



Physics Department

The co-authors marked by an \* on these are undergraduate physics majors from Smith College.

**Effects of wall friction on flow in a quasi-2D hopper  
(2017 March APS meeting)**

*NEIL SHAH, University of Massachusetts, Amherst, SUMIT BIRWA, TCIS, Hyderabad, BRENDA CARBALLO-RAMIREZ\*, MOL-LIE PLEAU\*, NALINI EASWAR, Smith College, SHUBHA TEWARI, University of Massachusetts, Amherst |*

Our experiments on the gravity-driven flow of spherical particles in a vertical hopper examine how the flow rate varies with opening size and wall friction. We report here on a model simulation using LAMMPS of the experimental geometry, a quasi-2D hopper. Keeping inter-particle friction fixed, the coefficient of friction at the walls is varied from 0.0 to 0.9 for a range of opening sizes. Our simulations show a steady rate of flow at each wall friction and outlet size. The Janssen effect attributes the constant rate of flow of a granular column to the column height independence of the pressure at the base, since the weight of the grains is borne in part by friction at the walls. However, we observe a constant flow regime even in the absence of wall friction, suggesting that wall friction may not be a necessary condition for pressure saturation. The observed velocities of particles near the opening are used to extrapolate their starting positions had they been in free fall. In contrast to scaling predictions, our data suggest that the height of this free-fall arch does not vary with opening size for higher frictional coefficients. We analyze the velocity traces of particles to see the range over which contact interactions remain collisional as they approach the hopper outlet.

**Investigation of the effect of wall friction on the flow rate in 2D and 3D Granular Flow  
(2016 March APS meeting)**

*Brenda Carballo-Ramirez\*, Mollie Pleau\*, Nalini Easwar, Smith College, Northampton, MA; Sumit K. Birwa, TCIS Hyderabad; Neil Shah, Shubha Tewari, University of Massachusetts, Amherst, MA.*

We have measured the mass flow rate of spherical steel spheres under gravity in vertical, straight-walled 2 and 3-dimensional hoppers, where the flow velocity is controlled by the opening size. Our measurements focus on the role of friction and its placement along the walls of the hopper. In the 2D case, an increase in the coefficient of static friction from  $\mu = 0.2$  to 0.6 is seen to decrease the flow rate significantly. We have changed the placement of frictional boundaries/regions from the front and back walls of the 2D hopper to the side walls and floor to investigate the relative importance of the different regions in determining the flow rate. Fits to the Beverloo equation show significant departure from the expected exponent of 1.5 in the case of 2D flow. In contrast, 3D flow

rates do not show much dependence on wall friction and its placement. We compare the experimental data to numerical simulations of gravity driven hopper granular flow with varying frictional walls constructed using LAMMPS.1

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1<http://lammmps.sandia.gov>

**Using the science of granular materials to engage middle and high school students in the process of scientific enquiry.**

**(2013 March APS meeting)**

*Jennifer Podel\*, Nalini Easwar, Smith College, Northampton, MA; Shubha Tewari, Karl Martini, Western New England University, Springfield, MA; Kristin Dolcimascolo, Amherst Regional Middle School, Amherst, MA; Eric Newman, Northampton High School, Northampton, MA.*

We describe ongoing outreach efforts that use the science of granular materials to engage middle and high school physics students in local public schools in scientific investigations. In the middle school setting, we formulated a set of investigations and related scientific questions for student groups to choose from, and provided them with starting materials to set up their experiments. Examples of investigations pursued by the students include looking at the influence of the size and shape of grains on (i) their rate of flow through a vertical hopper and (ii) their tendency to desegregate in a flow. The high school students were introduced to the properties of granular materials via a series of activities that explored the complex behavior of these commonplace materials. Following this, groups of students were challenged to pose a question and design an experiment to investigate a particular aspect of the properties of granular materials. Examples of questions that the students chose to investigate include: How does the shape of grains influence how well they stack in a pile? What factors affect the probability of avalanches down an incline? Both sets of students worked in groups over a period of two months to take quantitative data to test their hypotheses. The investigations culminated in a set of presentations by the students to local faculty and students.

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**Interplay between packing and flow in the shear zone at the wall of a granular hopper flow**

**(2013 March APS meeting)**

*Brenda Carballo-Ramirez\*, Maya Lewin-Berlin\*, Nalini Easwar, Smith College, Northampton, MA; Narayanan Menon, University of Massachusetts, Amherst, MA.*

A granular medium flowing through a vertical channel has a flat velocity profile in the bulk with a shear zone at the wall. The size of the shear zone and the dependence on flow parameters is poorly understood. To address this issue we image the flow of spherical

steel spheres under gravity in a vertical, straight-walled 2-dimensional hopper, where the flow velocity is controlled by a taper at the outlet. Our measurements focus on the role of microstructure in controlling the shear zone. We have found that the size of this zone is larger in bidisperse, disordered flow than in monodisperse, nearly-crystalline flows. We report the effect of packing as quantified by local dilation, as a function of flow rate for systems of both bidisperse and monodisperse grains.

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### **Spatial Force Correlations in 3D Granular Flow (2009 March APS meeting)**

*Kelsey Hattam\*, Alisa Stratulat\*, Efrosyni Seitaridou\*, Nalini Easwar, Smith College, Northampton, MA, Narayanan Menon, University of Massachusetts, Amherst, MA.*

We measure the force delivered at four locations on the boundary of a 3D flow of monodisperse glass spheres in a vertical, cylindrical chute. A variable opening at the bottom is used to change the flow velocity  $v_f$  from 3 to 30cm/s. The force is measured at 80KHz, allowing us to resolve individual collisions. We measure two-point spatial correlations in the flow direction and normal to it. The equal-time correlation between forces that are higher than a threshold shows a weak but measurable spatial correlation. This correlation shows no spatial directionality or dependence on flow rate. The time correlations are synchronous between diametrically opposed locations, and shifted in time between locations along the flow. From the time-lag we determine that the correlations are carried up the flow at speeds  $\sim 1000 v_f$ . This speed increases as the flow approaches jamming.

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### **Shear zones at the walls of a 2D gravity-driven flow of grains (2009 March APS meeting)**

*Kelsey Hattam\*, Nalini Easwar, Smith College, Northampton, MA; Narayanan Menon, University of Massachusetts, Amherst, MA.*

We study the flow of spherical grains under gravity in a vertical, straight-walled 2-dimensional hopper, where the flow velocity is controlled by a taper at the outlet. We perform these studies both for monodisperse steel spheres as well as for a bidisperse system of equal numbers of spheres with a ratio of diameters of 1.25. The monodisperse system shows crystalline order even in flow, whereas there is no obvious structural order in the bidisperse system. The velocity profile across the flow is profoundly different in the two systems: the wall shear zone in the monodisperse system extends only a few particle diameters, and there are only small velocity gradients in the bulk of the flow. In contrast to this nearly-plug-like flow, there are significantly broader shear zones in the disordered flow. We report these profiles as a function of the width of the hopper in order to study the scaling of the shear zone with the system size, and with the flow rate.

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### **Evidence for re-entrant behavior in laponite–PEO systems**

*Hossein A. Baghdadi, Elizabeth C. Jensen\*, Nalini Easwar, Surita R. Bhatia, Journal: Rheologica Acta, ISSN: 0035-4511, Vol: 47, Issue: 2,(2008)*

Abstract:

We observe evidence of re-entrant behavior in dispersions of a discotic clay, laponite, with added polymer. Under basic conditions, neat laponite forms a disordered colloidal glass. Rheologically, this phase behaves as a viscoelastic solid, and dynamic light scattering shows evidence of non-ergodic behavior. Addition of low molecular weight poly(ethylene oxide) (PEO) melts the glass, resulting in a low-viscosity liquid with fast dynamics. We believe this is due to a depletion force caused by excess PEO chains in solution. A viscoelastic solid is re-formed with the addition of high molecular weight PEO, which we believe to be caused by polymer chains bridging between laponite particles. The physics in our system is quite different from the hard sphere/nonadsorbing polymer systems for which re-entrant glass transitions have been reported in the literature; however, we believe there may be similarities between these phenomena. To our knowledge, this is the first evidence of a type of re-entrant behavior in anisotropic colloids

### **Force fluctuations in collisional and frictional granular flows**

*Emily Gardel\*, Efrosyni Seitaridou\*, Ellen Keene\*, Nalini Easwar, Smith College, Northampton, MA., Narayanan Menon, University of Massachusetts, Amherst, MA.*

We make measurements of the force delivered to the wall in 2D and 3D flow geometries to explore the difference between collisional and frictional flows, and between flow geometries with and without velocity gradients in the flow direction. The distribution of force fluctuations has an exponential tail at large force in collisional flows, but falls off slower than an exponential in frictional flows. We do not see a clear signature in the force distribution of the approach to jamming and therefore the connection to force distributions in quasistatic flows remains to be understood. However, the temporal characteristics of the force fluctuations do show the approach to jamming. As reported earlier, the distribution of collision times tends to a power law in collisional flows. Similarly, the power spectrum of forces in frictional flows develops power-law behaviour at low frequencies as jamming is approached.

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### **Crossover from collisional to frictional regime in a 3-dimensional granular flow**

*Efrosyni Seitaridou\*, Ellen Keene\*, Nalini Easwar, Narayanan Menon*

We have made measurements of the fluctuations in the pressure at several points on the boundary of a 3-dimensional, gravity-driven flow of slightly-polydisperse, smooth glass spheres. The flow is contained in a cylinder, with the flow rate being controlled over a factor of 30 by an aperture far downstream of the pressure measurement. As the flow velocity is decreased, we observe a crossover from a situation where momentum is transferred to the walls almost entirely by collisions to a situation where balls are almost always sliding against the walls. We parametrize this transition by measuring the fraction of time that a ball is in contact with the wall, a number that tends to unity in very slow flows prior to jamming. We present measures of the statistics and temporal fluctuations of the force delivered to the wall in both regimes. We find that in the collisional regime distributions of force are similar to those previously found in 2-dimensional flows<sup>(1)</sup>, however, the distributions in the frictional regime are fundamentally new.

Supported by NSF DMR 0305396 and NSF MRSEC DMR 0213695

(1) E. Longhi\*, N. Easwar and N. Menon, Phys.Rev.Lett, **89** (2002)

### **Spatial and temporal correlations of Velocity and Force in a 2D Granular Flow**

*Emily Gardel\**, *Sonia M. Dragulin\**, *Nalini Easwar (Smith College, Northampton, MA.)*,  
*Narayanan Menon (University of Massachusetts, Amherst, MA.)*

We have measured the impulsive forces delivered at the wall of a 2D hopper by a flowing granular medium consisting of 3mm steel spheres. We also report high-speed video measurements of the particle velocity at several points in the flow, synchronized with the force measurements. Equal-time correlations between the force at the wall and the flow velocity fall off only slowly when the wall force is correlated with the velocity at various points across the channel, but die away on the scale of 1 or 2 bead diameters upstream or downstream. These data support a picture of short-lived chains of frequently colliding particles<sup>1</sup> that are a particle diameter in width, but extend far enough transverse to the flow direction to make transient load-bearing bridges that cause bulk fluctuations in the flow velocity. However, the time-dependence of these spatial correlation functions also indicate that while the force-bearing structures are local in space, their influence on the flow velocity extends far upstream in the flow, albeit with a time-lag.

Supported by NSF CAREER DMR-9874833 and NSF MRSEC DMR-0213695.

<sup>1</sup> A. Ferguson, B. Fisher and B. Chakraborty, arXiv.org/abs/cond-mat/0301201

### **Local Correlations of Velocity and Force in a 2D Granular Flow**

*Emily Gardel\**, *Sonia M. Dragulin\**, *Nalini Easwar (Smith College, Northampton, MA.)*,  
*Narayanan Menon (University of Massachusetts, Amherst, MA.)*

We have reported measurements of the local force delivered to the wall of a 2D hopper by a flowing granular medium of 3mm steel spheres<sup>1</sup>. We now report improved measurements of the fluctuations in force at the wall in order to study the low-force end of the force distribution, which is thought to be an indicator of the approach to jamming. We also report high-speed video measurements of the particle velocity near the wall, synchronized with the force measurements. Autocorrelations of the velocity in the flow direction show a characteristic decay time that is much longer than the mean collision time. We present evidence that the velocity fluctuations are controlled by fluctuations in the wall force: the equal-time cross-correlations between the velocity fluctuations at the wall, and the average magnitude and frequency of impulsive forces show that wall forces and flow speeds are anti-correlated; an increase in the momentum transferred to the walls either due to an increased frequency of collisions or a larger impulse transmitted per collision leads to a decrease in the flow velocity.

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<sup>1</sup> E. Longhi, N. Easwar and N. Menon, Phys.Rev.Lett, **89** (2002)