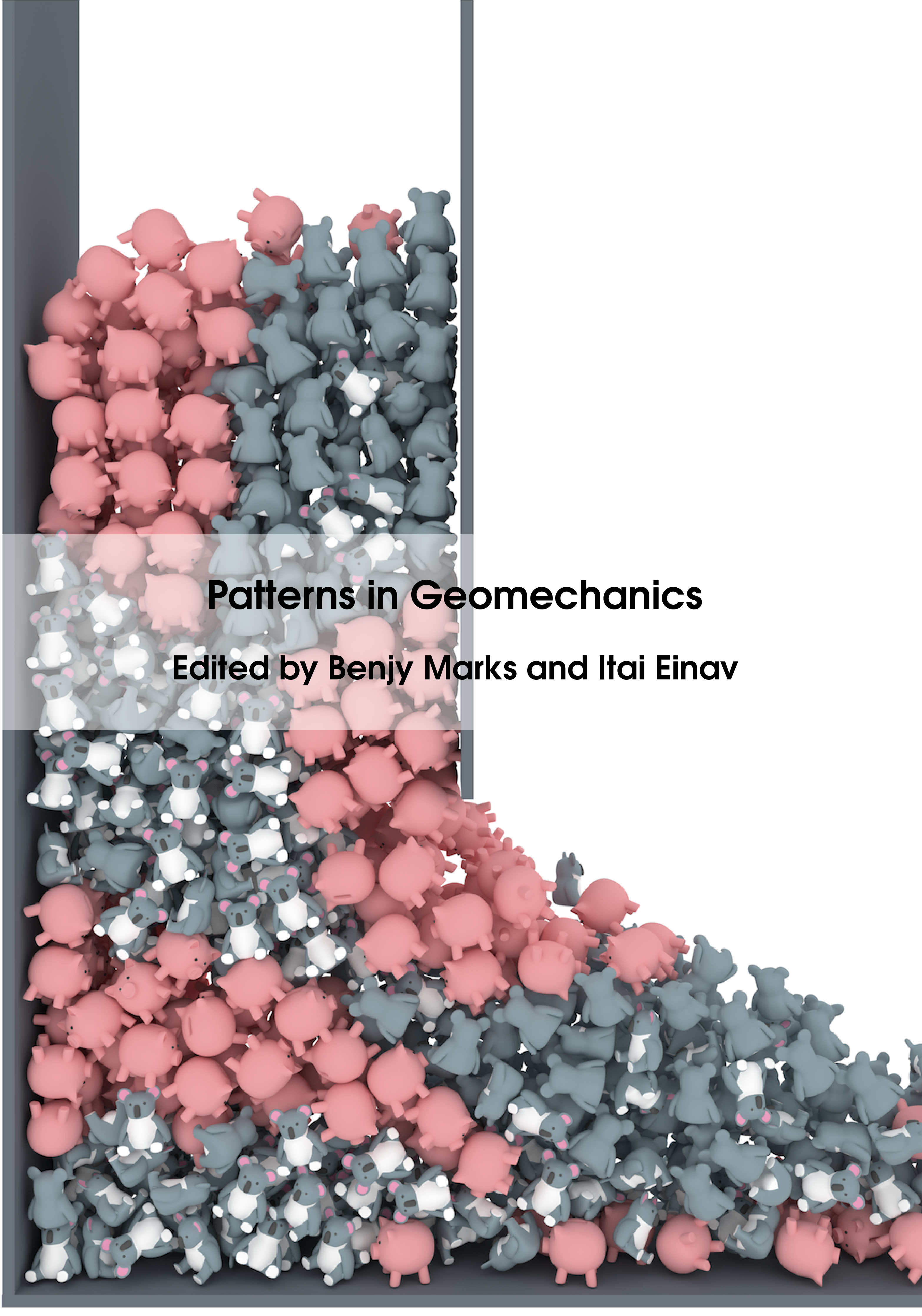
Patterns in Geomechanics

Edited by Benjy Marks and Itai Einav



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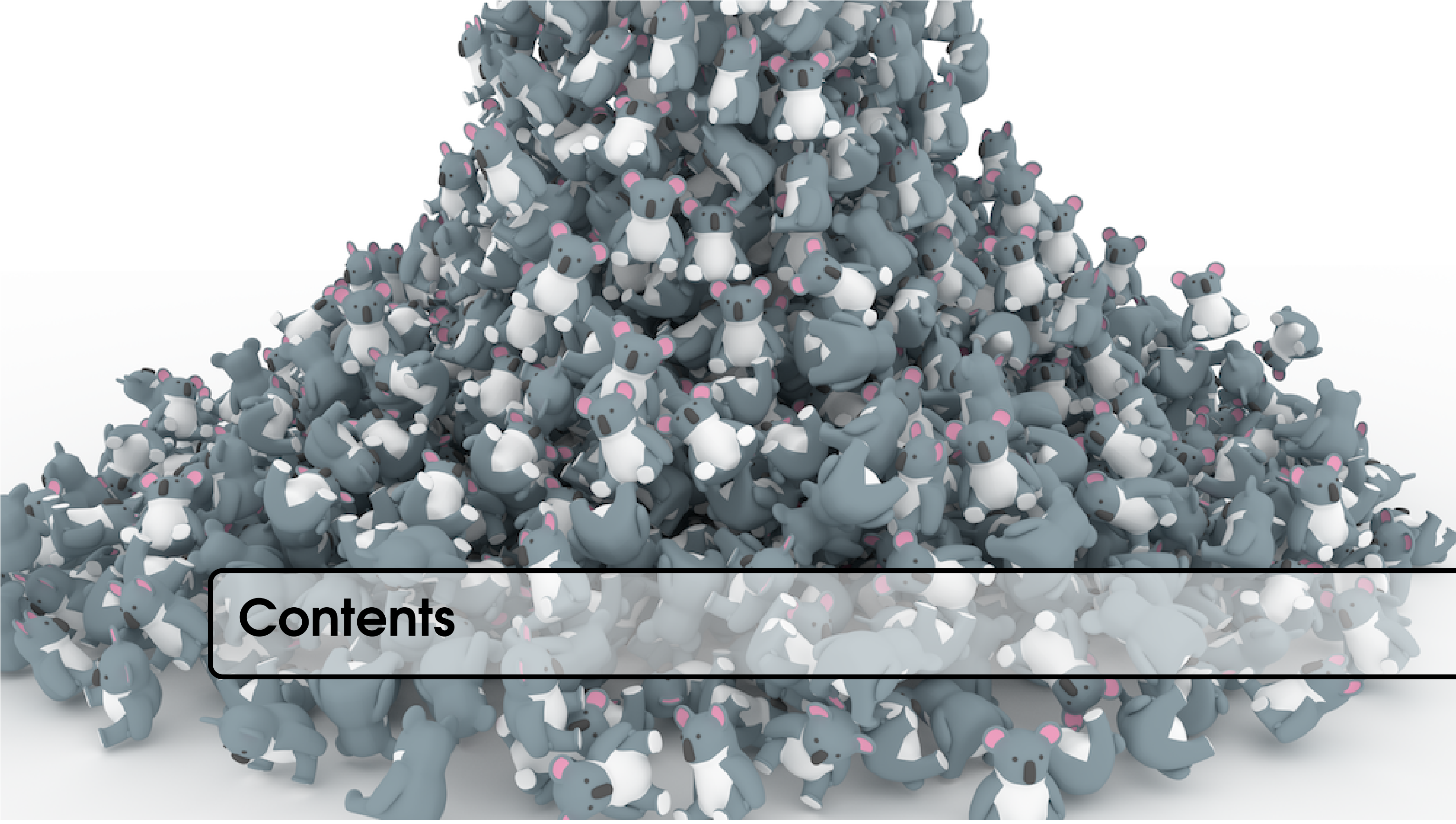

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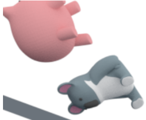


1. Cino Viggiani

Localized compaction in Tuffeau de Maastricht

Compaction bands have been observed in different kinds of materials (e.g., rocks, soils, metallic foams, cellular materials). They are usually promoted by a relatively high porosity, as well as by high mean stress levels. However, the inelastic mechanisms controlling localized compaction at the micro-scale can differ from one material to another. For instance, buckling of thin walls has been observed in metallic foams or honeycomb structures. In the case of geomaterials, due to their natural variability, the microstructural origin of compaction localization is still an open question, often complicated by the coexistence of multiple inelastic processes (e.g., pore collapse, grain crushing, and degradation of cementation bonds). Full-field nondestructive measurements have the potential to identify these micro-mechanisms and assess their relative role.

In this talk I will present some selected results from a large experimental study of compaction banding in Tuffeau de Maastricht, a bioclastic sedimentary limestone exhibiting up to 52% of porosity. Triaxial compression tests were performed at confining pressures ranging from 1 to 5 MPa, on samples cored perpendicular and parallel to the bedding plane. Systematic use of x-ray micro tomography combined with the use of advanced image analysis and Digital Image Correlation (DIC) provides quantitative 3D information about the strain field inside a sample and its evolution during a test.

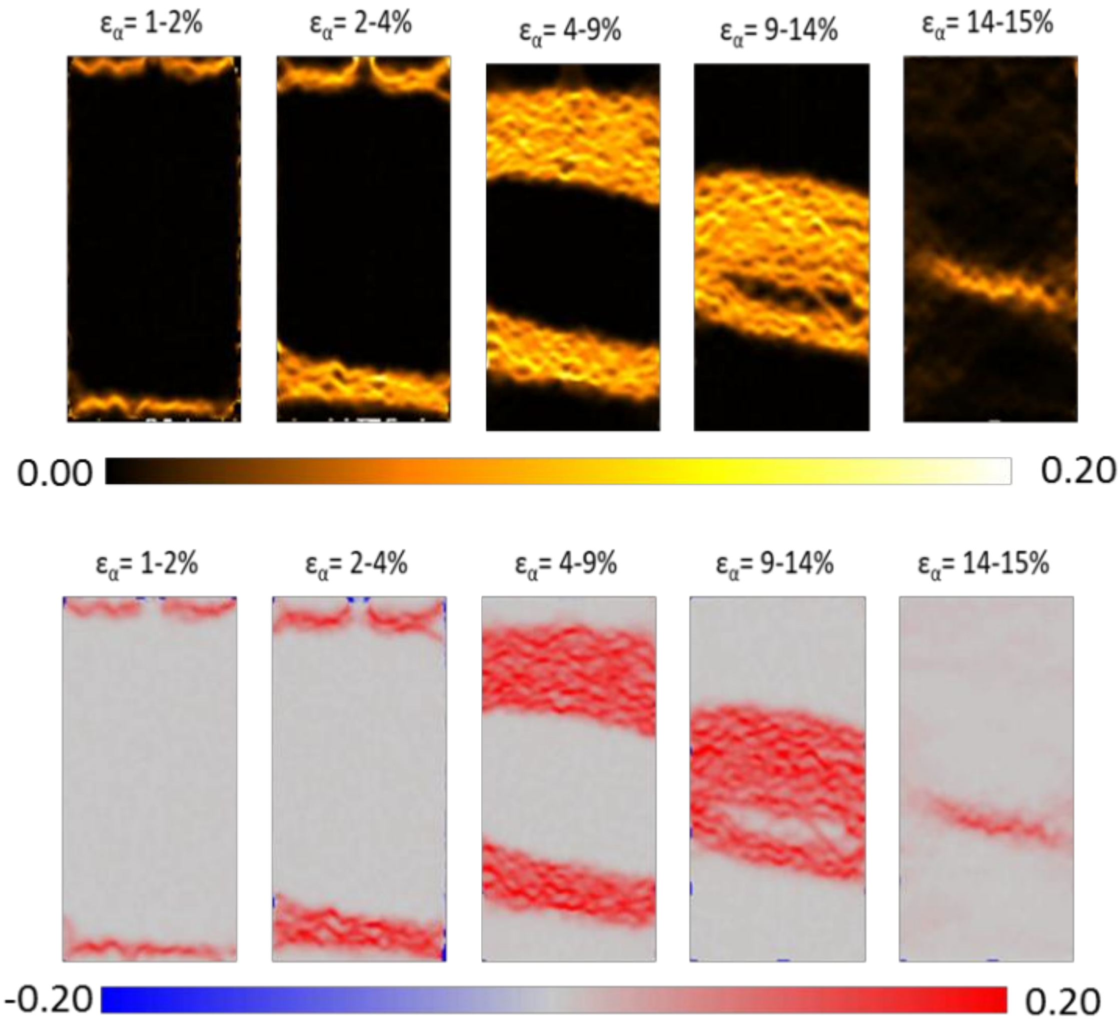
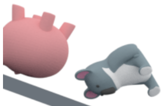


Figure 1: Vertical slices through 3D-DIC based incremental strain fields during a triaxial compression test on Tuffeau de Maastricht at 4 MPa confinement: deviatoric (upper row) and volumetric (bottom row).



2. Julio Valdes

Searching for breakage-borne sound patterns in loaded granular media

In a mechanically loaded granular pack, the breakage-borne alteration of the internal structure of grains and/or bonds produces elastic waves that propagate through the pack and ultimately reach the stiff boundaries that confine it. Sensors placed on or near these boundaries capture associated short-lived vibrations as acoustic emissions with amplitudes, rates, and frequencies that may be unique to the condition or mechanism in question. Laboratory investigations where breakage-borne acoustic emission analyses are complementary to load-deformation data are described. Examples include detecting the yield stress in oedometrically compressed sands, tracking debonding in loaded artificially cemented soils, and characterizing acoustic emission signatures that precede large localized compaction events in monotonically loaded porous packs.

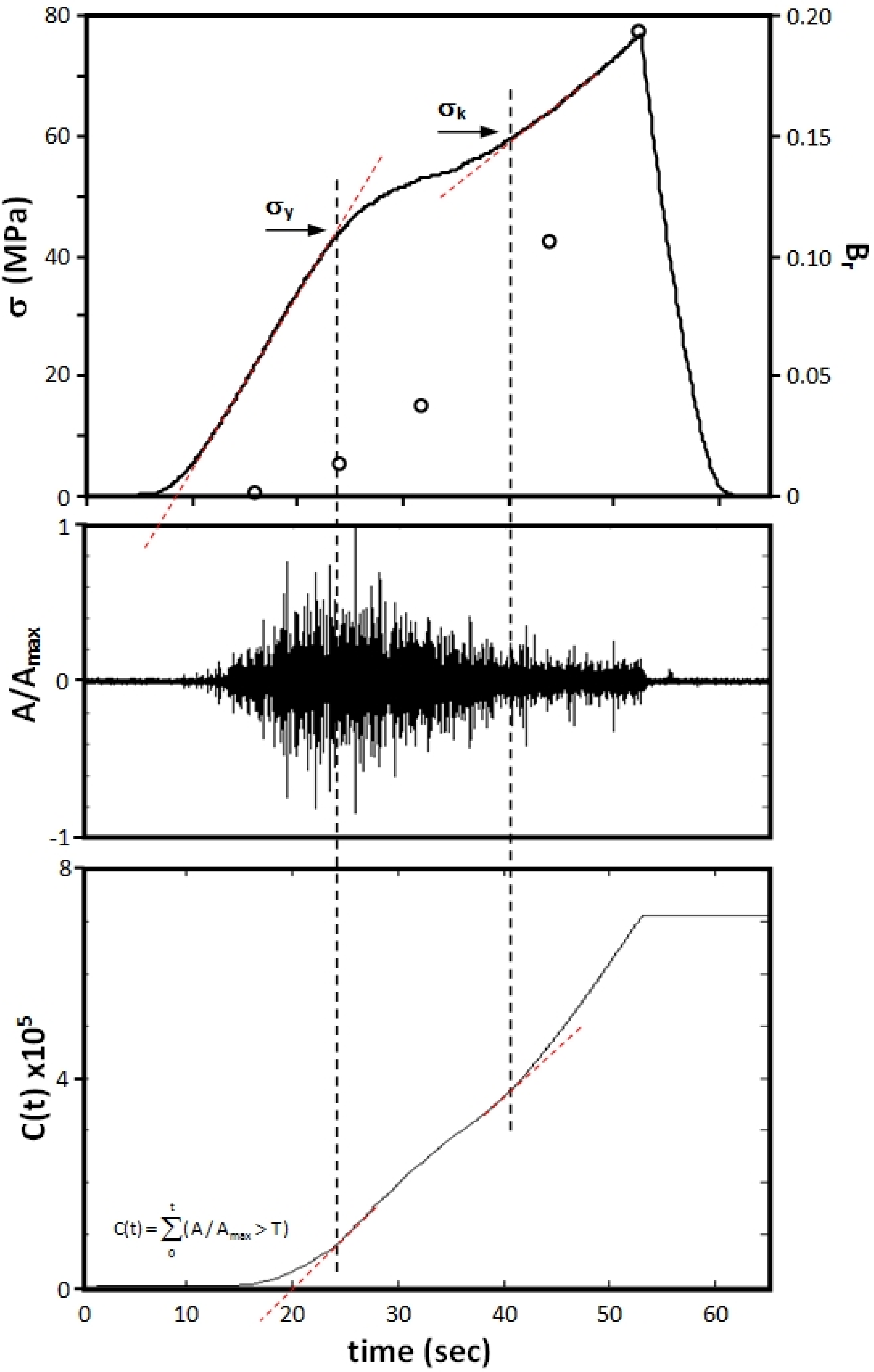


Fig. 1. AE-based detection of characteristic stresses suffered by 1D compression of rounded quartz sand.

3. Knut Jørgen Måløy et al.*

Pattern formation of frictional fingers in a gravitational potential

*Jon Alm Eriksen, Renaud Toussaint, Olivier Galland, Bjørnar Sandnes, Eirik Grude Flekkøy and Knut Jørgen Måløy

Aligned finger structures, with a characteristic width, emerge during the slow drainage of a liquid-granular mixture in a tilted Hele-Shaw cell. A transition from vertical to horizontal alignment of the finger structures is observed as the tilting angle and the granular density are varied. An analytical model is presented, demonstrating that the alignment properties are the result of the competition between fluctuating granular stresses and the hydrostatic pressure. The dynamics is reproduced in simulations. We also show how the system may explain patterns observed in nature, created during the early stages of a dike formation.

[1] Eriksen J.A., Toussaint R., Måløy K.J., Flekkøy. E.G., Galland O., Sandnes B., Pattern formation of frictional fingers in a gravitational potential. Phys. Rev. Fluids 3, 013801, (2018)
[2] B. Sandnes, H.A. Knudsen, K.J. Måløy, and E.G. Flekkøy, Labyrinth patterns in confined granular-fluid systems. Phys. Rev. Lett. 99, 038001, (2007).

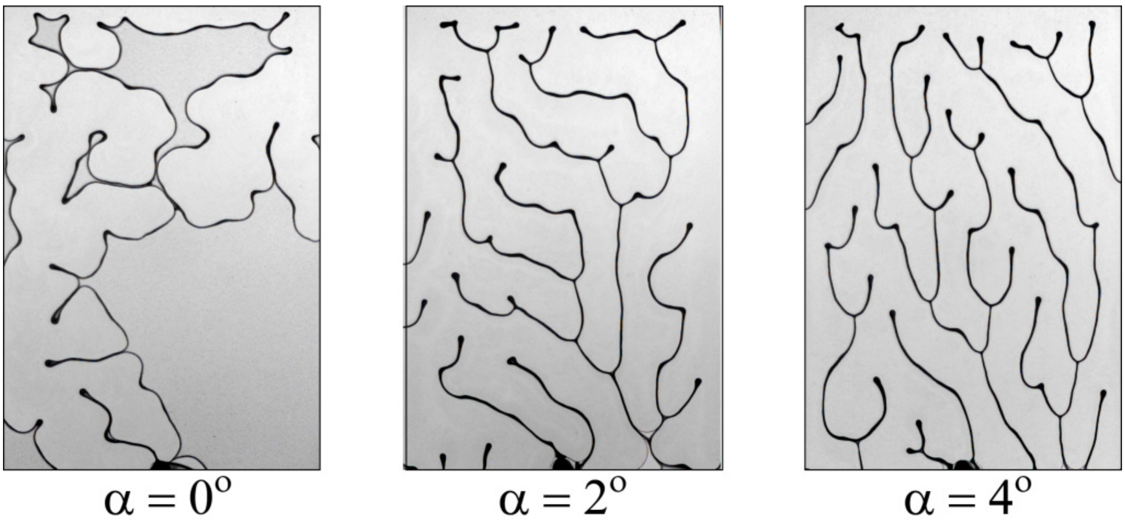
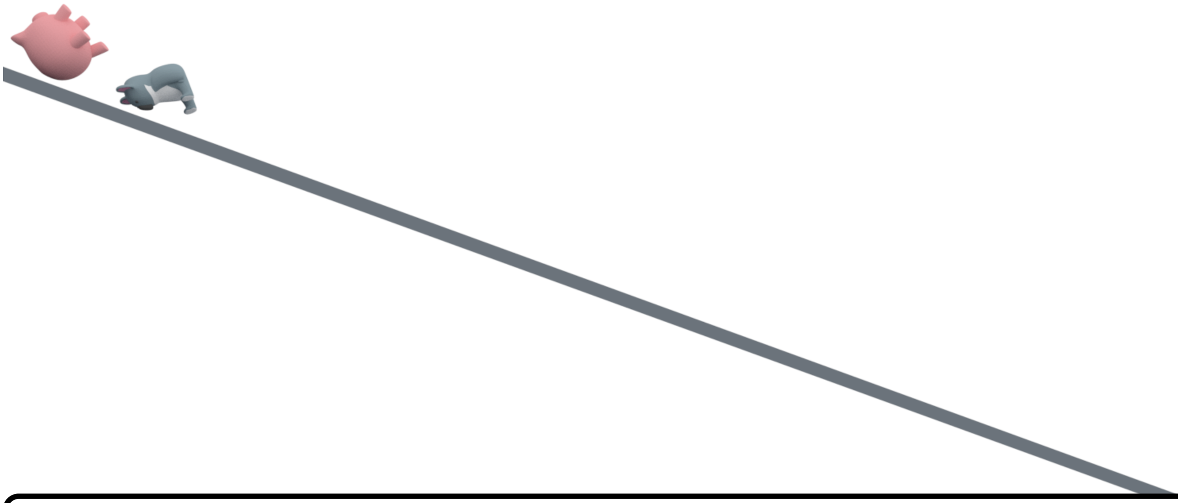


Figure 1: Examples of experimental patterns in a deformable porous medium at different tilt angles.



4. Anthony Thornton

Multi-scale modelling of bulbous head and stratification pattern formation in granular avalanches

Rapid shallow granular flows over inclined planes are often seen in nature in the form of avalanches, landslides and pyroclastic flows. In these situations the flow develops an inversely graded (large at the top) particle-size distribution perpendicular to the plane. As the surface velocity of such flows is larger than the mean velocity, the larger material is transported to the flow front. This causes size-segregation in the downstream direction, resulting in a flow front composed of large particles. Since the large particles are often more frictional than the smalls, the mobility of the flow front is reduced, resulting in a so-called bulbous head. After multiple flows a distinct layered pattern within the flow depositions is formed. Here we focus on a multi-scale approach where we use information from both continuum models and discrete particle simulations to create prediction parameter free models of this complex large scale geophysical pattern forming event.

Continuum methods are able to simulate the bulk behaviour of such flows, but have to make averaging approximations reducing the degree of freedom of a huge number of particles to a handful of averaged parameters. Once these averaged parameters have been tuned via experimental or historical data, these models can be surprisingly accurate; but, a model tuned for one flow configuration often has no prediction power for another setup.

On the other hand discrete particle methods are a very powerful computational tool that allows the simulation of individual particles, by solving Newton's laws of motion for each particle. With the recent increase in computational power it is now possible to simulate flows containing a few million particles; however, for 1mm particles this would represent a flow of approximately 1 litre which is many orders of magnitude smaller than the flows found in industry or nature.

This talk focuses on the formation and evolution of the bulbous head (see Figure 1a), which we show to emerge in both a depth-averaged continuum framework and discrete particle simulations (see Figure 1b). Furthermore, our numerical solutions of the continuum model converge to a travelling wave solution, which allows for a very efficient computation of the long-time behaviour of the flow. We use small-scale periodic discrete particle simulations to calibrate (close) our continuum framework, and validate the simple 1D model with full-scale 3D discrete particle simulations. The comparison shows that there are conditions under which the model works surprisingly well given the strong approximations made; for example, instantaneous vertical segregation.

Bulbous head formation in bidisperse shallow granular flow over an inclined plane I.F.C. Denissen, T. Weinhart, A. Te Voortwis, S. Luding, J.M.N.T. Gray and A.R. Thornton Accepted JFM

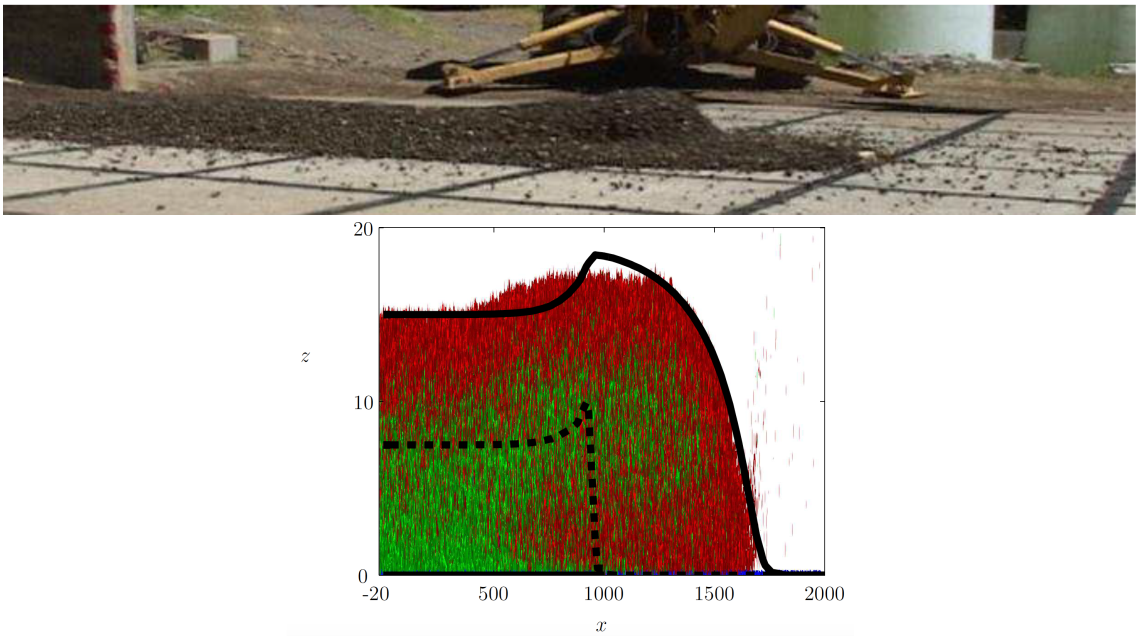
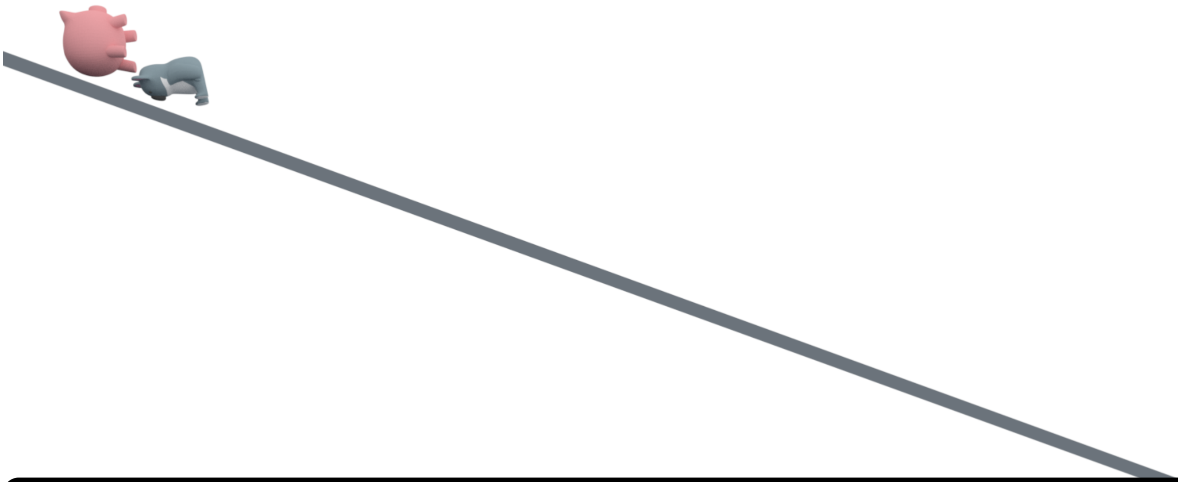


Figure 1: *Top*: Experimental debris flow deposit at the USGS flow flume, Oregon, USA, August 2008 (Logan & Iverson 2013). The back of the flow has a constant height, while the front shows evidence of a bulbous head; the flow is higher near the front than at the back of the flow. Picture courtesy of USGS. *Bottom*: Snapshots of discrete particle simulation of a bidisperse chute flow over a rough bottom. The inflow height is 15 particles diameters, resulting in supercritical inflow and the mixture is 50/50 large and small particles by volume. Red are the large particles, green are the small particles. The black lines denote the continuum (DGFEM) solution for the height. Both x and z are scaled by the large particle diameter in both the discrete particle simulations and DGFEM solutions. Note, that the x-axis is squeezed by a factor 100 compared to the z-axis, so the individual particles appear as very thin vertical stripes in this plot.



5. Pierre Rognon

Turbulent-like patterns in sheared granular materials

Granular materials do not flow in a neat and tidy way. Rather, grains spontaneously organise themselves into chaotic clusters, forming kinematic patterns that are reminiscent of vortices in classical turbulence. We have been able to measure the size and life-time of these clusters, and to evidence how they underpin macroscopic transport properties (viscosity and diffusion) controlling the flow and mixing of granular matter. This talk will present these findings and highlight their importance to continuum-scale granular flow models.

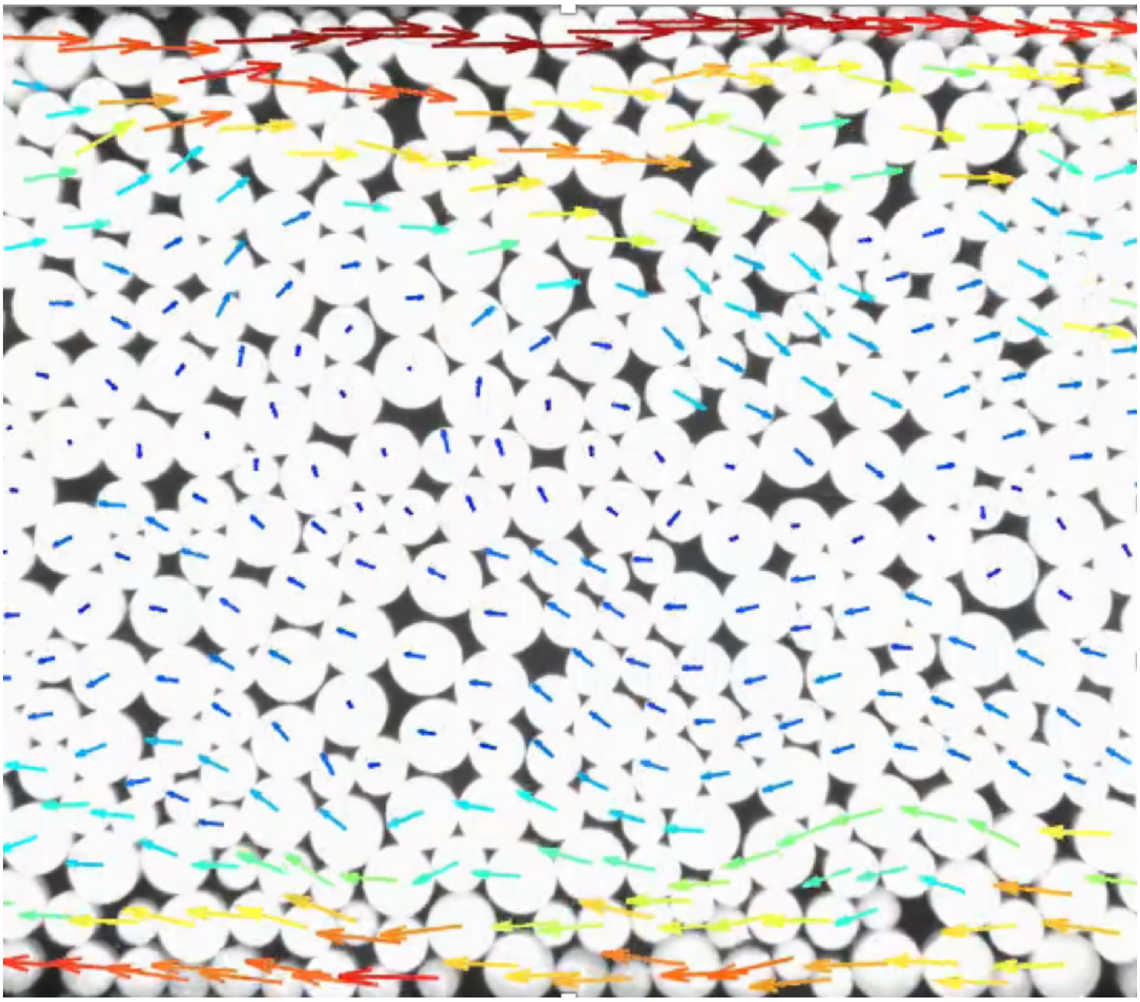
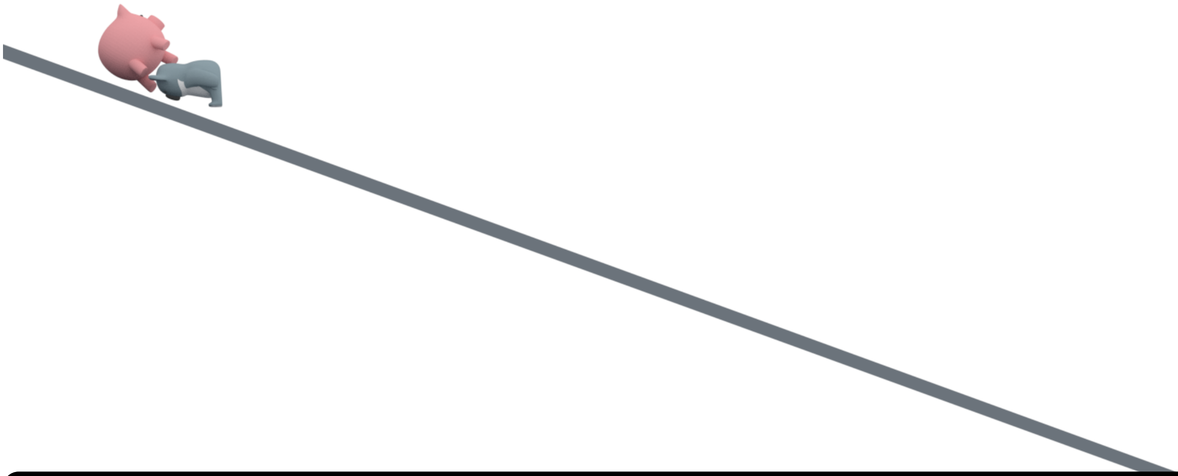


Figure 1: Turbulent like velocity pattern in granular flows: instantaneous velocity of grains being sheared between two moving plates (located at the top and bottom) measured in the Stadium Shear Device.



6. Ben Nadler, Francois Guillard and Itai Einav

Rheology of dense ellipsoidal grains

Ellipsoidal grains show a complex microscopic behavior associate with their ability to orient and align with respect to each other and the flow. These additional microscopic degree of freedom is an evolving property that gives rise to a complex anisotropic rheological response. Available continuum constitu- tive models of dense granular materials typically only consider grain size while ignoring grain shape, orientation and alignment and their effect on the rheological response.

This presentation discusses a simple generalization of the inertia rheology [1] to ellipsoidal grains. A continuum model that explicitly accounts for the grain shape and the microscopic arrangement is proposed based on physical observations that are used to motivate the mathematical construction of the model. The model consists of a constitutive law that relates the grain shape, microstructure arrangement and the flow to the developed stresses and an evolution law for the microstructure arrangement.

Limited meaningful experimental and micro-scale simulation data on the mechanics of ellipsoidal grain is available in the literature, which mainly consists of measurements of simple shear (Couette) flow [2, 3]. Available data is used to determine the model parameters and to investigate its performance. Comparison with micro-scale Discrete Element Method simulations shows that the model captures the complex mechanical response that is induced by the grain shape and the microstructure arrangement when subjected to simple shear.

[1] P. Jop, Y. Forterre and O. Pouliquen, A constitutive law for dense granular flows, Nature, 441:727- 730, 2006.

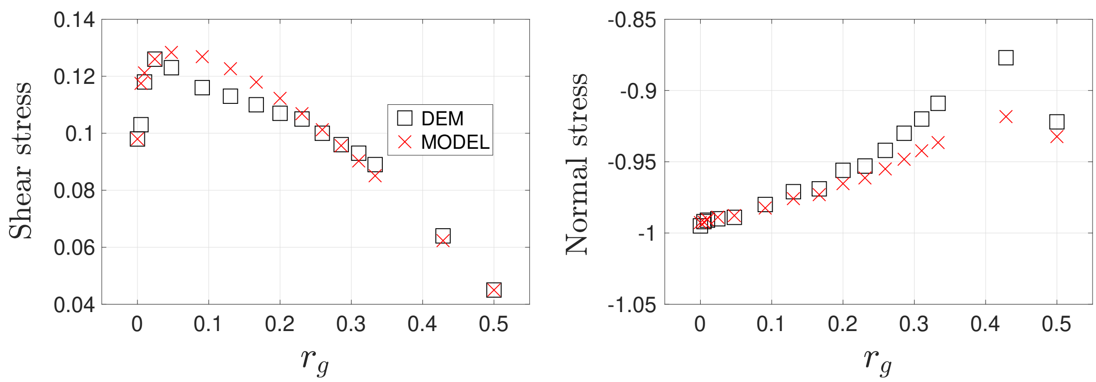
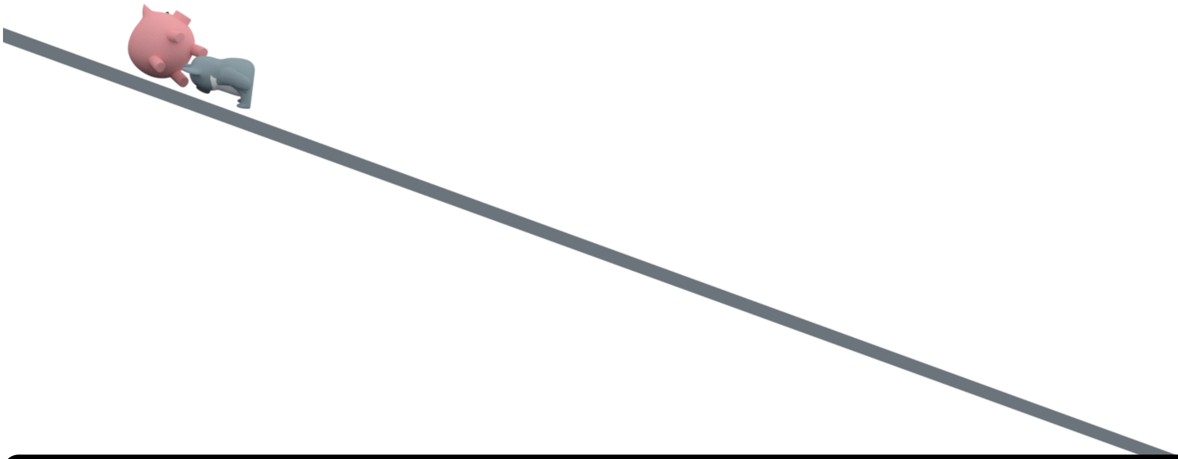


Figure 1: The macro-scale stress response vs. grain shape for frictionless grains subjected to simple shear.

[2] B. Nadler, F. Guillard and I. Einav, Kinematic Model of Transient Shape-Induced Anisotropy in Dense Granular Flow, Phys. Rev. Lett., 120: 198003, 2018
[3] D. Nagy, P. Claudin, T. Börzsönyi and E. Somfai, Rheology of dense granular flows for elongated particles, Phys. Rev. E, 96: 062903, 2017



7. Ioannis Stefanou, Hadrien Rattez and Jean Sulem

Combined role of the size of the microstructure and of Thermo-Hydro-Mechanical couplings on stability and fault reactivation

Fault reactivation depends on many factors involving strain and strain-rate dependency. Here we highlight the importance of the size of the microstructure and of the various multiphyscial couplings regarding pre- and co-seismic slip. It is shown that even though the microstructure and THMC couplings concern a finer length and time scale, they affect considerably the macroscopic behavior and stability of the system.

We propose a micromechanical, physics-based (Cosserat) continuum model by considering the characteristic size of the microstructure and the thermal- and pore-pressure-diffusion mechanisms that take place in the fault gouge during shearing. It is shown that even for rate-independent materials, the apparent, macroscopic behavior of the system is rate-dependent. This is due to the competition of the characteristic lengths and time scales introduced indirectly by the microstructure and the thermal and hydraulic diffusivities.

Numerical analyses show that both weakening and shear band thickness depend on the applied velocity, despite the fact that the constitutive description of the material was considered rate-independent. Moreover the size of the microstructure, which here is identified with the grain size of the fault gouge (D50), plays an important role and determines the slope of the softening branch of the shear stress-strain response curve and consequently influences the transition from aseismic to seismic slip.

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Rattez, H., Stefanou, I., Sulem, J., Veveakis, M., & Poulet, T. (2018). The importance of Thermo-Hydro-Mechanical cou-plings and microstructure to strain localization in 3D continua with application to seismic faults. Part II: Numerical im-plementation and post-bifurcation analysis. Journal of

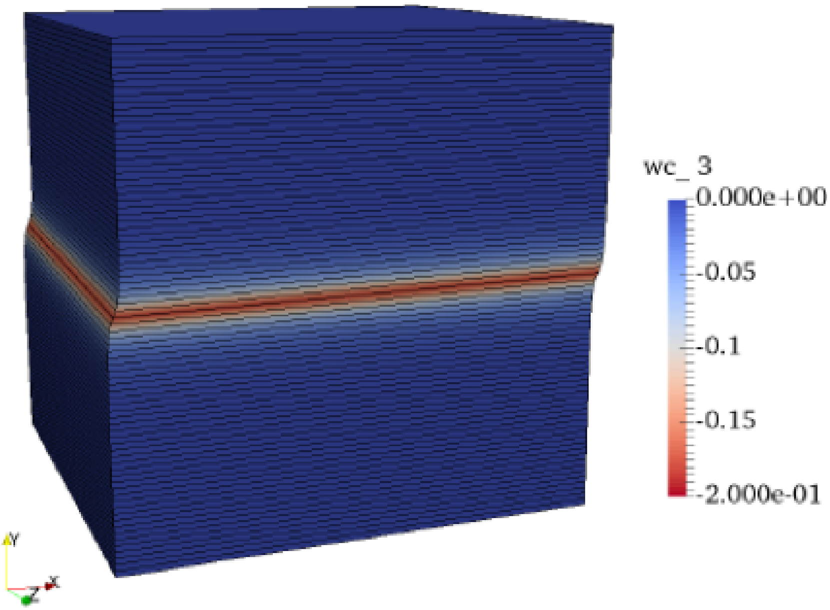
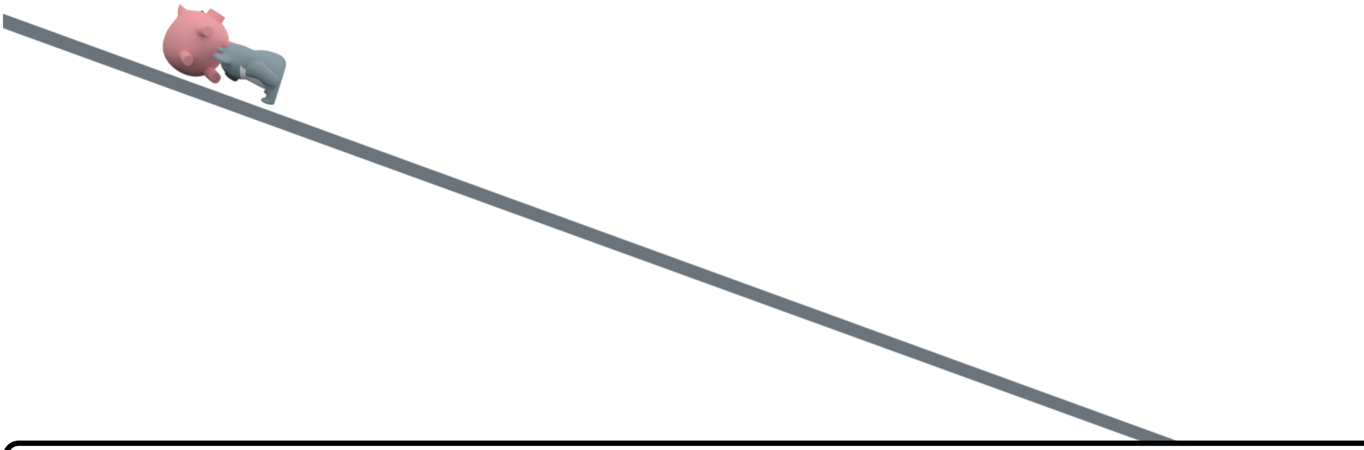


Figure 1: Strain localization inside fault gouge (colours represent Cosserat rotations, wc_3 [rad]).

the Mechanics and Physics of Solids, 115, 1–29. `http://doi.org/10.1016/j.jmps.2018.03.003`
Rattez, H., Stefanou, I., Sulem, J., Veveakis, M., & Poulet, T. (2018). Numerical Analysis of Strain Localization in Rocks with Thermo-hydro-mechanical Couplings Using Cosserat Continuum. Rock Mechanics and Rock Engineering. `http://doi.org/10.1007/s00603-018-1529-7`



8. G. Narsilio, W. Fei and M. Disfani

Heat transfer in granular materials: unveiling patterns

It has been estimated that a mere 1% of the heat energy stored in the upper 5 kilometres of Australia's landmass could supply Australia's energy needs for the next 2,600 years. As 'proof of concept', a demonstration geothermal power plant in the Cooper Basin was designed to produce 50 megawatts, enough to power a neighborhood of 3,000+ homes. In addition, shallow geothermal energy technology use ground heat exchangers together with heat pumps to provide space heating and cooling to buildings, there are more than 6 million such installations worldwide collectively harvesting gigawatts of thermal energy (equivalent to several large cities). Both these deep and shallow geothermal technologies have already demonstrated the promise of a truly sustainable, emission-free and continuous energy source, with potential to provide Australia's base-load power requirements.

At the core of all geothermal projects, fluid flow and heat transfer dominate in design and production. The microstructure of geomaterials controls these conduction properties. Indeed, soil and rock masses comprise complex assemblies of particles, varying in size, shape and mineral compositions, degree of inter-grain cementation and phase, all of which strongly influence macroscopic response.

Understanding and identifying patterns linking heat transfer in porous media and its microstructure including particle shape and connectivity is thus important for a number of engineering applications, including geothermal's. The use of X-ray micro-computed tomography (to extract 3D features of individual particles) together with Discrete Element method (for generating more irregular particle packings), Finite Element method (for simulating heat transfer) and machine learning techniques (for investigating the relationship between microstructure and thermal conductivity) compose our toolbox to unveil patterns related to heat transfer in granular media. In this work, the effect of particle shape on heat transfer was quantified using 3D physical descriptors and other non-geotechnical features arising from complex network theory, and this toolbox was used aiming to unveil patterns or relationships between these features.

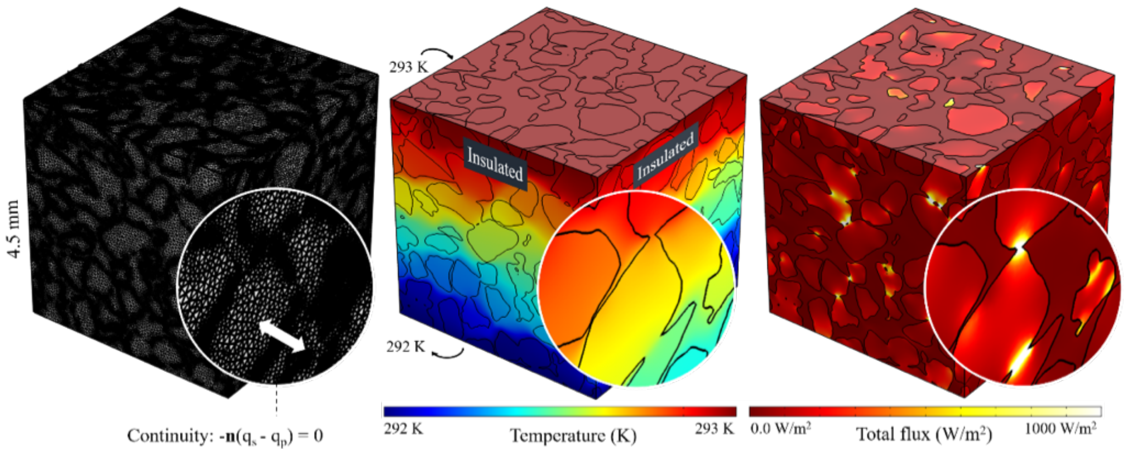
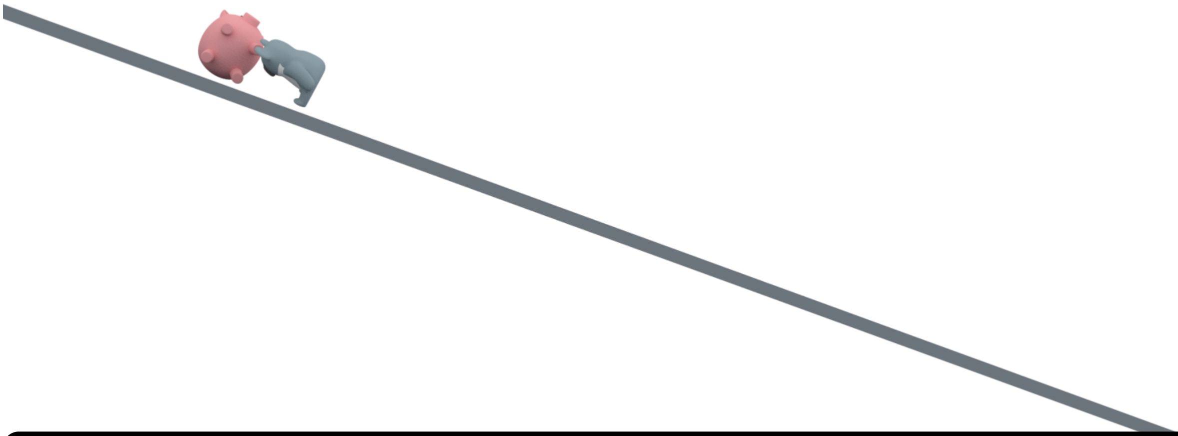


Figure 1: Heat transfer at the particle scale: (a) FEM mesh generated from a microCT scan an angular sand, (b) temperature and (c) total heat flux distributions arising from the heat transfer simulation. The process is repeated for other granular assemblies of distinct particle shapes to unveil relationships between microstructural features using physically based machine learning techniques.



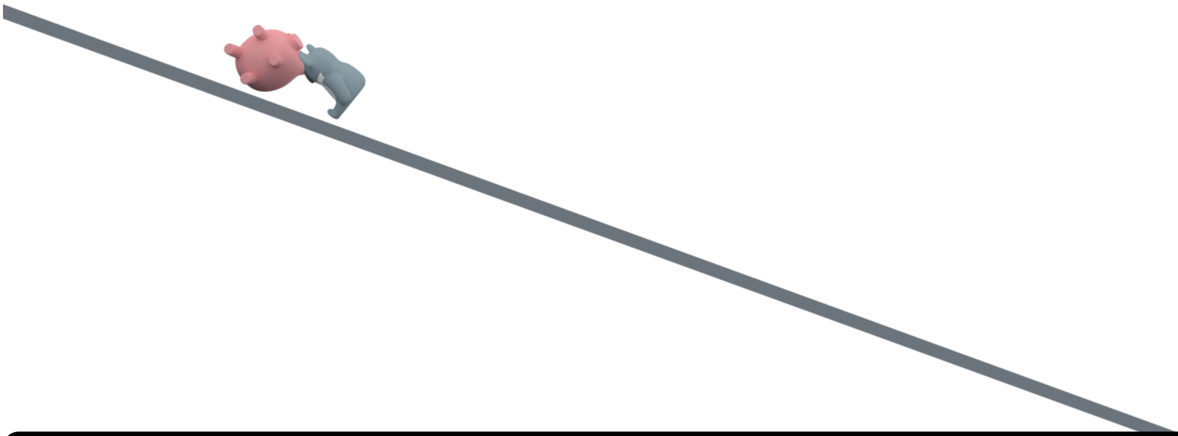
9. E. Pasternak and A. V. Dyskin

Strain localisation as a consequence of elastic instability

Strain localisation in geomaterials under compression is often observed, but its mechanism is not always apparent. In this presentation we consider a strain localisation mechanism based on the emergence of non-unique elastic solutions in unstable elastic materials.

Incompressible elastic materials and materials with negative stiffness are unstable, which manifests itself in the non-uniqueness of elastic solution and can produce strain localisation. In geomaterials incremental (and irreversible) incompressibility can emerge due to dilatancy. The negative stiffness in the form of incremental negative shear modulus or incremental negative Cosserat shear modulus are created by rotation of non-spherical grains or clusters thereof in the presence of compression. We demonstrate that in all these cases there exist solutions that do not involve unloading and hence just incremental incompressibility or negative stiffness are sufficient to induce strain localisation.

The existence of non-uniqueness of elastic solution is also controlled by the boundary conditions. We demonstrate that the emergence of incremental incompressibility or negative Cosserat shear modulus leave enough free parameters to satisfy the boundary conditions at the lateral surfaces of loaded samples – the only boundary conditions controllable in experiments. We argue that the boundary conditions at the sample ends strongly depend upon the conditions at the contact with the loading platens, which can change during loading and in particular as the result of emergence of strain localisation. On the other hand, the non-unique solutions in isotropic materials with negative shear modulus cannot satisfy the boundary conditions on the lateral surfaces of a loaded sample. Therefore the uniqueness of elastic solution is maintained and hence excludes strain localisation.



10. A. Alavoine, P. Dangla, J.M. Pereira

Modelling bonded granular materials: an upscaling perspective

Geomaterials in general and granular materials in particular are often encountered in natural conditions, engineering or industry. In many cases, the particles are bonded by either liquid bridges or solid bonds. This is the case for instance for unsaturated soils, where these bridges are capillary menisci. Another example concerns the frozen soils or methane hydrate bearing sediments where the solid skeleton (the assembly of grains) is cemented by the ice or hydrate phase.

The behaviour of such assemblies of bonded grains is peculiar. In an engineering perspective, having access to a modelling tool able to predict the macroscopic behaviour of such materials is of clear interest for many applications. However, bearing in mind the microstructural description of the material together with the underlying physics behind its basic constituents is clearly a challenge because of the gap between the scales where physics is better known and where the engineer has its interests.

In this work, we will present different modelling strategies used to upscale the behaviour of bonded geomaterials, including their non-linear and irreversible behaviour. A particular focus will be put on the finite element method and the fast Fourier transform used as tools to reach this goal.

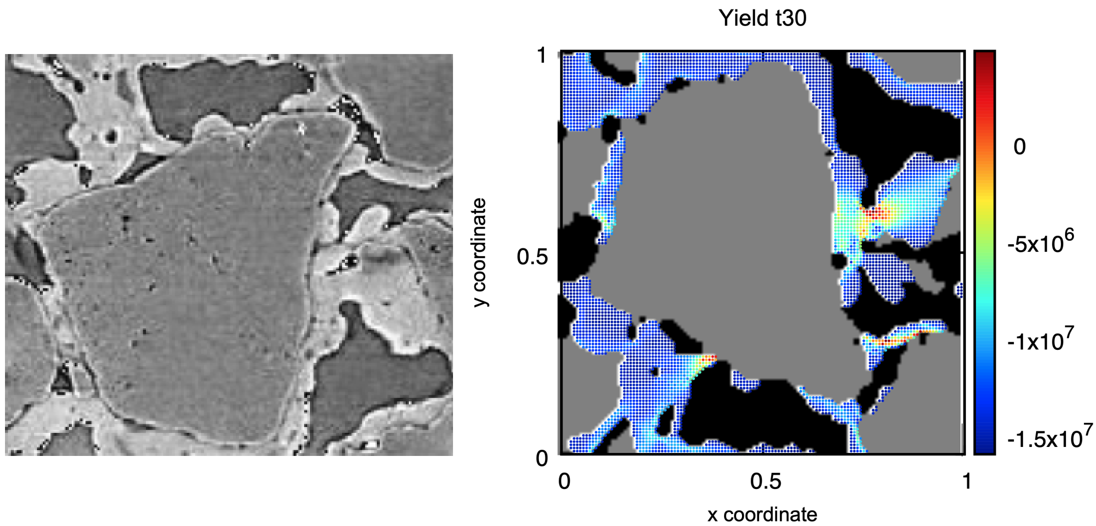
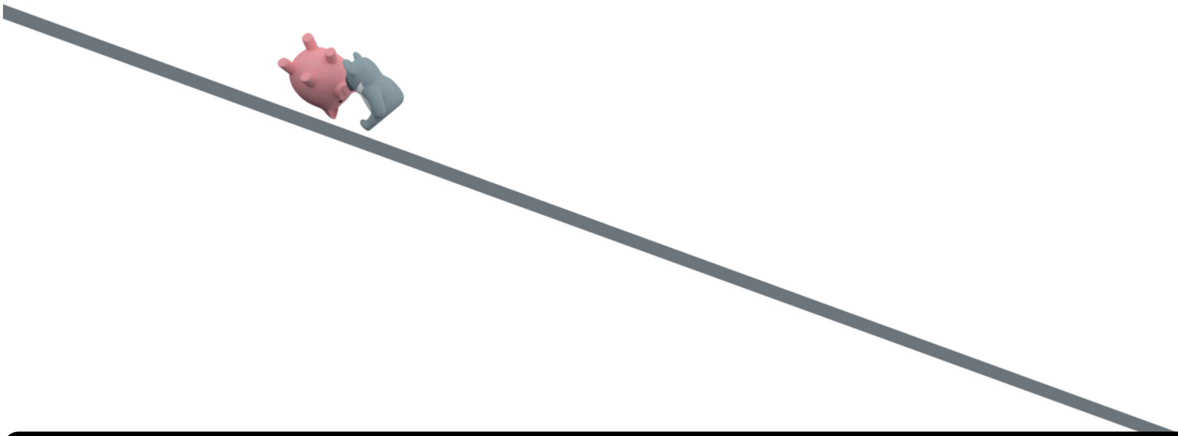


Figure 1: *Left*: Xenon gas hydrate film growth in sand specimen from (Chaouachi, 2016). *Right*: predicted yield criterion using FFT during a triaxial test.



11. A. Scheuermann, et al.*

Hydraulic fracturing of bridle materials: Fracture patterns and characteristics

*A. Scheuermann, F. Hamidi, S. Behraftar, S.G. Torres, D. Pedroso, H.B. Muehlhaus and L. Li

Hydraulic fracturing is a well-established method in enhanced oil and gas recovery or for deep geothermal systems for improving the permeability of the reservoir rock. It is also used for the preconditioning of rocks in mining methods such as block caving and long wall mining. Hydraulic fracturing is there applied to pre-weaken the rock for enhancing the disintegration of the rock without creating an uncontrolled rock burst or for intersecting seismically active structures. These examples clearly show that on the one hand, hydraulic fracturing is a frequently used measure for engineering the properties or the state of a rock to support the targeted application. However, on the other hand there are numerous parameters and conditions influencing the fracture propagation and characteristics making the prediction of the outcome of hydraulic fracturing applications difficult or even impossible.

In order to investigate the influence of the prevailing stress conditions of the host rock and the viscosity of the invading fracturing liquid on the hydraulic fracturing process, experimental investigations with an artificial homogeneous brittle material as a rock substitute have been conducted (Fig. 1d & 1e). A newly developed experimental set-up allowed the implementation of plane strain hydraulic fracturing tests with circular disc samples. The phases of the fracture development for the conditions of the test could be characterised using observations with a high-speed camera. A DEM/LBM code was validated based on Cracked Chevron Notched Brazilian Disc (CCNBD) Tests (Fig. 1a, 1b & 1c).Numerical simulations with this code have been conducted to reveal the influence of the viscosity on the fracture pattern.

The presentation will introduce the used artificial, rock-like material with the experimental set-up. Results of the experimental investigations and the numerical study will be presented and discussed.

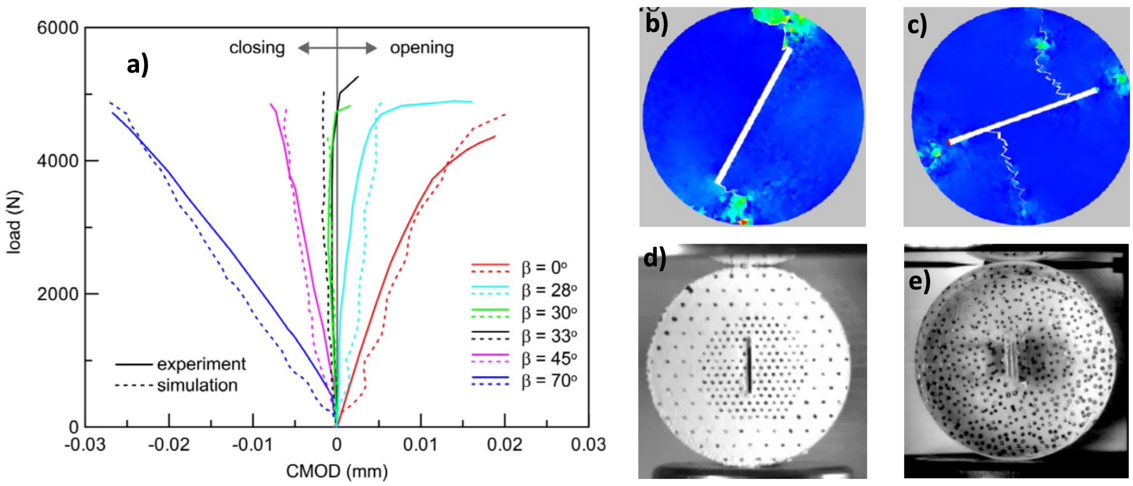


Figure 1: a) Comparison between experimental and numerical results for the Crack Mouth Opening Displacement (CMOD) during CCNBD tests. Result of numerical simulations of CCNBD tests using the DEM/LBM code for an angle of the crack of b) 28° and c) 70°. Cracked Straight Through Brazilian Disc (CSTBD) Tests with samples made of d) Sand/Epoxy mixture and e) Smash-It.

12. Daniel Dias-Da-Costa

Failure patterns, mechanisms and crack widths in concrete structures: assessment of the uncertainty of a discrete crack model

The ability to accurately predict failure patterns, mechanisms and crack widths in concrete is critical not only to achieve acceptable serviceability performance, but also to prevent the structural failure of new designs. The interaction of cracks and structural elements can become a highly complex and non-linear problem, in which case many aspects such as concrete cracking and crushing, steel yielding and hardening, need to be properly accounted for. For example, in reinforced concrete members strengthened with FRPs, the stress localisation created by the opening of small cracks can be enough to initiate debonding of the FRP and sudden structural failure, and this interaction cannot be analysed by standard models (Figure 1). This presentation assesses the performance of a discrete crack model in its ability not only to predict failure mechanisms, but also the uncertainty associated with crack patterns and widths (Figure 2). Experimental results measured during flexural tests are used for assessing the model uncertainty. The discrete crack model is shown to be a reliable tool to predict the structural behaviour, whilst requiring only a minimum set of material parameters easily available from design standards as initial input.

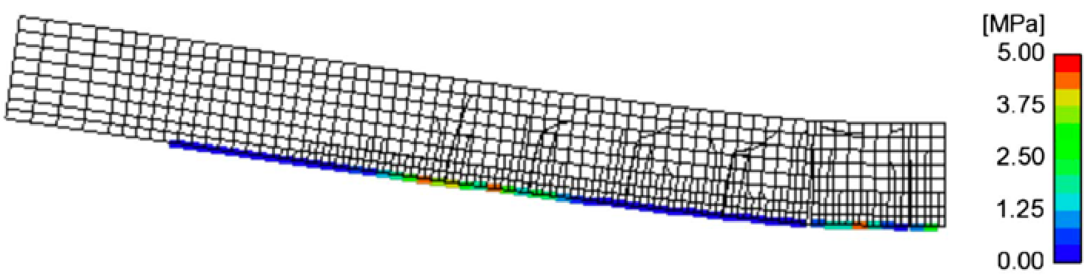


Figure 1: Interaction of cracks with FRP and debonding.

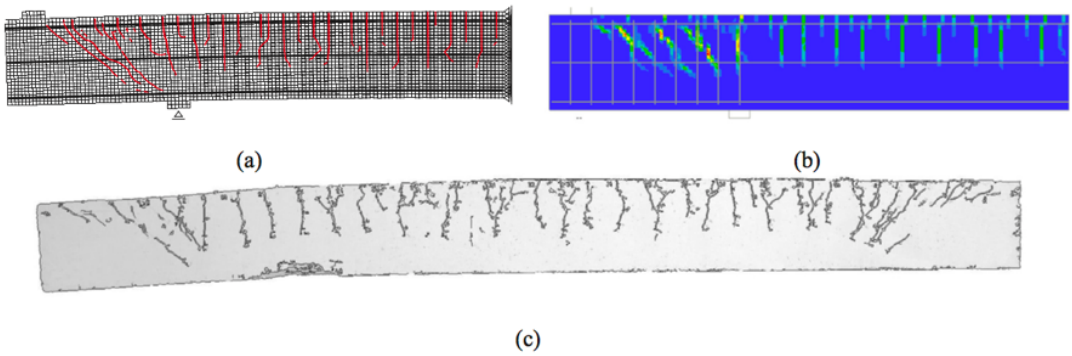


Figure 2: Crack pattern from: (a) discrete crack model; (b) smeared model; and (c) experiments.

Thursday, January 31

Patterns across scales . . . .

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Patterns across scales . . . .

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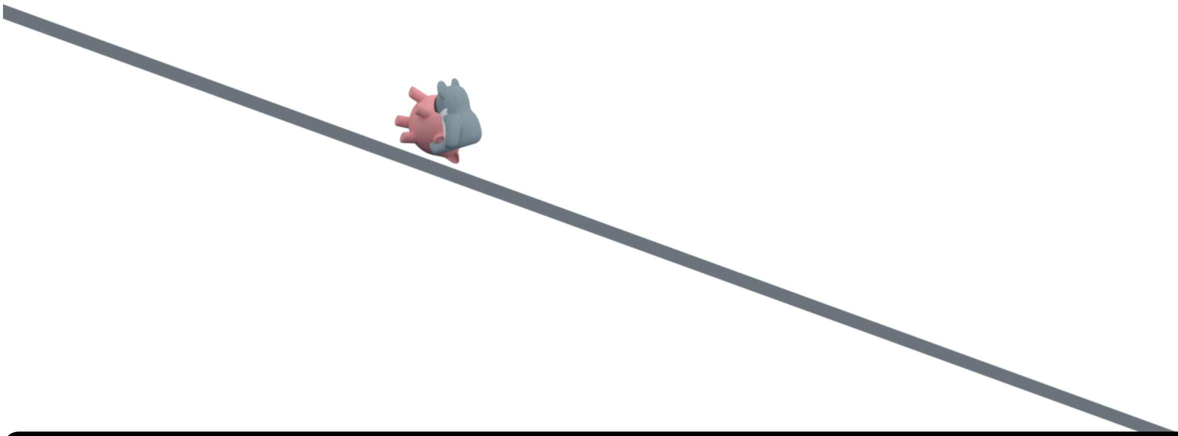


13. Jose Andrade

Celestial Soil Mechanics: What does it take to create patterns on Mars

The mechanics of regolith (celestial soils) is crucial to creation of natural and man-made patterns everywhere in the solar system.

In this talk, we will discuss the state of our knowledge about celestial soil mechanics and how this matters to our current and future exploration of the solar system.

Specifically, the necessary advancements to make infrastructure patterns (e.g., landing pads, habitats) will be explored. New developments in physics-based simulations, artificial intelligence, robotics, and 3D printing will be touched upon as areas where celestial soil mechanics plays a crucial role.

14. Stephen A Hall et al.*

Following stress, strain and fabric evolution in granular media using x-ray tomography and 3D x-ray diffraction

*Stephen A. Hall, Ryan C. Hurley, Jonas Engqvist, Chongpu Zhai, Eric B. Herbold, Marta Majkut & Jonathan Wright

In recent years the combination of grain-resolved 3D x-ray diffraction (3DXRD) and x-ray tomography have been developed to study details of granular mechanics across three scales; sample, individual grains and an intermediate, "continuum" scale. Grains stresses, and thus force transfer, can be studied in bulk granular systems using 3DXRD that, along with the granular kinematics and contact structure from tomography, allowing local comparisons of stress and strain and investigation of local evolution of elasto-plastic properties linked to the underlying granular fabric. Results from recent experiments involving confined-1D- and triaxial-compression will be presented to illustrate the method and the new information that can be gained towards better understanding of granular mechanics.

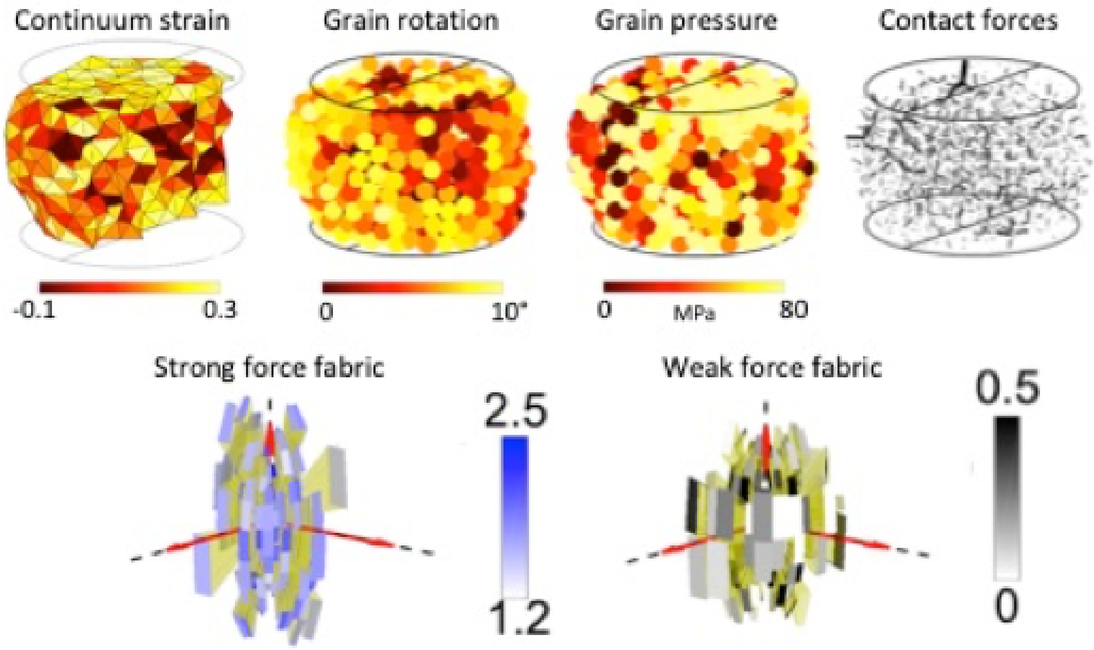
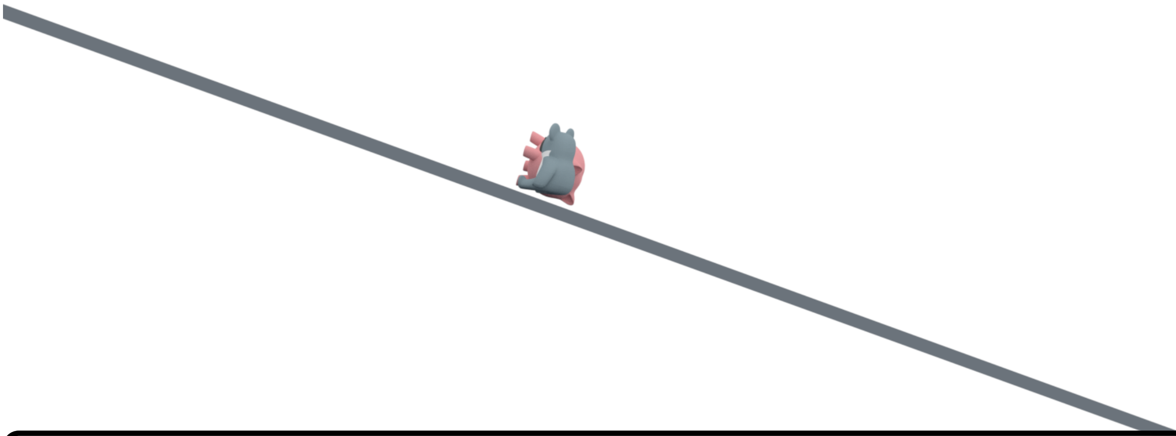


Figure 1: Results from the final load step, after macroscopic failure and before unloading, in a triaxial test monitored with x-ray tomography and 3DXRD showing the continuum strain and grain rotations distribution determined from the grain kinematics the grain pressures from the 3DXRD-derived grain strains and the contact forces from force inference using the grains stresses and the contact distribution. The lower plots show spherical distributions of the contact forces, excluding boundaries forces for the weak and strong forces, respectively. The distribution analyses were conducted by dividing forces into groups based on force directions and the averaged force magnitude for forces in each direction is indicated by the colour of the end of each bar. The red arrows indicate x-axis, y-axis and z-axis with lengths and the probability of force distribution corresponding to 0.02, 0.02, 0.005, respectively.



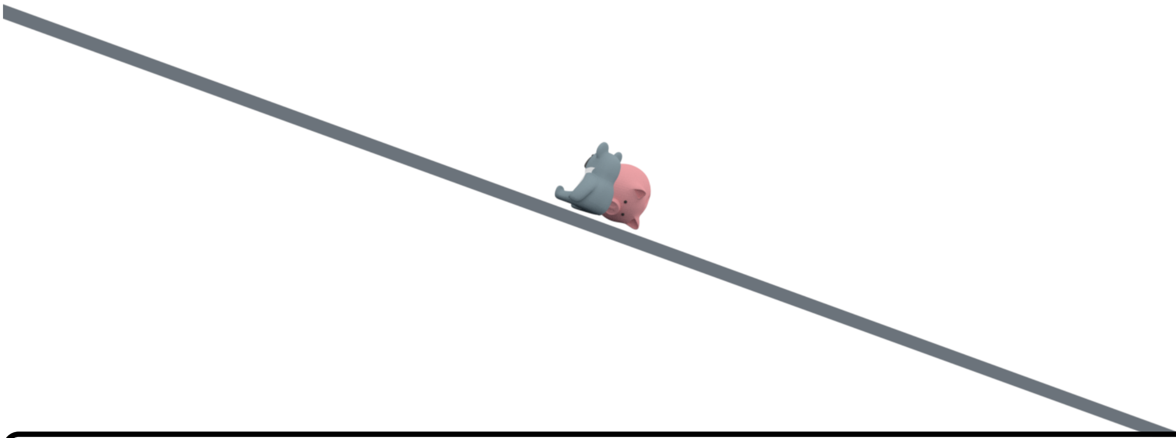
15. Stefan Luding

From particle simulations to macro-scale theory: Applications in geo, civil, mechanical and food processes.

The dynamic behaviour of granular materials and powders is of considerable interest in a wide range of industries like geotechnics, food, civil, or chemical/mechanical engineering. However, the full understanding or control of the different phenomena and mechanisms of the particle systems, natural phenomena, or processes is an essential challenge for both science and application due to the multi-scale nature from particle contacts via particles, force-chains, and collective macroscopic flow and structures.

The fundamentals can be studied by direct particle simulation methods, where often the fluid between the particles is important too, in order to gain a microscopic understanding of the processes and mechanisms. For large-scale applications, a micro-macro transition towards continuum theory is necessary, however, only smaller applications can be modeled nowadays directly by discrete micro-scale methods. Instead, more often meso-scale methods are used where the particles are up-scaled, representing a certain number of primary particles. As one example for such meso-models, we use experiments and discrete particle simulations (DEM) to investigate the dosing of cohesive fine food-powders. Other applications involve avalanches or chute flows, ring-shear rheology testing of granular flows as well as the study of the elastic, or elasto-plastic solid-like material behavior.

As alternative multi-scale approach, the micro-macro transition from discrete particulate systems to continuum theory involves a mathematical homogenization or coarse-graining that translates particle-positions, -velocities and -accelerations into density-, stress-, and strain-fields, by statistical spatial- and temporal averaging. The macroscopic fields are compatible with the conservation equations for mass and momentum of continuum theory, and also the fluctuating kinetic energy provides a measure for the importance of fluctuations in those systems. The ultimate goal is to find constitutive relations that contain information about the micro-structure and -fluctuations, and to solve those on the macro-level for solving application and optimization problems. Examples considered are chute-flows down slopes, ring-shear testers as well as rotating drums, where the same local rheology models all should work, independent of the geometry.



16. E. Ando, J. Desrues and G. Viggiani

Experimental observations of emergence of shear bands at different scales

The geomaterial pattern that is studied in this work is the emergence of strain localisation in granular media under quasistatic triaxial loading.

X-ray tomography has been used with great success, since the end of the 1980s to reveal 3D structures and processes in geomaterials. At the beginning of this adventure, spatial resolution in medical x-ray scanners was not sufficient to resolve individual sand grains (0.3mm size in this study), however important findings regarding the local significance of the value of critical state void ratio were made, e.g., in Desrues et al. 1996.

Synchrotrons and laboratory x-ray scanners now offer high spatial resolutions. However, the usual trade-off between spatial resolution and field-of-view still applies, so to take advantage of the gain in spatial resolution, experiments have had to be miniaturised. In this case, specimens of sand (always 0.3mm size) for triaxial compression have been reduced to cylinders 11mm diameter and about 22mm height, containing tens of thousands of grains. Experiments performed on such small speicmens have allowed the patterns of grain scale kinematics during the emergence of strain localisation to be measured.

In this work we return to larger specimens (70mm diameter and 140mm height) and always in triaxial compression study the complex patterns and elusive emergence of strain localisation when millions of grains are present in a sample.

The ability to test large specimens significantly facilitate the grain size dependence in shear bands with coarser grains, some preliminary results will be presented.

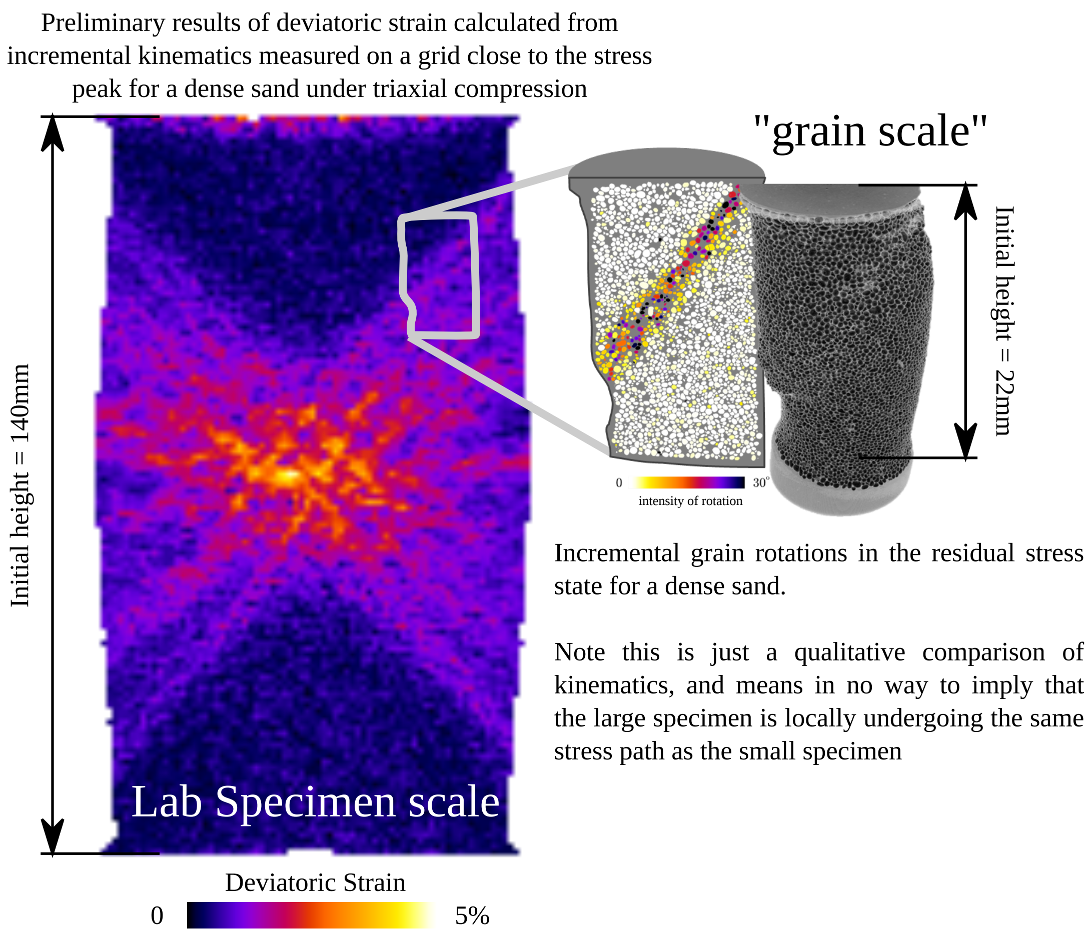
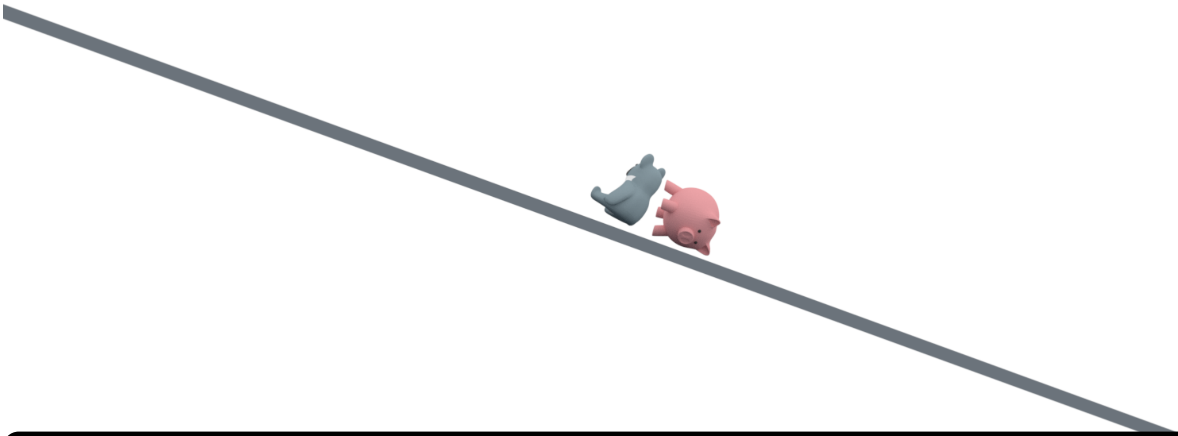


Figure 1: Illustration showing strain localisation patterns from large (complex pattern) and small-scale (simple pattern) triaxial compression tests performed with x-ray tomography



17. Mohammad Saadatfar

Patterns in sphere packings: a multi-scale view of the compaction process

The arrangements of particles and forces in granular materials have a complex organisation on multiple spatial and temporal scales that range from local structures to mesoscale and system-wide. This multiscale organisation can affect how a material responds or reconfigures when subject to external perturbations.

At the grain-scale, we identify four grain-scale deformation mechanisms that highlight basic grain-scale rearrangements underpinning sphere packing and granular compaction (Fig.a-d). Through these grain-scale pattern selection, we recover the connection between topological features of sphere packings and their mechanical stability. At the intermediate scale i.e. meso-scale; we find densely packed tetrahedral patterns of grains (Fig.e-f) that form polytetrahedral clusters (Fig.g-h). We show that sphere packing compaction is fundamentally connected to the disappearance of these polytetrahedral clusters . Finally at the global scale of the entire system; we utilise network analysis tools to show that the structural origin of the jamming transition in jammed sphere packing emerges as sudden appearance of k-cores at certain coordination numbers which are related not to the isostatic point, but to the emergence of the 3- and 4-cores as given by k-core percolation theory.

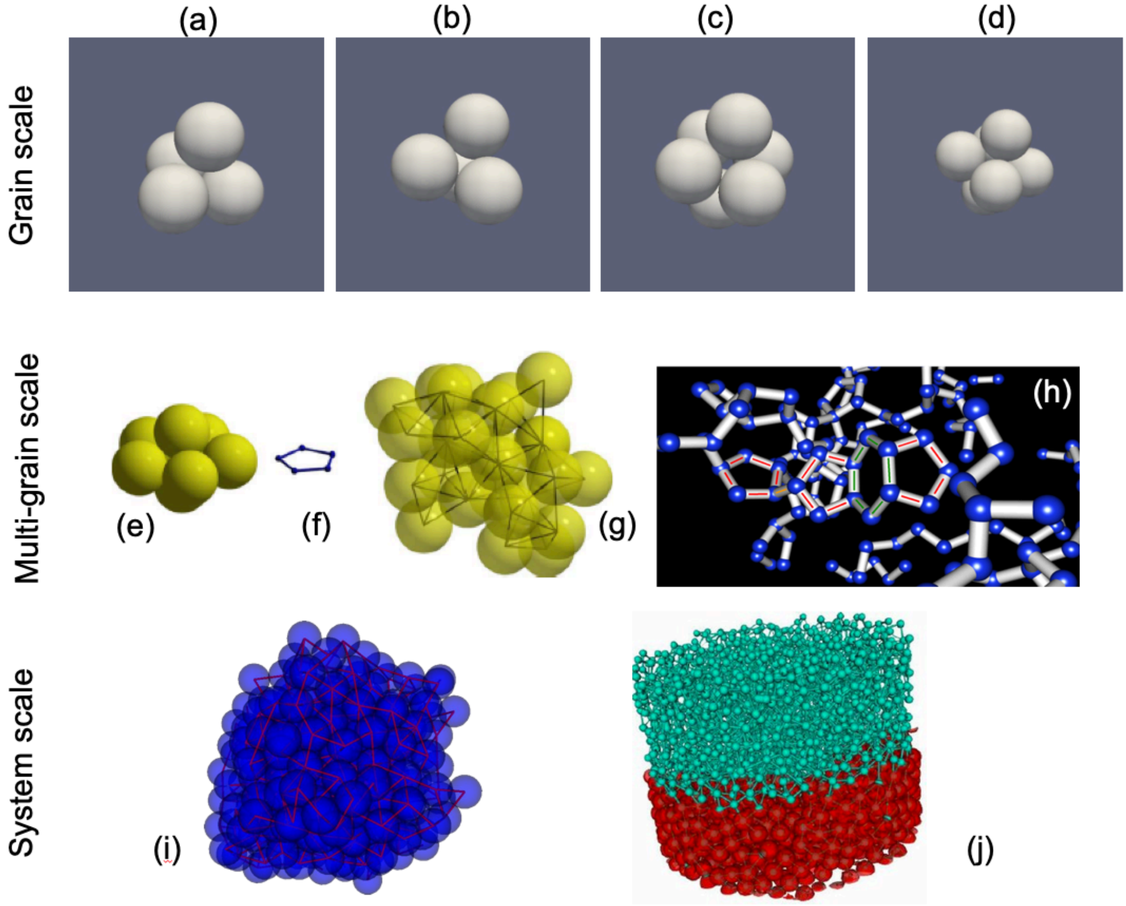
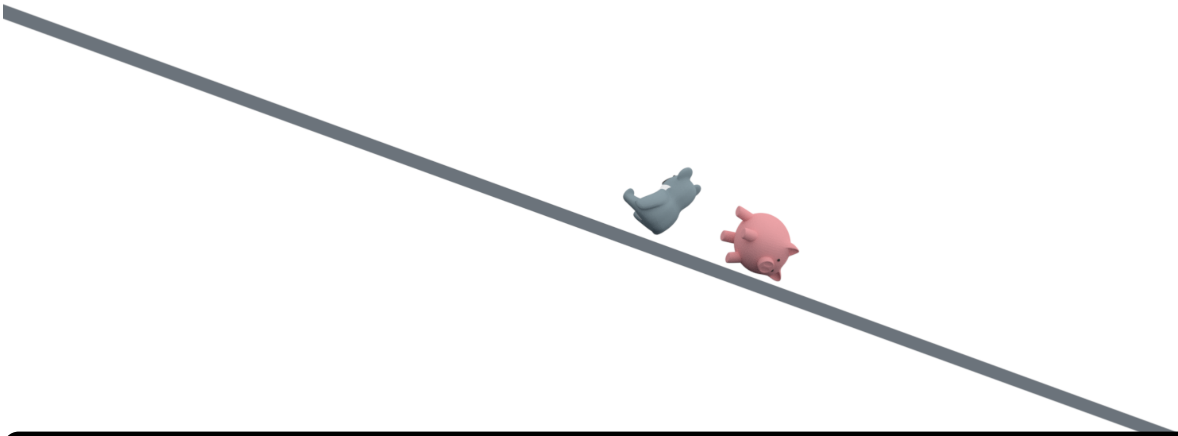


Figure 1: (a-d) Grain-scale deformations scenarios representing tetrahedral (a-b) and octahedral cavities that drive densification in sphere packing. (e-g) Formation of polytetrahedral clusters in jammed sphere packing. (h) Visualizations of the topology of polytetrahedral aggregates. Polytetrahedral clusters are represented as networks in which each vertex (blue nodes) is a dense tetrahedron and each bond (white tube) represents two tetrahedra sharing a face. (i-j) Network representation of sphere packings showing the formation of a giant percolating cluster of grains.



18. Giang Nguyen and Ha H Bui

Localisation — Material & Structural — Space & Time

Localisation of deformation destroys the assumption on the homogeneity of materials. The behaviour of the volume element in such cases depends on the size and orientation of the localisation zone inside it, which is usually at a much lower scale, their corresponding mechanical responses and interactions, besides the boundary conditions as usual. In short it should be considered as a "structural" problem given the heavy involvement of geometrical properties. The evolutions of the material responses inside and outside the localisation zone generally follow their own time scales, regardless of how the macro (and controlled) loading is. We present our attempts and preliminary results in tackling this significant difference in space and time evolutions in constitutive modelling and SPH simulations of problems involving localised failure (Figs. 1ab). Some interesting preliminary results in controlling the time evolution of inelastic behaviour inside the localisation zone, through the Brazilian disc tests on rocks (that usually fail instantly under quasi-static loading, leaving no time for the measurements; Fig. 1c), are also presented.

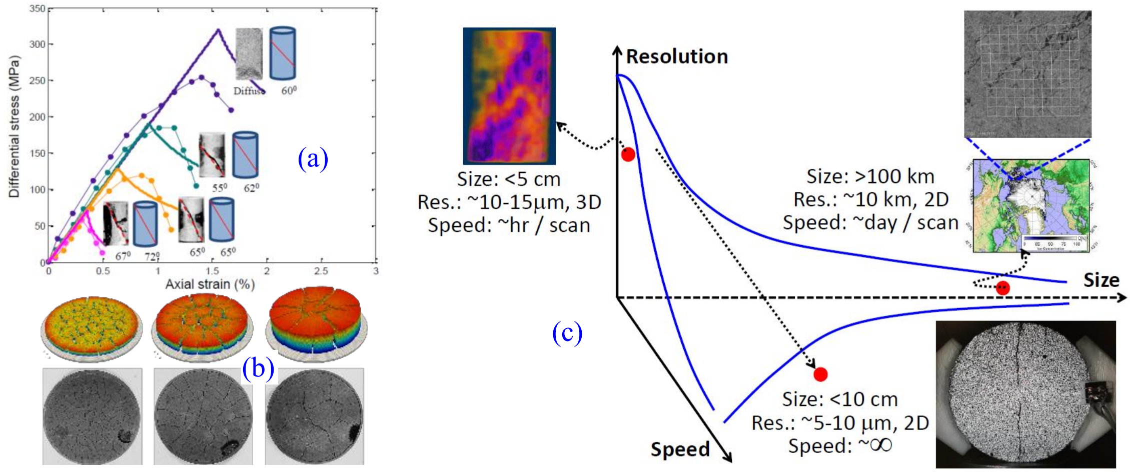


Figure 1: Localised failure: constitutive modelling (a), SPH simulations (b), and space & time relative to capabilities of experimental techniques (c).

Friday, February 1

Macro scale patterns

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Fracture patterns

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Unsaturated patterns

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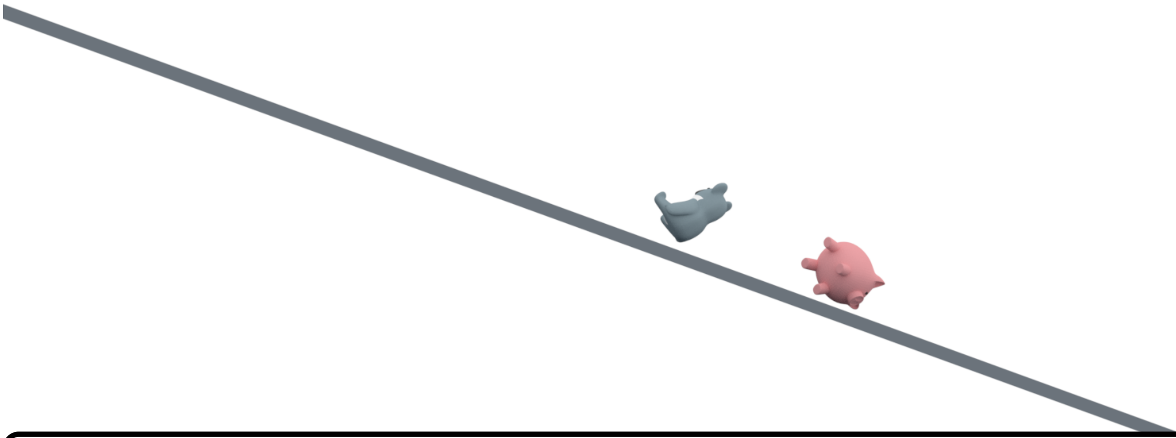
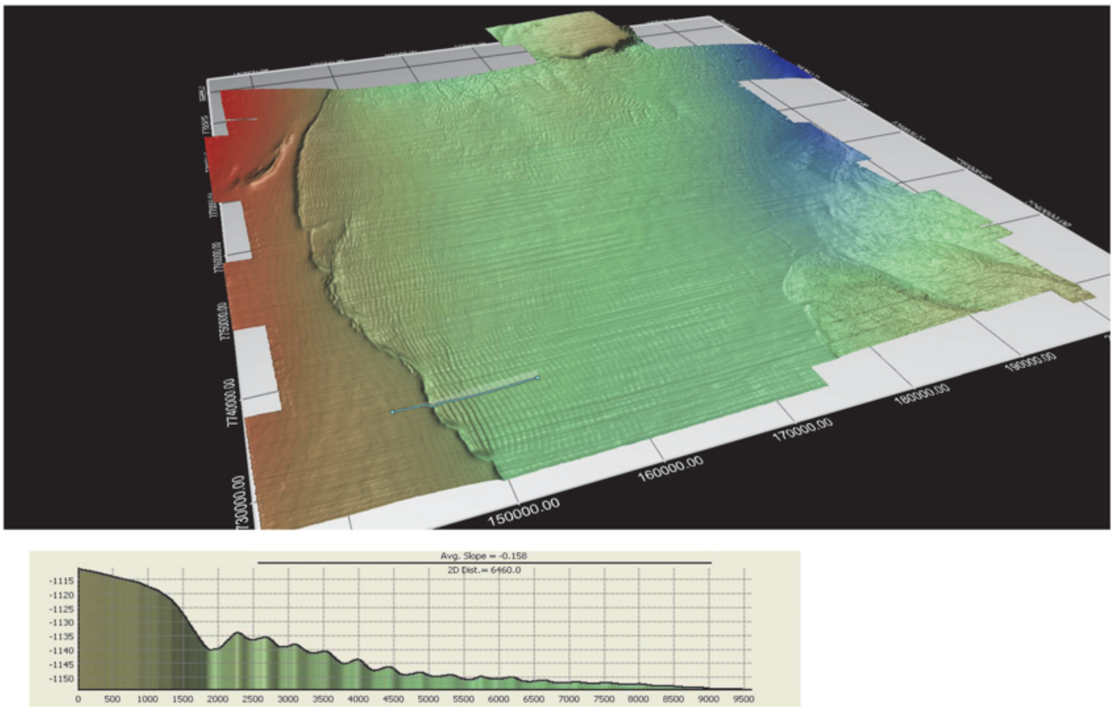


19. Alexander M. Puzrin and Andreas Stöcklin

Understanding geomorphological patterns in submarine landslides

The paper presents recent advances in analytical and numerical modelling and understanding of underlying mechanisms of spreading and ploughing failure, leading to observed geomorphological patterns in gigantic submarine landslides.

(a) Seafloor geomorphology



(b) Landslide simulations

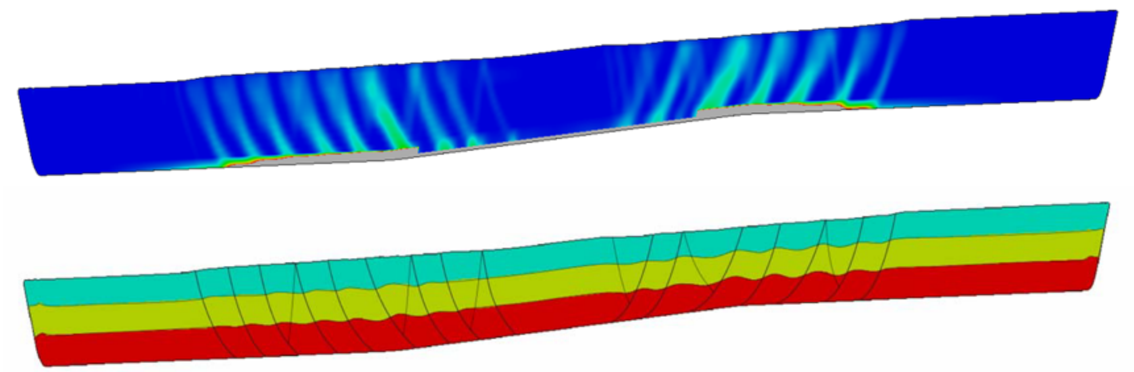


Figure 1: (a) Seafloor ripples in the Glencoe landslide offshore Western Australia (after Hengesh et al., 2013); (b) Equivalent plastic strain and cross section with localized shear surfaces for spreading and ploughing patterns of a submarine slope failure.

20. Takashi Matsushima

Patterns of landforms: A numerical study of fluvial geomorphological processes

Geomorphology is a scientific study to understand various landforms on/near a planetary surface. In particular, this study focuses on the fluvial processes, which is regarded as a primary geomorphological processes on the earth (Figure 1). It includes the erosion, transport, and deposition of granular geomaterials by surface water flow. Its first principle is the grain-scale dynamics involving complicated interaction between water flow and soil grains. The resulting collective sediment behavior leads to the topographic evolution from meter scale to kilometer scale during several to more than hundred years. This study attempts to simulate such complicated fluvial geomorphological processes using a depth-integrated particle method. Each computational particle represents a unit water mass that can take in and out the sediment mass as a suspended load from the bed surface. The bottom shear stress of each numerical particle is evaluated by the modified Manning's formula considering the threshold slope angle of flow (similar to Bingham fluid). Fluid pressure gradient is modeled by two-body interaction between numerical particles similar to Discrete Element Method. The effect of grain size is also incorporated into the model, which enables us to reproduce the resulting geological layers. Some examples of landforms are demonstrated (Figure 2) and its features are discussed in the presentation.

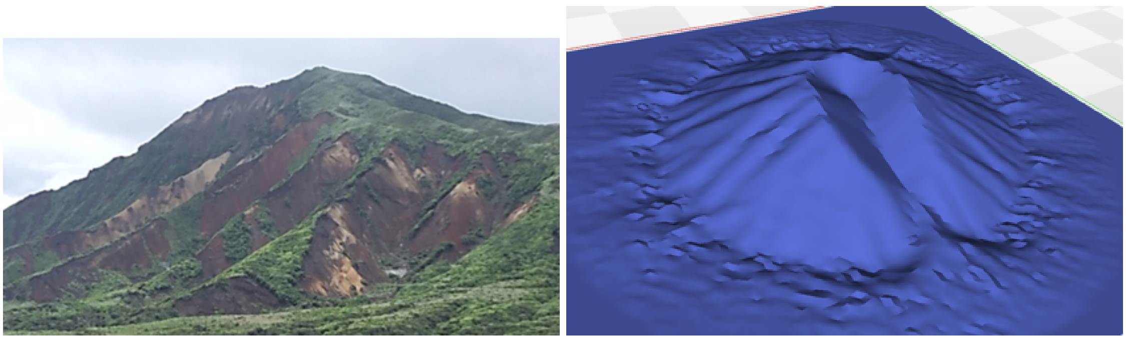
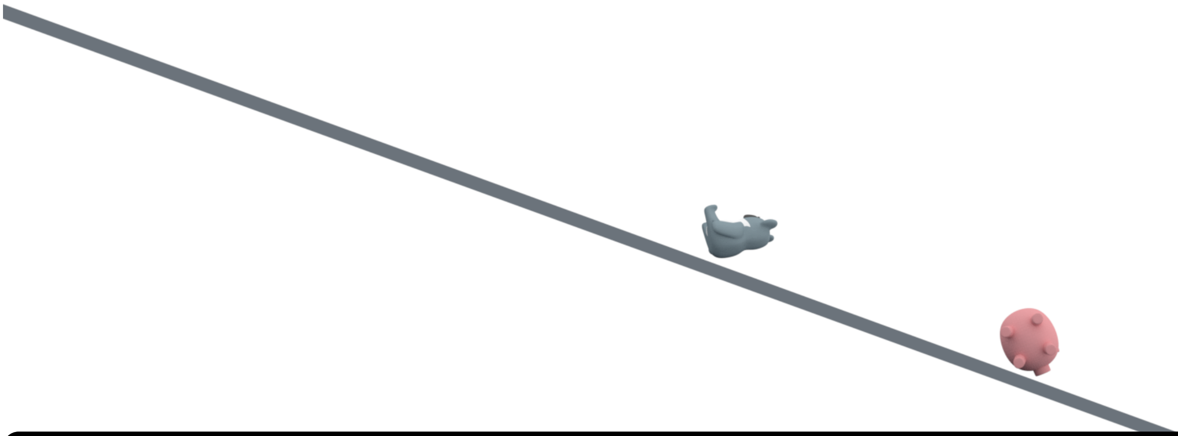


Figure 1: *Left*: Gully formation (Kumamoto, Japan). *Right*: Example of numerical simulation.



21. Thierry Faug

Snow and avalanche patterns: a wide range of grain sizes and time scales

Snow refers to the myriad of ice crystals that form in the atmosphere under varying air saturation, temperature and moisture conditions, then precipitate and finally undergo changes once they reach the Earth's surface (inset of figure 1).

After deposition on the ground, the coherent porous structure formed, which is made of more or less sintered ice crystals, alters. Because it is close to its melting temperature, seasonal snow on the ground changes constantly. The alteration is known as metamorphism. In addition, the weight of the overlying snow layers and the wind come into play. The mechanical and thermodynamical actions that snow experiences give rise to a rich variety of snow patterns, covering a broad range of scales in space from the millimeter (snow grain) to the large kilometer-scale in mountains.

Several situations may lead to the mechanical failure of the snowpack and then trigger avalanches. There are various expressions to characterize the rapid motion of snow masses: slab avalanche, loose avalanche, glide avalanche, dense/flowing avalanche, powder avalanche (aerosol), cold avalanche, warm avalanche, dry avalanche, wet/humid avalanche, granular avalanche, etc. There's no end of words to describe the perceptions of avalanches by high mountain guides, by ski resorts' managers, by snow scientists, etc., or by any observer who practices recreation activities in the snowy slopes. Those words refer to various complicated physical processes which take place when the avalanche initiates, then propagates along the slope and finally come to standstill. The prints and deposits left by avalanches (example in figure 1) reflect another rich variety of snow patterns.

The time scales of seconds to a few minutes for the snow mass motion during an avalanche are at odds with the time scales of hours to weeks involved in the alteration of snowpack, and the range of grain sizes largely extends when the avalanche propagates, especially when the water gets into the game. I will describe some amazing snow patterns by trying to explain their physical origin.

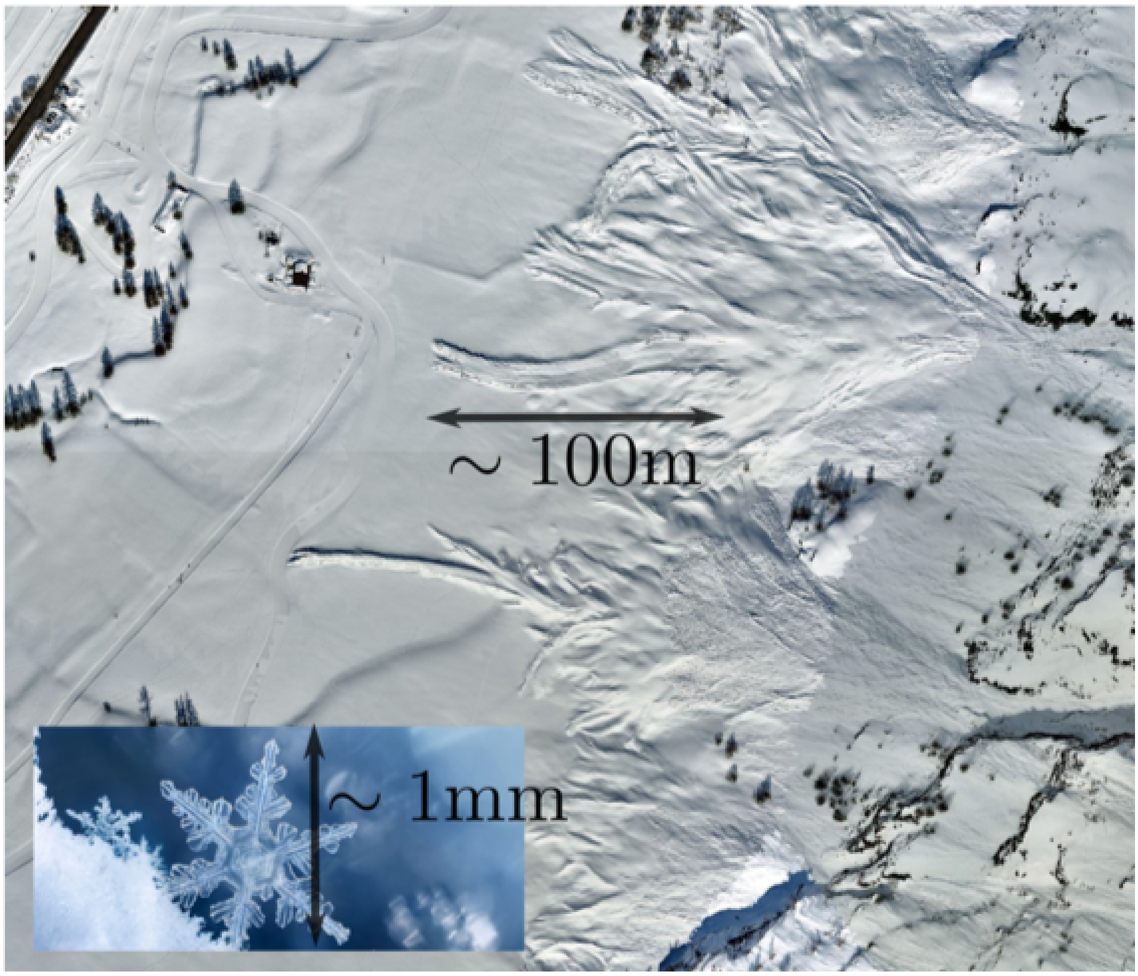


Figure 1: Non uniform and rough snow avalanche deposits (source: Irstea). *Inset*: digital composite of snowflakes and frost (adapted from jefunne/shutterstock.com).

22. Eleni Gerolymatou

Crack interaction and coalescence: peak and residual strength

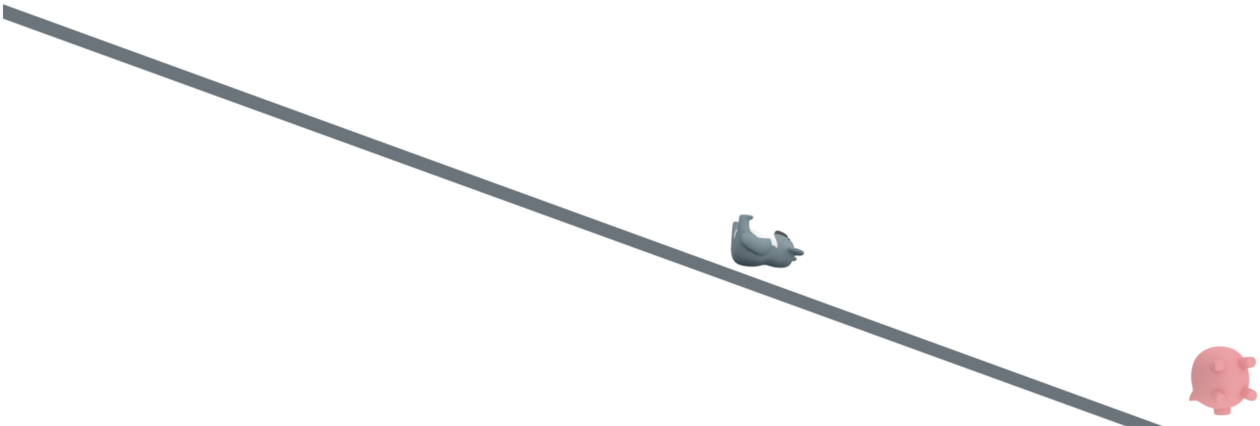
It is a well-known fact that the strength of rock mass is mainly dominated by the strength of its discontinuities. The shear strength of continuous joints has been investigated extensively in the laboratory, in situ and from a constitutive point of view. The strength of discontinuous rock joints on the other hand has not been systematically examined. Not a lot of works have been performed in this area. The existing ones are mostly concerned with laboratory tests on artificial or natural material with cracks under uniaxial, triaxial or shear conditions.

This work presents experimental results of shear tests at different normal pressures, both concerning the peak and the residual shear strength. The tests were performed on gypsum specimens created with intermittent cracks at different inclinations with respect to the shearing direction. The tests were interrupted just after the peak shear stress was observed to register the coalescence patterns formed by the cracks. The tests were then continued to relatively large displacements, exceeding the spacing between neighboring cracks. Both the patterns formed at crack coalescence and the peak and residual shear strengths were significantly influenced by the original inclination of the intermittent joints, as shown below.

To capture the peak strength observed several alternatives were tried, such as modifications of the law of Patton for discontinuous cracks and linear elastic fracture theory. It was found that the maximum circumferential strain criterion reproduced with satisfying accuracy both the peak strength and the wing crack angle. The consideration of fracture interactions was found to further improve the result, though the difference was not very large.

The residual strength was found to also vary significantly with the inclination of the initial cracks, in some cases being significantly lower than the residual strength of horizontal continuous joints. The phenomenon can be linked to rotations of the fragments resulting from the crack coalescence and is only apparent for a narrow band of initial inclinations. The same phenomenon has been also observed in shear tests performed by other authors. It is much harder to observe under symmetrical loading conditions, such as those of uniaxial and triaxial tests.

Figure 1: Coalescence patterns for different initial fracture orientations, in order of appearance 45, 75, 90, 135 and 165 degrees. The bottom plate was maintained constant, while the top one was displaced to the right.



23. A. V. Dyskin and E. Pasternak

Patterns of fracture growth under compression

Fracture growth in geomaterials under compression is one of the mechanisms of failure including such dangerous types of failure as rockbursts. Observations reveal three types of fracturing under compression: (a) splitting or column fracture observed in uniaxial compression when the sample is split along the compressive (major principal) axis; (b) spallation observed in samples under compression and underground excavations near a free surface; (c) “shear” failure whereby the sample is broken by formation of an oblique fracture inclined to the major principal axis.

The common understanding of the mechanics of fracture growth parallel to the axis of uniaxial compression causing splitting or spallation is based on the observations made on growth of through fractures or pores in plates or rectangular samples. In these, essentially 2D configurations, the initial defect sprouts secondary crack or wings growing extensively parallel to the direction of uniaxial compression. The real defects are however mostly internal defects. Experiments on transparent materials show that the initial cracks or pores produce wings that wrap, which arrests their further growth. We show that the extensive fracture growth can happen in two cases: (1) when there are several interacting wing cracks which produce a new extensively growing fracture; (2) when there exists biaxial stress state (this for instance happens near an excavation wall). It is the action of what can be termed intermediate principal stress that prevents wing wrapping thus enabling their extensive growth. It is interesting that the magnitude of the intermediate principal stress needed to ensure extensive fracture growth is about 6% of the major principal stress.

“Shear” fracture propagation happens in its own plane resembling that of a Mode II (shear) crack, which gave the name “shear”. However all direct experiments on Mode II fractures show that they cannot propagate in their own plane. Instead they kink producing the wing cracks. In order to resolve this conundrum we note that the “shear” fracture is observed at the peak load when the concentration of accumulated damage is sufficient to produce near zero effective stiffness. It is then natural to assume that the accumulated damage also permits independent rotations of grains or other constituents of the geomaterial. The presence of rotations induces a special mechanism of Mode II fracture propagation based on bending failure of remaining bonds between the rotating grains. This leads to a band-like planar propagation of the fracture. We formulate a criterion of fracture growth of this type.

24. Ha H. Bui and Giang Nguyen

Failure mechanism of highly porous cement-based materials

Highly porous cement-based materials compose of solid phases and air pores formed through the solid phases. The existence of a large amount of air pores in these materials causes their mechanical responses highly dependent on the density and the stress state, and their failure mechanisms to be complicated and significantly different from other solid materials. In particular, the constitutive responses and failure mechanisms of this material are highly controlled by the competition of the shear failure and pore collapse. In this work, we present our primarily results on the investigations of the failure mechanisms of this material under the true triaxial stress conditions. The experimentally validated discrete element method (DEM) is utilised to explicitly describe the internal pore-structure, while the cemented phase is modelled at the micro/meso-scale using a cohesive-frictional model. Some insights into the mechanisms of shear failure and pore collapse during the failure process, the transition from brittle failure to ductile, and the yield/failure surfaces of a typical highly porous material will be presented and discussed.

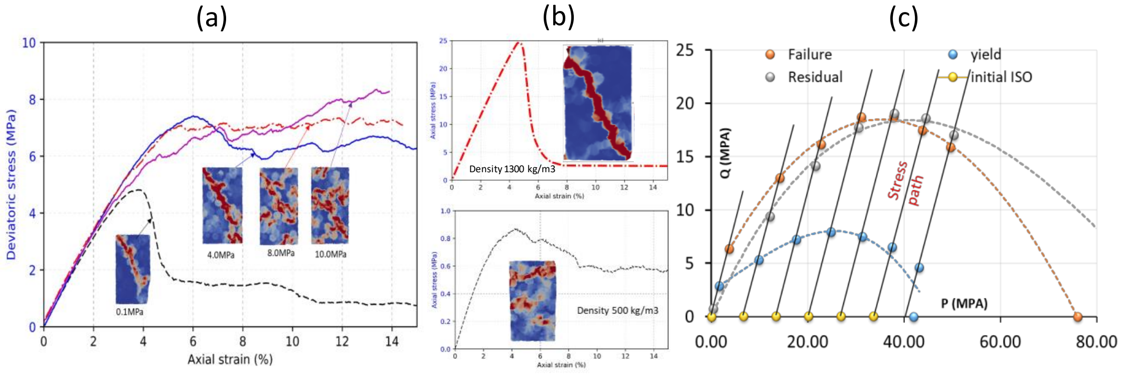
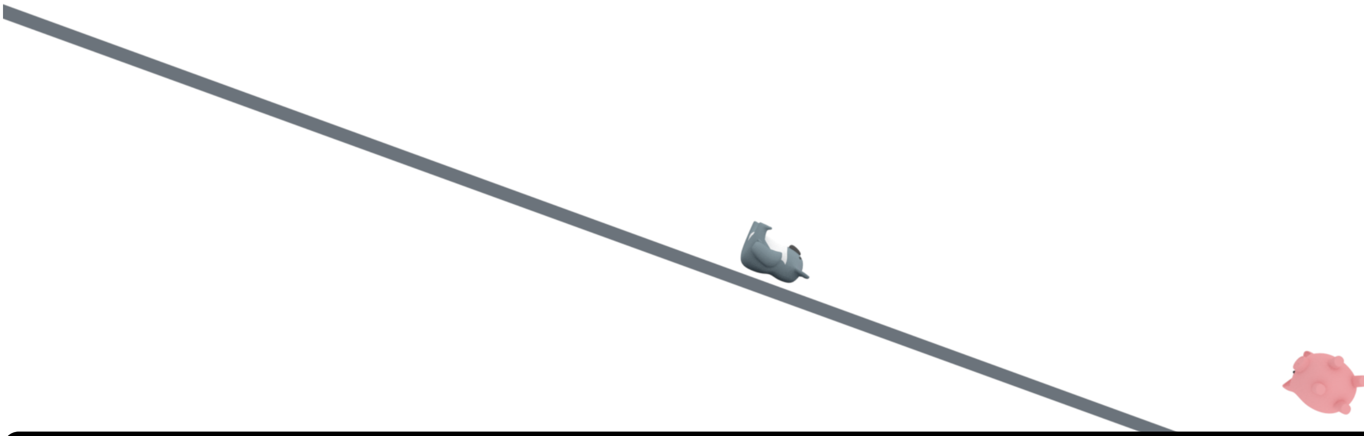


Figure 1: Behaviour of a highly porous material: (a) Effect of confining stress, (b) influence of material density and (c) meridian curve of yield-failure surfaces.



25. Francesca Casini

Placing the Fluid Retention Curve as the core of multiphase soils response under environmental loading

The presentation aims at providing a fundamental understanding of fluid retention curve effects on the mechanical behaviour of multiphase soils. In particular, the influence of the void ratio on the soil-water retention curves is discussed for a silty sand retrieved from a steep forested instrumented slope. The interpretation of a wide set of triaxial tests performed on the silty sand with different water content and obliquity are interpreted by means of a critical state constituive model extended to unsaturated conditions. Finally, it is presented and interpreted the hydro-mechanical of the steep forested slope during an artificail rainfall, which triggered a shallow slope failure fifteen hours after rainfall initiation. Coupled hydro-mechanical finite element analyses, using a critical state constitutive model and extended to unsaturated conditions, are used to interprete the in field response.

Further, it is presented the influence of a proper definition of the fluid retention curve (FRC) on the mechanical response of the frozen soils by means of the interpretation of the frost-heave tests. The evolution of the frost-heaving mechanism is discussed based on the definition of the FRC.

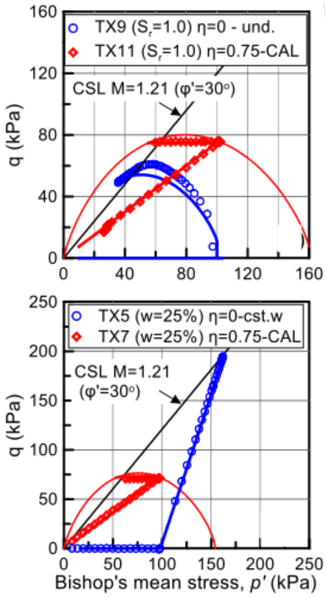


Figure 1 Model calibration against triaxial tests

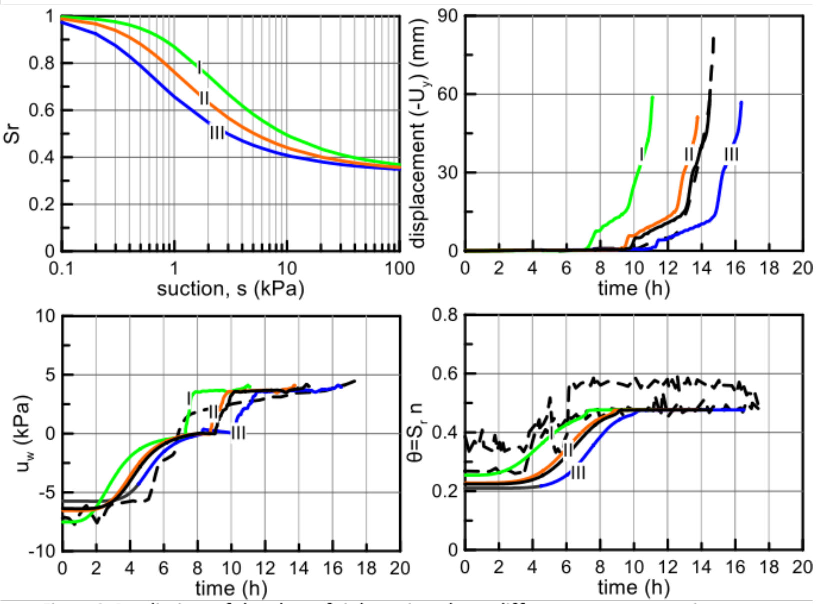


Figure2 Prediction of the slope faiulre using three different water retention curves

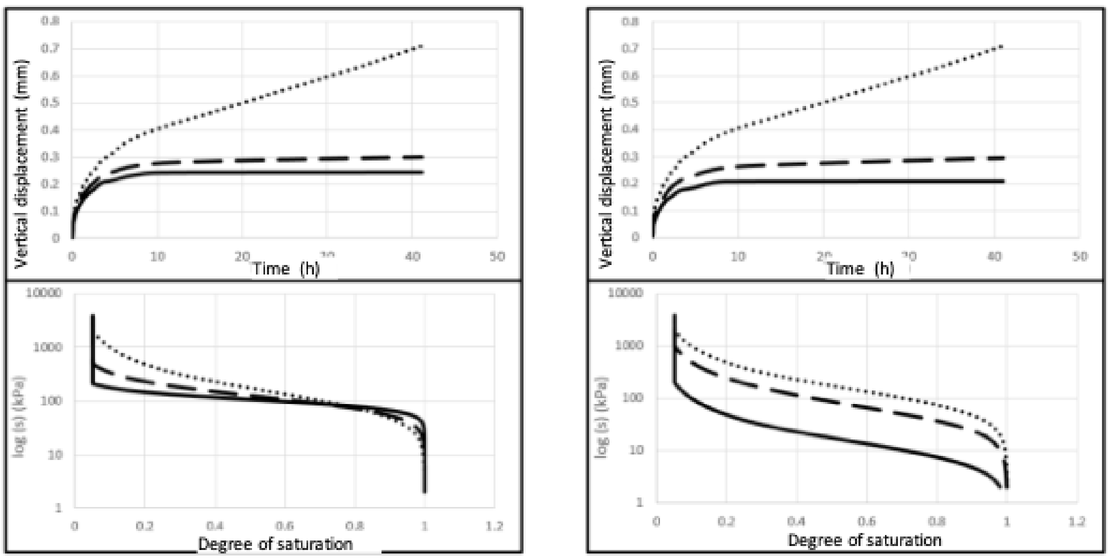
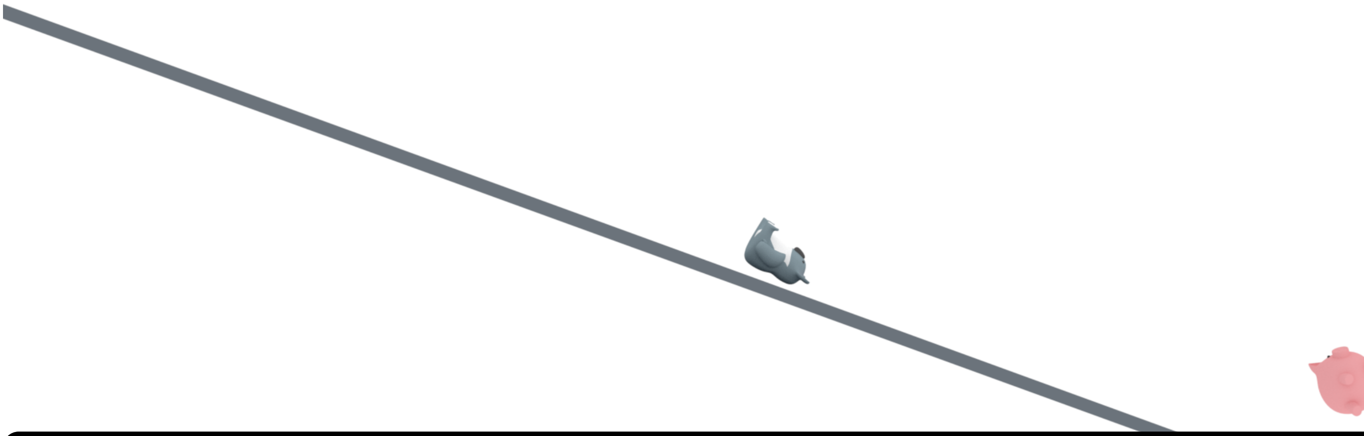


Figure3 Frost-heave predictions using different shape of the FRC



26. Jayantha Kodikara

Travelling with soil particles from sedimentation, consolidation, decohesion, re-compaction and environmental stabilisation

Soils are the most abundant naturally formed geomateirals on earth available for a geotechnical engineer to discharge his duties to make human habitat better. Although it can be just ‘dirt’ to a layman, it generally conforms to a complex three-phase particulate system with its highly variable interstitial pore spaces filled with water and (or) air giving different consistencies ranging from liquid-like soil to completely dry soil. In its natural form, soil can be subjected to internal stresses arising from gravity and other physico-chemical forces such as due to water surface tension and salts, commonly referred to soil suction. Then, in geotechnical engineering applications, soil can be completed reworked, compacted and consolidated through external forces, in addition to being subjected to sustained atmosphere/soil interaction. Tracking and modelling of soil behaviour in these processes generally is very complex, hence engineers have devised constitutive models subject to various approximations and limitations. This modelling complexity is further enhanced due to difficulty input parameter measurement, and the variability and uncertainty of the soil conditions in the field. None the less, as engineers, we need robust but (naked) physics-based tools that are easy to use yet capture most important phenomenological features of soil behaviour. This need will become increasingly important as the digital and automation age advances with intelligent robots and IoT. For example, we will need such tools to make intelligent robots to compact soil for performance-based specifications.

Following the above engineering need, the presentation will focus on tracking and modelling of soil behaviour in a framework developed by the author (i.e., MPK framework; Kodikara, 2012) and subsequently extended to develop a generalised model with his co-workers. The framework is based on macroscopic representation of soil system through state variables v, v_w, s, p and q, which are specific volume, specific moisture volume, mean net stress and deviator stress respectively. The novel feature of the model is that it has used the phenomenological volumetric behaviour in v, v_w, p space to build and relate the other state variables through classical plasticity theory approaches. While v, v_w, p volumetric space is a different way of looking at a four dimensional (when s is included) system with two independent variables, it offers a clear ease of input parameter determination and a direct link to the well-known (Proctor) compaction curve, which is routinely used in geotechnical engineering practice. When it is coupled through a volumetric plastic strain dependant water retention curve that evolves with internal and (or) external loading, most field stress paths may be modelled including wet/dry cycling in soil/atmosphere interaction. This multi-dimensional space then can be further extended to incorporate deviator loading to cater for general loading conditions.

Kodikara, J.K. (2012). New framework for volumetric constitutive behaviour of compacted unsaturated soils, Canadian Geotechnical Journal, Vol. 49, pp. 1227-1243.

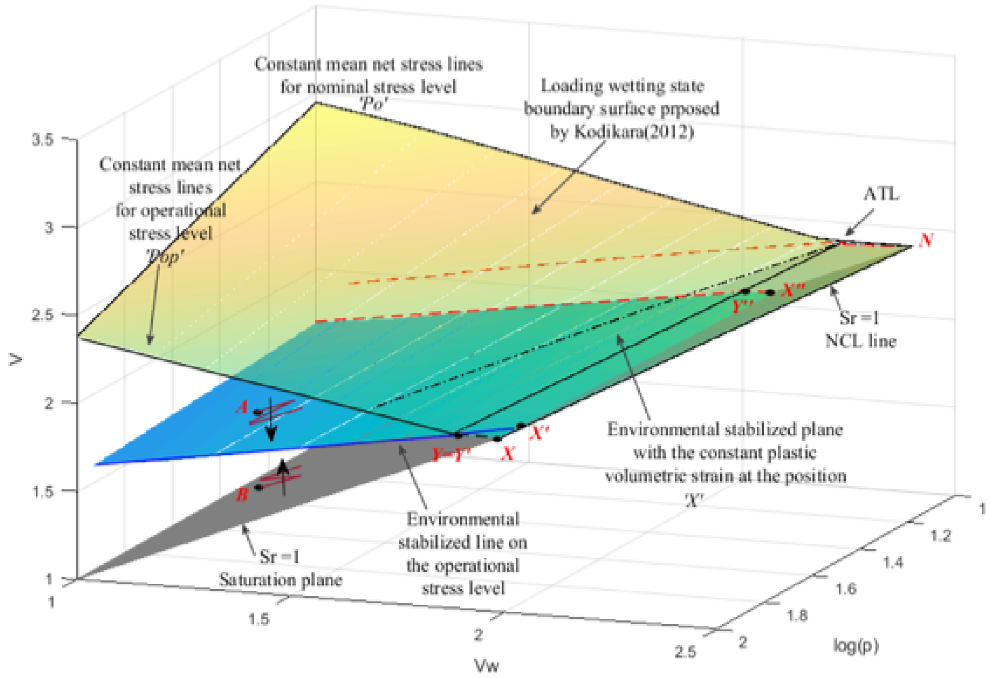
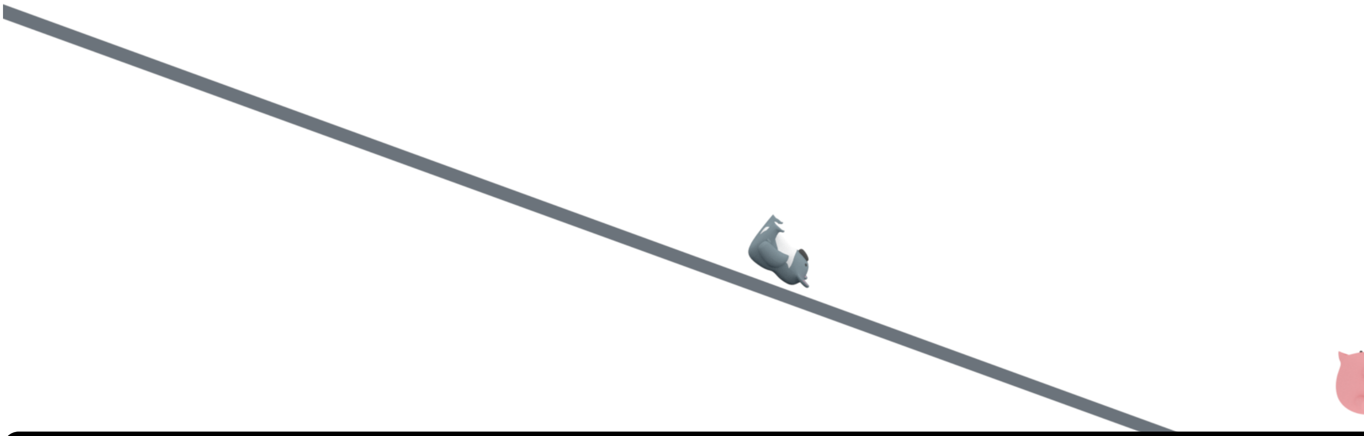


Figure 1: Generalized MPK Volumetric Surface in the v–v_w–p space (Kodikara, Jayasundera and Zhou, 2019)



27. Adrian Russell

Uniqueness of pore geometry in soils

Understanding pore geometry in soils is important when characterising water retention and flow as well as describing compression behaviour, strength and stiffness. Here it is shown how pore geometry exhibits uniqueness. It may be described using functions, analytically derived, which incorporate soil density and particle size distribution. Demonstrations will be given for well-graded 'fractal' soils and poorly-graded 'monodisperse' soils.

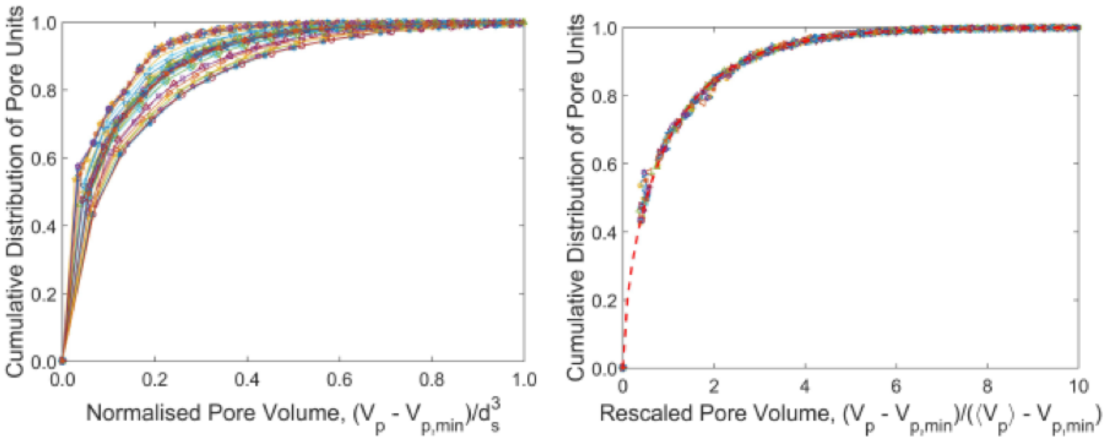


Figure 1: *Left*: Cumulative distribution of normalised pore volume for random assemblies of monodisperse spheres. *Right*: Rescaled cumulative distribution showing uniqueness, fitted with a k-Gamma function. (Sufian et al., 2015, Pore shapes, volume distribution and orientations in monodisperse granular assemblies, *Granular Matter*, 17:727-742. `http://dx.doi.org/10.1007/s10035-015-0590-0`).

IV

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