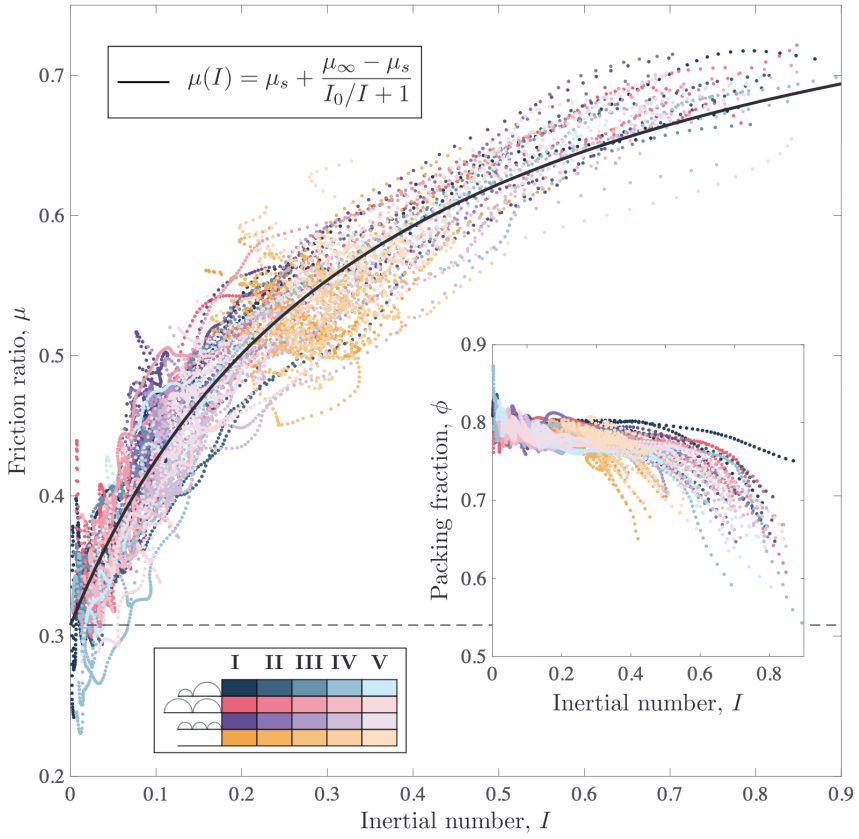


Figure 3: μ plotted as a function of I and compared against the $\mu(I)$ proposed by Jop et al. (2006). Reproduced from McMillan (2026).

Visualization Technique

Certain non-crystalline transparent materials, such as glasses and many polymers, are optically isotropic at rest but exhibit birefringence under anisotropic stress, meaning the refractive index at each point in the material depends on the local stress state (Daniels et al., 2017). In polymers, including the polyurethane we use, this response is due to molecular chain segments aligning along their lengths when the material is under strain (Tagaya and Koike, 2012).

When backlit and viewed between two polarizers, a quantifiable fringe pattern appears when a particle is loaded (see Figure 1). These fringe patterns are directly related to the direction and magnitude of contact forces (Abed Zadeh et al., 2019; Radjai et al., 2017). The stress-optic law relates the change in refractive index to the principal stresses:

$$n_1 - n_2 = C\,(\sigma_1 - \sigma_2), \tag{3}$$

where $n_1 - n_2$ is the difference in refractive indices between the two principal axes, $\sigma_1 - \sigma_2$ is the difference between the principal stresses, and C is the stress-optic coefficient, a material property measured in Brewsters. C is assumed to be independent of σ for low forces. We can describe the wavelength phase shift using the following equation:

$$\Delta = 2\pi\,\frac{h_t C}{\lambda}\,(\sigma_1 - \sigma_2) \tag{4}$$

where h_t is the thickness of the material the light is traveling through and λ is the wavelength of light traveling through the material.

In order to isolate this optical response, we use a circular polariscope, which allows only light that has gone through a phase shift to pass through the second polarizer. This is visible as a fringe pattern with an output intensity $\mathcal{I}$:

$$\mathcal{I} = \mathcal{I}_0\,\sin^2\left(\frac{1}{2}\Delta\right) = \mathcal{I}_0\,\sin^2\left(\pi\frac{h_t C}{\lambda}(\sigma_1 - \sigma_2)\right) \tag{5}$$

where $\mathcal{I}_0$ is the maximum possible light intensity through the polarizers (McMillan, 2026).

Photographic Technique

This footage was recorded using a Phantom V2012 high-speed camera at 6,000 frames per second at a resolution of 1280×800 px. We used a 50 mm lens at $f/1.4$ roughly 1 m from the avalanche chute. The field of view was approximately 510×270 mm. The exposure time was 100 μs. The playback speed was adjusted in Final Cut Pro.

Discussion

The video shows a dense avalanche of photoelastic particles shearing down a 20° incline. By leveraging photoelasticity, the force chains and networks are revealed, and by capturing the flow with a high-speed camera, we can capture the rapid fluctuations in the network. The video shows that, counterintuitively, a small number of particles carry a disproportionate amount of the load in a granular flow. By observing the high-speed footage, we can see force chains forming, growing brighter, breaking, and reforming within a few milliseconds. To continue this study, we would quantitatively resolve the flow with the PeGS code. That is, however, outside the scope of this

assignment. Beyond the scientific applications, I find videos of high-speed photoelastic granular flows mesmerizing. I'm happy with the way the footage turned out, and this experiment was a great trial run for collecting data to analyze in the future.

References

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