ACCOUNTING FOR PHASE TRANSITION IN GRANULAR MEDIA

from micromechanics to macroscopic unified modeling

International workshop

MILAN, SEPTEMBER 6-7, 2018

POLITECNICO DI MILANO
AUDITORIUM ROOM

POLITECNICO DI MILANO

Welcome Address

Dear all,

It is our pleasure to welcome you in Milan for this international workshop co-organized by the international research group GeoMech and Politechnico di Milano.

The initial motivation of this workshop was to offer some room and time to bring together researchers working on the behavior of granular media either form a geomechanics or physics point of view. For such materials, a great challenge lies in describing the transitional behavior between solid like and fluid like behaviors and in establishing a unified formalism to account for this transition.

This international free-of-charge Workshop will discuss the latest advances in theoretical and numerical modeling of the solid-fluid phase transition occurring in diverse physical phenomena such as flow-slides, rock and snow avalanches, debris flows, soil liquefaction or erosion. Both numerical particle-based methods and constitutive, continuum modeling will be concerned, in order to understand, from the microscopic point of view, the local mechanisms at the particle scale, and, from the macroscopic side, the collective behavior of the whole system.

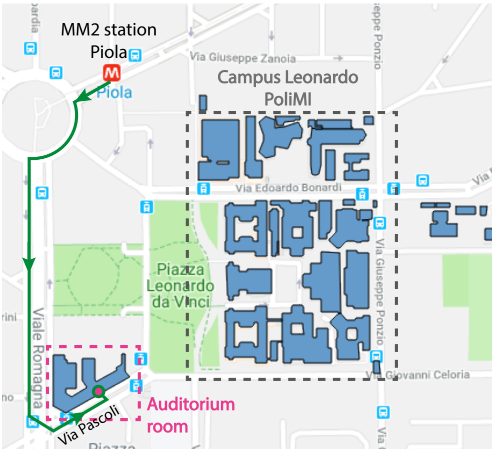
Without any doubt the list of forthcoming talks will bring us to the brink of current knowledge, will lead to fruitful discussion and we hope to future collaborations.

Please sit back, relax and enjoy the workshop!

Antoine Wautier and *Dalila Vescovi*

Practical information

During the two days of the workshop, lectures will be given in the Auditorium Room of Politecnico di Milano, Campus Leonardo. The coffee breaks and the lunches will be served in the Auditorium Room as well. Please note that the Auditorium Room is not inside the Politecnico di Milano Campus Leonardo, but is located at the students' residence "Casa dello Studente". The entrance to the room is in via Pascoli 53, as shown in the map. Otherwise, you can enter from the main entrance of the students residence, located in Viale Romagna, 62.



Casa dello Studente - detail

We are pleased to invite you to a nice dinner in town at the restaurant **Acquapazza** (Viale San Michele del Carso, 3, Milano). We will wait for you at the restaurant on Thursday night by 8 pm.

For those of you needing an accommodation during your stay in Milan, you will be hosted at the **Hotel Palazzo delle Stelline** in the city center (Corso Magenta, 61, Milano).

How to reach the Auditorium Room
(Via Pascoli, 53, Milano):

To reach the Auditorium Room take the Metropolitana MM2 (green line) and get off at the station Piola. From the Metropolitan station Piola to Auditorium Room is a short walk of about 6 minutes. Leave the underground MM2 station, reach Piazza Piola, turn into via Romagna, arrive at the traffic light, turn left into via Pascoli and arrive directly at number 53, the entrance to the Auditorium room.

If you prefer not to walk, you can catch the number 90 trolleybus from viale Romagna and get off at the first stop (Romagna-Pascoli). Cross the street at the traffic light walking towards Via Romagna, turn left into via Pascoli and you will arrive directly at number 53, the entrance to the Auditorium room.

The easiest way to go from Hotel Palazzo delle Stelline to the Auditorium Room is to take the Metropolitana MM2 (green line) in the direction of Gessate or Cologno Nord and exit at the station Piola.

How to reach the Hotel Palazzo delle Stelline
(Corso Magenta, 61, Milano):

From the Airport of Linate: take bus 73 departing from the piazza of the airport and exit at the end of the line, in piazza San Babila; take the Metropolitana MM1 (red line) in the direction of Fiera/Rho, exit at the station Cadorna Triennale, turn into piazza Cadorna, turn into via Carducci and continue to the first traffic light, crossing corso Magenta, finally arrive to number 61.
From the Airport of Malpensa: take shuttle train Malpensa Express and reach the head of the line at Milano Cadorna, turn into piazza Cadorna, turn into via Carducci and continue to the first traffic light, crossing corso Magenta, finally arrive to number 61.
From the Central Station of Milan, or from the station Porta Garibaldi: take the Metropolitana MM2 (green line) in the direction of Abbiategrasso or Assago/Milanofiori Forum and exit at the station Cadorna

Triennale, turn into piazza Cadorna, turn into via Carducci and continue to the first traffic light, crossing corso Magenta, finally arrive to number 61.

How to reach the Restaurant Acquapazza
(Viale San Michele del Carso, 3, Milano):

To reach the Restaurant Acquapazza take the Metropolitana MM1 (red line) and get off at the station Conciliazione. From Piazza della Conciliazione, reach Piazzale Baracca and turn into Viale San Michele del Carso.
The restaurant is located within walking distance from the Hotel Palazzo delle Stelline (8 min). From the hotel, turn left and walk on corso Magenta, reach Piazzale Baracca and turn into Viale San Michele del Carso.

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Thursday 9/6/2018

09.30 - 10.00	Opening ceremony
10.00 - 10.20	Johan Gaume
	Micromechanical modeling of crack propagation for snow slab avalanche release
10.20 - 10.40	Emmanouil Vairaktaris
	DEM modelling of landslide impact on rigid barriers
10.40 - 11.00	Alessandro Leonardi
	A DEM evaluation of the clogging probability of debris-flow barriers: from the contact parameters to the overall interaction mechanism
11:00 - 11.30	Coffee break
11.30 - 11.50	Raphaël Maurin
	Granular rheology in turbulent bedload transport: from quasi-static to dynamic granular flows
11.50 - 12.10	Marco Mazzuoli
	The role of turbulence in the onset of sediment buoyancy under sea waves
12.10 - 12.30	Thomas Barker
	The role of compressibility in confined granular flows
12.30 - 12.50	Ségolène Méjean
	Identifying several types of granular jumps during flows down a slope
12.50 - 14.30	Lunch
14.30 - 14.50	Irene Redaelli
	Steady state under 3D conditions for dry granular materials: from solid to fluid-like regimes
14.50 - 15.10	Stefan Luding
	From particles to continuum theory for phase transitions and co-existence
15.10 - 15.30	Pietro Marveggio
	Saturated granular flows: constitutive modelling under steady conditions
15.30 - 15.50	Vanessa Magnanimo
	Dilatancy in dry/cohesive/wet granular materials
15:50 - 16.20	Coffee break
16.20 - 18.00	Small group discussions or free time
20.00	Dinner

Friday 9/7/2018

09.30 - 10.00	Nicolin Govender
	Industrial Particle Simulations Using the Discrete Element Method on the GPU
10.00 - 10.20	Grégoire Bobillier
	Micromechanical modeling of crack propagation for snow slab avalanche release
10.20 - 10.40	Zeyd Benseghier
	Damage and erosion of cohesive granular media by shear-driven fluid flow
10.40 - 11.00	Li-Hua Luu
	Solid-fluid interface for a viscoplastic fluid flow in expansion-contraction confined geometry
11:00 - 11.30	Coffee break
11.30 - 11.50	Claudio di Prisco
	Fluid-solid transition in unsteady shearing flows
11.50 - 12.10	Bruno Chareyre
	Solid-fluid non-transition in dense suspensions
12.10 - 12.30	Closure, announcements and discussions
12.30 - 14.30	Lunch

Modeling solid-fluid transitions in snow avalanches using the Material Point Method.

Johan GAUME[1,2], Ted GAST[3,4], Joseph TERAN[3,4], Alec van HERWIJNEN[2] and Chenfanfu JIANG[4,5]

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Snow slab avalanches start with the failure of a weak snow layer buried below a cohesive snow slab. After failure, the very porous character of the weak layer leads to its volumetric collapse and thus closing of crack faces due to the weight of the overlaying slab. This complex process, generally referred to as anticrack, explains why avalanches can be remotely triggered from flat terrain. On the basis of a new elastoplasticity model for porous cohesive materials and the Material Point Method, we simulated the dynamics of propagating anticracks reported in snow fracture experiments [1] as well as the propagation and reflection of localized compaction bands [2]. Finally, we simulated the release and flow of slab avalanches at the slope scale triggered either artificially (bombing) or accidentally (remote triggering). Our unified model represents a significant step forward as it allows simulating the entire avalanche process, from failure initiation to crack propagation and solid-fluid phase transitions in snow, which is of paramount importance to mitigate and forecast snow avalanches as well as gravitational hazards in general.

[1] Gaume J, Gast T, Teran J, van Herwijnen A, Jiang C, 2018. Dynamic anticrack propagation in snow. Nature Communications. In Press.

[2] Barraclough, T. W., Blackford, J. R., Liebenstein, S., Sandfeld, S., Stratford, T. J., Weinlnder, G., Zaiser, M. 2018. Propagating compaction bands in confined compression of snow. Nature Physics, 13(3), 272.

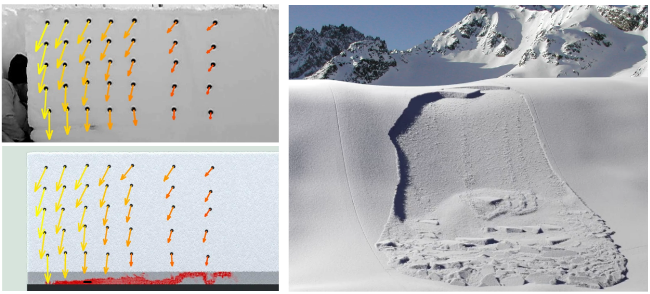

Figure 1: Left: Propagation Saw Test experiment (top) reproduced using our model (bottom). Right: Simulation of a snow slab avalanche using MPM.

DEM modelling of landslide impact on rigid barriers

Francesco Calvetti[1], Claudio di Prisco[1], Irene Redaelli[1] and Emmanouil Vairaktaris[2]

[1] Civil and Environmental Department, Politecnico di Milano, Italy.
[2] School of Applied Mathematical and Physical Sciences, NTU of Athens, Greece.

Landslides constitute massive failures that crucially affect modern structures and infrastructure and may even claim peoples lives. Debris flow is a form of landslide where significant soil masses flow with considerable speed; frequently, in order to intercept and stop such soil masses rigid barriers are employed. In previous works [1, 2] the authors presented the results of an extended parametric analyses on the maximum impact force (MIF) of debris flow on rigid barriers followed by an empirical formula for its estimation; MIF is recognized as the principal design parameter for mitigation measures, like rigid walls and earth embankments. The Discrete Element Method (DEM) was employed to model the debris avalanche impact by assuming quasistatic behaviour of the debris flow exactly before the impact.

The present work focuses on the micromechanical interpretation of impact of granular masses on rigid barriers; the macro-mechanical results concerning the bulk mass scale are correlated with micromechanical observations at the grain scale. In particular during impact, the initially considered quasistatic behaviour of the bulk mass is dramatically changing: depending on different micromechanical parameters of the grains but also on macromechanical parameters of the bulk mass, solid, fluid and gas like behaviour characteristics are observed in different areas of the granular mass. Specific attention is given on the evolution of the phase change of these areas especially with respect to the effect of less profound parameters of the impacting mass: the internal friction and the front inclination. It seems that these parameters dominate the overall behaviour of the impacted mass both qualitatively and quantitatively.

[1] Calvetti, F., Di Prisco, C. G., Vairaktaris, E. (2017). DEM assessment of impact forces of dry granular masses on rigid barriers. Acta Geotechnica, 12(1), 129-144.
[2] Calvetti, F., di Prisco, C., Vairaktaris, E. (2015). Impact of dry granular masses on rigid barriers. In IOP Conference Series: Earth and Environmental Science (Vol. 26, No. 1, p. 012036). IOP Publishing.

A DEM evaluation of the clogging probability of debris-flow barriers: from the contact parameters to the overall interaction mechanism

Alessandro Leonardi[1], Marina Pirulli[1]

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In this work, we study the interaction between geophysical phenomena such as debris flow, and retention structures. We propose a numerical tool based on the Discrete Element Method, where the frictional nature of natural grains is reproduced through the implementation of frictional contacts and rolling resistance. The relationship between the contact parameters and the overall behavior of the granular mass is investigated through a set of heap-formation calibration tests, which allow to track the transition from a fluid regime to stable granular structures. The information gathered in the calibration tests is then used to study the stoppage of a granular flow on an incline. This is induced by placing a slit dam with a single vertical opening. The relative size between slit opening and grain diameter determines the overall efficiency of the retention, but also the basal friction controlled by the channel inclination plays a vital role. Numerous threshold are in this way obtained. The grains clog instantly for small relative opening sizes, and flow freely when a very large slit is used. Two secondary thresholds exist in the intermediate range, corresponding to a partial release of the mass through multiple consecutive clogging and ruptures of the grains behind the slit, and to the delayed formation of a single two-dimensional arch at the base. The consequences for the design of structures of this type are then discussed.

Granular rheology in turbulent bedload transport: from quasi-static to dynamic granular flows

Raphaël Maurin[1], Thomas Paehtz[2], Julien Chauchat[3] and Philippe Frey[4]

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Considering a granular bed submitted to a turbulent fluid flow, bedload represents the part of the granular material entrained close to the bed, by opposition to suspension and aeolian saltation. This configuration can as well be seen as a granular flow over an erodible bed with a complex vertical forcing due to the fluid flow. Indeed, considering steady uniform turbulent bedload transport configurations, the average granular flow depends only on the vertical direction. As a consequence the granular rheology can be studied locally as a function of the depth, sampling the whole spectrum of granular motion from quasi-static behavior inside the granular bed to very dynamic dilute granular flow at the top of the flow.

Studying this problem at the grain scale with coupled fluid-discrete element simulations [1], we show that the fluid acts only as a forcing and does not influence the granular rheology in itself in the configurations sampled [2]. In addition, we show that the spatially reduced interval over which the granular flow transit from quasi-static behavior to dynamic one influences the rheology, and in particular the transition from dense to dilute granular flow behavior [2]. This transition is analyzed further in the framework of the rheology proposed by Paethz and Duran [3].

[1] Maurin R., Chauchat J., Chareyre B. and Frey P. (2015), Physics of Fluids 27, 113302

[2] Maurin R., Chauchat J. and Frey P. (2016), Journal of Fluid Mechanics 804, 490-512

[3] Paehtz T. and Duran O. (2018) https://arxiv.org/abs/1609.06005

The role of turbulence in the onset of sediment buoyancy under sea waves

Marco Mazzuoli[1]

[1] Department of Civil, Chemical and Environmental Engineering (DICCA), University of Genova, Italy.

In coastal environment, far away from the breakers, wind waves generate on the seafloor harmonic oscillations of pressure gradient which mostly act in the direction of propagation of the waves and result in an oscillatory flow. If the flow is energetic enough to set sediments into motion, then sediment particles which are located close to the bed surface are dragged to and fro, while beneath the bed surface particles are shaken by the oscillations of the pressure gradient associated with the wave propagation and by the fluctuations of pressure due to the vortex structures in the boundary layer. A known effect of the latter creep motion is that of compacting the bed, thereby generating overpressures of the pore water which can either dissipate rapidly if the material is sufficiently coarse (sand) or progressively accumulate if fine material is also present (silt), eventually resulting in the buoyancy of particles. Such phenomenon, known as residual liquefaction, must be predicted to guarantee the stability of structures that lay on the seefloor. However, even if the fine component of the bed material is absent, the pressure fluctuations stemming from the turbulent vortices propagating in the boundary layer can cause the buoyancy of sediments. In fact, although the flow velocity rapidly damps below the bed surface, pressure fluctuations associated with vortices impinging upon the bed penetrate much deeper into the bed and abruptly enough not to allow the pore pressure to dissipate. As a result, a significant amount of sediments can be lifted and then set into motion by the flow. The present contribution is aimed at investigating the latter phenomenon. The results obtained from the direct numerical simulation of the oscillatory flow over a bed made of mono-dispersed spheres in the intermittently-turbulent regime are shown. The values of the parameters are in the range of those observable in the field for which the sediments are transported in certain phases of the wave cycle and deposit during the flow reversal. Figure 2 sketches the particulate flow in one of the present simulations.

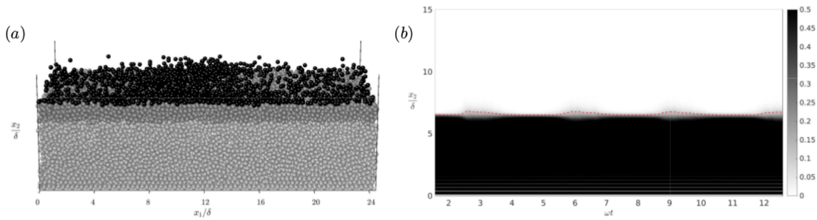

Figure 2: Panel (a): bed configuration at a phase of the wave cycle characterised by turbulent flow. Black particles are sheared by the flow while dark-grey spheres are somewhat influenced by the vertical pressure gradient induced by turbulent vortices. Panel (b): streamwise-and-spanwise-averaged solid volume fraction visualised as a function of time. The bed expands close to the bed-flow interface (red broken line) when the flow is turbulent, exhibiting local reduction of the concentration of sediments.

The role of compressibility in confined granular flows

Thomas Barker[1]

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Recent models for granular flow have relaxed the incompressibility constraint so that the solids volume fraction may vary. Here these models are put to the test in shear cells consisting of frictional parallel plates. Unfortunately the well established steady response, known as the $\mu(I)$, $\Phi(I)$-rheology, is found to lead to ill-posed dynamic equations. We introduce a new Compressible I-Dependent Rheology that is well-posed and recovers the $\mu(I)$, $\Phi(I)$-rheology only in the steady limit. This model is shown to allow transient numerical calculations to be reliably performed.

Identifying several types of granular jumps during flows down a slope

Ségolène MÉJEAN[1,2], François GUILLARD[2], Thierry FAUG[1] and Itai EINAV[2]

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When free-surface rapid shallow (supercritical) flows down an incline suddenly become thicker and slower (subcritical), the fluid forms a transition region called a jump. The properties and dynamics of such jumps in water have been widely studied in hydraulics and similar jumps have been observed in granular media [1, 2]. The granular jumps have been studied recently in a theoretical point of view in order to predict the height of the jumps through a general relation established using depth-averaged mass and momentum equations, and checked against a wide range of laboratory data. However, this work highlighted the to the need of knowing in more detail several properties like the length of the jump, the effective friction, or the density evolution, in order to make the relation fully predictive.

Discrete Element Method numerical simulations have been developed [4] to recreate the standing granular jumps observed in recent laboratory tests [2]. All the micro and macro parameters inside the jumps are accessible, thus allowing us to study how the geometry and flow regimes of the jump depend on the various parameters, such as the slope angle of the incline, the mass discharge, the grain diameter and the interparticle friction. This extensive numerical study revealed that, in a flow of granular materials, it is possible to identify several types of jumps.

In laboratory tests it is less obvious how to access the interior of the granular media, particularly in fast dynamic experiments of flowing granular jumps. An innovative non-invasive dynamic technique using X-ray radiography [5] has been recently developed to enable such measurements. This technique avoids boundary layer effects owing to the fact that the X-rays penetrate through the entire width of the flume, which gives a width-averaged value of the variable of interest, in contrast to optical methods that measure grain motion along the walls. This allows to recreate a two dimensional map of the width-averaged local density within the fast varying free-surface flow that occurs through the jump.

A series of carefully designed laboratory experiments have been carried out under different input conditions. Those experiments confirmed the results of the numerical simulations and the existence of several types of jumps in real three-dimensions conditions. By changing the shape of the particles, another type of jump was also revealed.

[1] Savage, S.B., Gravity flow of cohesionless granular materials in chutes and channels, Journal of Fluid Mechanics 92 (1979)
[2] Faug, T, Childs, P., Wyburn, E. and Einav, I., Standing jumps in shallow granular flows down smooth inclines, Phydics of Fluids 27 (2015).
[3] Mejean, S., Faug, T. and Einav, I., A general relation for standing normal jumps in both hydraulic and dry granular flows, Journal of Fluid Mechanics, 816, 331-351 (2017).
[4] Mejean, S., Faug, T. and Einav, I., Discrete Element Method Simulations of standing jumps in gramular flows down inclines, EPJ Web of Conferences 140, 03054 (2017).
[5] Guillard, F., Marks, B. and Itai, I., Dynamic X-ray radiography reveals particle size and shape orientation fields during granular flow, Scientific Reports 7, 8155 (2017).

Steady state under 3D conditions for dry granular materials: from solid to fluid-like regimes

Irene Redaelli[1], and Claudio di Prisco[1]

[1] Department of Civil and Environmental Engineering, Politecnico di Milano, Italy.

One of the most interesting feature of granular materials is their capability of behaving like solids as well as fluids according to grain packing and strain rate. According to the recent scientific literature in the field, at the macroscopic level, the state variables governing tis solid-to-fluid phase transition are the void ratio, the granular temperature and the fabric tensor.

This contribution focuses on the mechanical response of dry monodisperse granular materials under true triaxial steady conditions. DEM true triaxial simulations have been performed on periodic cells by imposing stress paths characterized by different Lode angles, pressures and deviatoric strain rates. In particular, the dependence of the material response on both the inertial number and loading path has been critically analyzed by taking into consideration void ratio, fabric tensor and granular temperature. The DEM numerical results have been compared with the prediction of a constitutive model based on kinetic and critical state theories, suitably modified to account for three dimensional conditions.

From particles to continuum theory for phase transitions and co-existence

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Soft, disordered, micro-structured materials are ubiquitous in nature and industry, and are different from ordinary fluids or solids, with unusual, interesting static/solid and dynamic/fluid-flow properties. The transition from fluid to solid at the so-called jamming density features a multitude of complex mechanisms, but there is no unified theoretical framework that explains them all. In this study, a simple yet quantitative and predictive model is presented, which allows for a variable, changing jamming density, encompassing the memory of the deformation history and explaining a multitude of phenomena at and around jamming. The jamming density, now introduced as a new state-variable, changes due to the deformation history and relates the systems macroscopic response to its micro-structure. The packing efficiency can increase logarithmically slow under gentle repeated (isotropic) compression or tapping, leading to an increase of the jamming density. In contrast, shear deformations cause anisotropy, changing the packing efficiency exponentially fast with either dilatancy or compactancy, dependent on the previous preparation history. The memory of the system near jamming can be explained by a meso-statistical model that involves a multiscale, fractal energy landscape and links the microscopic particle picture to the macroscopic continuum description, providing a unified explanation for the qualitatively different flow-behavior for different deformation modes. To complement our work, a recipe to extract the history-dependent jamming density from experimentally accessible data is proposed, and alternative state-variables are compared. The proposed simple macroscopic constitutive model is calibrated with the memory of microstructure. This approach can help understanding predicting and mitigating failure of structures or geo-physical hazards, and will bring forward industrial process design and optimization, and help solving scientific challenges in fundamental research.

Saturated granular flows: constitutive modelling under steady conditions

Pietro Marveggio[1]

[1] Department of Civil and Environmental Engineering, Politecnico di Milano, Italy.

Numerical simulations of flow-like landslides are commonly carried out by tackling separately the inception and evolution of the gravitational movement, by employing different numerical approaches and different constitutive models. This kind of computational analysis is quite challenging since large displacements, large strain rates and, when the soil is under saturated conditions, hydro-mechanical processes have to be considered.

In order to address the task by means of a single approach, working both for the inception and the evolution, a constitutive model capable of simulating the material behaviour in the two stages is required. In this presentation a model suitable for granular mixture saturated with water under steady simple shear conditions is presented.

The approach proposed is based on the assumption that the energy balance is governed by the combination of three different mechanisms. Concerning the granular phase, two are the contributions through which the granular system is assumed to dissipate energy: quasi-static and collisional. The former one is active when the grains interact in force chains, i.e. when the material behaves like a solid. On the other hand, the second contribution stands for particles interactions through collisions. Since the model is intended to simulate the behaviour of saturated granular mixtures, a third dissipation mechanism is introduced, in order to reproduce the interaction of grains with the liquid phase.

The model is based only on two state parameters: the granular temperature, representing a measure of the degree of agitation of the system, and the solid volume concentration.

Dilatancy in dry/cohesive/wet granular materials

Vanessa Magnanimo[1], H. Shi[1] S. Roy[1], T. Weinhart[1] and Stefan Luding[1]

[1] P.O.Box 217, 7500 AE Enschede, The Netherlands

Dry, cohesive and wet granular materials in a quasi-static steady state shear flow have been studied with the aid of Discrete Element Method (DEM). Macroscopic quantities, consistent with the conservation laws of continuum theory, are obtained by time averaging and spatial averaging of ensembles of particles. Initial studies involve understanding the effect of liquid content and liquid properties like the surface tension on the macroscopic quantities.

First, we analyse the coupled effect of particle/contact friction, softness and cohesion (that resembles different fluid/particle interaction) on the dilatancy of sheared granular materials. We focus on the local volume fraction in the steady state. We compare the results from two different geometries: (i) an inhomogeneous, three dimensional, unconfined, slowly sheared split-bottom ring shear cell, that features a wide, stable shear-band away from the system walls, and (ii) homogeneous, stress-controlled simple shear in a 3D cuboidal box with periodic boundaries. We find that local and global volume fractions at the steady state agree between the two geometries for different particle properties.

The inter-particle cohesion has an interesting impact on compaction in interplay with the friction. With increasing inter-particle cohesion, we observe a decrease in volume fraction, which we attribute to the role of an enhancement of contact friction by cohesion.

Moreover, in the case of soft particles, high inter-particle cohesion causes significant attractive tensile stresses, causing an increase in volume fraction. This effect is not visible in a system with stiff particles. These two consequences of inter-particle cohesion are highlighted in a particle friction bond number phase diagram, which can be used to predict sample dilation/compaction (see Fig. 3).

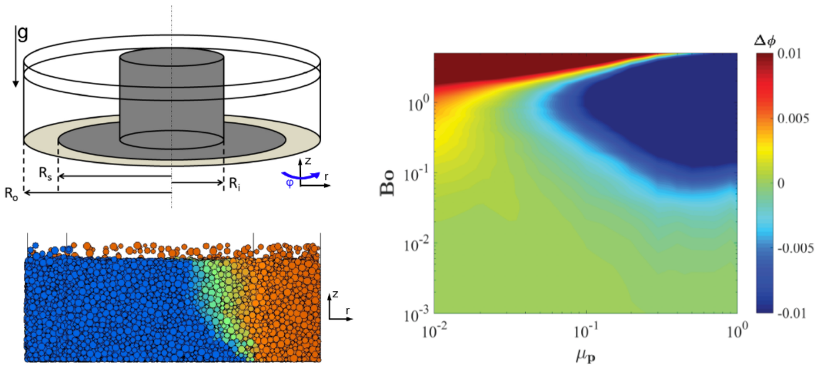

Figure 3: Left) Schematic representation of split bottom ring shear cell, showing shear band formation in the simulation. Right) Phase diagram of Bond number (cohesion level) and interparticle friction, blue/red indicate strong compression/dilation.

Industrial Particle Simulations Using the Discrete Element Method on the GPU

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Accurately predicting the dynamics of particulate materials is of importance to numerous scientific and industrial areas with applications ranging across particle scales from powder flow to ore crushing. Computational simulation is a viable option to aid in the understanding of particulate dynamics and design of devices such as mixers, silos and ball mills, as laboratory tests comes at a significant cost. However, the computational time required to simulate an industrial scale simulation which consists of tens of millions of particles can take months to complete on large CPU clusters, making the Discrete Element Method (DEM) unfeasible for industrial applications. Simulations are therefore typically restricted to tens of thousands of particles with detailed particle shapes or a few million of particles with often simplified particle shapes. However, numerous applications require accurate representation of the particle shape to capture the macroscopic behavior of the particulate system of tens of millions of particles.

The advent of general purpose computing on the Graphics Processor Unit (GPU) over the last decade and the development of dedicated GPU based DEM codes such as the open-source software BlazeDEM has resulted in simulations of tens of millions of particles to be simulated on a desktop computer. In this paper we discuss the computational algorithms that enable this performance and explore a variety of industrial applications that can be now be simulated in sufficient detail using a realistic number of particles.

Damage and erosion of cohesive granular media by shear-driven fluid flow

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Onset of granular bed erosion due to shear fluid flow is well controlled by a critical Shields number as confirmed in the past by many researchers. However, it is not the case for cohesive granular materials, where erosion laws are used to estimate the critical fluid shear stress at which incipient erosion occurs. Our primary focus is to check the validity of the excess shear stress erosion laws using numerical simulations. The lattice-Boltzmann method (LBM) has been used for describing the fluid flow, the LBM is fully coupled with the Discrete Element Method (DEM) for describing inter-particles collision and motion. The cohesion between particles is insured by a visco-elastic cohesive model with paraboloidal yield surface, and was enriched by a time-dependent damage model. The chosen erosion configuration is a shear driven (Couette) fluid flow at the top of cohesive granular layer, the fluid shear stress remains approximately constant during the erosion process by moving the upper fluid boundary.

The erosion rate was found to increase linearly with the flow shear stress intensity. Moreover, the erosion rate remains qualitatively the same at the same shear stress values with a slight dependency of particle Reynolds number. To fulfill this condition, the particle Reynolds number should be at least equal or higher with respect to the reference shear stress values.

Micromechanical modeling of crack propagation for snow slab avalanche release

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Dry-snow slab avalanche release is a multi-scale fracture process. It starts with the formation of a localized failure in a highly porous weak snow layer underlying a cohesive snow slab, followed by rapid crack propagation within the weak layer and finally a tensile fracture through the slab leading to its detachment. About 15 years ago, the propagation saw test (PST) was developed, it's a fracture mechanical field test that provides information on crack propagation propensity in weak snowpack layers. It has become a valuable research tool to investigate processes involved in crack propagation. While this has led to a better understanding of the onset of crack propagation, much less is known about the ensuing propagation dynamics. To shed more light on this issues, we therefore modeled a three-dimensional PST with the discrete element method (DEM). Using cohesive ballistic deposition, we numerically materialize a highly porous and brittle weak layer covered by a dense cohesive slab. We tuned the DEM particle and bond parameters between to obtain realistic macroscopic behavior of the slab and the weak layer consistent with laboratory and field experiments. We then disturbed this stable snowpack sample by cutting the weak layer with a numerical snow saw. From this perturbation, the fracture process can be studied such as a field propagation saw tests (PST). The simulations nicely reproduced the process of crack propagation observed in field PSTs. This novel numerical modeling approach is an alternative, yet complementary, to field experiments. Our results highlight the influence of the mechanical properties of slab and weak layer on the stress distribution and bond states during crack propagation. The long-term objective will be to extend this model to the slope scale.

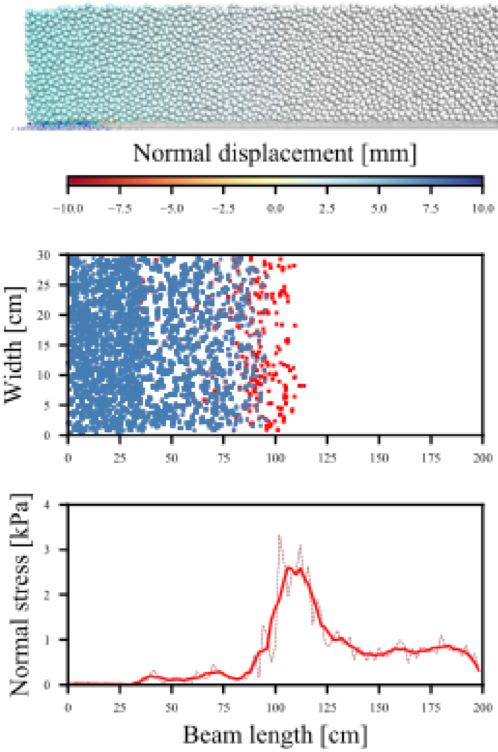

Figure 4: Simulated DEM PST state at one time step during the dynamic crack propagation process. Screenshot of the simulation, top view of the weak layer bond states, in blue broken bonds, in red breaking bonds, normal stress σ_z distribution along the PST beam.

Solid-fluid interface for a viscoplastic fluid flow in expansion-contraction confined geometry

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Through both an experimental and a numerical study, we studied the mechanisms underlying the coexistence of flow zones and dead zones within a same viscoplastic fluid. The hydrodynamic configuration of interest consists in a closed rectangular channel with a cavity in its base. By means of high-resolution optical velocimetry (PIV), we evaluated precisely the velocity profiles of a model Hershel-Bulkley flow, the Carbopol micro-gel, at the vicinity of the solid-fluid interface, separating an upper yielded flowing layer and a lower unyielded dead zone [1, 2]. In parallel, numerical simulations based on Augmented Lagrangian and Finite-Differences methods provided a complementary approach of the same flow problem with a simple Bingham rheology [3]. Using the interplay between physical experiments, theoretical derivation and numerical simulations, we extensively analyzed the viscoplastic boundary layer located between the solid-fluid interface and the bulk Poiseuille flow and proposed an extension to moderate Bingham numbers of recent refinements of Oldroyds theory [4].

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Fluid-solid transition in unsteady shearing flows

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Granular systems can behave like either fluids, meaning that they yield under shear stress, or like solids able to resist applied stresses without deforming. If grains are widely spaced, the medium behaves like a fluid and the stresses are proportional to the square of the strain rate. On the other hand, when particles are densely packed, a network of persistent contacts develops within the medium, and the granular material shows a solid-like, rate-independent behaviour. The mechanical response of the system during the solid-fluid transition is still an open question.

In this work, we investigate the fluid-solid transition in unsteady, homogeneous, shear flows of a collection of spheres, by particle simulations. Discrete element numerical simulations have been performed by applying a constant shear rate to a static assembly of spheres, under constant volume conditions.

For steady, shearing flows, volume fraction larger (lower) than a critical value, indicates that a granular system is solid-like (fluid-like), i.e., rate-independent components of the stresses are present (absent). The critical volume fraction is the largest volume fraction at which a granular material can be sheared without force chains spanning the entire domain. Time-evolving simulations have been performed considering three volume fractions, such that, after reaching the steady state, the three specimens are in fluid, solid, and near-to-critical conditions.

The three systems follow very different evolutionary paths, in terms of pressure and coordination number. The fluid-like behaviour is characterized by large fluctuations in pressure and coordination number, due to the continuous destruction/re-building of multi-particles aggregations. Conversely, the fluctuations are much smaller when a contact network spanning the entire domain develops in the granular material (solid-like behaviour), since particles are more compacted and cannot easily abandon the own force chain. The fluid-solid transition is characterized by a critical value of the coordination number.

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Solid-fluid non-transition in dense suspensions

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The idea that phase transitions might help understanding and modeling the mobility of geomaterials in situations such as lanslides, debris flow, quicksands and other liquefaction phenomena, emerged in the recent years. In many cases it implies that a bulk solid (typically a saturated or nearly saturated soil) is turned into a fluid material as a result of changes in external conditions. On the other hand, it is recognized since Terzaghi's pioneering work that the deformation of saturated porous media implies a mechanical coupling between the deformation of the (so-called) solid skeleton and movements of the pore fluid. This feature of porous media turns boundary value problems (BVP) into diffusion-type problems, which can't be addressed solely by any kind of stress-strain relationship for an equivalent single-phase (bulk) material. For instance, Terzaghi's solution to one-dimensional consolidation of a soil layer is inherently out of reach of any single-phase visco-elasto-plastic model. Consequently, the idea of changing the rheology of a bulk phase depending on external conditions - be it through phase transitions - is not sufficient in general.

In this contribution it is further suggested that retaining the multiphase nature of geomaterials and the implied couplings is enough to explain the empirical facts in terms of geomaterials mobility. This view is illustrated by experimental facts and micro-mechanical simulations of dense mixtures of non-colloidal particles and viscous fluids. It is shown that the complex and across-scales interplay between solid contact interactions and hydromechanical interactions leads to a variety of phenomena, including rate dependency and transient shear thickening/thinning [1], fluidization [2], or liquefaction [3,4]. While some of these phenomena might be described as "phase transitions" in a broad sense, they can all be described at the macro-scale by coupled systems of equations which do not resort on phase transitions. The conclusion that phase transitions might be not sufficient nor necessary is thus offered and the motivations for introducing them are questioned.

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