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Laurent LACAZE - IMFT / CNRS, Toulouse, France
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Invited Keynote Speakers

James T. JENKINS - Cornell University, Ithaca, New York, USA
Eric LAJEUNESSE - ICGP, Paris, France
Jim McELWAINE - Durham University, Durham, UK
Olivier POULIQUEN - IUSTI / CNRS, Marseille, France



The aim of this colloquium is to gather the European scientific community to exchange on recent developments regarding the coupling mechanisms in granular fluid-flows at different scales, from that of the single grains to that of the mesoscopic deformation of an assembly of grains. A specific attention is to be paid on the two types of granular transport mostly encountered in geophysical and industrial applications, namely granular-fluid flows induced by gravity and/or shearing fluid on top of grains. Contributions should help at improving our knowledge on (i) the coupling mechanisms between grains and the surrounding fluid, and/or (ii) the multiscale modelling of granular-fluid flows for geophysical and industrial purposes.

Web Site

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MONDAY

9h30|10h30

Fluid-particle interaction and rheology / Keynote/

Complex suspensions - *O. Poulique*

10h30|11h00

Coffee break

11h00|12h30

Fluid-particle interaction and rheology/ Single grain dynamics

12h30|14h00

Lunch

14h00|16h00

Fluid-particle interaction and rheology/ Complex shape and interaction force

16h00|16h30

Coffee break

16h30|18h30

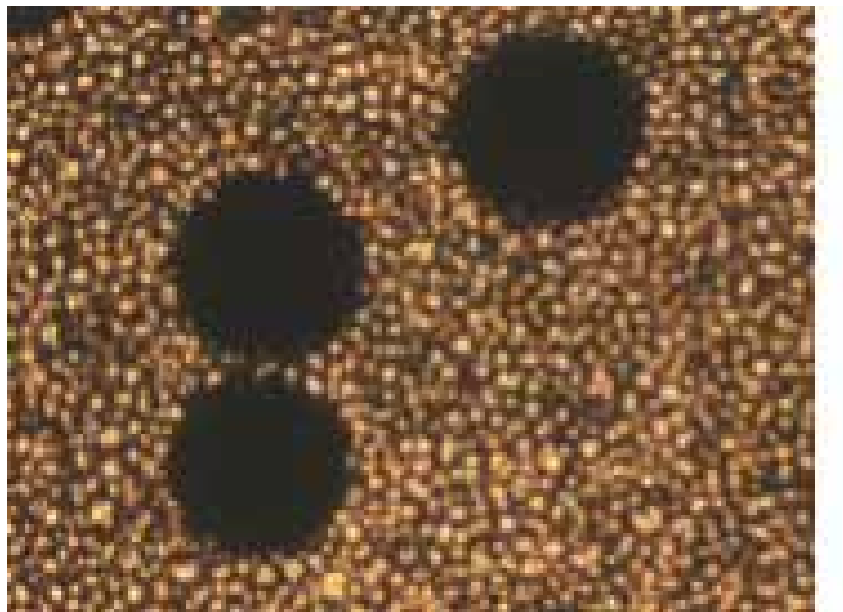
Fluid-particle interaction and rheology/ Rheology and Continuous modelling

Complex suspensions

OLIVIER POULIQUEN¹

¹IUSTI – Université Aix-Marseille, CNRS, UMR 7343, 13453 Marseille, France

Adding rigid particles in a fluid is known to change its properties, which might be a strategy to control the behavior of complex fluids. However, despite its long research history and its practical relevance both in industrial applications and in geophysical problems, the mechanics of suspensions in the dense regime remains poorly understood. In this talk, we will first discuss results obtained for suspensions of rigid spheres and rigid fibers in a newtonian fluid, with a special attention to the very dense regime close to the jamming transition. The investigation of this extreme regime has been made possible thanks to the development of a pressure imposed rheometer . We will then present the case of suspensions in a yield stress fluid, showing how empirical constitutive laws can be proposed from the knowledge of the rheology of newtonian suspensions. Finally, experiments on the rheology of a suspension in cornstarch will be presented, with a special interest on how the discontinuous shear thickening transition is modified by the presence of rigid coarse particles.



11h00|12h30 Fluid-particle interaction and rheology/
Single grain dynamics

I11h00| Modelling and Numerical Simulations of Contacts in Particle-Laden Flow - *Lambert et al.*

I11h30| Bouncing dynamics of a sphere on a textured wall in a viscous fluid - *Chastel et al.*

I12h00| Incipient motion of a single sphere on regular substrates at low particle Reynolds numbers - *Wierschem et al.*

Modelling and Numerical Simulations of Contacts in Particle-Laden Flow

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In particle laden flow, hydrodynamic effects due to close interacting particles play an essential role in the suspension phenomenon. For Stokes flow, the lubrication theory indicates that the dominant order of the lubrication between two spherical particles evolves as a function of the inverse of the separation distance. The divergent behaviour of the lubrication force challenges the accuracy of numerical simulations when the particles are almost in contact (see figure 1).

Lubrication is classically modeled using the dominant order of the force given by the lubrication theory. However, these results are rigorously valid only for Stokes flows and spherical particles. We aim at extending the lubrication theory to inertial fluids and more complex particle geometries.

We are proposing a subgrid lubrication model for Navier-Stokes flows of particles. In our approach, corrections of the lubrication are made locally at the particle surfaces when there is not enough grid cells between interacting particles to properly compute the hydrodynamic effects. Hence the validity of the correction depends only on the particle curvature and the flow properties near the contact point. Thereby, the method can be generalized any particles with a convex surface, for instance.

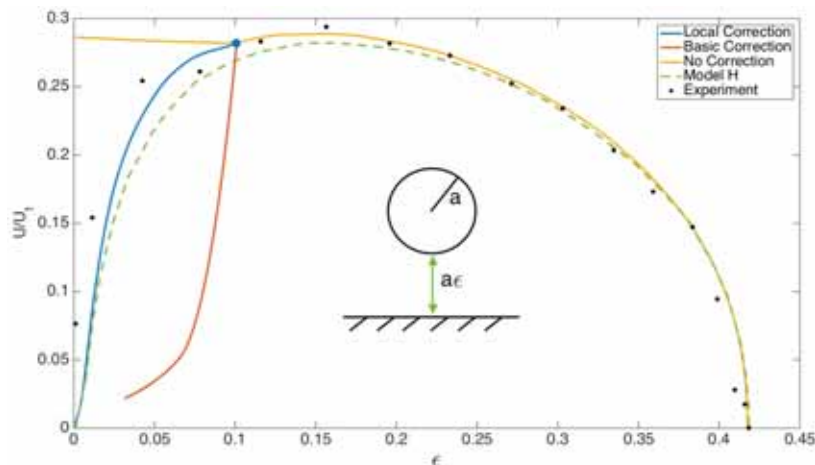


Figure 1: Comparison of the dimensionless velocity of a particle falling on a wall in function of the dimensionless separation distance ϵ between the particle and the wall ($St_{impact} \approx 3$, $Re_{impact} \approx 25$). These results are from identical configurations using on one hand our local lubrication correction (blue line) and on another hand simulation using a classical approach of lubrication correction (red line). The blue dot shows the last output before lubrication correction are activated. The dash line is an analytical model used as reference.

Bouncing dynamics of a sphere on a textured wall in a viscous fluid

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The collision process of grains in a fluid is a key phenomenon for a good understanding of the complex dynamics of numerous industrial and natural multiphase flows, such as particle laden-flows, fluidised beds or submarine avalanches. The present work investigates how the collisional process of a solid sphere onto a wall in a viscous liquid is influenced by a wall texture, with a special attention given to the bouncing transition. The texture considered here consists of a network of square micro-pillars at the wall surface, whose geometrical parameters can be easily controlled and varied. To resolve the sphere motion not only before and after the collision but also during the collision, we use a high-frequency interferometric technique where the sphere acts as a moving mirror. Such an interferometric technique was already used by [1] to investigate the near-wall dynamics of a sphere settling towards a smooth wall at finite Stokes and Reynolds numbers, just below the bouncing transition ($1 < St < St_c$). The influence of a wall texture on the near-wall approach dynamics of a sphere was also studied with the same device for Reynolds and Stokes numbers ranging from very low values [2] to finite values up to the bouncing regime [3]. In this regime, the time duration of the collision and the maximal penetration depth of the sphere into the wall texture can be measured, together with the impact and rebound velocities [3]. A modified Hertz contact model was derived to take into account the geometry of the wall texture and then to predict the scaling laws for the collision time and penetration depth [3]. The predicted scalings that differ from the classical Hertz theory compare favourably with the experimental measurements. The viscous dissipation during the collision has been neglected in this previous modeling, but there is evidence of such a dissipation during the collision. The analysis of the viscous dissipation by the squeezing flow through the network of pillars during the collisional process will be presented here. The precise knowledge of the dissipative force term is essential to predict the critical Stokes number for bouncing and to reduce the computational cost for the numerical simulations of fluid-particulate systems [4-5].

[1] A. Mongruel, C. Lamriben, S. Yahiaoui & Feuillebois, “The approach of a sphere to a wall at finite Reynolds number”, *J. Fluid Mech.* **661**, 229–238 (2010).

[2] T. Chastel & A. Mongruel, “Squeeze flow between a sphere and a textured wall”, *Phys. Fluids* **28**, 023301 (2016).

[3] T. Chastel, P. Gondret & A. Mongruel, “Texture-driven elasto-hydrodynamic bouncing”, *J. Fluid Mech.* **805**, 577–590 (2016).

[4] J.A. Simeonov & J. Calantoni, “Modeling mechanical contact and lubrication in Direct Numerical Simulations of colliding particles”, *Int. J. Multiphase Flow* **46**, 38–53 (2012).

[5] E. Izard, T. Bonometti & L.Lacaze, “Modelling the dynamics of a sphere approaching and bouncing on a wall in a viscous fluid”, *J. Fluid Mech.* **747**, 422–446 (2014).

Incipient motion of a single sphere on regular substrates at low particle Reynolds numbers

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Republic of Korea

We study the incipient motion of single bead in steady shear flow at low particle Reynolds numbers. The substrates consist of a monolayer of regularly arranged fixed beads. Spacing between substrate spheres varies resulting in different angles of repose and exposures of the particle to the flow. Experimental studies show a strong dependence on the substrate geometry. The flow-induced forces and the level of flow penetration into the substrate are determined numerically. Numerics indicates that rolling motion is always preferred to sliding and that the flow penetration is linearly dependent on the spacing between the substrate particles. Based on the effective zero level of the flow penetration, we propose a model for the incipient motion at low particle Reynolds numbers. The model is an extension of Goldman's classical result for a single sphere near a plain surface taking into account the angle of repose, flow orientation with respect to substrate topography and shielding of the sphere to the shear flow. The effective level of flow penetration is the only external parameter. The model, applied to triangular and quadratic arrangements with different spacings, is able to predict the dependence of the critical Shields number on the geometry and on the orientation of the substrate. The model is in very good agreement with numerical results. For well-exposed particles, we observed that the minimum critical Shields number for a certain angle of repose does not depend sensitively on the considered arrangement.

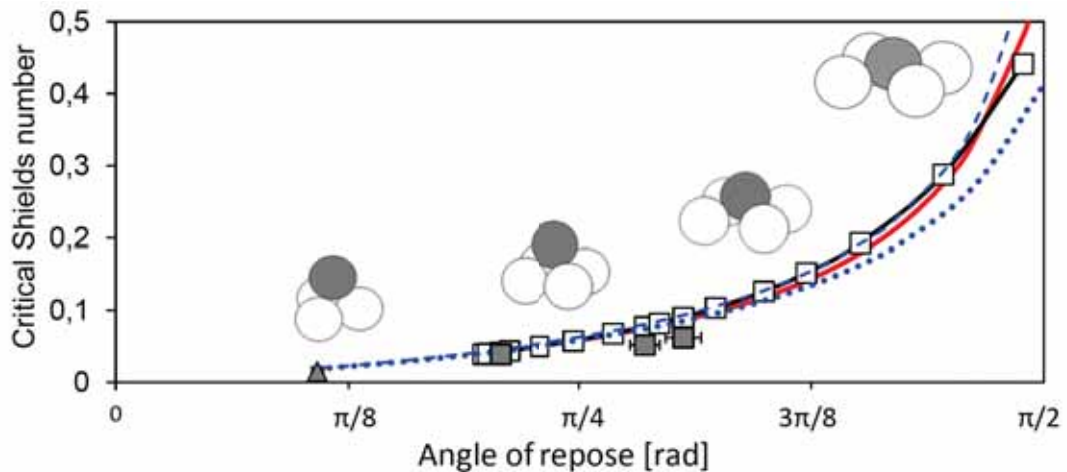


Figure 1: Comparison between the critical Shields numbers. Grey symbols: experiments. Open symbols and black solid line: numerics. Red solid line: model for quadratic substrates. Blue dashed and dotted lines: model for triangular substrates with different effective zero levels.

14h00|16h00 **Fluid-particle interaction and rheology/
Complex shape and interaction force**

|14h00| Collision model for ellipsoidal particles with application to sediment transport - *Jain et al.*

|14h30| Grain-Resolved Simulations of Cohesive Sediment - *Vowinckel et al.*

|15h00| Fluid flow erosion of cemented granular media - *Philippe et al.*

|15h30| Accretion Dynamics on Wet Granular Materials - *Saingier et al.*

Collision model for ellipsoidal particles with application to sediment transport

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A number of simulations addressing sediment transport have considered spherical particles of uniform mass and diameter despite the fact that most of the natural sediments are non-spherical. In case of arbitrary shaped particles the collision handling becomes more involved and the penalty-based collision models commonly used for spherical particles are less suitable. Here, a constraint-based collision model for ellipsoids is presented which can be applied to more complex particle shapes as well. In addition, an improved lubrication model is developed to take care of viscous forces during the phases of approach and rebound. The entire model also covers the situation of simultaneous multiple collision of numerous particles as a linear complementary problem which accounts for all the collision momentums being transferred to a particle from its neighbors. Furthermore, it is capable of representing various types of motion such as slipping, spinning and rolling. To depict the complexity of the problem and the capabilities of the model, a simulation

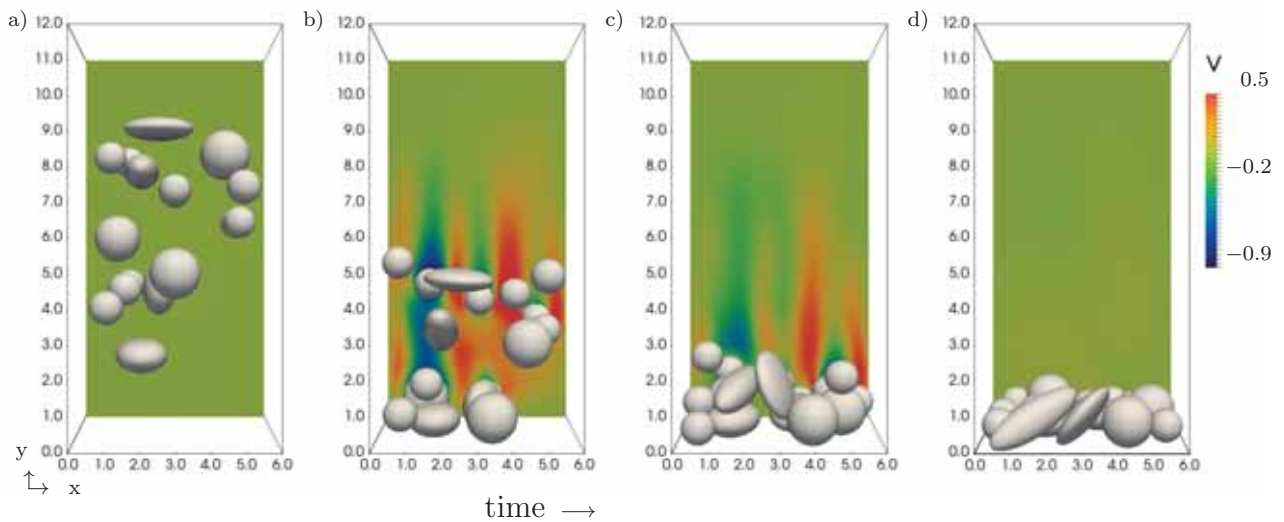


Figure 1: Sedimentation in a viscous fluid at four different instances of time applying the new model. The particles have various shapes such as oblate, prolate, spherical and ellipsoidal.

with particles of different shapes, sizes and densities was conducted (Fig 1). A total of 17 particles, randomly placed in the domain, sediment in a viscous fluid until they reach the bottom while colliding in various ways. The new model is presently used to extend simulations of sediment erosion of [1] towards ellipsoidal particles which will be reported in the final presentation.

References

[1] Vowinkel, B., Jain, R., Kempe, T., and Fröhlich, J. : Erosion of single particles in a turbulent open-channel flow: a numerical study. *Journal of Hydraulic Research* 54, 2 (2016), 158-171.

Grain-Resolved Simulations of Cohesive Sediment

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Cohesive sediment is ubiquitous in natural environments such as rivers, lakes and coastal ecosystems. For this type of sediment, the short-range attractive forces can no longer be ignored, which results in flocculation of aggregates that are much larger than the individual grain size. These flocs are known to carry substantial amounts of nutrients and/or contaminants. Hence, understanding the complex dynamics of the interplay between flocculated sediment and the ambient fluid is of prime interest to manage aquatic environments, but a comprehensive understanding of these phenomena is still lacking. In the present study, we address this issue by carrying out grain-resolved simulations of cohesive particles settling under gravity using the Immersed Boundary Method. First, we present a suitable model formulation to accurately resolve the process of flocculation as will be illustrated by means of the classical Drafting-Kissing-Tumbling test case. The cohesive model is then applied to a complex test case. A randomly distributed ensemble of 1261 polydisperse particles is released in a tank of quiescent fluid. Subsequently, larger particles start to settle faster than smaller ones, thereby replacing fluid at the bottom of the tank, which induces a counter flow opposing the settling direction (Figure 1). This mechanism, known as ‘hindered settling’, will be compared to experimental studies from literature as well as to the non-cohesive counterpart to address the impact of flocculation on sedimentation. The present study will serve as a benchmark for experimental efforts in our group to study flocculation under the presence and absence of gravity. The latter configuration will be realized by experiments on the International Space Station.

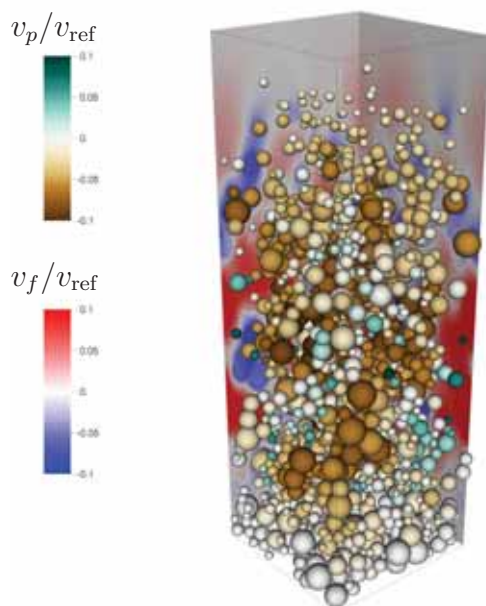


Figure 1: *Cohesive particles settling under gravity colored by their vertical velocity component. Contours of the vertical fluid velocity.*

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Fluid flow erosion of cemented granular media

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The present contribution reports both experimental and numerical investigations of soil erosion by a fluid flow with a specific focus on the microscale. To this end, artificial granular systems have been developed, made of spherical particles interconnected by solid bonds. More specifically, the cemented granular material used for the experiments was constituted of glass beads, solid resin bridges and a mixture of mineral oils as interstitial liquid, all phases being approximately matched in terms of refractive index. The resultant medium was therefore almost translucent, enabling a direct visualization of the grains' erosion by an immersed impinging fluid jet thanks to planar laser induced fluorescence [1]. At the same time, several specific tensile strength tests have been carried out both at the contact scale and at the sample scale. With regard to numerical modelling, a 2D coupled DEM-LBM simulation has been implemented [2] and has proven its capacity to describe accurately fluid/grains interaction at the microscale in our particular context of cemented soil erosion where solid bonds were expressed through a specific contact law based on a parabolic yield envelope with critical thresholds in traction, shear and rolling [3].

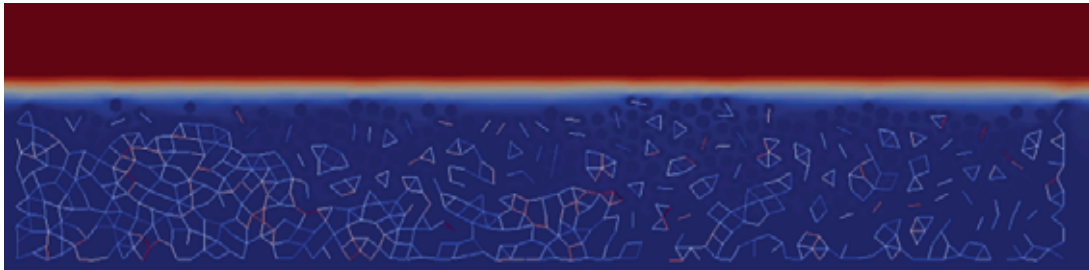


Figure 1: DEM-LBM simulation of cemented soil erosion by a tangential fluid flow.

[1] Brunier-Coulin, F., Cuéllar, P., Philippe, P. (2017) Erosion onset of a cohesionless granular medium by an immersed impinging round jet. *Phys. Rev. Fluids*, **2**, 034302.

[2] Cuéllar, P., Philippe, P., Bonelli, S., Benahmed, N., Brunier-Coulin, F., Ngoma, J., Delenne, J.-Y., Radjai, F. (2015) *Micromechanical analysis of the surface erosion of a cohesive soil by means of a coupled LBM-DEM model*. *Proc. 4th Int. Conf. on Particle-based Methods, PARTICLES*, 2015.

[3] Delenne, J.-Y., El Yousoufi, M.S., Cherblanc, F., Bénet, J.-C. (2004) Mechanical behaviour and failure of cohesive granular materials, *Int. J. Numer. Anal. Meth. Geomech.*, **28**, pp.1577–1594.

Accretion Dynamics on Wet Granular Materials

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Wet granular materials are common precursors of construction materials, food, and health care products as well as relevant in many geophysical processes. However, the addition of liquid drastically modifies the behavior of a granular medium, and its rheological properties strongly depend on the proportion of the liquid [1,2]. Understanding how dry grains interact with wet grains requires coupling the dynamical interplay between the grains and the liquid.

In this study, we investigated experimentally the accretion process between a static wet granular material and flowing grains using a model experiment shown in Fig. 1(a). The accretion process results in the growth of the wet saturated aggregate upon impact of dry grains. We performed X-ray tomography experiments, which highlighted that this aggregate is fully saturated and its cohesion is ensured by the capillary depression at the air-liquid interface.

We showed that the growth dynamics is controlled only by the liquid fraction at the surface of the aggregate and exhibits two regimes as illustrated in Fig. 1(b). In the viscous regime, where the aggregate grows at a speed proportional to \sqrt{t} , the growth dynamics is limited by the capillary-driven flow of liquid through the granular packing to the surface of the aggregate. In the capture regime, the capture probability depends on the availability of the liquid at the saturated interface, which is controlled by the hydrostatic depression in the material and the aggregate growth is linear with the time t . We propose a model that rationalizes our observations and captures both dynamics based on the evolution of the capture probability with the hydrostatic depression [3].

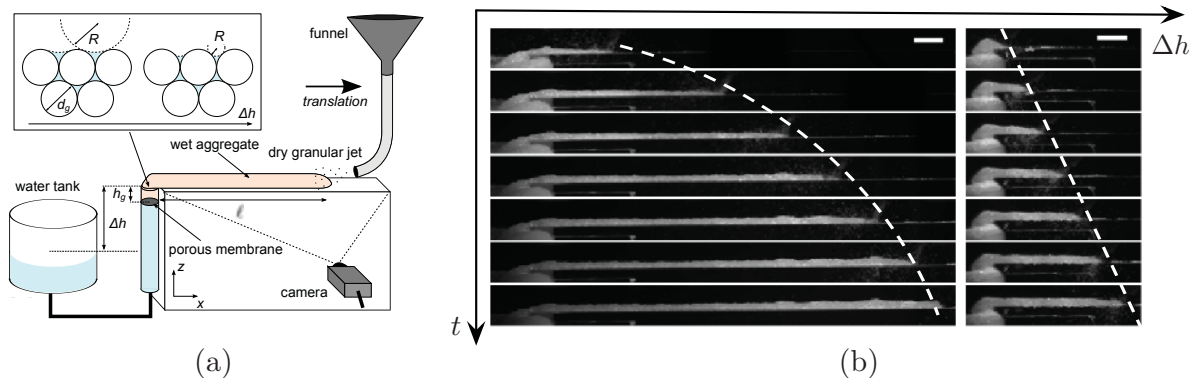


Figure 1: (a) Schematic of the experimental set-up. Inset: Schematic of the meniscus for increasing Δh . (b) Time evolution of the length of the aggregate for two different hydrostatic depressions, expressed as a function of Δh .

- [1] S. Herminghaus, Adv. Phys. **54**(3), 221-261 (2005).
- [2] S. Nowak, A. Samadani, and A. Kudrolli, Nat. Phys. **1**, 50 (2005).
- [3] G. Saingier, A. Sauret, and P. Jop, Phys. Rev. Lett. **118**(20), 208001 (2017).

16h30|18h30 Fluid-particle interaction and rheology/
Rheology and Continuous modelling

16h30 | Gradient regularization of the $\mu(I)$ model of dense granular flow - *Goddard et al.*

17h00 | Hysteresis and non-Newtonian rheology of a sheared gas-solid suspension - *Alam et al.*

17h30 | Turbulence locality and granularlike fluid viscosity in collisional suspensions - *Berzi et al.*

18h00 | Particle resolved simulation of a 3D periodic Couette dense bidispersed fluid-particle flow - *Scorsim et al.*

Gradient regularization of the $\mu(I)$ model of dense granular flow

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²Department of Chemical and Environmental Technology, Inha Technical College, Incheon, South Korea

This paper deals with the Hadamard (short-wavelength) instability of the so-called $\mu(I)$ model of dense rapidly-sheared granular flow, as reported recently by Barker *et al.* (2015, *J. Fluid Mech.*, **779**, 794-818). The present paper presents a more comprehensive study of the linear stability of planar simple shearing and pure shearing flows, with account taken of convective Kelvin wave-vector stretching by the base flow. The latter leads to asymptotic stabilization of the non-convective instability found by Barker *et al.*. We also explore the stabilizing effects of higher velocity gradients achieved by an enhanced-continuum model based on a dissipative analog of the Van der Waals-Cahn-Hilliard equation of equilibrium thermodynamics. This model involves a dissipative hyper-stress, as the analog of a special Korteweg stress, with surface viscosity representing the counterpart of elastic surface tension. We also present a model of shear bands based on the enhanced-continuum model. Finally, we propose a theoretical connection between non-convective instability of Barker *et al.* and the loss of generalized ellipticity in the quasi-static field equations.

Apart from the theoretical interest, the present work may suggest stratagems for the otherwise difficult numerical simulation of continuum field equations involving the $\mu(I)$ rheology or other visco-plastic models of fluid-particle flow that exhibit Hadamard instability.

Hysteresis and non-Newtonian rheology of a sheared gas-solid suspension

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May 26, 2017

The hydrodynamics and rheology of a sheared dilute gas-solid suspension, consisting of inelastic hard-spheres suspended in a gas, are analysed using anisotropic Maxwellian as the single particle distribution function. The closed-form expressions for three invariants (ϕ , η , λ^2) of the second-moment tensor and granular temperature (T) are obtained as functions of the Stokes number (St), the mean density (ν) and the restitution coefficient (e). Multiple states of high and low temperatures are found when the Stokes number is small. The phase diagram is constructed in the three-dimensional (ν , St , e)-space that delineates the regions of ignited and quenched states and their coexistence. Analytical expressions for the particle-phase shear viscosity and the normal stress differences are obtained, along with related scaling relations on the quenched and ignited states. At any e , the shear-viscosity undergoes a discontinuous jump with increasing shear rate (i.e. discontinuous shear-thickening) at the “quenched-ignited” transition. The first (\mathcal{N}_1) and second (\mathcal{N}_2) normal-stress differences also undergo similar first-order transitions: (i) \mathcal{N}_1 jumps from large to small positive values and (ii) \mathcal{N}_2 from positive to negative values with increasing St , with the sign-change of \mathcal{N}_2 identified with the system making a transition from the quenched to ignited states. The superior prediction of the present theory over the standard Grad’s method and the Chapman-Enskog solution is demonstrated via comparisons of transport coefficients with simulation data for a range of Stokes number and restitution coefficient. For both granular and gas-solid suspensions, it is shown that the excess temperature along the vorticity direction is responsible for $\mathcal{N}_2 \neq 0$, while the shear-plane anisotropies (ϕ and η) are responsible for $\mathcal{N}_1 \neq 0$.

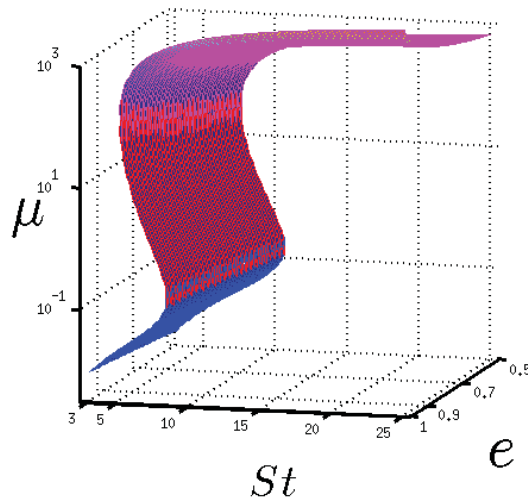


Figure 1: Hysteresis in viscosity for a dilute gas-solid suspension

Turbulence locality and granular-like fluid shear viscosity in collisional suspensions

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We re-analyse previous experimental measurements of solid volume fraction, mean velocity and velocity fluctuations in collisional suspensions of plastic cylinders and water flowing over inclined, erodible beds. We show that the particle pressure scales with the granular temperature as predicted by kinetic theory of granular gases. Assuming that also the particle shear stress is well predicted by kinetic theory permits the determination of the fluid shear stress and the effective fluid viscosity from the experiments. We suggest that the effective fluid viscosity in collisional suspensions has two components: one associated with the turbulence generated near the surface of the particles and one associated with the transfer of momentum of the fluid mass in conjugate motion with the fluctuating particles (Figure 1). We model the first contribution using a mixing length approach, and show that the mixing length is local, as it does not scale with distances from boundaries. The mixing length is less than one diameter and decreases with increase in the solid volume fraction. We introduce a granular-like viscosity to model the second contribution to the effective fluid viscosity, by replacing the particle mass density with the density of the added mass of the fluid in the expression of the granular viscosity of the particles of kinetic theory. Finally, we also show how the granular temperature scales in the turbulent and granular limits of the effective fluid viscosity.

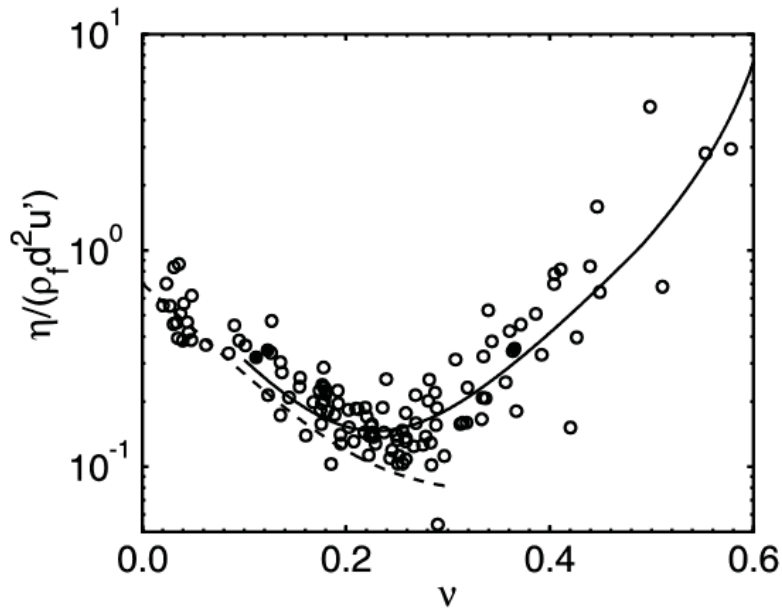


Figure 1: Measured (circles) and theoretical (lines) effective fluid viscosity scaled with the shear rate. At solid volume fractions less and greater than 0.2, the effective fluid viscosity has mainly a turbulent and a granular-like origin, respectively.

Particle resolved simulation of a 3D periodic Couette dense bidispersed fluid-particle flow

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Poly-dispersed fluid-particle flows are encountered in many industrial applications. Typical example is the fluidized bed reactor used for the polymerisation of olefins or the circulating fluidized bed employed for the Fluid Catalytic Cracking (FCC) of oil. These industrial flows are generally computed by using N-Euler approach. Despite the success of such methodology, it still relies on some assumptions, which are quite difficult to access or prove, given the fact that it is very difficult to measure particle-laden flows with enough resolution. Particle Resolved Direct Numerical Simulation (PR-DNS), enables high spatial and temporal resolution of the flow field around the particles, coupled with Discrete Element Method (DEM), for treating the inter-particle collisions, permit to test fundamental assumptions used in the industrial macro-scale (N-Euler) modeling.

PR-DNS of a 3D periodic Couette dense bidispersed fluid-particle flow was performed. The poly-dispersion is obtained by varying the density of the particles, thus creating lighter and heavier particles with same diameter. A mean shear is imposed by two moving walls with no-slip condition for the fluid and elastic bouncing for the particles. In the stream-wise and span-wise directions periodic boundaries are imposed.

The numerical simulations are analysed in terms of Eulerian statistics for both the fluid and the particle species. In the wall normal direction, the domain is decomposed in slabs where it is assumed that the particles are homogeneously distributed for performing spatial averaging of particle Lagrangian properties. It permits to measure the particle statistics as the mean density number of particles, the mean particle velocity and the particle kinetic stress tensor as others high-order moments. Such a methodology allows to perform a budget analysis of the Euler-Euler set of equations term-by-term. Especially, the particle-particle collision terms can be accurately measured and split in a source and a flux contribution as it is done in the framework of the kinetic theory of granular flows. The results show the redistribution of particle kinetic stress between particle species by inter-particle collision.

TUESDAY

9h30|10h30 **Granular avalanches/Keynote/**

Particle-Fluid Flows on Earth and Mars - *J. McElwaine*

10h30|11h00 Coffee break

11h00|12h30 **Granular avalanches/Dry and immersed granular flows**

12h30|14h00 Lunch

14h00|15h30 **Granular avalanches/Three-phase flows**

15h30|16h00 Coffee break

16h00|17h00 **Granular avalanches/Wave generation**

17h00 Visit IMFT labs

Particle-Fluid Flows on Earth and Mars

J. N. McELWAIN^{1,2}

¹Department of Earth Sciences, Durham University, UK

²Planetary Science Institute, Tucson, USA

Powder snow avalanches, turbidity currents, debris flows, and pyroclastic flows are all examples of Terrestrial geophysical flows with a strong coupling between particles and a fluid. The particles are suspended by turbulence and the excess weight of the mixture drives the flow down or along a slope. Similar flows have now been directly observed on Mars and there is indirect evidence on other planetary bodies. Observations of dune gullies and recurring slope lineae on Mars are evidence for entirely new classes of flows. There is controversy about the flow mechanisms but they are possible caused by carbon dioxide sublimation and thermo-diffusion, respectively. To understand these observations physics based models that can be correctly scaled to very different temperatures, pressure and gravitational fields are necessary. We describe several such models and how they can be tested and developed using a combination of direct numerical simulation, laboratory experiments and field observations.

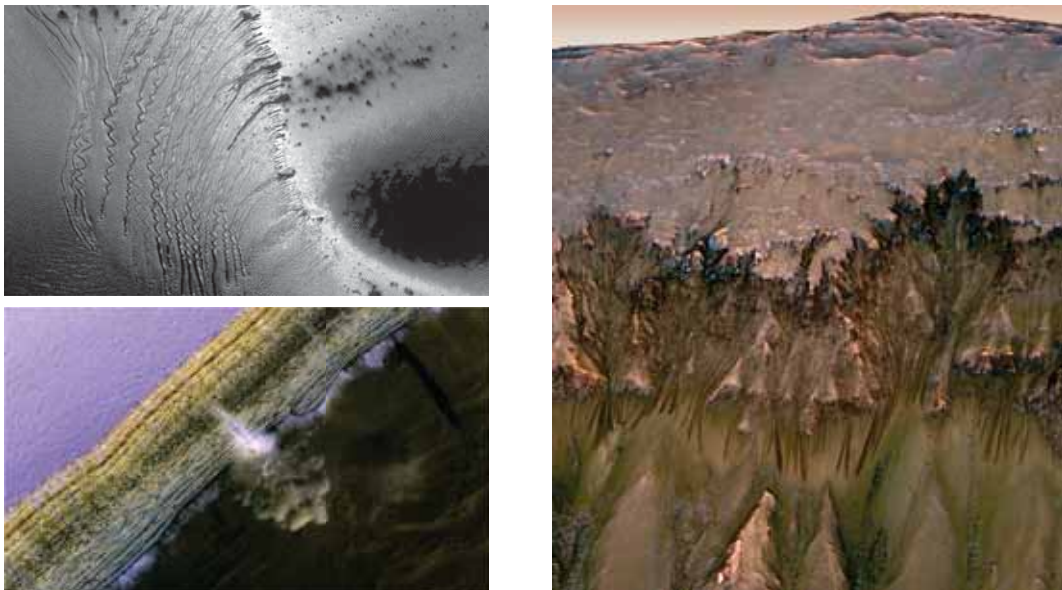


Figure 1. All picture are of Mars with HiRISE. Top left: Gullies in a dune field in Kaiser Crater. Bottom Left: CO₂ powder snow avalanche. Right: Recurring slope lineae in Newton Crater.

11h00|12h30 Granular avalanches/Dry and immersed granular flows

11h00 | A laboratory-numerical approach for quantifying scale effects in dry granular slides - *Kessler et al.*

11h30 | Immersed granular collapse : numerical modelling - *Lacaze et al.*

12h00 | A two-phase solid-fluid model for dense granular flows including dilatancy effects: comparison with submarine granular collapse experiments - *Bouchut et al.*

A laboratory-numerical approach for quantifying scale effects in dry granular slides

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Granular slides are ubiquitous in nature and industry though a universal model to predict granular slides is difficult to realise due to their complex and transient nature. Laboratory experiments are essential in enhancing our physical understanding of granular flows and supporting hazard mitigation. However, scale effects are a major drawback of using laboratory experiments in a predictive manner [1], resulting in safety issues when modelling natural events (e.g. by underestimation of the runout) and hindering efficient industrial design. Quantifying scale effects in granular slides is thus an essential open question.

Thus, a new experimental setup has been developed to quantify scale effects in both 2-D and 3-D geometries (Figure 1a), using Froude scaling. Granular slides up to 1 m wide consisting of 2 – 4 mm large polydisperse diameter particles have been investigated at 1:2 and 1:4 scales and compared to a 1:1 scale reference slide. Measurements of the slide surface kinematics and flow thickness were recorded with high-speed imaging and particle image velocimetry. Photogrammetry techniques were used to measure the slide deposits. These physical model tests are complemented by Discrete Element Modelling (DEM) using LIGGGHTS-DEM [2,3], allowing a wider range of scales to be evaluated. The numerical model has been validated with axisymmetric column collapse laboratory tests and the classical granular slide tests of Hutter and Koch [4], before being applied to the new laboratory tests (Figure 1b). Here we focus on physical model tests conducted at the scales 1:2 and 1:4 in two dimensions, complemented by DEM simulations. DEM results show excellent agreement with the 1:2 laboratory experiments for slide surface velocities (Figure. 1c) and runout distance. DEM was further used to investigate a larger scale range from 5:1 to 1:20, currently not capturing any scale effects. We will continue to explore this combined laboratory-numerical multi-scaling approach to identify and quantify scale effects.

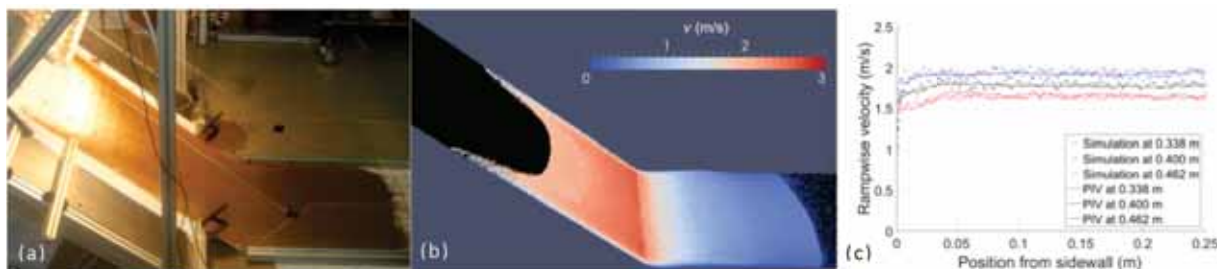


Figure 1: Granular slides at scale 1:2 (a) Laboratory experiment, (b) DEM simulation and (c) comparison between laboratory and numerical instantaneous surface velocities at $t = 0.61$ s (relative to initial front position at $t = 0$).

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Immersed granular collapse: numerical modelling

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The spreading of a granular column in a liquid is investigated using numerical modellings at two different scales. The granular phase is solved with a discrete elements method (DEM) while the fluid phase is solved either at the grain scale (immersed boundary method - IBM) or at a scale of few grains (spatially averaged Navier-Stokes equations - ANS). The larger scale approach (ANS) allows to increase the size of the system and therefore the number of grains used to define the granular medium but closure terms are then needed to model fluid-grain interaction at the fluid sub-mesh scale. A comparison between the two methods then allows to select the pertinent closure models for the present configuration among the numerous models available in the literature.

While the mostly pertinent dimensionless parameter was shown to be the initial aspect ratio a for the dry case, i.e. when neglecting the influence of the surrounding fluid, the Stokes number St is shown here to be also a significant dimensionless parameter to describe the dynamics of the column collapse when the surrounding fluid is accounted for. The influence of this parameter is discussed through the analysis of the collapse dynamics and morphology of the final deposit.

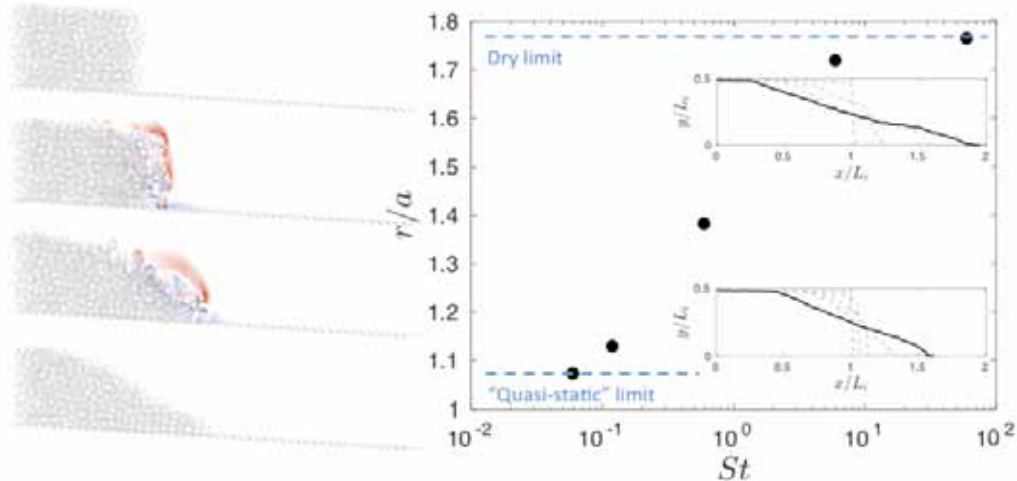


Figure 1: Snapshots of the collapse of an initial $a = 0.5$ column (IBM/DEM simulation). Evolution of the dimensionless runout r (spreading length) as a function of St .

A two-phase solid-fluid model for dense granular flows including dilatancy effects: comparison with submarine granular collapse experiments

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Describing grain/fluid interaction in debris flows models is still an open and challenging issue with key impact on hazard assessment [1]. We present here a two-phase two-thin-layer model for fluidized debris flows that takes into account dilatancy effects. It describes the velocity of both the solid and the fluid phases, the compression/dilatation of the granular media and its interaction with the pore fluid pressure [2]. We first compare experimental and numerical results of dilatant dry granular flows. Then, by quantitatively comparing the results of simulation and laboratory experiments on submerged granular flows [3], we show that our model contains the basic ingredients making it possible to reproduce the interaction between the granular and fluid phases through the change in pore fluid pressure (Figure 1). In particular, we analyse the different time scales in the model and their role in granular/fluid flow dynamics.

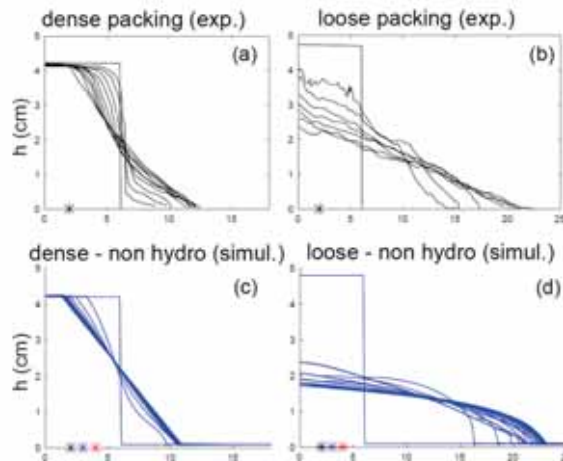


Figure 1: Comparison between experiments (a-b) and simulation (c-d) of submerged granular collapse.

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14h00|15h30 Granular avalanches / Three-phase flows

14h00| Wet granular collapse on a horizontal plane : from immersed to fluid-saturated granular columns - *Bougouin et al.*

14h30| Just-saturated column collapse - *Turnbull et al.*

15h00| Collapse of a water-saturated granular column in air - *Aussillous et al.*

Wet granular collapse on a horizontal plane : from immersed to fluid-saturated granular columns.

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The slumping of complex fluids on a horizontal plane is one of the most popular laboratory configuration to mimic natural hazards such as avalanches or landslides. In the case of granular materials, referred to as granular collapse, studies are mainly focused on dry granular flows, for which the surrounding fluid can be neglected [1, 2]. In this case, the relevant dimensionless parameter which controls the final deposit was shown to be the aspect ratio of the initial column. When the surrounding fluid can not be neglected, other parameters, such as the initial volume fraction among others, were shown to affect the dynamics of the granular medium [3].

In the present contribution, two different experimental configurations are presented. First, the case of a granular collapse immersed in a liquid bath is revisited [3]. The dynamic of the collapse is shown to depend on the relative contribution of the driving force induced by gravity and the viscous dissipation leading to the three different regimes: *free fall*, *viscous* and *inertial* [4]. The velocity and time scales as well as scaling laws of the final deposit are analysed and discussed according to these regimes. A specific attention is paid to the the inertial regime which remains probably one of the most pertinent regime for geophysical applications. In this regime, the dynamics is shown to highlight very specific features such as a turbidity current-like dynamic at large aspect ratio for instance. This study is then extended to the case of the collapse of a fluid-saturated granular column in air. In this case, the capillary effect is also shown to play a role on the final morphology of the granular column. In this case, the final deposit is shown to mostly depend on both the Bond number and the initial aspect ratio.

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Just-saturated column collapse

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Debris flows are gravity-driven sub-aerial mass movements containing water, sediments, soil and rocks. These elements lead to characteristics common to dry granular media (e.g. levee formation) and viscous gravity currents (viscous fingering and surge instabilities). The importance of pore fluid in these flows is widely recognised, but there is significant debate over the mechanisms of build up and dissipation of pore fluid pressure within debris flows and the resultant effect this has on dilation and mobility of the grains.

We start with a simple experiment constituting a classical axisymmetric granular column collapse, but with fluid filling the column up to the depth of grains (Figure 1). As the column collapses, capillary and viscous forces may be generated between the grains that inhibit dilation. We explore a parameter space to uncover the effects of fluid viscosity, surface tension, particle size, column size, aspect ratio and the effects of fine sediments in suspension, which can alter the capillary interaction between wetted macroscopic grains. A scaling analysis shows how Capillary (Ca) and Bond (Bo) numbers control different phases of the collapse - from drainage controlled slumping to surface tension controlled run out - and how different characteristic length scales each play their part.

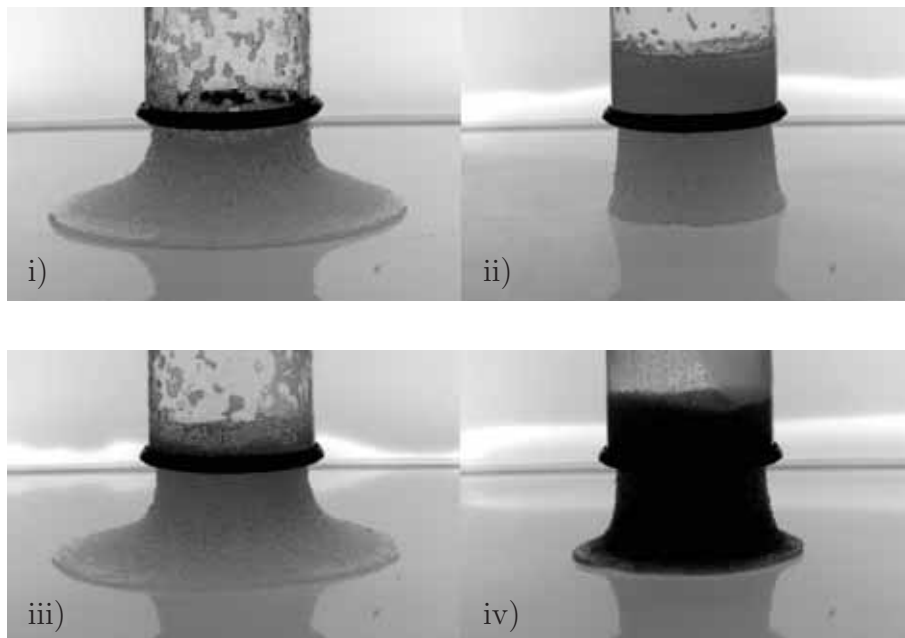


Figure 1: The initial stages of a just-saturated axisymmetric column collapse, aspect ratio 1, 2 mm glass beads, column diameter 110 mm: i) with water, $Ca \approx 1$, $Bo \approx 10$; ii) with glycerol solution $Ca \approx 10$, $Bo \approx 10$; iii) with water-surfactant $Ca \approx 1$, $Bo \approx 10^2$; iv) with 10% by volume kaolin suspension $Ca \approx 1-10$, $Bo \approx 10$.

Collapse of a water-saturated granular column in air

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We study experimentally the collapse of a granular column saturated with water. The granular column is initially stabilized by an air interface with an imposed Laplace pressure difference. We study the dynamics of the column when the Laplace pressure suddenly vanishes. The collapse is initiated either by a light knock, imposing the volume of water constant, or by imposing a constant positive fluid pressure.

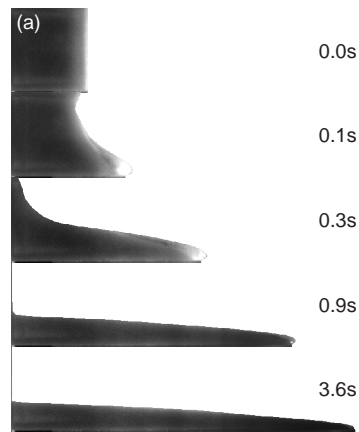


Figure 1: Collapse of an initially loose water-saturated granular column

Similarly to the collapse of a fully immersed granular column ¹, the morphology of the deposit is mainly controlled by the initial volume fraction of the granular mass. Different regimes are identified according to the initial packing and the way the collapse is initiated. The initial loose packed columns give long and thin deposits with a fast dynamic that do not seem to depend on the collapse initiation (figure 1). For dense packing, no motion is seen when the volume of water is kept constant, whereas the slow dynamics seem to depend on the imposed fluid pressure. We compare the results to a depth-averaged two-phase continuum model, having a frictional rheology to describe particle-particle interactions ^{2,3}, and taking into account the mechanisms of dilatancy ⁴, which can capture most of the experimental observations for the collapse of fully submerged granular columns.

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²Ouriemi et al., *J. Fluid Mech.* **636**, 295–319 (2009).

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⁴Pailha et al., *J. Fluid Mech.* **633**, 115–135 (2009).

16h00|17h00 Granular avalanches / Wave generation

16h00| Tsunami wave generation by a granular collapse - *Robbe-Saule et al.*

16h30| A granular model for snow avalanches entering water basins - *Zitti et al.*

Tsunami wave generation by a granular collapse

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Although many tsunamis arise from tectonic events, various past geological events have shown that landslides near coastlines can lead to tsunami waves of significant amplitude [1]. Despite this important hazard, tsunamis generated by landslides remain poorly understood and difficult to model, leading to a very approximated estimate of the associated hazards. While the generation of tsunamis by a solid block has been widely studied since the 1970s, more realistic modeling requires taking into account the granular nature of the landslide [2]. Here, we investigate a model situation consisting in the collapse of a dry granular column into shallow water, leading to the generation of an impulse wave. We focus our attention on the generation mechanisms of the first wave and not on its later propagation.

The experimental set-up consists of a rectangular tank of 2 m long and 0.15 m wide in which a sliding gate maintains initially a column of mass M , height H_i and length L_i of monodisperse dry grains. The dynamics of the granular collapse into water of depth h_0 and the subsequent wave generation are recorded by means of a video camera from the side of the tank (fig. 1). In particular we extract the wave amplitude and wavelength when varying the aspect ratio $a = H_i/L_i$ of the granular column, the total mass of grains M and their diameter d , and the water depth h_0 .

The experimental results show that both the amplitude and the width of the leading wave are proportional to the mass of the falling column for small aspect ratio of the column ($a \lesssim 4$) while they both saturate for larger aspect ratio ($a \gtrsim 4$), suggesting that the leading wave is generated before the collapse is fully completed.



Figure 1: Three successive images separated by the same time interval $\Delta t = 0.6$ s from the time origin $t = 0$ (left image) where the granular column (aspect ratio $a = 2.5$ and mass $M = 3.9$ kg) of $d = 5$ mm glass beads is released by the gate opening and fall into water of depth $h_0 = 55$ mm.

This work was supported by CNRS through its multidisciplinary program “Défi Littoral” in 2015 and 2016 via the projects SlideWave and SlideWave2.

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- [2] S. Viroulet, A. Sauret, O. Kimmoun, *EPL* **105**, 34004 (2014).

A granular model for snow avalanches entering water basins

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The description of snow avalanches entering a water body is a challenging matter, mainly because of the density of the impacting material. Snow particle density is slightly lower than water density and the bulk also undergoes a significant volume expansion during the slide. In particular, snow avalanche bulk density can range from 10 to 500 kg/m³ during the flow and, when the avalanche strikes a water basin, it experiences an uplift buoyancy force and complicated solid-fluid interactions. We study the dynamics of the impacting mass and impacted fluid by means of a simplified two-dimensional model, which exploits the analogy between flowing avalanches and granular flows. Using a granular flows enables one to vary the bulk density at impact and choose a material with a particle density comparable to that of the snow.

The problem has been first tackled analytically, by applying the theory of multi-phase mixtures to a control volume located at the inlet (left panel in Figure 1). The application of the conservation principles leads to dimensionless numbers featuring avalanche impact. Furthermore, observations suggest that the motion of the bulk after the impact may be described as a simple damped harmonic oscillator.

The experimental set-up was based on the Froude similarity with snow avalanches. It was composed of a wooden inclined chute, whose downstream end was in contact with a prismatic flume filled with water. The bulk of expanded clay particles was released from the upstream end of the chute and slid until it hit the water basin (right panel in Figure 1), generating a water wave that propagated along the flume. The characteristics of both the generated wave and the motion of the impacted mass have been recorded with high-speed cameras and related, using nonlinear regressions, to the avalanche characteristics. As a result, a simple damped harmonic oscillator with constant coefficients is found able to capture the motion of the submerged mass barycentre with an error smaller than 10% in 75% of the cases.

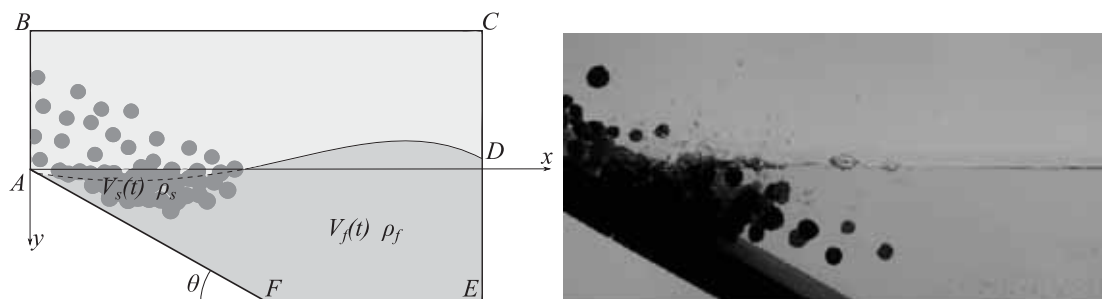


Figure 1: Control volume (theoretical model in the left panel and correspondent experimental model in the right panel). In the left panel the impacting granular mass is in dark grey, the water in grey and the air in light grey. V_s , V_f , ρ_f and ρ_s are the granular volume, the fluid volume, the particle density and the fluid density, respectively.

WEDNESDAY

9h00|10h00 **Sediment transport / Keynote**

Fluid-Particle Flow at and near a Particle Bed - *J. Jenkins*

10h00|10h30 Coffee break

10h30|11h30 **Sediment transport Hydrodynamics modelling**

11h30|12h30 **Sediment transport / Weak and intense sediment transport**

12h30|14h00 Lunch

14h00|16h00 **Sediment transport / Focus on bedload**

16h00|16h30 Coffee break

16h30|18h00 **Sediment transport / Focus on bedload**

20h00 Social Event : dinner

Fluid-Particle Flow at and near a Particle Bed

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We describe continuum models for the interaction of particles at and near a horizontal particle bed, under a turbulent shearing flow of a liquid. We focus on situations that are steady and uniform in the flow direction. The particles are subject to gravity and the drag of the liquid above bed; they also experience fluid-mitigated collisions with particles of the bed and, perhaps, similar collisions with particles above the bed.

For modest strengths of shearing flow, a dilute cloud of saltating (jumping) particles above the bed exchange momentum with the fluid and collide with and rebound from particles of the bed. Because the cloud is dilute, regions of the bed subject to collisions are able to relax between collisions.

As the strength of the turbulent shearing above the bed increases, the momentum transfer between the fluid and particles above the bed is augmented by collisions between particles, and regions of the bed that experience a collision are not able to relax between collisions. With further increases in shearing strength, a dense cloud of colliding particles forms beneath a more dilute cloud of saltating and colliding particles over a bed that is agitated, with an agitation that diminishes into its interior.

We will introduce models for the flow and the bed in the limits of pure saltation and pure collision and discuss possible ways that the two extremes can be linked and/or combined to provide the transition from one to the other.

10h30|11h30 Sediment transport / Hydrodynamics
modelling

|10h30| Mixing length and friction factors in the transitional regime -
Colombini et al.

|11h00| Fluid flow over ripples and dunes - *Charru et al.*

Mixing length and friction factors in the transitional regime

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The law of the wall is ultimately a simple way to describe the mean velocity profile in wall-bounded flows. Indeed, this concept has been so successful in the study of turbulence that the term 'universal' is often added to testimony its generality. Moreover, by suitably modifying the constant of integration (or, equivalently, the reference level at which the logarithmic profile of velocity vanishes), the effect of the wall roughness can be accounted for. Three different degrees of roughness can be distinguished [1]: i) hydraulically smooth, where the roughness is entirely embedded in the viscous sublayer; ii) transient roughness, whereby the velocity profile depends on the roughness Reynolds number; iii) completely rough, when the size of the roughness elements is so large than the viscosity of the fluid has little or no influence on the whole motion.

The first part of the present contribution is devoted to an analysis of the relationships which relate, in pipe and open-channel flows, the reference level of the logarithmic profile with the friction factor and with the roughness function that expresses the 'slip-velocity' at the roughness height. These three quantities are obviously interrelated so that only one of them needs to be fitted with experimental results, which also allow for the determination of a suitable morphing function that covers the transitional regime as well.

The second part deals with the mixing length. The concepts of logarithmic law and of mixing length went hand in hand from the very beginning. Indeed, it is a simple matter to show that the logarithmic law of the wall is obtained if the mixing length is assumed to linearly increase with the distance from the wall and the velocity vanishes at the reference level. The effect of viscosity can be accounted for making use of the van Driest [2] exponential correction and introducing a vertical shift, which depends on the roughness Reynolds number [1]. However, following this approach, the region influenced by viscosity extends far more than necessary since, in the rough regime, the velocity profile is slow in recovering the expected logarithmic law. In order to correct this behaviour, the van Driest factor is considered herein as dependent on the roughness Reynolds number, so that the van Driest correction progressively vanishes moving from the smooth to the rough regime.

Finally, an example of application of the above concepts to the linear stability analysis of ripple formation in rivers is presented.

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Turbulent flow over a wavy boundary

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The linear response of the shear stress exerted by laminar flow over a wavy surface (i.e. for small-amplitude bottom topography) is characterized, as shown by Benjamin (1959), by a boundary-layer scaling that produces analytical formulas; it occurs in a range of wave numbers bounded on the right (high wavenumbers) by the viscous Couette flow limit, and on the left (small wavenumbers) by the interaction with the free surface or opposing wall. The ensuing phase shift between shear stress and wall waviness plays a crucial role, in particular, in the growth of sand ripples and dunes (Charru *et al.*, 2013).

However, the flow over ripples and dunes is most often turbulent. For such turbulent flow, the existence, for intermediate wavenumbers, of a laminar region has been plausibly conjectured; we show that direct numerical simulations support this conjecture, when the laminar perturbation equation is solved around the mean turbulent flow (Luchini and Charru, 2017). This response may thus be denominated quasilaminar.

Because the quadrature response decays on both sides of the wavenumber spectrum, for short waves because of viscous effects and for long waves as an empirical observation in both experiments and direct numerical simulations, the quasilaminar region acquires a dominant role. A quadratic rational approximation allows the dominant response to be interpolated accurately, in a dimensionless form independent of the Reynolds number or any other parameter, and is available as a reference for further studies of sand transport.

References

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- Luchini, P., and Charru, F. 2017 Quasilaminar regime in the linear response of a turbulent flow to wall waviness, *Phys. Rev. Fluids.* **2**, 012601(R).

11h30|12h30 **Sediment transport / Weak and intense sediment transport**

|11h30| Inhomogeneous aeolian sand transport - *Selmani et al.*

|12h00| SedFoam: an open-source multi-dimensional two-phase flow model for sediment transport applications - *Chauchat et al.*

Inhomogeneous aeolian sand transport

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We investigate experimentally the relaxation process toward the equilibrium regime of saltation transport in the context of spatial inhomogeneous conditions. The relaxation length associated to this process is an important length scale in aeolian transport. This length stands for the distance needed for the particle flux to adapt to a change in flow conditions or in the boundary conditions at the bed. Predicting the value of this length under given conditions of transport still remains an open issue. We conducted wind tunnel experiments to document the influence of the upstream particle flux and wind speed on the relaxation process toward the saturated transport state. In the absence of upstream particle flux, data show that the relaxation length is independent of the wind strength (except close to the threshold of transport). In contrast, in the case of a finite upstream flux, the relaxation length increases with increasing air flow velocity. Importantly, in the latter case, the relaxation is clearly non-monotonic and presents an overshoot (see Figure 1). The experimental outcomes are finally analyzed in the light of the available models of the literature.

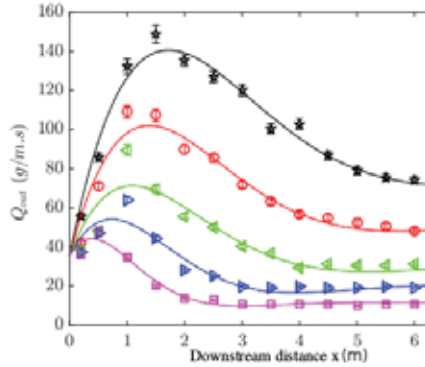


Figure 1: Spatial evolution of the mass flow rate Q as a function of the downstream distance x for various wind speeds (6, 7, 8, 9 and 10 m/s): The upstream mass flux at $x = 0$ is set at a finite value: $Q_{upstream} = 35.6g/s$

sedFoam: an open-source multi-dimensional two-phase flow model for sediment transport applications.

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In this communication, we report on a community research effort to develop and disseminate an open-source multi-dimensional two-phase flow Eulerian sediment transport model under the CFD toolbox openFoam. Two granular stress models and different turbulence models are implemented, namely the $\mu(I)$ dense granular flow rheology (*GDRmidi*, 2004) and the kinetic theory of dense granular flows (*Jenkins and Hanes*, 1998); and zero equation eddy viscosity model (mixing length), Reynolds averaged two equations turbulence models ($k - \epsilon$ and $k - \omega$) and Large Eddy Simulation (LES). The model has been tested on unidirectional sheet flows using different combinations of granular stress and turbulence models. Figure 1 shows an intercomparison based on *Revil-Baudard et al.* (2015) experimental data using the $\mu(I)$ rheology or the kinetic theory and a $k - \epsilon$ model or a LES model. The model results, for a given turbulence model, are sensitive to the choice of the granular stress model. The $\mu(I)$ rheology reproduces the velocity profile in the denser region of the flow whereas the kinetic theory exhibits too strong velocity gradients in this region suggesting that the frictional component in the kinetic theory (Coulomb model) underestimate the dissipation. The LES results, using a dynamic Smagorinsky and a functional subgrid stress and drag models respectively coupled with the kinetic theory, is able to predict almost quantitatively the velocity and concentration profiles. Consistently with *Revil-Baudard et al.* (2015) observations, this result confirms the role played by the large scale turbulent coherent structures on the sediment bed dynamic. Beyond this rather simple flow configuration, the multi-dimensional capabilities of the numerical model has been used to study the scour phenomenon in different geometries. A short summary of preliminary results will be presented during the conference and an overview of future research perspectives will be drawn.

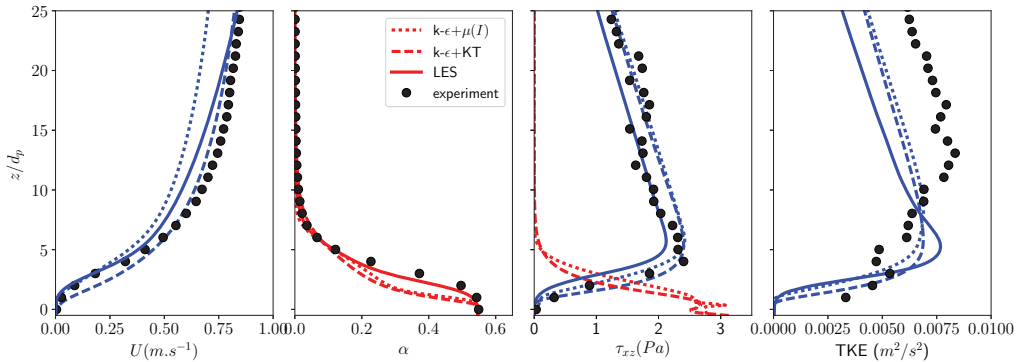


Figure 1: Comparison of two-phase numerical results with experiments of *Revil-Baudard et al.* (2015) in terms of velocity, volume fraction, Reynolds shear stress and turbulent kinetic energy using different combinations of granular stress and turbulence models.

14h00|16h00 Sediment transport / Focus on bedload

14h00 | Sediment transport in laminar channel flow: On the rheology of the mobile sediment layer - *Kidanemariam et al.*

14h30 | Unified Theory of Sediment Transport Cessation - *Pähtz et al.*

15h00 | Wandering grains: entrainment and movement of sediments along a streambed - *Fraccarollo et al.*

15h30 | On length and duration of bed-load particle hops: can we obtain unbiased mean values from biased samples? - *Ballio et al.*

Sediment transport in laminar channel flow: On the rheology of the mobile sediment layer

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We have performed a series of fully-resolved direct numerical simulations of a horizontal laminar channel flow over a thick bed of mobile sediment particles. The simulations are identical to those reported in [1, 2]. Therein, we have investigated, among other aspects, the scaling of the particle flow rate as a function of the Shields number. In this talk, we present results of our further analysis with respect to the contribution of the hydrodynamic and inter-particle collision forces to the momentum transfer between the two phases. As is shown in figure 1, for the considered parameter values, the flow exhibits three distinct regions: the clear fluid (I), the mobile granular layer (II) and the stationary bed (III) regions. In region I, the driving pressure gradient forcing is almost entirely balanced by fluid viscous shear force while in region III, it is balanced by the inter-particle collision forces. In region II on the other hand, both phases contribute to the stress balance. Moreover, based on the DNS data, we have evaluated the rheological properties of the sediment-fluid mixture to assess the prediction of a suspension rheology model [3].

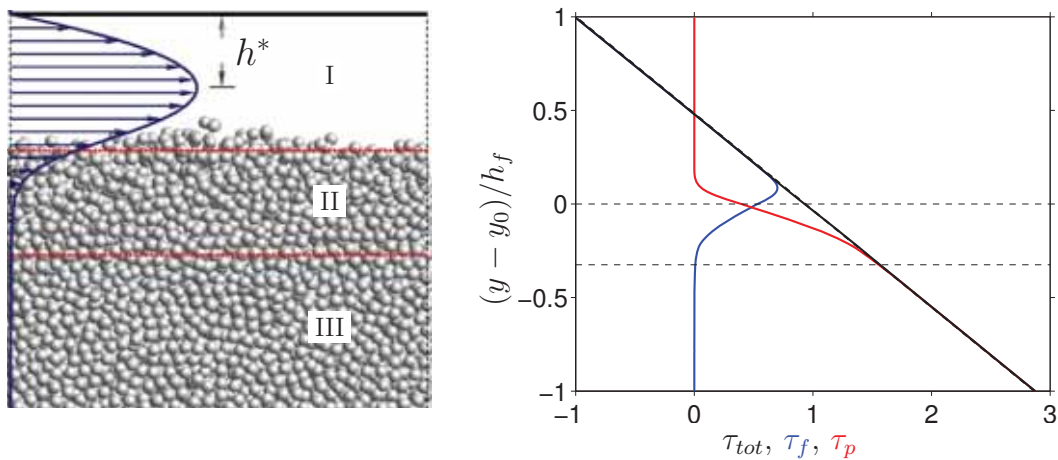


Figure 1: (a) Schematic diagram showing the configuration of the bedload transport simulations. The clear fluid region, the mobile granular layer and the stationary bed region are denoted by I, II and III consecutively. (b) Wall-normal profiles of the mean fluid shear stress (τ_f), mean particle shear stress (τ_p) and the mean total shear stress ($\tau_{tot} = \tau_f + \tau_p$)

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Unified Theory of Sediment Transport Cessation

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Here we study sediment transport cessation using direct numerical simulations of sediment transport in an arbitrary Newtonian fluid. We find that there are two distinct threshold values of the dimensionless fluid shear stress (‘Shields number’) Θ : Below the rebound threshold Θ_t^r , steady transport states cease to exist because the flow is not strong enough to compensate momentum losses of transported particles during an average rebound so that a continuous rebound state cannot be maintained. This threshold is the one that appears in formulas predicting the sediment transport rate and thus highly relevant for geomorphological applications. Below the larger entrainment threshold Θ_t^e , steady transport states cease to be stable and become metastable because entrainment of bed sediment, which is predominantly caused by particle-bed impacts in our simulations (except for viscous bedload transport), is not strong enough to compensate random losses of rebounding particles by supplying the transport layer with sufficient high-energy particles that can participate in the continuous rebound state. Metastable transport states are therefore characterized by a potentially long period of transport that, however, will eventually stop. We find that the frequency of particle-bed impacts has a major influence on the outcome of a single impact and thus controls Θ_t^e . Guided by the simulations, we derive a theory predicting Θ_t^r in arbitrary environments that is based on describing a continuous rebound state rather than sediment entrainment. Despite not considering lift and history forces, and fluctuations around the mean turbulent flow, both theory and simulations are, simultaneously, quantitatively consistent with available measurements in air and viscous and turbulent liquids *without being fitted to them*. Based on the theory, we propose a threshold diagram that unifies bedload and saltation transport (Fig. 1).

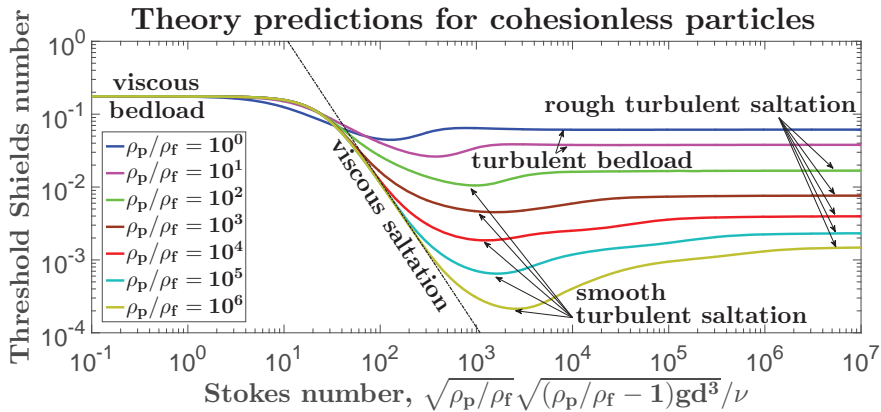


Figure 1: **Threshold diagram unifying transport regimes.** Shields number Θ_t^r at rebound threshold versus Stokes number for various particle-fluid-density ratios.

Wandering grains: entrainment and movement of sediments along a streambed

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At low values of bed slope and of Shield stress, bedload transport results from the entrainment, migration and disentrainment of grains which interact mainly with the fluid and with the grains at rest, paving the bed. During the displacement, grains roll, slide and/or jump above the bed. The sediment flux may be devised, on one side, as the crossing of particles at a given section or, on the other side, as a discontinuous exchange of particles between the bed and the layer of moving grains. The former view represents an Eulerian approach, the latter a Lagrangian one. The different views imply a different approach to the evaluation of the sediment transport. Given the random occurrence of all the steps taking place in a grain trajectory, including the resting stage in the bed, statistical approaches and information have been exploited to describe the ordinary bedload process, in particular within the Lagrangian description. Quite schematic mechanical or statistical approaches have been developed, in the past, to express the capacity of a given reach, under uniform steady conditions and well sorted sediments, to carry sediments. Well known and widely used algebraic relations (Shields, 1936; Meyer-Peter and Müller, 1948; Einstein, 1950; Bagnold, 1956) have been developed decades ago, forming the basis of a huge scientific deepening and validation effort.

In this work we first tried to provide experimental information on the predictors associated to the statistical interpretation. Then, we exploited a simple schematic description of the momentum and energy balance associate to grains flights to recover a mechanical interpretation of the experimental results. In Figure 1 it is shown a sequence of snapshot illustrating the progressive modification of a bed domain with time. Our experimental dataset consists of such images and of the reconstruction of pieces of trajectories.

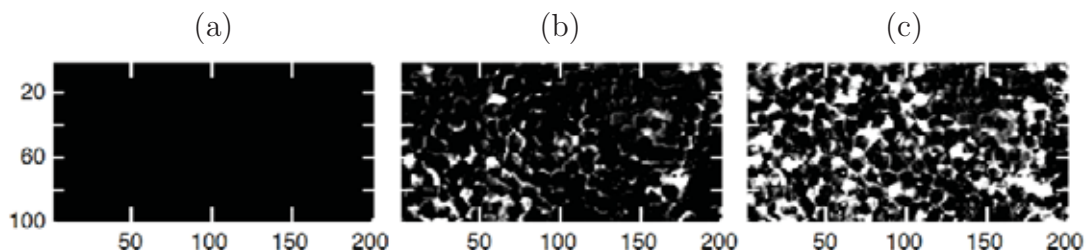


Figure 1: Panels a, b, c: time sequence of artificial images, evolving with time from left to right, where black pixels indicate no variation between the image at the present time and a reference initial image. White spots, on the contrary, indicate local changes (i.e., entrainment/distrainment) in the bed surface. Units are pixels

On length and duration of bed-load particle hops: can we obtain unbiased mean values from biased samples?

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We present results from several experiments with weak bed load. The friction velocity ranged from 1.2 to 1.8 times the threshold value for sediment transport. The experiments were performed releasing bed-load particles over a fixed, rough bed, that was created gluing sediment grains over plates. Both the bed particles and the released particles were Polybutylene-Terephthalate material with size of 3 mm and density of 1.27 g/cm³. Image analysis was applied to track each moving particle along its trajectory; to simplify the tracking procedure, the rough bed was painted in black while the released particles were white.

At any instant, a particle was either moving or at rest, due to the intermittent nature of the bed-load process. Identification of the instantaneous particle state from experimental data is not a trivial issue, and was addressed introducing an appropriate criterion based on comparing the position of the particle at a certain instant with all the positions taken before and after that instant. A binary function thus represented the state of motion or rest for each particle. Transitions in this function identified particle entrainment and disentrainment events. Based on these events, particle hops could be identified as a particle history between an entrainment and the following disentrainment.

Statistics of particle hops were obtained for all the performed experiments. Mean values of the hop properties (length, duration) could be computed. However, many incomplete hops were observed when a particle crossed the boundaries of the focus area maintained during the experiments (Figure 1). Mean values computed above were therefore considered biased, because many particle hops had to be excluded from the samples as non-completely observed. A method is proposed to compute unbiased mean values of hop length and duration based on the experimental data for completely and non-completely observed hops. A comparison is proposed between the obtained mean values (both biased and unbiased) and analogous values from the literature.

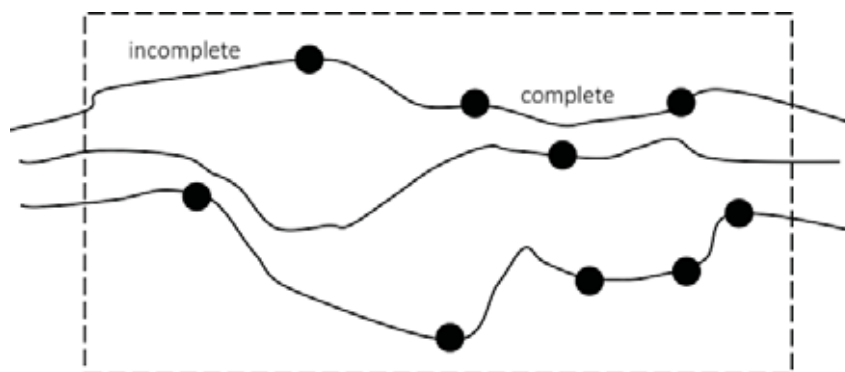


Figure 1: Sketch of complete and incomplete hops, with dashed lines representing an area of observation and circles as particle rest positions.

16h30|18h00 Sediment transport / Focus on bedload

16h30| Revisiting slope influence in turbulent bedload transport: consequences for vertical flow structure and transport rate scaling - *Maurin et al.*

17h00| Comparison of theory, simulations, and experiments for turbulent bed-load profiles - *Ni et al.*

17h30| Derivation of a bedload transport model with viscous effects - *Audusse et al.*

Revisiting slope influence in turbulent bedload transport: consequences for vertical flow structure and transport rate scaling

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Slope influence in sediment transport has been extensively studied [1, 2] regarding its importance in natural configurations such as mountain streams, dunes or coasts. Focusing on turbulent bedload transport, we put in evidence that the classical slope correction derived for the critical Shields number relies on an erroneous expression of the buoyancy force. Going further by analyzing the two-phase continuous equations, we explicit the entrainment mechanisms of the granular phase and underline the ommitted importance of the fluid flow inside the granular bed. The analysis allows us to predict the scaling of the sediment transport rate and the evolution of the vertical depth profiles in gravity driven turbulent bedload transport. Performing simulations with a coupled fluid-discrete element model [3], we show that the prediction are validated in idealized bedload transport [4]. This work allows us to clarify the role of the slope in turbulent bedload transport and make theoretically the link between bedload transport and debris flow.

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Comparison of theory, simulations, and experiments for turbulent bed-load profiles

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Although measurements of bed-load transport rates have been available for a long time, it is only recently that experiments have started to resolve profiles of velocity, granular concentration, and stresses within bed-load transport layers. This provides new opportunities to test and improve theoretical and modeling approaches. Combining results from previous experiments and preliminary data from new experiments, we will report comparisons with two different modeling approaches: 1) a simplified continuum two-phase theory, and 2) hybrid simulations coupling a continuum model of the fluid phase with a discrete particle model of the granular phase. By triangulating between theory, simulations and experiments, we hope to clarify key mechanisms and identify some current model limitations.

Derivation of a bedload transport model with viscous effects

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The simulation and prediction of sediment transport are relevant for environmental engineering purposes. Two transport modes exist: bedload transport, and suspended load transport. We deal here with the former and we focus on the context of river hydraulics. The Shallow Water-Exner system is commonly used to model it. However, this model requires an empirical closure relationship for the sediment discharge. Many closure relationships exist, and the choice of the relationship is not always obvious. We aim at proposing a new bedload transport model without closure relationship. Our model is deduced from a fluid description of the sediment layer. It is obtained by performing simultaneously the Shallow-Water approximation and the diffusive limit in the Navier-Stokes equations, see figure 1. Different scalings of the viscosity coefficient allow to obtain an equation for the solid discharge with or without viscous term. The bilayer model (water and sediment layer) has an associated energy. In the inviscid case, the correspondence with classical solid discharge formulas used in hydraulic engineering is shown. A threshold for the onset of motion can be added in the model. Numerical results are presented.

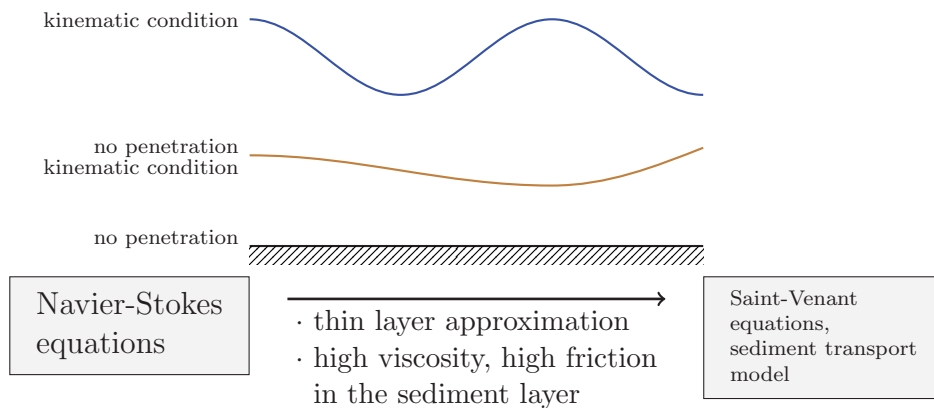


Figure 1: Strategy for the model derivation

THURSDAY

9h30|10h30 Morphodynamics - Bed stability /
Keynote/

Shape, size and stability of alluvial rivers - *E. Lajeunesse*

10h30|11h00 Coffee break

11h00|12h30 Morphodynamics - Bed stability /
Morphodynamics and dunes

12h30|14h00 Lunch

14h00|16h00 Morphodynamics - Bed stability /
Ripples

Shape, size and stability of alluvial rivers

ANAIS ABRAMIAN¹, GRÉGOIRE SEIZILLES¹, OLIVIER DEVAUCHELLE¹, AND ERIC LAJEUNESSE¹

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Alluvial rivers build their bed with the sediment they carry. They obey Lacey's law which states that the width of a river scales with the square root of its discharge. This universal behavior suggests a common physical origin, but there is no consensus yet about what mechanism selects the size and shape of an alluvial river. Here we produce a small river in a laboratory experiment by pouring a viscous fluid on a layer of plastic sediment (Figure 1). With time, this laminar river reaches a steady-state geometry. In the absence of sediment transport, the combination of gravity and flow-induced stress maintains the bed surface at the threshold of motion¹.

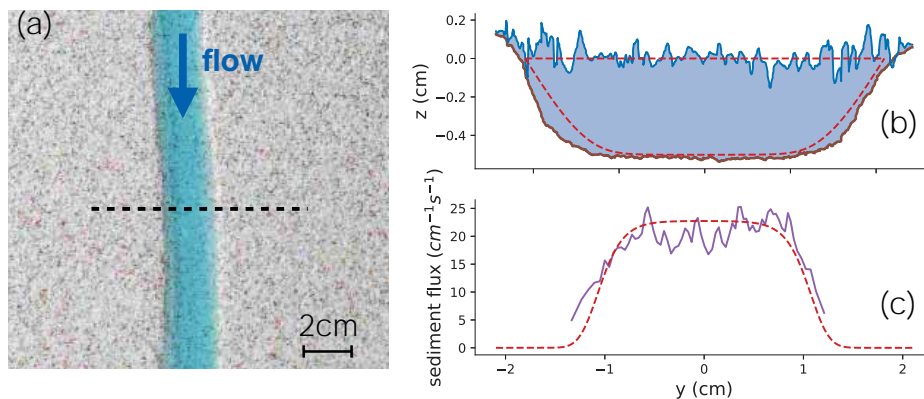


Figure 1: (a) Laboratory river, (b) cross-section and (c) downstream sediment flux. The dashed red lines show the theoretical predictions.

If we impose a sediment discharge, the river adjusts by widening its channel. Particle tracking then reveals that the grains entrained by the flow behave as a collection of random walkers. Accordingly, they diffuse towards the less active areas of the bed². The shape of the river's cross-section results from the balance between this diffusive flux, which pushes the entrained grains towards the banks, and gravity, which returns them towards the center of the channel.

As the sediment discharge increases, the channel gets wider and shallower. Eventually, it destabilizes into new channels. A linear stability analysis suggests that the diffusion of the sediment causes this instability, which could explain the formation of braided rivers.

¹Seizilles et al., **Phy. Rev. E.** 87, 052204

²Seizilles et al., **Phy. Fluids.** 26, 013302

11h00|12h30 Morphodynamics - Bed stability /
Morphodynamics and dunes

11h00| Oscillating Sand Ripples in the Laboratory - *Rousseaux*

11h30| Subaqueous ripples and dunes: Formation and evolution in the lab - *Jarvis et al.*

12h00| Direct numerical simulation of the formation of rolling-grain ripples in an oscillatory boundary layer - *Mazzuoli et al*

Oscillating Sand Ripples in the Laboratory

ROUSSEAUX G.¹

¹Institut Pprime, CNRS-Université de Poitiers-ISAE-ENSMA

In this talk, I will review my PhD thesis work on orbital sand ripples [1-2-3-4-5-6]. I will present old but unpublished results on the interplay between the fluid and sand phases. In particular, movies of the simultaneous particles motions in the fluid and in the bulk of the sand bed will be shown. We will insist on the internal grain motions below the interface. A rapid comparison with backwash ripples observed on sand beaches will end our discussion.



Figure 1: Vortex ripples in a cylindrical oscillating water tank [5]

[1] Rousseaux, G., Stegner, A. and Wesfreid, J.E., Wavelength selection of rolling-grain ripples in the laboratory, *Phys. Rev. E*, **69**, pp. 031307, 2004.

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Subaqueous ripples and dunes: Formation and evolution in the lab

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The formation of sand ripples and dunes, and their continued evolution and co-interaction have applications both industrially and in the natural world. Whilst theoretical models for the initial formation as a linear stability problem exist experimental validation is incomplete. Additionally, non-linear effects including the interaction between bedforms in a dune field remain poorly understood. We have constructed a novel experiment to study both the early stages of subaqueous ripple formation from a flat, erodible bed, and the later-time evolution of the system. The apparatus consists of a narrow, large-diameter (2 m) circular channel containing a flat bed of sand overlain by water (Fig. 1). Counter-rotation between the channel and a submerged paddle assembly drives a shear flow in the water which erodes and transports the sand. Measurements of the bed profile are used to calculate the initial distribution of wavelengths within the profile, the growth rate of perturbations, and the temporal evolution of the wavelength spectrum. We compare the early-time results with predictions from linear stability models whilst also quantifying the later-time coarsening behaviour.

During the evolution of the bed profile, different modes of bedform interaction are observed: coalescence, and mass-exchange (also called ejection). A second set of experiments are performed to investigate this in detail, whereby the interaction between a pair of dunes, migrating on a non-erodible surface, is studied. Smaller dunes migrate faster than larger ones, and so an upstream small dune will catch up to a larger downstream dune. By varying the size ratio between the dunes, we are able to reproduce the coalescence and mass-exchange modes observed in our bed evolution experiments. We use our results to constrain the parameters that control the interaction and discuss the implications for understanding how a dune field evolves.

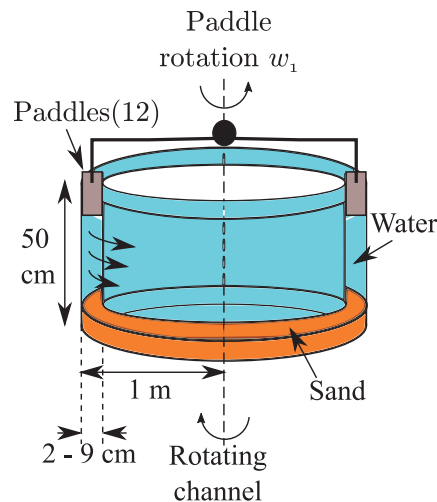


Figure 1: Sketch showing the experimental setup

Direct numerical simulation of the formation of rolling-grain ripples in an oscillatory boundary layer

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The basic mechanism at the origin of the small-scale bedforms associated with the flow induced at the sea bed by wind waves is presently investigated by numerical means. Two direct numerical simulations of the oscillatory flow over a movable bed of spheres were performed. The numerical approach is based on a second-order-accurate finite-difference approximation of the incompressible Navier-Stokes equations, for the fluid phase, and on a discrete element method to simulate inter-particle contacts. The no-slip condition at the surface of the spheres is forced by means of the immersed boundary method. The simulations reproduced two laboratory experiments where the formation of rolling-grain ripples was observed. The flow was generated by harmonic oscillations of pressure gradient and remained laminar throughout the simulations. As predicted by the linear stability analysis of the mathematical problem, after a few oscillation periods, steady two-dimensional re-circulation cells characterized by wavelength comparable with that of ripples observed experimentally, formed over the bed. Contextually, sediment particles were grouped in the zones where adjacent re-circulation cells converged. Thereby, patterns of spheres formed on the bed surface which then developed into rolling-grain ripples (see figure 1). The surface of the bed was identified and a description of its time development was given. Moreover, the sediment flux was computed, on the basis of the velocity of sediment particles, at different phases of the oscillation period and at different positions along the ripple profile. The contributions to the sediment flux associated with the shear stress and the oscillating pressure gradient were identified and related to the hydrodynamic forces. In one of the two simulations, which is still running, the values of the parameters were compatible with the possible development of vortex-ripples, which are generated as the flow separates behind the crests of ripples. This occurrence could be confirmed by the numerical results obtained so far, which show that the amplitude of ripples is currently growing with an exponential rate. The latest results will be showed at the conference.

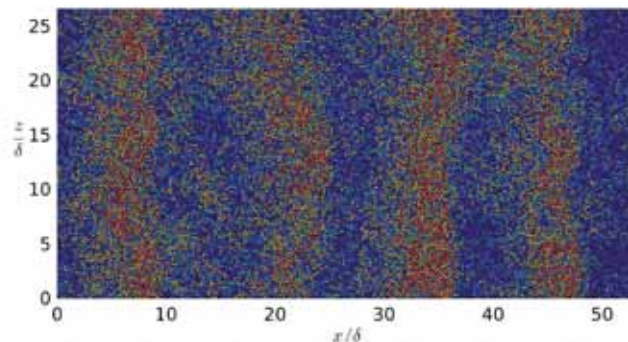


Figure 1: Topview of bed after 20 wave cycles. Particle elevation is shaded by colors.

14h00|16h00 Morphodynamics - Bed stability /
Ripples

14h00 | Growth of dunes under a multidirectional flow regime -
Gadal et al.

14h30 | Dune steady state shape under turbulent unidirectional
flow - *Kiki et al.*

15h00 | Morphogenesis of laboratory rivers - *Abramian et al.*

15h30 | Erosion in the vicinity of a vertical cylinder - *Lachaussée et al.*

Growth of dunes under a multidirectional flow regime

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Key words Sediment transport, multidirectional flows, dune instability

A turbulent flow over an erodible bed can produce various dune patterns, which are usually classified according to their growth mechanism, their orientation and their shape [1]. The way a flat sand bed destabilizes is well described under unidirectional flow conditions, and this mechanism leads to a pattern with a characteristic wavelength and a transverse orientation [2]. However, under multidirectional flow conditions, oblique and longitudinal dune orientations are also observed.

Here we extend the linear stability analysis done under unidirectional flow to multidirectional flow conditions over a planar sand bed, taking into account the deflection of the flow which is caused by the 3D topography when the imposed flow is oblique to the dunes. We verify that dunes select the predicted orientation for which the divergence of the flux is maximum at the crest [1] and show how the most unstable wavelength depends on the distribution of sand flux orientation. These predictions can be compared to dune patterns observed in arid deserts on Earth (Figure 1) and can be used to study transitions in both dune shape and orientation.

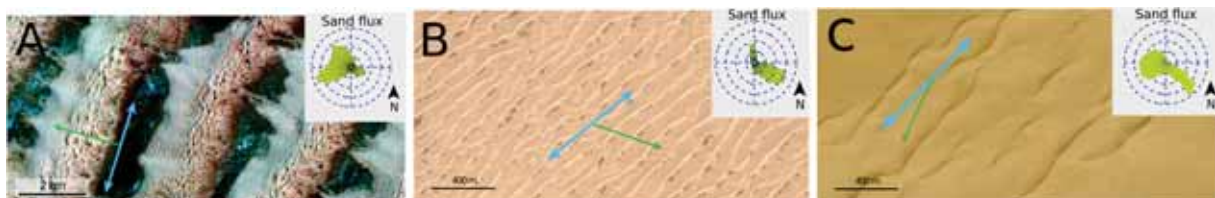


Figure 1: **Different dune orientations under multidirectional wind regimes.** Green and blue arrows show the resultant sand flux and the predicted dune orientations, respectively. The angle ϕ between these two orientations can be used to classify dunes as **(A)** transverse, $\phi \geq 75^\circ$ (Edeyen Ubari desert, $26^\circ 58'N$ $12^\circ 59'E$, Libya) **(B)** oblique, $15^\circ < \phi < 75^\circ$ (Mu Us desert, $38^\circ 50'N$ $107^\circ 41'E$, China) **(C)** longitudinal, $\phi \leq 15^\circ$ (Rub Al Khali desert, $19^\circ 14'N$ $45^\circ 42'E$, Saudi Arabia)

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Dune steady state shape under turbulent unidirectional flow

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The dunes dynamic under real conditions is far from being entirely understood. On the one hand, because the forcing agent vary in time and space in direction and intensity. On the other hand, because of the complexity to describe the resulting sedimentary flux responsible for the dunes deformation and migration. We choose to study the equilibrium state of aqueous dunes under turbulent unidirectional flow with a continuum minimal model. This model is inspired of that of *K. Kroy & al.*¹. It uses the *Jackson & Hunt*² equation to calculate the shear stress over the dune and a relaxation law that introduces a saturation length l_{sat} for the bedload sand flux. We show there exists a critical mass which delimits two regimes (Fig.1). In the first one, the dune height increases linearly with the mass of the dune while its longitudinal extension remains constant. In the second one, the dune height and length both scale as the square root of its mass. The model predictions are in good agreement with the experiments by *Groh & al.*³. who investigated two-dimensional aqueous dunes in a narrow flume. However, their study was limited to the large dune regime (i.e, the second regime). Conducting similar experiments than Groh et al., we confirm the existence of a small dune regime (i.e., the first regime) where the longitudinal extension of the dune is independent of its mass. Importantly, the identification of this regime allows us to estimate the saturation length which is found in our experiments to be about 9 grain size (using 400 microns glass beads of density $\rho = 2500 \text{ kg.m}^{-3}$).

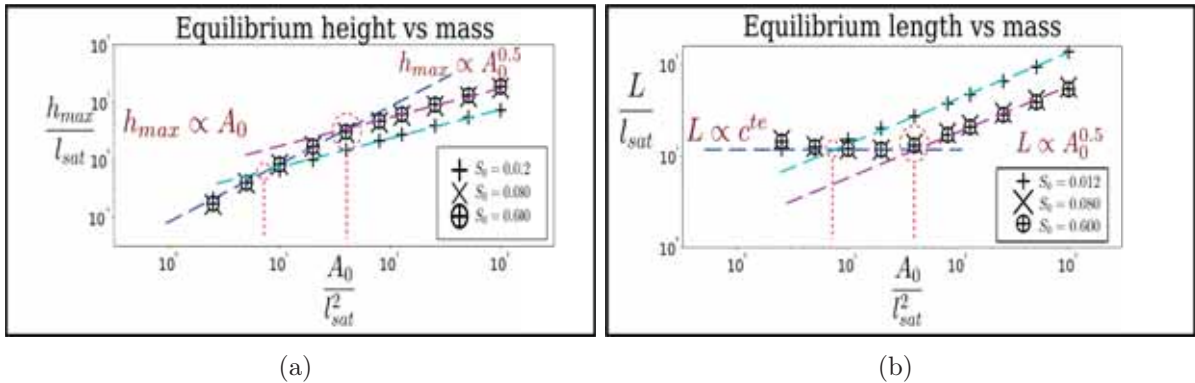


Figure 1: Model predictions of the equilibrium height (a) and length (b) vs dune area for various Shields number (S_0) of the flow.

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Morphogenesis of laboratory rivers

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An alluvial river forms its bed with the sediment it transports, either in the bulk of the flow (suspended load) or in a thin layer near the bed surface (bedload). The channel bounds the flow, which in turns deforms the channel by erosion and sedimentation. This coupling between flow and bedload transport spontaneously selects the shape and size of the river.

The first ingredient of this coupling is gravity, which pulls the moving grains towards the center of the channel, thus eroding the banks continually [1]. However, laboratory observations show that, due to the roughness of the bed, the trajectory of a moving grain fluctuates in the transverse direction [2]. The bedload layer is therefore a collection of random walkers which diffuse towards the less active areas of the bed. In a river at equilibrium, bedload diffusion counteracts gravity to maintain the banks.

When gravity and diffusion are out of balance, their interaction causes an instability. Indeed, if an initially flat bed of sediment is perturbed with longitudinal streaks, the flow-induced shear stress is weaker where the flow is shallower. Therefore, we expect bedload diffusion to induce a flux of sediment towards the crests of the perturbation. This positive feedback induces an instability which can generate new channels. We suggest that this mechanism could explain the transition from single-thread rivers to braided ones.

References

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Erosion in the vicinity of a vertical cylinder

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Erosion and sediment transport are encountered in numerous natural and industrial situations. For instance, scouring may appear in the vicinity of bridge piers or wind turbines and lead to serious damage of the structure. The presence of the structure disrupts the flow and creates complex flows such as a horseshoe vortex at the foot of the pier and wake vortices downstream. These vortices strengthen the flow near the obstacle and thus facilitate scouring. Despite the hazard it represents, erosion near structures is still lacking a complete physical description, which arises from the poor quantification of the coupling between the complex fluid flow around the obstacles and solid particles transport [1].

Here, we investigate the erosion of a granular bed (glass beads of diameter 0.3 mm) in the vicinity of a cylinder in a 3.6 m racetrack–shape channel. Experiments are performed in the straight section of the channel of 0.1 m large and 0.6 m long. A cylinder of diameter $D = 10$ mm to 20 mm is located at the middle of the channel. By varying the flow speed V from 0.1 m s^{-1} to 0.3 m s^{-1} , different erosion patterns are observed, associated with different flows around the cylinder. For large velocities, near the erosion threshold without obstacle, an intense “horseshoe” vortex is generated at the bottom of the cylinder [2] leading to a scour hole surrounding the cylinder [Fig. 1(a)]. For slower flows, the erosion appears downstream of the obstacle and is characterized by two “bunny ears”–shape holes due to wake vortices [Fig. 1(b)].

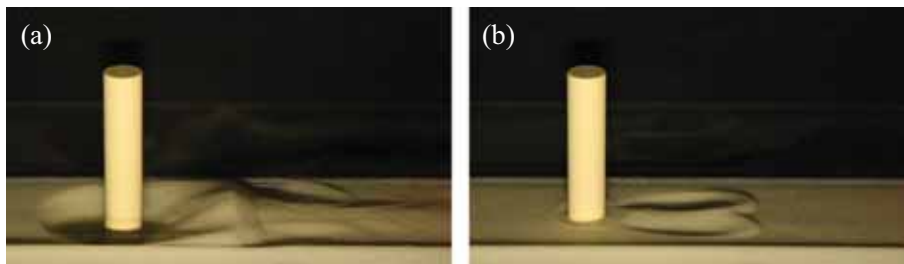


Figure 1: Erosion patterns observed close to a cylinder of diameter $D = 20$ mm: (a) Classical scour hole due to “horseshoe” vortex; (b) “Bunny ears” pattern.

Erosion patterns obtained by 3D-scans of the granular bed are discussed and correlated to the complex flow around the obstacle deduced from Particle Image Velocimetry measurements. This study highlights the thresholds of appearance of the different patterns in terms of Reynolds numbers and Shields numbers.

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