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Abstracts

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Nonmonotonic flow curves and shear banding in granular flows

Chris Ness

Dense granular packings, both dry and suspended in liquid, are among the most abundant materials on earth. They are relevant to manifold geophysical phenomena, e.g., landslides and debris flows, and to industrial processes such as paste extrusion. Understanding their flow properties is thus of major practical importance. Here we use particle simulations to map comprehensively the shear rheology of dry and wet granular matter, in both fixed pressure and fixed volume protocols. At fixed pressure we find nonmonotonic constitutive curves that are shear thinning, whereas at fixed volume we find nonmonotonic constitutive curves that are shear thickening. We show that the presence of one nonmonotonicity does not imply the other. Instead, there exists a signature in the volume fraction measured under fixed pressure that, when present, ensures nonmonotonic constitutive curves at fixed volume. In the context of dry granular flow we show that gradient and vorticity bands arise under fixed pressure and volume respectively, as implied by the constitutive curves. For wet systems our results are consistent with a recent experimental observation of shear thinning at fixed pressure. Reconciling these rich banding dynamics with a detailed mechanistic description accounting also for non-locality and boundary effects remains an open challenge.

Rheology of a sheared granular suspension

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One of the most challenging open problems in granular flows is to understand the flow of dilute particles in a carrier fluid. Due to the technical difficulties involved in the kinetic description of this type of system, it is very common to adopt a coarse-grained approach where the effect of the surrounding gas on the grains is accounted for by an effective fluid-solid force [1, 2]. On the other hand, although this approach has given reliable results in the past (especially when the particles of the molecular gas are much lighter than those of the granular gas), it would be more convenient from a fundamental point of view to consider a suspension model where the real collisions between grains and particles of the molecular gas are taken into account. Recently, a collisional suspension model has been proposed [3]. In this model it is first assumed that the granular particles are sufficiently rarefied so that the state of the interstitial gas is not perturbed by the presence of grains. Thus, the surrounding gas can be considered as a bath or *thermostat* at a certain temperature. In addition, apart from the elastic collisions between solid and molecular gas particles, the *inelastic* collisions between the grains themselves (modeled as a gas of smooth hard spheres with inelastic collisions) are also accounted for.

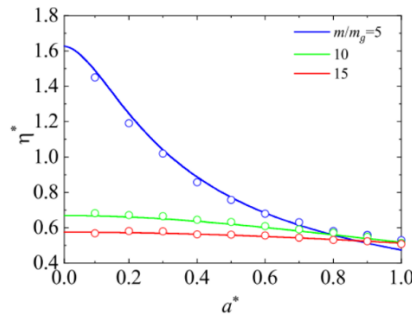


FIG. 1: Plot of (reduced) Non-Newtonian shear viscosity of the granular suspension η versus the (reduced) shear rate a for several mass ratios. Symbols refer to DSMC results.

In this talk we will consider the above collision model [3] to determine the rheological properties of a sheared granular suspension. In the low-density regime, the rheological properties of the granular suspension are determined by solving the (inelastic) Boltzmann kinetic equation [4] by two independent but complementary approaches: (i) Grad's moment method and (ii) a numerical solution of the Boltzmann equation by means of the Direct Simulation Monte Carlo (DSMC) method [5]. As expected, our results show that for sufficiently high values of the mass ratio m/m_g (where m and m_g are the masses of the grains and gas particles, respectively), the kinetic granular temperature and the non-Newtonian shear viscosity exhibit a discontinuous shear

thickening effect (i.e., these quantities increase drastically with increasing shear rate). Comparisons between theoretical and numerical results generally show very good agreement (an example of these comparisons is shown in Fig. 1) [6]

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Granular material in a rotating drum: cohesion and size effects

Antonio Pol

In this work, we present experiments on a cohesive granular material in a rotating drum. The data highlight the crucial role played by the drum geometry - particularly the lateral walls - on the dynamics of the material, with the potential emergence of finite-size effects.

First, we discuss the existence of distinct motion regimes, ranging from intermittent avalanches to continuous flow, accompanied by a transition from a concave to a convex material surface. Second, we show how avalanche dynamics is fundamentally influenced by both the intensity of cohesion and the drum geometry. Finally, we introduce two dimensionless characteristic lengths - defined as the ratio of the drum dimensions to a cohesive length - that help rationalize the experimental observations and offer a phenomenological yet physically sound interpretation of the variations in surface morphology, transitions between flow regimes, and avalanche dynamics.

Unsteady rheology of dense inertial granular flows

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Dense granular flows occur widely in nature—such as in debris flows—and in industrial applications like powder spreading in 3D printing. Their transition from quasi-static to inertial behaviour is characterized by the inertial number (I), defined as the ratio of the microscopic rearrangement timescale to that of macroscopic deformation. In steady inertial flows, the $\mu(I)$ rheology successfully describes both the shear stress-to-pressure ratio (μ) and the solid volume fraction as functions of I . However, applying $\mu(I)$ rheology directly to unsteady flows assumes that stresses adjust instantaneously to changes in I , thereby neglecting any history-dependent effects. This raises an important question: are history effects significant in unsteady inertial flows?

To address this, we investigate the relaxation behaviour following abrupt perturbations in flow conditions using discrete element simulations of simple shear in a system of monodisperse spheres. We introduce step changes in volume fraction, inertial number, and flow direction, and observe complex evolutions in stress and microstructure post-perturbation. Notably, the relaxation period correlates with the magnitude of the imposed changes. These findings clearly indicate that history effects are crucial for accurately describing unsteady inertial flows. However, the optimal method for incorporating these effects into predictive models remains an open question.

Pressure-controlled granular shear flows between bumpy planes: kinetic theory and numerical simulations

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In the most of real engineering problems and natural phenomena involving systems of flowing particles, boundaries strongly affect the local behaviour of the granular material, generating spatial heterogeneities. A theoretical continuum model must be supplemented with appropriate boundary conditions in order to deal with boundary-valued problems. The goal of this work is to test the reliability of the kinetic theory of granular gases and its boundary conditions in steady, pressure-controlled bounded shear flows. To this purpose, we perform discrete numerical simulations of steady flows of identical, inelastic spheres sheared between two parallel, bumpy planes, under a fixed normal load, by systematically varying the particle properties, the imposed pressure and the bumpiness of the boundaries. We then phrase and numerically solve a boundary-valued problem based on the kinetic theory, by employing appropriate boundary conditions for the rates of supply of momentum and fluctuation energy into the flow by the bumpy planes. We finally compare the predicted spatial distributions of several quantities against the results of the discrete numerical simulations, and show a remarkable qualitative and quantitative agreement, for all the combinations of input parameters investigated.

Rheology of coated granular materials: Cohesion vs Lubrication

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During the last two decades, the understanding of how dry, cohesion- less granular materials flow has undergone a significant change in paradigm with the development of the $\mu(I)$ rheology and its affluents. When cohesion comes into play, flow properties are way less understood, and the rheology of cohesive grains is still the subject of active research. One fundamental challenge in experimentally studying cohesive flows is controlling microscopic interactions between individual grains, such as cohesion and friction. In this talk, we study a model granular material with a controlled cohesion force between particles. The material consists of spherical glass beads coated with a polyborosiloxane polymer, which makes it stable in time and insensitive to temperature and humidity. We perform pressure-imposed rheological measurements to measure the bulk friction μ as a function of the inertial number I and the confining pressure for different coating conditions. We observe a competition between cohesion and lubrication effects, in which the dominant effect is set by the particle size: small particles behave as a cohesive material, whereas coarse particles show a lubrication transition in the rheology. To better understand this complex rheology, we precisely characterise friction and adhesion at the particle scale, which evidences a complex interparticle friction law induced by the polymer coating. Combining experiments with discrete-element-method simulations, we rationalise the different regimes in a mean-field theoretical model capable of predicting the macroscopic bulk rheology from the microscopic friction interaction.

Experiments of wet unsaturated grains flowing over a rough inclined plane: rheology with friction, cohesion and aggregates

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Multi-phase flows, encountered in nature or in industry, exhibit non-trivial rheological properties that can be understood better thanks to model materials and appropriate rheometers. Here, we use model unsaturated wet granular materials: frictional spherical particles bonded by a small quantity of a wetting liquid, flowing down a rough inclined plane. Our results show steady uniform flows for a wide range of parameters (the liquid content, the inclination angle and the mass flow rate), despite the cohesion and the existence of grain aggregates.

We analyse our experimental results in the framework of the cohesive Mohr-Coulomb yield criterion extended to inertial granular flows, with a cohesion stress dependent on the liquid content and an internal friction coefficient dependent on the inertial number. Such a rheology gives predictions in good agreement with our experimental measurements, when one introduces a grain aggregate size, which defines the appropriate length and relaxation time scales in the inertial number.

Interestingly we found that the grain aggregate size is a function of the liquid content, and its variation is not monotonic, in agreement with our predictions, based on static forces balance and using experimental measurements of the liquid distribution from the literature. This aggregate size does not scale with the cohesion length induced by the cohesion stress, due to the non-trivial distribution of the liquid within the granular material. This raises the open question of the size of aggregates in other cohesive granular materials, in case of cohesion of another nature than capillary.

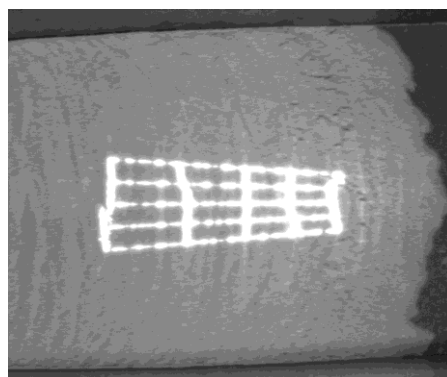


Figure 1: A picture of the free surface of an unsaturated wet granular flow on the incline from Deboeuf & Fall, Journal of Rheology (2023).

General scaling law for the velocity of steady, homogeneous granular flows down rough inclines

Thomas Paehtz

We use discrete element method simulations and laboratory chute experiments to study the steady-state velocity of granular flows down rough inclines. The simulations explore a wide range of contact parameters and grain shapes, including rods of varying aspect ratio, flat grains of varying flatness, cubes, pyramids, and a realistic grain shape. The experiments are performed for a number of granular materials, consisting of spheres and/or diverse sands. We find a universal scaling law consistent with all numerical and experimental data. It exhibits three surprising properties. First, the stop thickness, which has been an integral part of previously proposed scaling laws, seems not to be an important parameter. Second, there seems to be a power-4/3 rather than the classical power-3/2 asymptotic dependence on the flow thickness. Third, both the grain-grain friction coefficient and dynamic angle of repose, but no other contact-related or friction-related parameter, appear in the scaling law. The latter two properties are (probably) inconsistent with existing granular flow rheology models.

Surface curvature and secondary vortices in dense shallow granular flows

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Dense granular flows exhibit both surface deformation and secondary flows due to the presence of normal stress differences. Yet, a complete mathematical modelling of these two features is still lacking. Here, we focus on the case of a shallow dense flow down an inclined channel of arbitrary cross-section, for which we derive exact solutions by using a linear expansion based on the flow shallowness combined with a second-order granular rheology. At the leading order, the flow results in a streamwise velocity corresponding to a lateral juxtaposition of Bagnold profiles scaled by the varying flow depth. The linear correction exhibits two counter-rotating vortices in the plane perpendicular to the main flow direction, with downwelling in the centre. These solutions are compared to DEM simulations, that they match quantitatively. Another interesting result is the simple relationship between the surface and channel shapes. Using laboratory experiments, we show that this result can be used to infer measurements of the second-normal stress difference in dense dry granular flow.

Clogging of continuum wet granular suspensions in confined channels

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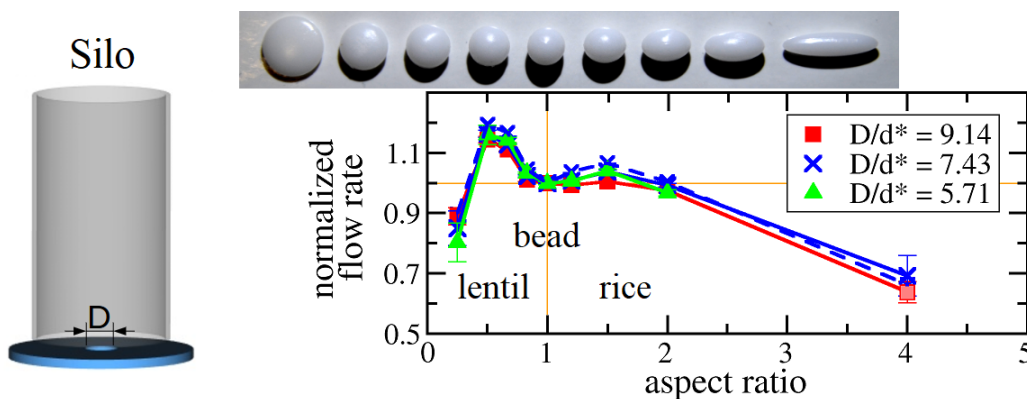
Wet granular and particulate suspensions in confined geometries can clog and jam up because of geometric constrictions or changes in material properties along the channel. It is widely observed in industrial processing that geometric constrictions result in clogging, for example, while clogging caused by stiffening of deoxygenated red blood cells is a key signature of sickle cell disease. Here we consider a continuum model of a particulate suspension, using a two-phase construction to capture the key rheological behaviour of the suspension and the differential seepage of fluid through the particulate phase under a pressure drop (Darcy flow): the model - based on the so-called $\mu(J)$ construction - captures the traditional frictional rheology of granular suspensions, with a pressure-dependent yield-stress and a shear-dependent particulate volume fraction, which is modulated by the Darcy flow of the suspending fluid. Results are presented showing how the particle flux is limited by this Darcy flow, and illustrating how this feature leads to dramatic emergent clogging in time-dependent computations, that can be triggered by a geometric constriction or a localised change in particle properties.

Effect of particle shape on the flow of an hourglass

Presenting author: Tamas Borzsonyi

Coauthors: Bo Fan, Tivadar Pongo, Raul Cruz Hidalgo

The flow rate of a granulate out of a cylindrical container was studied as a function of particle shape for flat and elongated ellipsoids experimentally and numerically [1]. We found a nonmonotonic dependence of the flow rate on the grain aspect ratio a/b (see figure). Starting from spheres the flow rate grows and has two maxima around the aspect ratios of $a/b \approx 0.6$ (lentil-like ellipsoids) and $a/b \approx 1.5$ (ricelike ellipsoids) reaching a flow rate increase of about 15% for lentils compared to spheres. For even more anisometric shapes ($a/b=0.25$ and $a/b=4$) the flow rate drops. Our results reveal two contributing factors to the nonmonotonic nature of the flow rate: both the packing fraction and the particle velocity through the orifice are nonmonotonic functions of the grain shape. Thus, particles with slightly nonspherical shapes not only form a better packing in the silo but also move faster through the orifice than spheres. We also show that the resistance of the granulate against shearing increases with aspect ratio for both elongated and flat particles; thus change in the effective friction of the granulate due to changing particle shape does not coincide with the trend in the flow rate.



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Constitutive relations for idealised granular flow - are we there yet?

Thomas Barker

Here the minimal ideal granular material is taken to consist of many hard frictional spheres with identical material properties and radii lying in a narrow range. I will review a selection of rheological continuum models for the flow of these materials, focusing on methods to derive and to close them. The successes and limitations of each framework will be highlighted by application to key flow geometries. The talk will conclude with a summary of open challenges, that is, if we are not already 'there' yet.

Robust, simple and efficient time-stepping schemes for dense granular flow models with pressure-dependent viscosity

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The $\mu(I)$ -rheology is used in the simulation of various granular flow scenarios, especially in debris flows applications. The numerical treatment of this highly nonlinear model imposes substantial challenges, such as non-physical instabilities for certain ranges of the inertial number I . Furthermore, standard flow solvers are often not immediately equipped to handle pressuredependent viscosities. In this talk, we will see a novel implicit-explicit (IMEX) time-stepping scheme that addresses, among other aspects, the pressure nonlinearity. The method is IMEX in that the convective nonlinearity, the pressure gradient and the μ -dependent viscosity are treated explicitly (that is, they are evaluated using values from previous time steps), while all other terms are kept implicit. The resulting scheme is fully decoupled and linearised: the nonNewtonian, incompressible Navier—Stokes equations are broken, at each time step, into a linear advection-diffusion-reaction problem for the velocity and a Poisson equation for the pressure. Besides computational simplicity and efficiency, a major advantage is that there is no need to perform Newton or Picard iterations, whose convergence might otherwise be very delicate. Furthermore, our method is mathematically proven to be unconditionally stable, that is, no CFL conditions arise. We will present the method and numerical results involving debris flow benchmarks.

Exploring Noisy Jeffery Orbits: A Combined Fokker-Planck and Langevin Analysis

Julian Talbot

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The dynamics of non-spherical particles in shear flow has long been a topic of theoretical and practical significance. Research in this area began with Jeffery's seminal work a century ago, which described the deterministic motion of isolated, ellipsoidal particles in shear flow. Later studies incorporated the influence of noise into this framework. The theory has been applied to various systems, including colloidal particles, macromolecules, anisometric granular particles, and microswimmers such as bacteria. I will present our study of the Jeffery orbits of elongated particles (uniaxial, prolate) under noise using Langevin simulations and the Fokker-Planck equation. Building on Doi and Edwards' analytical solution for infinitely thin particles ($\beta=1$), we generalize the theory to particles with arbitrary shape factors ($0 \leq \beta \leq 1$) and validate it through simulations. We analyze particle rotation about the vorticity axis and evaluate the orientational order matrix, from which we derive scalar nematic and biaxial order parameters. Our results show that former increases monotonically with the Péclet number, while the biaxial order parameter exhibits a maximum value. Using perturbation theory, we derive simple expressions that accurately describe the low-noise (high Péclet number) regime. We also study the orientational distribution of particles within the $\mathbf{v}$ -grad $\mathbf{v}$ plane and its perpendicular direction. Finally, we solve the Fokker-Planck equation for a two-dimensional (2D) system, finding that for the same noise level, particles in 3D exhibit faster average rotation than those in 2D. The relevance of these findings for real granular systems will be discussed.

Energetics of particle-size segregation

Tomas Trewhela

We introduce a continuum framework for the energetics of particle-size segregation in bidisperse granular flows. Building on continuum segregation equations and a recent segregation flux model, the proposed framework offers general analytical expressions to study the physics of granular flows from a mechanical energy perspective. We demonstrate the framework's applicability by examining the energetics of shear-driven granular flows. Numerical experiments with varying frictional coefficients and particle-size ratios reveal two distinct phases in the energetics, marked by the separate onset of particle segregation and diffusive remixing. Furthermore, our numerical simulations alongside previous experimental results show that the bulk Richardson number Ri , defined as the potential energy to kinetic energy ratio at steady state, scales with the inverse of the square root of the segregation-rheology Péclet number. Finally, we present a Péclet-number-dependent theoretical expression for the degree of mixing (or segregation), validated by the compiled numerical and experimental dataset. Our findings hint that the bulk segregation-mixing state can be predicted and controlled using the segregation Péclet number Pe and Pe_{sr} , both determined from known system parameters, providing an instrumental tool for engineering and geophysical applications.

Particle-size segregation in confined dense granular flows

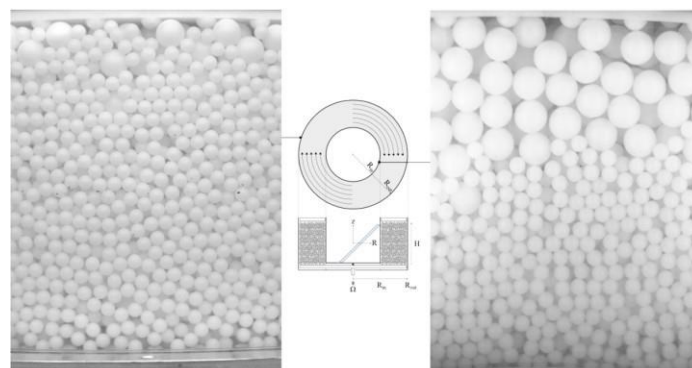
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Segregation by size is a critical issue for both industrial and geophysical processes. While existing models capture particle transport in simplified flow scenarios, accounting for segregation in more complex granular flows remains a significant challenge.

We investigated the coupling between size segregation and granular flow rheology in confined flows of bidisperse mixtures of spheres. Experiments were conducted in an annular shear cell with smooth cylindrical walls, a rotating bumpy bottom, and a load applied to the top bumpy wall. In these flow configurations, which generate a non-uniform shear rate, segregation occurs both vertically and horizontally. Vertical segregation fluxes are proportional to the size ratio of large to small particles and the concentration of large particles within the mixture. Horizontally, small particles accumulate near the sidewalls, displacing large particles toward the center. This results in the formation of a persistent, dense core of large particles that inhibits complete vertical segregation.

It is tempting to explain these phenomena by the interaction between collisional and gravitational segregation. However, the presence of enduring inter-particle contacts challenges the use of collisional models, such as those based on kinetic theory, to describe and predict the behavior of the deep, highly loaded flows analyzed in this study



Transient segregation of different density granular mixtures

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We study time-dependent density segregation of granular mixtures flowing over an inclined plane. Discrete Element Method (DEM) simulations in a periodic box are performed for granular mixtures of the same size and different density particles _ flowing under the influence of gravity. In addition, a continuum model is developed to solve species transport equation along with the momentum balance equations by accounting for the inter-coupling of segregation and rheology. The particle force-based density segregation model (Sahu et al., 2023) has been used along with the μ / I rheology to predict evolution of flow properties with time for binary and multicomponent mixtures. The effect of particle arrangements on the transient evolution of flow properties for different initial configurations is investigated using both continuum and DEM simulations. Three initial configurations are considered: light particles near the base, heavy particles near the base, and a mixed case. The inter-coupling of rheology and segregation leads to non-monotonic variation of the average velocity which is very well captured by the one continuum model. The DEM simulations also reveal existence of a quick, instability-driven, segregation for situations which require the generalization of the continuum model to three dimensions.

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Size segregation of granular mixtures in recirculating flows

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Particle-size segregation is a common phenomenon in granular materials that has attracted increasing attention in recent years. Yet segregation in recirculating flows remains underexplored compared to segregation in gravity-driven flows. In this study, we investigated how a saturated granular mixture with a bimodal grain size distribution flowed over an inclined conveyor belt, which created recirculation in the channel. By matching the refractive indices of the fluid and the particles, we were able to visualise the internal structures of granular flow in a vertical plane lit by a laser. Applying Hough Transformation to the experimental images, we reconstructed the spatial arrangement of the particles. Our observations revealed a curved interface between large and small particles, in contrast to the typically straight interfaces in bi-dispersed granular avalanches. This curvature was attributed to the interplay between recirculation and segregation: 1) particles were recirculated, with bottom particles moving upstream and surface particles moving downstream; 2) size segregation induced particle separation, resulting in an upstream accumulation of small particles and downstream accumulation of large particles. To quantify this phenomenon, we developed a depth-averaged convective-diffusion equation, providing new insights into the coupled mechanisms of recirculation and segregation in granular materials.

Segregation in convecting granular flows

Amber Pearce

Particle-size segregation is a common feature of granular materials whereby particles of the same size collect in regions of the flow. This process often produces striking patterns which can inform us about the flows underlying dynamics. Here, small-scale experiments demonstrating granular convection in a bidisperse mixture are presented. The counter-rotating vortices in the downstream direction, termed convection rolls, are visualised through the distinct segregation pattern they form. Although the driving mechanism is unclear, we show that a simple segregation model is sufficient to reproduce the particle-size distribution formed by a convecting granular flow. Three-dimensional numerical solutions are presented across the full parameter space alongside an analytical solution in the absence of diffusion.

From seismic waves to landslide and tsunami processes

Anne Mangeney

As they flow down the slope or travel in the ocean, landslides and tsunamis generate seismic waves that propagate for 100's of km from the source. In effect, the potential energy of a landslide is dissipated across a granular medium at intermediate scales down to the grain scale, giving rise to waves that span a broad range of frequencies. These waves, recorded by dense seismic arrays, carry crucial details on the source processes such as bulk landslide accelerations and decelerations at low frequencies. Advanced numerical models of the source coupled with wave propagation codes provide unique tools for extracting information about source processes from the recorded seismic waves. Indeed, by comparing simulated and recorded signal characteristics, it is possible to discriminate the signature of the different processes on the seismic signal (mass, topography, friction, presence of fluid, etc.). I will show here how seismic inversion of low frequency waves associated with landslide simulations can be used to recover key landslide characteristics such as its volume, friction coefficient, or erosion/deposition processes. I will also present very recent results where landslide-tsunami models were shown to be necessary to explain the origin of a 9-day monochromatic seismic signal recorded all over the world.

Granular Approach for the Continuum Modeling of Sea Ice

Félix St-Denis¹, Bruno Tremblay¹, Damien Ringeisen², Mathieu Plante², and Jean-François Lemieux²

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Sea ice behaves as a granular material, consisting of individual floes varying in size and shape ranging from a few meters to several kilometers. These floes, subject to winds, ocean currents, waves and tides, interact mainly through friction and collisions. High-resolution RADARSAT Constellation Mission images reveal sea ice deformation along fracture lines, called Linear Kinematic Features (LKF), where large heat, moisture, and salt exchange occurs between the ocean and atmosphere. However, existing continuum-based sea ice models fail to capture the granular nature of sea ice, and poorly reproduce LKF intermittency, density, and intersection angles. This work adapts the $\mu(I) - \phi(I)$ rheology, which links macroscopic flow dynamics to microscopic floe interactions using the dimensionless inertial number I for sea ice continuum modeling. The goal is to develop a seamless model that captures the deformation along LKFs and its effect on the macroscopic dynamical shear viscosity. Our adaptation of the $\mu(I) - \phi(I)$ rheology includes reformulating the sea ice strength and a revised temporal evolution of the dilation angle. Preliminary results from idealized uniaxial loading experiments show some promise with the simulation of smaller fracture angles between conjugate pairs of LKFs.

Monitoring flow dynamics of natural debris flows

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Debris flows are gravitational mass flows in mountain regions that are important drivers for landscape evolution, but can also represent severe hazards when human settlements or infrastructure are affected. The granular nature of debris flows is given by the high concentration of solid particles, which can span from clay-sized sediment to boulders of several meters in diameter. The grain size distribution and water content are expected to not only control the flow resistance, but also processes like particle segregation, erosion and the development of roll waves. In this contribution we report of results from the monitoring station at Gradria creek, where, besides flow depth and basal normal stress and pore fluid pressure, we derive vertical profiles of the velocity component in downslope direction at sub-second temporal resolution within natural debris flows. Over the duration of a debris-flow event we typically find strong variations of flow depth and the shapes of velocity profiles, including periods of complete stoppage and subsequent remobilization of the material. The results of this study aim to be related to controlled laboratory experiments and may serve as a benchmark for model development and testing.

Phase Separation in debris flows and their feedback on bulk dynamics

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Abstract: Debris flows, comprising particle–fluid mixtures, pose significant hazards to many communities throughout the world. Bouldery debris flows are often characterised by a deep dry granular flow front, followed by a progressively thinner and increasingly watery tail. The formation of highly destructive bouldery wave fronts is usually attributed to particle-size segregation. However, both small-scale and large-scale experiments show that discrete surges with dry fronts and watery tails can also develop in monodisperse particle–fluid mixtures. These observations have motivated the development of a novel depth-averaged mixture theory for debris flows, which explicitly takes account of the distinct granular and phreatic surfaces, velocity shear, and relative motion between grains and fluid to explain these phenomena. The proposed theory consists of four coupled conservation laws that describe the spatial and temporal evolution of the grain and water thicknesses and depth-averaged velocities. This system enables the construction of travelling wave solutions, which consist of: (i) a large-amplitude dry flow front that transitions smoothly into (ii) an undersaturated flow body, (iii) an oversaturated region, and (iv) a pure water tail. It also allows us to capture transient evolution of a travelling debris flow wave for the first time. By applying high-resolution shock capturing scheme to solve the depth-averaged model equations, the simulations demonstrate that the velocity shear and the vertical structure of the flow provide a plausible mechanism to explain the formation of phase separation in debris flows, along with its feedback on the bulk dynamics.

Keywords: Debris flows, Phase separation, Depth-averaged model, Velocity shear, Vertical flow structure

Regolith dynamics and long term surface evolution on asteroids

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Small planetary bodies, such as asteroids, have surfaces covered with loose granular material known as regolith. This regolith can flow under disturbances from impacts, tidal interactions, or spin variations caused by thermal torques. In this study, regolith movement is triggered by impact events that induce seismic shaking on the asteroid's surface. To simulate the stochastic history of these collisions, we employ the size frequency distribution of the main asteroid belt. While the majority of the collision energy contributes to crater formation, a smaller portion is transmitted as seismic waves. We propose that regolith flow initiates when seismic waves produce stress levels that satisfies Mohr-Coulomb yield criteria. Once movement begins, we assume the regolith remains fluidized as long as seismic shaking continues on the asteroid. Our regolith flow model incorporates elements for erosion and deposition, a rotating frame to account for the asteroid's spin, curvilinear coordinates to capture complex topography, and mass loss from the surface. We have developed a software, ARES (Asteroid Regolith Evolution Software), to integrate these physical models and enable the simulation of diverse surface granular flow scenarios on asteroids. Using ARES, we investigate how collisional history and spin variations affect regolith dynamics and drive long-term surface evolution over millions of years.

Shallow debris flow models with multiple phases are often ill posed

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In order for practical geophysics models of fluid–sediment mixture flows to be useful, they must be predictive and robust. Most state-of-the-art systems are comprised of depth-averaged conservation laws, similar to the classical shallow water equations. The desire to capture ever greater levels of physical detail has motivated the derivation of models featuring two or more phases corresponding to different materials in the flow, as well as the inclusion of various processes that mutually couple the momenta of the phases. We conduct a general analysis of these systems and show that in most cases they lead to equations that are only conditionally well posed. Where the equations are ill posed, catastrophic instabilities emerge that cannot be reliably simulated, since no underlying solutions exist for numerical codes to converge upon. Crucially, this can happen within physically accessible flow regimes. Our analysis encompasses models with diffusive terms, which can suffer these issues in spite of the regularizing influence of these processes. However, we also derive conditions under which such terms are guaranteed to alleviate ill posedness.

Field Observation of Erosion-deposition Debris-flow Surges

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The erosion-deposition propagation of granular avalanches is prevalent and may increase their destructiveness. However, this process has rarely been focused for debris flows on gentle slopes. Since the establishment of Dongchuan Debris Flow Observation and Research Station (DDFORS) at Jiangjia Ravine (China), long-term observation and research on the initiation, transportation, and accumulation of debris flow have been carried out, and a relatively complete debris-flow database has been established. The erosion-deposition propagation of debris-flow surges is confirmed by surge-depth hydrographs measured at the Jiangjia Ravine. Based on simple hydraulic jump equations, the eroded deposition depth of surge flow is quantified. For surge flows with erosion-deposition propagation, significant downward erosion potential is confirmed. The total momentum of surge flow not only originates from the apparent surge front, but also includes the momentum within the eroded deposition layer. Seismic observation of debris flows was also carried out at Jiangjia Ravine. It is conspicuous that, with similar surge scales, the surges on dry channel bed generate higher magnitude of vibration (power spectral densities) than those riding on deposition layer. We interpret that the deposition layer is highly liquefied and therefore serves as a poor media for seismic wave propagation. The field observation at Jiangjia Ravine enhances our understanding on debris-flow dynamics.

Flows of ice powders at very low temperatures

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Several planetary surfaces in the solar system are covered by granular ices resulting from various processes. Anticipating the properties of the icy surfaces is important for both better understanding the evolution of surface morphologies and minimizing the technical issues that future missions may face when landing, sampling, or drilling.

In this study we investigated the cohesive behavior of ice powders (relevant for bodies like Enceladus or Europa) as a function of temperature. Experiments were performed on ice powders differing by particle size and composition, on a wide range of temperatures (~ 80 -250K) in a liquid-nitrogen cooled rotating drum where the flow was characterized through bed slope statistics. We observed a strong increase of the cohesion of pure ice with temperature, which was not present for other reference powders. The presence of salts may reduce the effect of temperature. Different micromechanical explanations can be proposed for this intriguing phenomenon.

In order to better understand the experimental result, we also performed discrete numerical simulations of rotating drum flows of cohesive grains varying particle size, cohesion and stiffness. Different flow regimes were observed, and both the regime transitions and the angle statistics were shown to depend on the parameters cited above. This complex behaviour can be justified by a simple analysis of the adhesive collision dynamics.

Three-dimensional simulations of snow-avalanche flow with incompressible granular $\mu(I)$ rheology

Tómas Jóhannesson, Alexander H. Jarosch

Snow- and landslides pose a threat to settlements in avalanche-prone areas, where protective measures are widely used to improve safety. Simulations of the flow of avalanches against obstructions are essential for the design protective measures in avalanche run-out zones. We present an efficient computational fluid dynamics (i.e. OpenFOAM) implementation of incompressible granular flow based on recent advances in the theory of $\mu(I)$ rheology that we call “Open- $\mu(I)$ ”. The implementation includes a novel interface-stabilization method that proves to be essential for realistic simulation of the moving air-granular-phase interface. Model parameters have been calibrated with observations from eight large Icelandic avalanches. Our simulations reproduce observed shapes of avalanche deposits in the run-out zones and radar measurements of avalanche velocities. Observed and estimated values for avalanche volume and release depth in starting areas serve as initial conditions for our simulations. Our approach represents an important improvement with respect to existing, depth-averaged models for snow-avalanche flow in complicated terrain geometries as it is able to simulate the full three-dimensional flow at impact with obstacles such as catching and deflecting dams and braking mounds. We present several simulations of avalanche flows against protective dams and natural terrain obstacles in Iceland.

Modelling debris flow waves

Jamie Webb, Xiannan Meng, Chris Johnson, Nico Gray

It is well documented that debris flows exhibit surges or waves. We demonstrate that a numerical model based on mixture theory can capture the break-up of a flow into multiple waves formed of relatively dry granular fronts followed by more watery tails. The observed wave structure is consistent with field observations and our reduced-scale experiments. The formation of small levees is also evident in both our simulations and experiments. The production of levees is enhanced by the geometry of the channel. At the flow front, material is pushed towards the edges of the flow, onto the banks of the channel. The fluid phase drains down the banks back into the centre of the channel faster than the solid phase. As a result, a small amount of statically stable solid material is deposited at the edge of the flow, in the form of small levees.

Steady parallel flows of dense granular suspensions

Jonathan Watts, Duncan Hewitt

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The rheology of dense non-Brownian suspensions is a problem with applications in biological, geophysical and industrial flows. There has been success in modelling their behaviour under steady simple shear using the family of " $\mu(I)$ " models, but it is known that these models are inadequate to describe inhomogeneous flows. For example, dense suspensions have been observed flowing below the locally-predicted yield stress apparent in the $\mu(I)$ models. In the case of dry granular flows, there has been success in reproducing this behaviour using nonlocal models, in which the stress response of a region of the flow depends on the flow in neighbouring regions. In this talk, we will explore a number of steady parallel dense suspension flows, with and without gravity, and investigate the predictions of $\mu(I)$ models and some nonlocal models, in particular suspension analogues of the Nonlocal Granular Fluidity and I-gradient models of granular rheology. We will compare these predictions to results from experiments and particle-based simulations.

MPM Modeling of Alpine Mass Movements with Granular Rheologies

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In this talk, I will show our group's recent developments in modeling alpine mass movements as continuum granular flows using the Material Point Method (MPM). This numerical scheme naturally handles free surfaces and avoids mesh-distortion issues under extreme deformations. It also facilitates explicit modeling of entrainment, which can have a significant effect on the behavior and flow of mass movements. Presenting some real events of snow avalanches, rock and ice avalanches as well as slushflows, I will show how we have modeled them. Aiming to accurately capture the mechanics and flow of these processes, I will highlight and discuss granular rheologies which we have implemented in our in-house MPM software. In particular, I will focus on the $\mu(I)$ -rheology combined with elastoplastic models, most notably the Modified Cam-Clay model, a combination recently proposed in Blatny et al. (2024) *JFM* 997, A67. Considering both the solid and liquid properties of granular media in a single framework, this model can capture cohesive behavior through appropriate yield surfaces and permits the direct treatment of dilation and compaction through hardening laws.

Wind-blown sand : Intermittent and periodic transport events in moist environment

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Moisture has a significant influence on the initiation of motion of sand by wind and also on the resulting spatial and temporal evolution of the sand transport rate. While moisture is usually very low in sandy desert areas and can be disregarded, aeolian sand transport on sandy beaches or in the context of coastal dune is expected to be crucially dependent on the moisture content within the sand. The literature regarding the impact of the moisture on wind blown sand is sparse and available data present considerable discrepancies regarding the magnitude of the moisture effects. We present here a new wind-tunnel study carried out with wet sand and controlled relative humidity of the turbulent air flow. Our experiments reveal that transport with wet sand is characterized by large fluctuations of the mass flow rate resulting in intermittent transport events. These transport events are shown to be strongly correlated with the drying process of the superficial layer of the sand bed. The interplay between transport and drying produces periodic oscillations of the mass flow rate. A simple description based on a convection-diffusion model suggests that the periodicity of the flow rate is related to the efficiency of the drying process.

Sliding block analogy for gravity-driven free-surface granular flows

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This work presents a reduced sliding block analogy that simplifies the analysis of gravity-driven free surface flow of granular materials. The granular material flow is modeled as a solid block sliding down an inclined plane under the influence of gravity and velocity dependent friction force. We first consider the flow of granular materials over a periodic chute and predict the time evolution of the average velocity, inertial number, and packing fraction using the sliding block approach. Comparison with DEM data demonstrates that sliding block analogy greatly simplifies the analysis while giving accurate results in case of periodic chute flow. Subsequently, this approach is extended to predict the behavior of granular flow over a long chute without sidewalls. We obtain the variation of average velocity and layer height as they evolve along the length of the chute using this approach. To check the validity of this sliding block approach, we also solve 2D steady state momentum balance equations for the inertial number-based $\mu(I)$ rheological model. The predicted flow properties from the continuum model are found to be in good agreement. The success of the sliding block approach for accurately describing chute flows holds promise for exploring more complicated free surface flows.

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Kinetic theory of granular flow during bedload transport : insights from discrete simulations and continuum modeling.

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In this work, the modelling of collisional bedload transport is investigated with a focus on the continuum modelling of the granular flow. For this purpose, a frictional–collisional approach, combining a Coulomb model with the kinetic theory of granular flows, is developed. The methodology is based on a comparison with coupled fluid–discrete simulations that the classical kinetic theory model fails to reproduce. This inaccuracy may be explained by the assumptions of negligible interparticle friction and the absence of a saltation model in the continuum approach. In order to provide guidelines for the modelling, the fluctuating energy balance is computed in the discrete simulations and systematically compared with the kinetic theory laws. Interparticle friction is shown to affect the radial distribution function and to increase the energy dissipation, in agreement with previous observations. In addition, a saltation regime is identified, leading to departure from the viscosity and pseudo-thermal diffusivity laws of the kinetic theory in the dilute regime. Based on these observations, modifications to account for interparticle friction are included in the two-fluid model, and the kinetic theory is coupled with a saltation model. The results show that for inelastic frictional particles, interparticle friction controls energy dissipation, and the macroscopic behaviour of the granular flow does not depend on the microscopic particle properties. The proposed model reproduces the $\mu(I)$ rheology in the dense regime of the granular flow.

Micromechanics of Cam-Clay and beyond.

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Granular materials exhibit complex mechanical behavior governed by particle-scale interactions, yet continuum models like the Cam-Clay model have long been employed to describe their yielding and hardening under shear. This talk explores the micromechanical origins of Cam-Clay plasticity by linking particle-scale information to the macroscopic critical state framework, via Discrete Element simulations (DEM). Clay particles are modelled as rod-shaped elements made of spherical elementary units. The contact laws implemented in the adopted DEM framework account for both the mechanical interaction developing between particles in contact, and the long-range electro-chemical interaction in the form of Coulombian attraction/repulsion between charged particles. The DEM framework is challenged against its ability to reproduce qualitatively key aspects of the macroscopic behaviour of normally consolidated and over consolidated clays during shearing, including contractive and dilative behaviour, and monotonic and non-monotonic stress-strain behaviour.

Building on these insights, the work proposes an extension toward a unified model bridging CamClay plasticity rheological models for granular flows. By integrating critical state concepts with rate-dependent flow regimes, the proposed approach aims to describe granular collapse and subsequent flow dynamics, offering a micromechanically grounded continuum model for transient and steady-state granular behavior.

Size segregation due to finer grain infiltration in bedload transport

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Bedload, the coarser material transported in contact with the bed by turbulent flow in stream channels, has major consequences for public safety, and environmental sustainability. Size segregation is largely responsible for our limited ability to predict sediment flux and river morphology, especially in mountains where steep slopes drive an intense transport of a wide range of grain sizes.

Specific experiments [1, 2] were carried out in a 10% steep, narrow, glass-sided channel, with a constant turbulent and supercritical flow rate in two stages. In the first stage, coarse spherical beads of diameter 5 mm were introduced at a constant feed rate to obtain a sediment bed in one-size-equilibrium (sediment outflux equal to influx). In the second stage, beads of different diameters (from 0.7 mm to 4mm) were introduced at different feed rates, the coarse feed rate remaining the same. The objective was to study the influence of (1) the grain size ratio and (2) the percentage of the fine feed rate in the total feed. Depending on these parameters, the slope of the bed evolved eventually reaching a new two-size equilibrium value either larger (aggradation) or smaller (degradation) than the one-size slope [1,2]. A variable thickness layer of fine grains on top of which coarse grains moved was observed. Each experiment was recorded at high temporal frequency. Image processing algorithms

[3] improved with a continuous minimisation energy method [4] permitted us to detect the coarse beads, and to track their trajectories. We will analyse the depth profiles of particle streamwise velocity and concentration, and the sediment transport rate of the coarse beads once the two-size equilibrium is reached. Depending on the grain size ratio and the percentage of the finer feed rate in the total feed, coarse grains moved either in concentrated low velocity clusters or individually at higher velocity. Better understanding of bedload size segregation at the grain scale should permit upscaling to river morphology modelling.

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The mechanics of entangled fibers.

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The packing of long, flexible fibers, as observed in bird nests, cotton balls, or dust bunnies, represents a class of granular materials with mechanical properties that remain poorly understood [1]. A striking feature of these packings is the emergence of an effective cohesion, despite the absence of any adhesive or attractive forces between the particles [2]. This cohesion arises from the interplay between geometry, elasticity, and friction, enabling the packing to resist tensile stresses. However, the factors controlling the strength of this cohesion and the behavior of these entangled materials under different mechanical solicitations remain largely unknown.

In this study, we experimentally investigate the tensile strength and compressibility of packings of model fibers. By systematically varying the geometry and properties of the fibers, we identify scaling laws for both the cohesive stress and the compressibility. These findings are discussed in the context of homogenization theories developed within the textile community [3,4]. We also demonstrate how 3D visualization using microtomography, along with numerical simulations, help in understanding the underlying mechanisms controlling the behavior of packings of entangled fibers.



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