PRF# 56888-UNI-9
Dense Granular Flows: Connecting Dynamics Across Scales
Kerstin Nordstrom, Mount Holyoke College

Overview: For this project, we are studying the flow of granular materials in a quasi-2D "silo" geometry. Briefly, the silo is a container with vertical walls with a hole ("aperture") of linear size *d*, and the particles themselves have a diameter *D* (For polydisperse systems this corresponds to the largest particle size.) When the aperture is larger than approximately 5*D*, grains will free flow out of the system with a constant flow rate, which can be fit to the empirical Beverloo equation. Below 5*D,* the grains will eventually clog. The timescale for clogging is not a fixed number for a given aperture size, and can vary quite dramatically from experiment to experiment. However, on average smaller apertures result in faster clogging. A standard way to characterize this is by measuring the average mass outflow preceding a clog, called the "avalanche size."

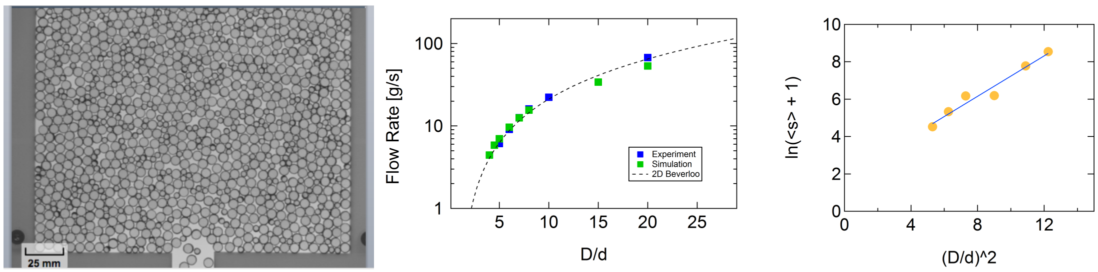


*Figure 1:* (left) Particles flowing out of a silo. (center) Flow data from simulations and experiments showing the fit to the emprircal Beverloo equation. (right) Avalanche size <*s*> fit to an empirical form previously proposed.

Our interest lies in determining what microscopic and mesoscopic motions and forces control flow and clogging in this system, and to contrast this with the similar (but distinct) jamming transition. Specifically, we can measure particle motions in real time by using ultra high speed video and particle tracking. We can also measure forces in the system by using photoelastic particles. We also run MD simulations in using LAMMPS to complement our experiments. In the last year, we have validated our experiments and simulations to show they replicate results from previous studies and that the simulations adequately mimic our real experiments (Figure 1).

Mesoscale Dynamics: We have collected raw data for many experiments and have adapted and developed our own tools for particle tracking and mesoscopic metrics of motion. Two metrics of interest are worth mentioning here. The first is $D^2_{min}$, a local measurement of non-affine motion, roughly the amount of local plastic rearrangements of particles. We have seen a sharp difference in the plastic deformations between flows of bidisperse disks and monodisperse spheres. In some ways this is not surprising, as the monodisperse systems have a more crystalline packing structure, and so are prone to failure along grain boundaries. However, both systems appear to give rise to the same bulk flow behavior. This observation led us to consider introducing additional length scales into the packing – since crystalline systems and amorphous systems will still roughly have the same particle length scale, perhaps adding more length scales will alter the flow. We are testing this idea both in experiment and simulation by adding intruders of varying size to the packing, and are seeing interesting differences in the bulk flow and clogging statistics. The second mesoscale metric of motion is the measurement of the four-point susceptibility, also sometimes called $\chi_4$. Measuring this quantity tells not only how heterogeneous the dynamics are, but also

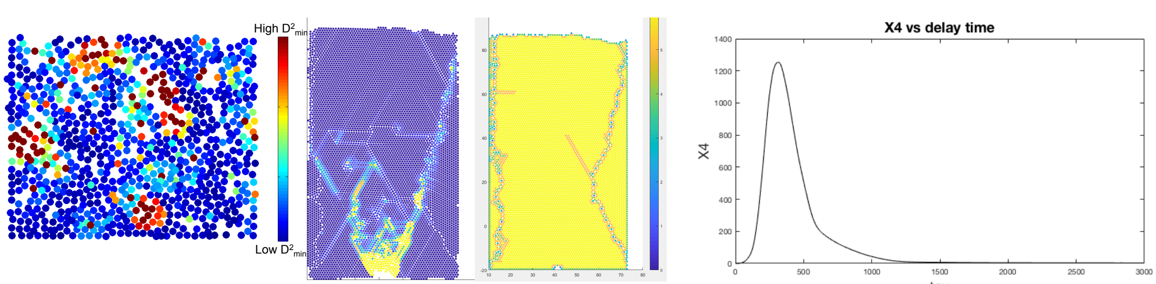


*Figure 2:* (from left) $D^2_{min}$ for bidisperse flow, $D^2_{min}$ for monodisperse flow, neighbors (6 = crystal) for same flow, $\chi_4$ measured for a flowing system near the clogging regime, note kink indicating 2nd timescale.

indicate the presence of cooperative dynamics. This measure is typically made “globally” using particle motion data from an entire run. We chose this metric as it has been studied extensively in the context of the jamming and glass transitions. As a system approaches jamming, $\chi_4$ grows, indicating a growing dynamical length scale (and time scale). We want to see if this is true for the clogging transition. We are just starting to analyze the data in this fashion, and can already see the presence of what seem to be two length/time scales, which may not be surprising as our system is not spatially nor temporally symmetric. Nonetheless the signal is clear and we are eagerly analysizing more data now after this proof-of-concept.

Packing structure: We have also been looking at local and global methods to characterize the packing. One way is to simply measure the number of nearest neighbors (to capture 5-7 defects) but we have developed/adapted three others. One local measure is $Q_k$, which measures the local free space via radical Voronoi tesselation, and has been shown to have a characteristic signature in jammed systems. We are extending this to clogged systems. We are also measuring the pair correlation function as flow proceeds in the monodisperse systems, and the segregation fraction (fraction of particle contacts between same species) in the bidisperse systems.

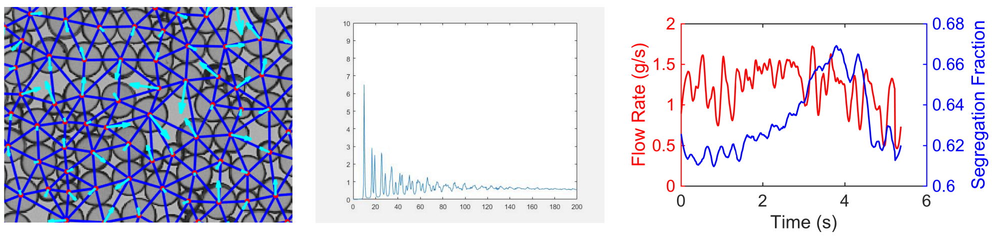


*Figure 3:* (left) Blue arrows are the Voronoi anisotropy field, whose divergence is $Q_k$. (center) Pair correlation $g(r)$ for a monodisperse packing, peaks evolve with flow. (right) Segregation fraction for a bidisperse system.

Force network: By using photoelastic particles, we can obtain measurements of forces on each particle, measured by interference fringe patterns. We are currently working to improve our optical setup to capture these. Our previous setup allowed us to see a clear photoelastic signal (particles were “brighter” under more stress) but did not allow detailed force measurements.

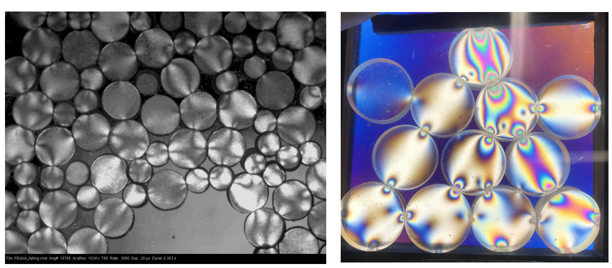

*Figure 4:* (left) Still frame with photoelastic particles. The brighter regions indicate higher stress, thus force chains are visible. (right) Improved resolution gives fringe patterns which can be used to calculate actual contact forces.

Impact on Participants: We are preparing two manuscripts right now, one specifically on $D^2_{min}$ measurements in both systems, and one specifically on results from placing intruders into the system. I anticipated using this funding to have one student present at the 2019 APS March Meeting in Boston, and will have one additional summer of funding for 1 student. The three students involved in this work have seen great benefits. One student wrote a senior thesis and is now taking a gap year, working on analyzing drone data while applying to engineering graduate schools. Another also wrote a senior thesis and is now in a physics PhD program. The third (who will be the presenter at APS) is a senior and is still working on the project. I am spending much more time on the project myself (even with my substantial teaching and advising duties) as the road to manuscripts becomes clearer. I anticipate bringing 1-2 more students onto the project in the Spring. I was invited to present on this work at the Northeastern Granular Materials Workshop in the summer, unfortunately, I was already scheduled to be overseas at the time. However, I have been assured that I will be re-invited for next year’s workshop. Upcoming publications resulting from this project as well as the exposure I will get from APS and the workshop (as well as various department seminars) will greatly increase my reputation as an independent researcher at this critical stage in my career.