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Perspectives

Dense granular flow — A collaborative study

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ABSTRACT

The International Fine Powder Research Institute (IFPRI) has funded an extensive program in dry powder and granular flows, including a focused study on dense flows of interest to a range of industrial handling and process unit operations, especially dense flows at relatively high shear rates. The dense flow program included experimental studies of granular rheology in 3D axial Couette and 2D hopper geometries, wherein the effect of force chains and jamming interactions were investigated as relevant to flow, stress and packing dynamics. The program cumulated in a collaborative study funded by the NSF, wherein a group of academic collaborators was invited to model experimental systems used in IFPRI-sponsored projects. This paper provides a summary of the IFPRI program, details of the collaborative modeling study, and perspective on what is needed to progress the work further.

1. Background

The International Fine Particle Research Institute (IFPRI), a consortium of industrial companies and academics, has supported through pooled industrial funding a rich program of research in particulate flow extending over 35 years (Appendix 1). Over the past decade, much of IFPRI's focus on particulate rheology has been toward understanding and manipulation of flow and stress fields in granular and powder materials across industrially relevant process conditions, i.e., as a function of operating conditions, material properties, and particulate characteristics. In one aspect associated with process throughput of granular solids, there are opportunities in gaining insight into efficiencies associated with fluid-like rheology of granules having a relatively high bulk packing fraction and high shear rate. While there is a good body of engineering and science for very slow, dense-packed flows (friction analogies based on soil mechanics principles), and a good body of work for very rapid, dilute flows (gas-like analogy), there is relatively little work in the intermediate regime.

Classification of dry particulate flow regimes has been done in several ways and is dependent on applications [1–5]. Overall, we can consider a quasi-static regime with friction-like flow behavior, an intermediate (or elastic–inertial) regime having particles with concentrated packing structure and high enough shear rate to incite transient contact networks, and a rapid-kinetic (or inertial–collisional) regime with relatively dilute conditions characterized by binary particle interactions. In the quasi-static regime, stress is independent of the strain rate; in the inertial–collisional regime, the stress scales as the square of the strain rate [6]. In between these two regimes is an intermediate regime where stress is related to the strain rate in the form of a power law [7]. The transition from intermediate to inertial–collisional has been characterized as a dense-inertial regime having clusters of particles whose

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structure has little effect on the stress transmission [8]. The transition from collisional to intermediate flow, i.e., the onset of stress-bearing networks, is very sensitive to packing fraction and boundary conditions.

Particulate flow regimes are of interest over a range of applications:

- Quasi-static flows are applicable to bulk storage and handling. Jenike's analysis [9] predicts the necessary conditions for onset and type of flow pattern in a hopper that may have multiple regimes including entirely static regions, flowing regions, and empty regions.
- At the other extreme, fluidization is heavily dependent on the interaction of particles with a gas flow; rapid flow in risers can be approximated using kinetic theories with fluctuation terms (i.e., granular temperature) and turbulence contributing to the description of bubbling, clustering, and streaming phenomena. While there remains some debate on the measurement and modeling of fluctuations in gas-fluidized systems [10,11], a range of useful modeling methodologies have been developed for well-fluidized systems [12,13]. Additionally, Geldart's empirical classification [14] relating particle size to the density difference between the gas and solid phases remains useful for many fluidized bed applications.
- The focus of the current work is the intermediate regime having relatively dense flows of particles in significant shear flow, typically with transient, multiple contacts, i.e., force chains in an evolving network. Stress fluctuations in dense flows may originate from the transient behavior of stress-bearing networks, i.e., the dynamics of network formation and breakage. In one aspect of this rheology, stress-bearing particle networks and transient jamming may lead to build up of material on boundaries and even clogging of industrial devices. In another aspect, transient networks are crucial to the efficient transmission of stress in a dense granular flow, for example in dense conveying or in a convective flow through a mechanical mixer or reactor. In yet another aspect, fluctuations in structure are critical to particle-scale interactions including micro-mixing and dispersion in dense flows.

In 2006 and 2007, IFPRI commissioned two research projects aimed at dense, intermediate flow: Constitutive Characterization of Dense Flows in the Intermediate Regime (Prof. G. I. Tardos and Dr. M. Kheiripour Langroudi), and Dynamics and Rheology of Cohesive and Deformable Granular Materials (Prof. R. P. Behringer and Dr. Junyao Tang). The Tardos project was engineering-based, suitable for both model and industrial materials, consisting of a full 3D bulk flow device (i.e., an axial Couette-flow) instrumented to measure normal and shear stress components of the bulk flow along with solids packing fraction in the shear gap. The Behringer project used a variety of imaging techniques to investigate the micro-structural aspects of photo-elastic particle flows in 2D hoppers, specifically packing and velocity fluctuations, dynamics of jamming, and probability of clogging. While particle-scale and force-chain physics revealed by the 2D experiments (Behringer) are relevant to the bulk flow and stress fields measured in the 3D axial Couette (Tardos), the physical connection of the two programs was not achieved through experimental collaboration. Modeling efforts were proposed to help bridge this gap.

In 2010, with support of the U.S. National Science Foundation (NSF), the study was expanded to include additional participants with expertise in modeling and simulation. The scope of the NSF grant included support for modeling and a Collaboratory Workshop adjacent to the 2011 IFPRI meeting. The first goal was to see how well the 2D Hopper and axial Couette datasets could be replicated by existing simulation techniques. This effort was to not only assess modeling accuracy, but to see what insights the modeling could give to the experiments. A further goal was to span the two datasets, relating the micro-mechanics elucidated by the 2D study to the bulk-rheology characterization in the 3D Couette experiments. A summary of the Collaboratory, lessons learned about its process, and future recommendations are detailed in Appendix 2.

The Collaboratory includes coordinated work by Profs. L. Kondic and M. Shattuck using discrete element method (DEM) modeling to simulate the 2D hopper experiments and independent work by Profs. C. Campbell and C. Wassgren using DEM to simulate the 3D Couette experiments. Additionally, results of several other collaborations using various continuum approaches to simulate the 3D flows and/or using rheological data obtained in the axial Couette experiment to model other flow geometries are reviewed.

2. Experimental, 2D hopper flow

Two categories of 2D hopper data were included in the Collaboratory. The first category consisted of measurements for: 1) mean time to empty the hopper; 2) mass flow rate; and 3) mean survival time for flow without a jam sufficient to clog the flow. Data in the second category describe the flow locally within the hopper, including: 1) local density, 2) local flow velocity, and 3) local stress.

The 2D hopper developed by Behringer and Tang (Fig. 1) comprises a pair of Plexiglas plates that are spaced slightly more than the thickness of disk-shaped particles. Particles are made from approximately 0.32 cm thick polymer sheet, PSM, manufactured by Vishay Inc. for photo-elastic observations. The diameter of the disks is either 0.770 cm or 0.602 cm, with 62% by number of the sample consisting of the smaller diameter particles. In total, there are approximately 8750 of these disks. The nominal elastic modulus of the particles is 4.8 MPa, nominal solid density is 1.15 g/ml, and the static friction coefficient is ~0.7 to 0.8.

The hopper is formed from pairs of aluminum plates which can be moved laterally so as to change the opening size at the bottom of the hopper. In addition, the hopper opening is closed by a pair of slats that can be pulled open in order to initiate flow. The width of the hopper is 43 cm and the height above and below the opening is approximately 100 cm.

The mass flow rate, Q, and by inference, the time to empty the hopper are related to the Beverloo equation [15], modified for a 2D system.

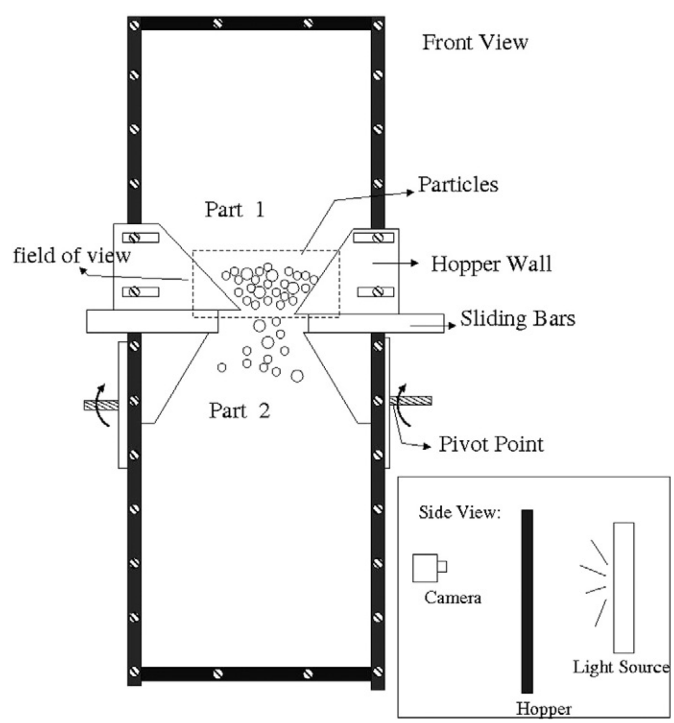

Fig. 1. Schematic of 2D hopper.