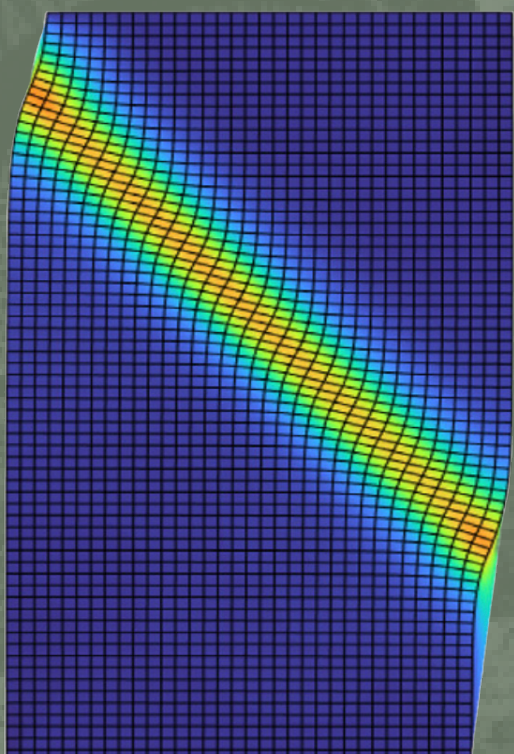
BOKU UNIVERSITY

13th International Workshop on Bifurcation and Degradation in Geomaterials

June 22-25, 2026, Vienna, Austria



Programme book

Dear Colleagues,

It is our great pleasure to welcome you to IWBDG 2026 in Vienna. This workshop brings together researchers from many parts of the world to present recent advances in geomechanics research. The broad spectrum of topics includes, but is not limited to, instability and localisation in geomaterials, constitutive modelling, granular mechanics, rock mechanics and fracture, coupled THM processes, experiments, and advanced computational methods.

The oral presentations are arranged in a single-track format across ten sessions, creating opportunities for discussion and interaction throughout the meeting. We thank all authors and participants for contributing to this high-level scientific event and wish you a productive and enjoyable workshop in Vienna.

Wei Wu

Conference chairman

General Information

Location and conference information

Welcome Reception	Mon, 22 June 2026, 18:00	BOKU	An informal welcome reception is planned.
Opening Ceremony	Tue, 23 June, 08:45-09:00	BOKU	Official opening of the workshop.
Conference Banquet	Tue, 23 June, 19:00-22:30	Plachutta Gruenspan	Traditional Viennese tavern
Musical	Wed, 24 June, 18:30-21:00	Raimund Theater	Musical Evening: The Phantom of the Opera
Closing words	Thu, 25 June, 11:40-12:00	BOKU	End of workshop.

Registration and Information Desk

The registration desk opens on Monday afternoon before the Welcome Reception. Organiser support remains available during the technical programme.

Mon, 22 June, 15:00-21:00	Registration / check-in	Onsite desk
Technical sessions and breaks	Organiser support	Available throughout the programme

Internet

Wireless internet details will be announced at check-in or displayed onsite.

Lunch

Tue, 23 June, 12:30-14:00	Lunch break	Venue details announced onsite.
Wed, 24 June, 12:30-14:00	Lunch break	Venue details announced onsite.
Thu, 25 June, 12:00-14:00	Lunch	Venue details announced onsite.

Oral Presentation

Each oral presentation slot is 20 min. Please arrive before your session begins and share your slides with the chair or organisers in advance when possible.

Program overview

Monday 22 June 2026	Tuesday 23 June 2026	Wednesday 24 June 2026	Thursday 25 June 2026
Registration	08:45-09:00 Opening		
	09:00-10:20 S1 Technical Session	09:00-10:20 S5 Technical Session	09:00-10:20 S9 Technical Session
	10:20-10:40 Coffee	10:20-10:40 Coffee	10:20-10:40 Coffee
	10:40-12:20 S2 Technical Session	10:40-12:20 S6 Technical Session	10:40-11:40 S10 Technical Session
			11:40-12:00 Closing
	12:30-14:00 Lunch	12:30-14:00 Lunch	12:00-14:00 Lunch
	14:00-15:20 S3 Technical Session	14:00-15:20 S7 Technical Session	
	15:20-15:40 Coffee	15:20-15:40 Coffee	
	15:40-17:20 S4 Technical Session	15:40-16:40 S8 Technical Session	
18:00 Welcome Reception	19:00-22:30 Conference Banquet	18:30-21:00 Musical	

Social events

The teacher-approved timetable includes a Monday Welcome Barbecue plus the two booked evening events highlighted below.
Your name badge is required for admission to organised events.

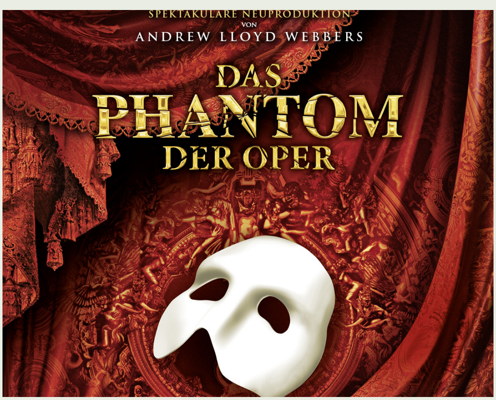
1. Conference Banquet at Plachutta Gruenspan

Tuesday, 23 June 2026, 19:00-22:30
Address: Ottakringer Str. 266, 1160 Vienna

Plachutta Gruenspan is a traditional Viennese tavern in the historic beer district of Vienna, known for Austrian pub cuisine, Plachutta classics and a spacious beer garden. The conference banquet provides a relaxed setting to meet fellow participants and continue discussions after the first full technical day.

2. Musical Evening: The Phantom of the Opera

Wednesday, 24 June 2026, 18:30-21:00
Raimund Theater, Vienna
Address: Wallgasse 18-20, 1060 Vienna
Duration: approx. 2 h 30 min



One of the most celebrated musicals of all time has returned to Vienna. After the success of CATS, Vereinigte Buehnen Wien brought Andrew Lloyd Webber masterpiece back to the city in Cameron Mackintosh spectacular new production, presented for the first time in the German-speaking world. With its famous score, lavish stage imagery and grand theatrical atmosphere, the show offers a classic musical evening at the Raimund Theater. Presented in German with English surtitles, the Vienna staging brings the iconic chandelier, sweeping romance and large-scale theatrical effects back to the stage in a landmark musical production.

Images: Musical Vienna; Plachutta Gruenspan.

Technical Session 1

13th Bifurcation and Degradation in Geomaterials

Tuesday, 23 June 2026 | 09:00-10:20

09:00-09:20

Partial second gradient regularization applied to shear band modelling.

Denis Caillerie; Pierre Bésuelle

Speaker: Denis Caillerie, Université Grenoble-Alpes, France

09:20-09:40

Length-regularized B-spline material point method for discretization-insensitive strain localization analysis

Jinhyun Choo

Speaker: Jinhyun Choo, Seoul National University, South Korea

09:40-10:00

Is failure state of soil unique?

Jian Chu

Speaker: Jian Chu, Nanyang Technological University, Singapore

10:00-10:20

The role of bedding planes orientation and true triaxial loading on the macroscopic response and strain localization pattern in a porous sandstone

Cyrille Couture; Pierre Bésuelle

Speaker: Cyrille Couture, Université Grenoble-Alpes, France

Technical Session 2

13th Bifurcation and Degradation in Geomaterials

Tuesday, 23 June 2026 | 10:40-12:20

10:40-11:00 **Large strain rate constant volume simple shear strain localization in granular media**

Claudio G. di Prisco; Matteo Zerbi; Alessandro Leonardi

Speaker: Claudio G. di Prisco, Politecnico di Milano, Italy

11:00-11:20 **Particle equilibrium based exact equation for average interparticle forces in granular materials**

Ge Duan; Chaofa Zhao

Speaker: Ge Duan, Zhejiang University, China

11:20-11:40 **Rock spallation. Mechanism and energy release**

Arcady Dyskin; Elena Pasternak

Speaker: Arcady Dyskin, The University of Western Australia, Australia

11:40-12:00 **On vertex instability of pressure-sensitive non-associated plasticity with Lode angle dependency**

Paul Hofer; Matthias Neuner; Günter Hofstetter

Speaker: Paul Hofer, University of Innsbruck, Austria

12:00-12:20 **Environmental Impact on Cracking in Degradable Rocks**

Man-man Hu

Speaker: Man-man Hu, The University of Hong Kong, Hong Kong, China

Technical Session 3

13th Bifurcation and Degradation in Geomaterials

Tuesday, 23 June 2026 | 14:00-15:20

14:00-14:20

Modeling of non-coaxial deformation in sands: Roles of fabric anisotropy and non-proportional loading

Lei Huang; Zhongxuan Yang; Yannis F. Dafalias

Speaker: Lei Huang, Zhejiang University, China

14:20-14:40

Short review of limestone rock masses geomechanical degradation and its peridynamic modelling perspective

Łukasz Kaczmarek; Yunteng Wang; Agnieszka Dąbska; Wei Wu; Katarzyna Misiołek; Bartosz Bednarz; Adam Kasprzak; Jiaxin Liu

Speaker: Łukasz Kaczmarek, Warsaw University of Technology, Poland

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14:40-15:00

Learning gravity-driven granular flows

Konstantinos Karapiperis

Speaker: Konstantinos Karapiperis, École Polytechnique Fédérale de Lausanne, Switzerland

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15:00-15:20

Microscopic evolution of pore water characteristics in partially saturated sand associated with development of dilative shear bands

Ryunosuke Kido; Yosuke Higo

Speaker: Ryunosuke Kido, Hiroshima University, Japan

Technical Session 4

13th Bifurcation and Degradation in Geomaterials

Tuesday, 23 June 2026 | 15:40-17:20

15:40-16:00

Effects of fluid flow, particle fragmentation, and temperature on behavior of cohesive-frictional materials using a novel DEM-based thermal-hydro-mechanical model

Marek Krzaczek; Michał Nitka; Jacek Tejchman

Speaker: Marek Krzaczek, Gdańsk University of Technology, Poland

16:00-16:20

A unique DEM-based coupled 3D thermo-hydro-mechanical mesoscopic model incorporating phase changes for simulating of cohesive-frictional materials

Marek Krzaczek; Jacek Tejchman

Speaker: Marek Krzaczek, Gdańsk University of Technology, Poland

16:20-16:40

Effective medium theory for micropolar granular elasticity

Xia Li; Zijun Shi; Muhammad Shahkar

Speaker: Xia Li, Southeast University, China

16:40-17:00

Micro-macro methods: states and transitions

Stefan Luding

Speaker: Stefan Luding, University of Twente, Netherlands

17:00-17:20

Damage evolution and functional failure mechanisms of buried pipelines induced by geomaterial degradation and strain localization in complex geotechnical sites

Junyan Han, Xiaoqiang Wang, Chengshun Xu, Xiuli Du, M. Hesham El Naggar

Speaker: Junyan Han, Beijing University of Technology, China

Technical Session 5

13th Bifurcation and Degradation in Geomaterials

Wednesday, 24 June 2026 | 09:00-10:20

09:00-09:20 **Mechanical behavior of sedimented clay in relation to their initial microstructure**

Mengyu Ma; Fares Bennaia; Mahdia Hattab; Pierre-Yves Hicher; François Nicot

Speaker: Mengyu Ma, Université de Lorraine, France

09:20-09:40 **Numerical investigation of the influence of material heterogeneity on strain localisation development**

Lou-Anne Marchadour; Pierre Bésuelle; Quentin Rousseau

Speaker: Lou-Anne Marchadour, Université Grenoble-Alpes, France

09:40-10:00 **On the definition of the tensor A in hypoplastic constitutive models for sand**

Luis Mugele; David Mašín; Hans H. Stutz

Speaker: Luis Mugele, Karlsruhe Institute of Technology, Germany

10:00-10:20 **Multiscale bifurcation analysis in granular materials: discrete-continuum duality**

Richard Wan; Mojtaba Farahnak; Mehdi Pouragha; François Nicot

Speaker: Richard Wan, University of Calgary, Canada

Technical Session 6

13th Bifurcation and Degradation in Geomaterials

Wednesday, 24 June 2026 | 10:40-12:20

10:40-11:00

Beyond the bifurcation in geomaterials: controlling snapback response and strain rate inside the localisation zone

Giang D. Nguyen; Nhan T. Nguyen; Murat Karakus; Ha H. Bui

Speaker: Giang D. Nguyen, Adelaide University, Australia

11:00-11:20

Granular materials and thermodynamics: the missing link

François Nicot; Xiaoxiao Wang; Antoine Wautier; Richard Wan; Félix Darve

Speaker: François Nicot, Université Savoie Mont Blanc, France

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11:20-11:40

Fractures with constricted opening across the scales

Elena Pasternak; Arcady Dyskin

Speaker: Elena Pasternak, The University of Western Australia, Australia

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11:40-12:00

Insights into the potential of ALE and CEL analyses for large deformations in geomechanics

Frank Rackwitz

Speaker: Frank Rackwitz, Technische Universität Berlin, Germany

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12:00-12:20

Chemo-mechanical bifurcation and deformation band formation in low-permeability granite

Klaus Regenauer-Lieb; Yongqiang Chen; Sam Xie

Speaker: Klaus Regenauer-Lieb, Curtin University, Australia

Technical Session 7

13th Bifurcation and Degradation in Geomaterials

Wednesday, 24 June 2026 | 14:00-15:20

14:00-14:20 **Unified Peridynamic modeling of THM coupled fracturing problems in geomechanics**

Jidong Zhao; Changyi Yang

Speaker: Jidong Zhao, The Hong Kong University of Science and Technology, China

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14:20-14:40 **A numerical study of the role of water phase change in the propagation of catastrophic landslides with reference to Vaiont landslide (Italy, 1963)**

Lorenzo Sanavia; Maria Lazari; Chiara Montorio

Speaker: Lorenzo Sanavia, University of Padua, Italy

14:40-15:00 **3D centrifuge model tests and numerical simulations of bearing capacity problems**

Yoshiteru Teranaka; Shigeaki Oka; Hideaki Takahashi; Noboru Nakatani; Takahiro Konda; Teruo Nakai

Speaker: Teruo Nakai, Geo-Research Institute, Japan

15:00-15:20 **Hydraulic hysteresis as a degradation mechanism promoting localisation in unsaturated slopes under intermittent rainfall**

Jialu Wang; Ha H. Bui; Giang D. Nguyen

Speaker: Jialu Wang, Monash University, Australia

Technical Session 8

13th Bifurcation and Degradation in Geomaterials

Wednesday, 24 June 2026 | 15:40-16:40

15:40-16:00

Particle size effect in gap-graded soil-rock mixture: a large-scale triaxial test investigation

Pei Zhang; Changsheng Zou; Jie Yang; Shiwei Hou; Xiuli Du

Speaker: Pei Zhang, Beijing University of Civil Engineering and Architecture,China

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16:00-16:20

Controllability criteria for bridging bifurcation and progressive localization in geomaterials

Dawei Xue; Xilin Lu; Jiangu Qian; Giuseppe Buscarnera

Speaker: Dawei Xue, Tongji University, China

16:20-16:40

Synergistic mechanism and failure evolution process of pile-anchor structure reinforced rock slope based on centrifuge shaking table tests

Xi Xu; Xiuli Du; Wei Wu; Yu Huang

Speaker: Xi Xu, Beijing University of Technology, China

Technical Session 9

13th Bifurcation and Degradation in Geomaterials

Thursday, 25 June 2026 | 09:00-10:20

09:00-09:20

How subtle changes in microstructure can mitigate the liquefaction susceptibility of granular materials: from experimental and numerical evidences to multi-scale modeling

Antoine Wautier; Fan Chen; Abhijit Hegde; Aoxin Li; Nadia Benahmed; Pierre Philippe; Claudio Carvajal; Mehdi Pouragha; François Nicot

Speaker: Antoine Wautier and Aoxin Li, UMR RECOVER, INRAE/AMU, France

09:20-09:40

Friction and dilatancy of geomaterials: Another look

Jun Yang; Runze Zhang; Zhi Liu

Speaker: Jun Yang, The University of Hong Kong, China

09:40-10:00

Mesoscopic mechanism of enhanced liquefaction resistance of fiber reinforced sand

Bin Ye; Yuan Din

Speaker: Bin Ye, Tongji University, China

10:00-10:20

The reinforcing mechanism of disposable face mask chips in sand: insights from numerical analysis and experiments

Zhen-Yu Yin

Speaker: Zhen-Yu Yin, The Hong Kong Polytechnic University, China

Technical Session 10

13th Bifurcation and Degradation in Geomaterials

Thursday, 25 June 2026 | 10:40-11:40

10:40-11:00

Micromechanical insights into the influence of cementation on shear localisation in cemented sands

Aoxi Zhang; Antoine Wautier; Frédéric Collin; Anne-Catherine Dieudonné

Speaker: Antoine Wautier, UMR RECOVER, INRAE/AMU, France

11:00-11:20

Fractional derivative modeling approaches to rock mechanics

Hongwei Zhou

Speaker: Hongwei Zhou, China University of Mining and Technology, China

11:20-11:40

Assessing and anticipating the potential for static liquefaction at the structure scale: application to tailing dams

Antoine Wautier; Fegdong Chi; Guillaume Veylon

Speaker: Antoine Wautier, UMR RECOVER, INRAE/AMU, France

Table of Contents

Partial second gradient regularization applied to shear band modelling.

Denis Caillerie (Université Grenoble-Alpes, France)
Authors: *D. Caillerie; P. Bésuelle*
Affiliations: *Université Grenoble-Alpes - CNRS - Grenoble INP, 3SR, Grenoble, France*

The shear band strain localization is a common phenomenon occurring in the deformation of geomaterials. It is paired with a characteristic thickness and a softening constitutive behaviour which is the source of singularities leading to countless solutions in the framework of the Cauchy modeling of continuous media yielding the stress σ in terms of the strain ε. Moreover for those constitutive equations the thickness of the shear bands occurring in FEM simulations depends on the size of the elements. The modeling is unable to exhibit a proper band thickness since it has no any parameter the dimension of which is a length.

There are different ways to regularize the modeling of the shear banding, among them is the resorting to the generalized modeling of micro-structured continuous media as the Cosserat and the second grade media which proved their efficiency. To avoid the use of conformal elements in a FEM simulation of a second grade material, it was chosen in [3] to consider it as a peculiar case of a micro-structured medium the internal virtual power of which reads:

$$-\int \left(\sigma : \varepsilon^* + \tau \left(E^* - \nabla\vec{u}^*\right) + \chi \therefore \nabla E^*\right) dv$$

where, for the second grade medium, the micro-stress τ is the Lagrange multiplier of the condition $E - \nabla\vec{u} = 0$ compelling the micro-strain E to be equal to the gradient $\nabla\vec{u}$ of the displacement field $\vec{u}$. That formulation was implemented in the code Lagamine [1]. The drawback of that formulation is the increase of the number of degrees of freedom. Indeed the FEM simulation of such a formulation needs to discretize the fields E and τ besides $\vec{u}$ which, for a 2D problem, have each four components. To overcome that drawback while keeping the second grade regularization and avoiding the use of conformal elements, Fernandes et al. [4] proposed to limit the second gradient components to the gradient of the volumic strain $\varepsilon^V = \mathrm{tr}\,\varepsilon$. The problem in that case is that the fully developed elasto-plastic regime is often isochoric, particularly in a possible shear band, which effaces or at least reduces the regularization effect of the second gradient.

In this work we propose a formulation including not only the gradient of the volumic strain but also that of a second scalar invariant of the strain, precisely the square of the norm $\|\varepsilon^D\|$ of the deviatoric strain. The introduction of two scalar variables E_1 and E_2 constrained by $E_1 = \varepsilon^V$ and $E_2 = \|\varepsilon^D\|^2$ yields an internal virtual power of the proposed formulation that reads:

$$-\int_\Omega \left(\sigma : \varepsilon^* + \tau_1\left(E_1^* - \varepsilon^{V*}\right) + \tau_2\left(E_2^* - 2\varepsilon^D : \varepsilon^{D*}\right) + \vec{\chi}_1 \cdot \nabla E_1^* + \vec{\chi}_2 \cdot \nabla E_2^*\right) dv$$

τ_1 and τ_2 are the two Lagrange multipliers relating to the constraints $E_1 = \varepsilon^V$ and $E_2 = \|\varepsilon^D\|^2$. As E_1 and E_2 are scalar, $\vec{\chi}_1$ and $\vec{\chi}_2$ are two vector fields.

In the spirit of [2], the following numerical simulation is a preliminary test in which the first gradient constitutive equation is classically elastic and, past a threshold, presents a softening only concerning the deviatoric part of the constitutive equation, precisely it reads:

$$\sigma = (\lambda + \mu)\varepsilon^V \mathbf{I} + \sigma^D, \quad \mathrm{tr}\,\sigma^D = 0$$

$$\sigma^D = \begin{cases} 2\mu\varepsilon^D, & \text{if } \|\varepsilon^D\| \leq S, \\ 2\mu\left(S + \alpha\left(S - \|\varepsilon^D\|\right)\right)\dfrac{\varepsilon^D}{\|\varepsilon^D\|}, & \text{if } S \leq \|\varepsilon^D\|. \end{cases}$$

$\vec{\chi}_1$ and $\vec{\chi}_2$ are taken proportional to ∇E_1 and ∇E_2: $\vec{\chi}_1 = k_1 \nabla E_1$ and $\vec{\chi}_2 = k_2 \nabla E_2$. Similarly to that of [3], the considered 2D problem is posed in a band $0 \leq x \leq \ell$, $-\infty < y < +\infty$, with the assumption that all the unknowns, stress, displacement, ... only depend on the variable x. The boundary $x = 0$ of the band is fixed, a tangential displacement U_y and a zero normal pressure are set on the boundary $x = \ell$. The problem is solved using the Newton's method. For the values of the parameters given below, the displacement u_x along x is zero and the derivative du_y/dx is not constant and different from U_y/ℓ which would be the case for a less value of U_y.

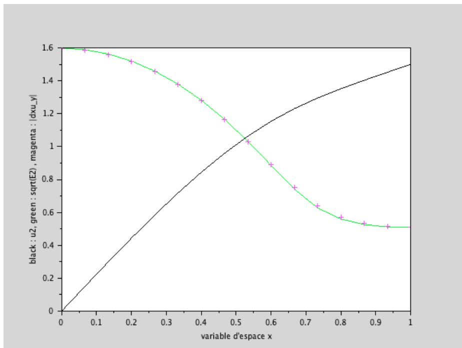

Figure 1. Functions $u_y(x)$, $\sqrt{E_2(x)}$ *and* $\left|\frac{du_y}{dx}\right|$ *for* $\ell = 1$, $k_2 = 0{,}1$, $S = 0{,}7$, $\mu = 4$, $\alpha = 0{,}7$, $U_y = 1{,}5$

References

[1] Bésuelle, P.; Chambon, R.; Collin, F. (2006). Switching deformation modes in post-localization solutions with a quasi-brittle material. Journal of Mechanics of Materials and Structures 1(7), 1115-1134.
[2] Chambon, R.; Caillerie, D.; El Hassan, N. (1998). One-dimensional localisation studied with a second grade model. Eur. J. Mech. A/Solids 17(4), 637-656.
[3] Chambon, R.; Caillerie, D.; Matsuchima, T. (2001). Plastic continuum with microstructure, local second gradient theories for geomaterials: localization studies. International Journal of Solids and Structures 38, 8503-8527.
[4] Fernandes, R.; Chavant, C.; Chambon, R. (2008). A simplified second gradient model for dilatant materials: theory and numerical implementation. International Journal of Solids and Structures 45, 5289-5307.

Length-regularized B-spline material point method for discretization-insensitive strain localization analysis

Jinhyun Choo (Seoul National University, South Korea)
Authors: *Jinhyun Choo*
Affiliations: *Seoul National University*

Strain localization is central to bifurcation and degradation in geomaterials, and the material point method (MPM) is well suited for simulating such phenomena under large deformation. However, standard MPM formulations exhibit pathological discretization sensitivity in strain-softening problems, where solutions depend on the mesh resolution rather than converging to a physically meaningful result. Existing remedies typically require heuristic parameter adjustments or substantial modifications to the formulation. This presentation introduces a length-regularized B-spline MPM that addresses this issue by decoupling the kernel support size from the grid spacing, thereby embedding an intrinsic length scale at the interpolation level. The governing equations and constitutive models of standard MPM remain entirely unchanged, and the modification enters only through a discretization-independent support size of the B-spline weighting function, making the method easy to incorporate into existing MPM frameworks with minimal algorithmic changes. Through numerical examples involving both damage- and plasticity-induced strain localization under large deformation, we demonstrate that the proposed approach consistently mitigates pathological mesh sensitivity, offering a practical route toward reliable MPM simulation of localization and degradation phenomena in geomaterials.

Is failure state of soil unique?

Jian Chu (Nanyang Technological University, Singapore)
Authors: *Jian Chu*
Affiliations: *Nanyang Technological University, Singapore*

In many constitutive models for soil, failure state of soil is modelled as a unique boundary. However, there are cases where different failure states can be defined for the same type of soil when subjected to different loading conditions or different stress or strain paths. For example, the failure state for static liquefaction of loose sand can be different from the failure line obtained from drained tests. We all know that we can use either undrained shear strength or drained failure envelop for clay. However, the undrained strength may not be necessarily related to the drained strength for either NC clay or OC clay. It is also not merely a choice of using effective stress or total stress for Morh-Columb failure equation as the undrained strength can be related to a physical condition that is different from the failure state under drained condition. Further experiments using different shear rates or different loading modes (i.e., load controlled or deformation controlled) for clayey soil also show that failure is also shear rate or loading mode dependent. In terms of mechanisms, this can be different from the shear rate effect that we observed from undrained triaxial tests on clay. All the above lead to the following two questions: 1) Is failure state of soil unique and 2) if not, how should failure state of soil be defined and modelled. This presentation attempts to address the two questions.

The role of bedding planes orientation and true triaxial loading on the macroscopic response and strain localization pattern in a porous sandstone

Cyrille Couture (Université Grenoble-Alpes, France)
Authors: *Cyrille Couture; Pierre Bésuelle*
Affiliations: *Univ. Grenoble Alpes, CNRS, Grenoble INP, 3SR, Grenoble, France*

The mechanical response of sedimentary rocks is influenced by their inherent anisotropy and triaxial stress states induced by their depositional and long-term deformation history. To assess risks related to site conditions and the effect of induced and natural stress perturbations, it is necessary to understand the combined role of different deviatoric loading paths and rock anisotropy orientations on the emergence and evolution of localization patterns, which controls later deformation modes. In this communication, we present a series of laboratory experiments and numerical simulations to study the mechanical behavior and localized deformation of a high- porosity bedded sandstone containing alternating layers of distinct porosity. The experimental campaign was conducted using a true triaxial apparatus, where mechanical deviatoric loading of the sandstone specimens was applied at prescribed Lode angles, for five different angles from axisymmetric compression (0°) to axisymmetric extension (60°), and at a constant mean stress of 90 MPa. To evaluate the effect of the material anisotropy, these experiments were also conducted at five bedding plane orientations rotated with respect to the major and minor principal stresses. The results of the experimental campaign show the strong influence of the Lode angle on the mechanical response, the strain localization orientation and the brittle-ductile transition. Moreover, in operando full-field Digital Image Correlation (DIC) measurements revealed that bedding planes, for a range of intermediate orientations, act as localization attractors for strain precursors and later emerging deformation bands. Post-mortem X-ray tomography confirmed that deformation can concentrate within higher porosity layers. The experimental observations are corroborated by a series of numerical simulations performed using a double scale FEM x DEM approach, bridging the macroscopic response to a microstructural model by computational homogenization. The numerical results for structural bedding anisotropy are further compared to a distinct microstructural anisotropy type at the granular scale. The results underline the differences of the anisotropy type both on the macroscopic response and on the manifestation of deformation bands.

Large strain rate constant volume simple shear strain localization in granular media

Claudio G. di Prisco (Politecnico di Milano, Italy)
Authors: *C. G. di Prisco; M. Zerbi; A. Leonardi*
Affiliations: *Department of Civil and Environmental Engineering, Politecnico di Milano, Milan, Italy*

In practical applications, particularly interesting is clarifying if and how strain localozation in granular materials is affected by strain rates. For this reason, in this paper, some multiregime model driven dry constant volume simple shear DEM numerical results are critically discussed to approch theoretically strain localization phenomena in opposition to diffuse modes of failures.

According to both total volume and mean strain rate imposed, bifurcation may occur or not and, in some intermediate cases, strain localization is uncomplete and testified by the occurrence of more rapid looser zones, alternating with denser slower ones.

Particle equilibrium based exact equation for average interparticle forces in granular materials

Ge Duan (Zhejiang University, China)
Authors: *Ge Duan; Chaofa Zhao*
Affiliations: *Zhejiang University*

The macro behavior of granular materials is strongly influenced by their micro-structure. In developing multi-scale models for granular materials, group-averaged quantities (i.e. averages over groups of contacts with the same contact orientation) serve as a bridge between the micro and macro behaviors. In micromechanical models, the particle equilibrium equations are only used in deriving the micromechanical expression for the stress tensor. Here an additional, exact equation is derived for group-averaged forces of contacts with similar orientations, based on the particle equilibrium equations. The formulated equation is obtained by adding subsets of particle equilibrium equations and is independent of particle shapes and loading conditions. The equation involves a geometrical structure function that characterizes three-particle correlations for the particle positions. The obtained relationship is validated through two-dimensional DEM simulations on specimens with disk- and peanut-shaped particles. The research results contribute to developing multi-scale constitutive models that account for neighbouring contacts.

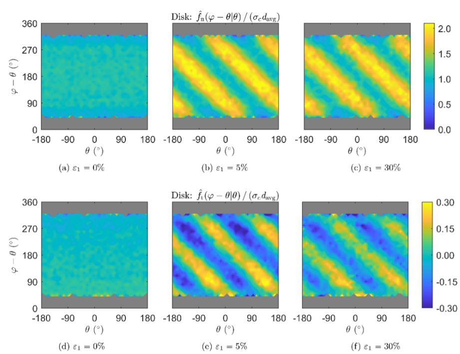

Figure 1. Distribution of the normal and tangential components of normalized $\hat{f}(m \mid n)$ for the specimen with disk-shaped particles.

Rock spallation. Mechanism and energy release

Arcady Dyskin (The University of Western Australia, Australia)
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Spallation is a type of rock failure producing thin rock fragments (spalls) detached from a rock surface. A common cause of spallation is the compressive stress acting in the planes normal to the surface. The compressive stress is either caused by sample loading or it is a result of stress concentration at the wall of excavation. This stress can also result from heating of the surface before bulk of the rock is heated through uniformly. At small scales spallation is sometimes observed at uniaxial compressive loading of rock (and concrete) samples as well as in the process of thermal spallation. At larger scales spallation can become a mechanism of strain rockburst. In all these cases spallation is caused by the extensive crack/fracture growth parallel to the free surface. The compressive stress acting in the planes normal to the surface produces wing cracks from the largest pre-existing defects, cracks or pores. The compressive stress is usually accompanied by the intermediate principal stress. In the presence of intermediate principal compressive stress, the wing crack is able to grow into a large crack of a size greater than the distance to the free surface. Interaction with the free surface considerably accelerates the crack growth to the stage when it separates a layer sufficiently large to buckle. Since the rock is brittle and has low tensile strength buckling leads to breakage of the layer into small pieces flying out. The kinetic energy comprises the energy release from crack growth and buckling. After buckling of the surface layer, a new surface is created and the process repeats itself. We present a model of spallation based on asymptotics of cracks situated very close to a free surface and parallel to it. The results will provide tools for optimising thermal spallation and developing methods of rock burst monitoring and prevention.

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On vertex instability of pressure-sensitive non-associated plasticity with Lode angle dependency

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Elastoplastic constitutive models encompassing non-associated plastic flow are widely used for modeling the pressure-sensitive mechanical behavior of cohesive-frictional materials, such as concrete and rock. Although the potential instabilities of such models are well established in the literature, they remain a common-and often overlooked-source of numerical difficul- ties in simulations of cohesive-frictional materials. In a recent contribution [1], which aimed at increasing the awareness about the numerical difficulties associated with such constitutive instabilities, we investigated the stability of non-associated Drucker-Prager plasticity subjected to oedometric extension-a highly constrained loading con- dition characterized by a single nonzero component of the strain rate tensor. Even though the perfectly plastic model did not encompass material softening, we derived analytically a condi- tion for structural softening based on a critical value for the model parameters governing friction and dilation. Specifically, structural softening is attained if one of these parameters exceeds this critical value while the other remains below it. While the dilatancy angle of cohesive-frictional materials is generally smaller than their critical friction angle, hyperbolic plastic potential functions-commonly employed for preserving differentiability of the plastic potential function at the vertex of the yield surface-locally increase the plastic dilatancy near the vertex of the yield surface. Therefore, hyperbolic plastic potential functions were identified as a potential source of constitutive instability. In the present contribution, we investigate this potentially destabiliz- ing effect of hyperbolic plastic potential functions in more detail. To this end, the near-vertex constitutive behavior of a non-associated elastoplastic model with Lode angle dependency is investigated and the stability of the obtained solution is assessed based on the acoustic tensor criterion. Complementary numerical simulations are performed to validate the analytical investigations and highlight the numerical difficulties stemming from constitutive instabilities. By means of this investigation, the destabilizing effect of hyperbolic plastic potential functions for non-associated elastoplastic models with Lode angle dependency is highlighted. The results indicate that the near-vertex behavior of elastoplastic constitutive models should be carefully evaluated to identify potentially unstable constitutive behavior linked to numerical difficulties in simulations of cohesive-frictional materials.

References

[1] Hofer, P.; Neuner, M.; Hofstetter, G. (2025). A note on the stability of pressure-sensitive non-associated plasticity. Computers and Geotechnics 186, 107363. DOI: 10.1016/j.compgeo.2025.107363.

Environmental Impact on Cracking in Degradable Rocks

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Cracking is ubiquitous in a geomaterial when it is subject to an environmental perturbation. Controlling environmentally assisted subcritical crack growth plays an essential role in a safe and active geo-energy adaptation to Climate Change, particularly in the emerging areas of unconventional shale hydrocarbon recovery, Carbon Capture Utilisation and Storage (CCUS), as well as enhanced geothermal systems (EGS). The common feature of these applications is aiming to achieve an enhanced permeability and injectivity in the target formation by the means of hydraulic fracturing. In order to limit the extent of chemical footprint left in the subsurface as well as to ensure the effectiveness of the technique, a sophisticated understanding of the feedback between the mechanics of a geomaterial and the surrounding environment it is subject to is required. We present here constitutive modelling approaches focusing on the effect of an acidic environment on subcritical crack propagation in a stressed geomaterial undergoing mineral dissolution, which depends on the extent of micro-cracking within the process zone. The rate of mineral dissolution is described as a function of acid intensity and a variable specific surface area (SSA) of solid-fluid interface. Our models capture the effect of mineral dissolution on Young's modulus, damage enhancement on chemical softening, as well as a chemically enabled ductilization effect observed in the post-yield behavior of dissolvable rocks. In parallel, analogue experiments on fluid-driven crack propagation assisted by chemically reactive environment using transparent hydrogels were designed and conducted. Our experimental results highlight the following findings: (1) an intensified chemical environment accelerates tensile crack propagation in the subcritical crack growth through chemo-mechanical feedbacks; (2) a competing mechanism between the crack-tip geometry induced toughening and the chemically induced softening within the process zone arises as the crack advances.

Modeling of non-coaxial deformation in sands: Roles of fabric anisotropy and non-proportional loading

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Experimental investigations have demonstrated that granular soils can exhibit non-coaxial deformation, whereby the principal directions of stress and plastic strain rate do not coincide. This behavior originates primarily from two mechanisms: inherent fabric anisotropy and non-proportional loading paths, such as stress principal axes rotation (SPAR). Such responses deviate from the coaxial assumptions inherent in classical plasticity theory and have therefore become a central issue in the constitutive modeling of soils. In this study, a bounding surface model, termed SANISAND-FZ, is developed to describe non-coaxial soil behavior. Building on its immediate predecessor SANISAND-Z, the model adopts a zero purely elastic range, such that the yield surface collapses to the current stress point. Within the framework of anisotropic critical state theory and by incorporating a fabric-based modified stress, the model consistently captures the influence of fabric anisotropy on stiffness, dilatancy, and plastic flow. With the adopted stress-rate mapping rule, plastic loading can be activated for any stress ratio rate direction, with both the loading and the plastic strain-rate directions depending on that direction. On this basis, non-coaxial deformation under non-proportional loading is further reproduced through appropriate modifications to the constitutive expressions. This is achieved without introducing additional plastic loading mechanisms or piecewise formulations commonly employed in traditional approaches. The capability of the proposed model to simulate non-coaxial behavior is validated through comparisons with experimental results from both proportional and non-proportional loading tests under drained and undrained conditions.

Short review of limestone rock masses geomechanical degradation and its peridynamic modelling perspective

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Limestone rock masses are subject to progressive geomechanical degradation through an interplay of fracturing, physical and chemical weathering, dissolution, and fluctuating hydraulic conditions. A key process in this context is karstification, which involves the development of voids, the formation of sinkholes, rock fissuring, and the instability of slopes and escarpments in limestone terrains. Even without weathering, limestone may develop cracks under stress-driven loading conditions. In such a case, the crack growth is directly linked to stress-driven factors. Modern modeling of the development of such cracks involves not predefining the crack geometry (a continuum mesh). The following study provides a review of the literature on the mechanisms of limestone massif degradation and predictive numerical modeling, with particular emphasis on hydrogeological conditions that serve as specific accelerators. Based on the identified research gaps, a peridynamic (PD) modeling framework is proposed as a non-local alternative capable of simulating coupled fracture-flow-transport processes without pre-defined discontinuity surfaces. The potential of the framework is discussed in the context of limestone terrains where hydrogeological and geophysical field data are available for model calibration. This work establishes the rationale for advancing peridynamic methods in the geomechanics of degraded limestone terrains.

Keywords: limestone degradation, fracture propagation, weathering, karst geohazards, peridynamics, hydro-geomechanical coupling

Learning gravity-driven granular flows

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We develop a physics- and thermodynamics-informed machine-learning framework to uncover constitutive laws governing transient granular flows. Using discrete element simulations of anisotropic gravity-driven flows, we generate high-fidelity experimentally-validated datasets and obtain continuum fields through coarse-graining. Carefully designed neural networks, constrained by physical principles, are used to learn for the first time closure relations, while symbolic distillation extracts interpretable equations that reveal the dominant mechanisms driving the dynamics. The resulting framework enables accurate prediction of granular flows and provides new insights into the transient rheological processes that are often poorly captured by existing models, while paving the way for uncovering and understanding a wider class of complex rheologies.

Microscopic evolution of pore water characteristics in partially saturated sand associated with development of dilative shear bands

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We present new insights into the microscopic evolution of pore water characteristics in partially saturated sand associated with the development of dilative shear bands. Triaxial compression tests were conducted on dense partially saturated sand specimens under both drained and undrained water conditions. During shearing, X-ray micro-computed tomography (CT) was performed at several axial strain levels using two different spatial resolutions. This multi- resolution CT approach enabled the capture of both the global deformation of the specimen and the local microstructural evolution in regions where strain localization progressively developed. Advanced image analysis techniques were applied to quantify the evolution of shear band geometry and pore water characteristics, including spatial distribution, morphology, cluster size distribution, and water retention behavior. The experimental results provide clear evidence that the microscopic evolution of pore water characteristics plays a significant role in governing the mechanical response of dense partially saturated sand during the development of shear bands.

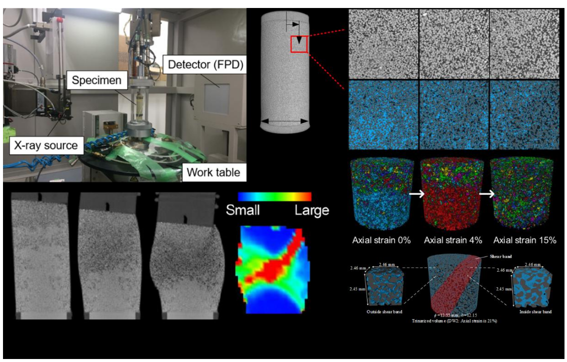

Figure 1. Multi-scale behaviors of partially saturated sand associated with shear band

Effects of fluid flow, particle fragmentation, and temperature on behavior of cohesive-frictional materials using a novel DEM-based thermal-hydro-mechanical model

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This numerical study investigates the effects of fluid flow, particle fragmentation, and temperature on the response of cohesive-frictional materials in 2D and 3D simulations of uniaxial compression and tension under different strain rates. A novel fully coupled DEM/CFD technique, based on a pore-scale thermal-hydro-mechanical model [1], was used to predict the effect of strain rate, fluid flow, and particle fragmentation on the response of both partially and fully fluid-saturated materials. The method's concept generated a network of channels between 3D discrete elements in a continuous space to produce fluid flow. Partly saturated material with low porosity was suggested to have a two-phase laminar fluid flow (air and water). The fluid in channels was immiscible and incompressible in all flow regimes. Unlike the channels, the fluid was compressible in pores and cracks (grid elements). Heat transfer was governed by fluid dynamics (diffusion and advection), cohesive granular particles (conduction), and phase changes. The model [1] was extended by phase changes at high temperatures. To accurately track the liquid/gas content, the positions and volumes of pores and cracks were determined. A so-called clump breakage algorithm [2] was applied to imitate intra-granular fragmentation of particles. Clumps composed of small spheres were used to describe the particles of different diameters and shapes. Different particle strengths were assumed. Numerical analyses were performed using YADE, a 3D open-source DEM program, using the so-called soft-particle approach. Attention was paid to the strength, brittleness, fracture, free water pressures and velocities, and temperatures in cohesive- frictional specimens during simulations of uniaxial compression/tension at different strain rates. The impacts of fluid viscosity and fluid saturation were also investigated. The numerical results were compared with the corresponding experiments.

References

[1] Krzaczek, M.; Tejchman, J.; Nitka, M. (2023). A novel DEM-based pore-scale thermal-hydro-mechanical model for fractured non-saturated porous materials. Acta Geotechnica 18, 2487-2512.
[2] Krzaczek, M.; Tejchman, J.; Nitka, M. (2025). Impact of strain rate, free water, and aggregate fragmentation on the dynamic behavior of concrete in compression regime using a unique coupled DEM/CFD technique. Granular Matter 27, 79, 1-20.

A unique DEM-based coupled 3D thermo-hydro-mechanical mesoscopic model incorporating phase changes for simulating of cohesive-frictional materials

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A novel DEM-based pore-scale 3D thermo-hydro-mechanical (THM) model of two-phase fluid flow and heat transfer in fluids and solids was employed to investigate the behavior of cohesive-frictional materials (such as rocks) at the meso-scale [1]. The model also accounted for phase changes in the fluid when the temperature was high. The THM model implemented the Lee model [2] for interfacial mass transfer via evaporation-condensation. Heat transfer was governed by fluid dynamics (diffusion and advection), cohesive granular particles (conduction), and phase changes. The model used a direct numerical simulation approach, incorporating two coexisting domains: the three-dimensional discrete (solid) domain and the three-dimensional continuous (fluid) domain. Both 3D domains were partitioned into a coarse tetrahedral mesh. The authors built the DEM-based THM model in the open-source software package YADE, using the soft-particle technique. The calibration was performed using single numerical tests (mechanical, hydrological, and thermal). The efficacy of the THM model was demonstrated by a thermal contraction test on a particle assembly during cooling, leading to the formation of a macro-crack. The computations examined the influences of strain rate, particle fragmentation, fluid saturation, fluid viscosity [3], and temperature. An approach for clump breakdown was used to simulate intra-granular fragmentation of aggregates. The numerical results were directly compared with relevant experiments documented in the literature. An acceptable agreement was achieved. The 3D results were compared with the 2D ones [1].

References

[1] Krzaczek, M.; Nitka, M.; Tejchman, J. (2023). A novel DEM-based pore-scale thermal-hydro-mechanical model for fractured non-saturated porous materials. Acta Geotechnica 18, 2487-2512.

[2] Lee, J.; Alam, A.; Ju, H. (2021). Multidimensional and transient modeling of an alkaline water electrolysis cell. International Journal of Hydrogen Energy 46(26), 13678-13690.

[3] Krzaczek, M.; Tejchman, J.; Nitka, M. (2025). Impact of strain rate, free water, and aggregate fragmentation on the dynamic behavior of concrete in compression regime using a unique coupled DEM/CFD technique. Granular Matter 27, 79, 1-20.

Effective medium theory for micropolar granular elasticity

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We present the prediction of granular elasticity with consideration of particle rotation and meso-scale heterogeneity. The work has been established based on the recently developed macro-micro relationship of couple stresses. This paper elaborates on its role as the kinematic drive of local particle rotation. We also present topologic characteristics of granular packing and elaborate on the local structural fluctuations and their important relevance with non-affined displacements and internal force transmission in aid of a structural analysis approach. The effective medium theory for micropolar granular elasticity is hence established with the theoretical significance that local heterogeneity and particle rotation are reflected quantitatively. The proposed theory has been validated against numerical experimental results covering a wide range of contact stiffness, confining pressure, void ration.

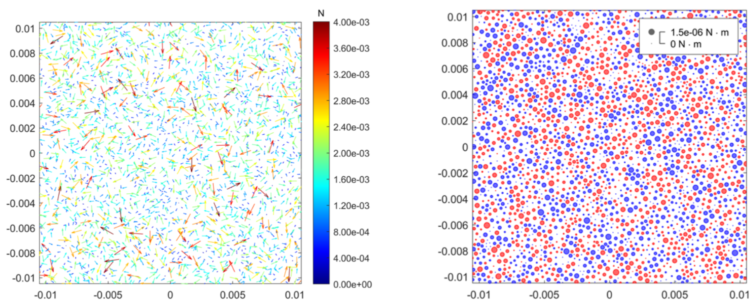

Figure 1. Quantification of local structural heterogeneity

Micro-macro methods: states and transitions

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The behavior of particulate and granular matter - like sand, powder, suspended particles/colloids - is of considerable interest in a wide range of industries and research disciplines. Such materials are intrinsically disordered, often come with a wide distribution of particle sizes, shapes, or materials/mixtures. Granular matter can behave both solid- or fluid-like, including all the various transitions between these states [1,2,3,4]. The related mechanisms/processes in particle systems are active at multiple scales (from nano-meters to meters, from micro-seconds to hours) and understanding them is an essential challenge for both science and application, i.e., finding the reasons for natural/industrial disasters like avalanches or silo-collapse. To understand the fundamental micro-mechanics one can use particle simulation methods [2,4], where often the fluid between the particles is important too, but neglected here. Large-scale applications (due to their enormous particle numbers) have to be addressed by coarse-grained models or by continuum theory. To bridge the gap between the scales, so-called micro-macro transition methods are necessary, which translate particle positions, velocities and forces into density-, stress-, and strain-fields. These macroscopic quantities must be compatible with the conservation equations for mass and momentum of continuum theory. Furthermore, some additional non-classical fields might be needed to describe the micro- structure or the statistical fluctuations, e.g., the fabric or the kinetic energy, before one can reach the ultimate goal of understanding and solving application problems. The granular transitions from fluid to solid, and back from solid to fluid, as well as the transient evolutions between those states are still not fully understood. We present a universal, nonlinear, visco-elasto-plastic material model for the mechanics related to the failure of solids (solid-fluid-transitions) and to the stagnation or jamming (fluid-solid transitions) that includes also the history of material structure and the dynamics as state variables [3], as based on DEM particle simulations [2,3,4].

References

[1] Berzi, D.; Vescovi, D.; Ji, S.; Li, X.; Luding, S. (2022). Topical Collection: Flow regimes and phase transitions in granular matter: multiscale modelling from micromechanics to continuum (Editorial). Granular Matter 24, 3.
[2] Vescovi, D.; Luding, S. (2016). Merging fluid and solid granular behaviour. Soft Matter 12, 8616.
[3] Luding, S.; Jiang, Y.; Liu, M. (2021). Un-jamming due to energetic instability: statics to dynamics. Granular Matter 23, 80.
[4] Vescovi, D.; Berzi, D.; di Prisco, C. (2019). Fluid-solid transition in unsteady, homogeneous, granular shear flows. Granular Matter 20, 27.

Damage evolution and functional failure mechanisms of buried pipelines induced by geomaterial degradation and strain localization in complex geotechnical sites

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The functional failure of buried pipelines in complex sites is governed not only by structural damage of the pipeline itself, but also by the degradation, instability and strain localisation of surrounding geomaterials. In line with the scope of bifurcation and degradation in geomaterials, this study investigates the damage evolution and functional degradation mechanisms of buried pipelines subjected to corrosive soil environments, non-uniform ground settlement, fault displacement, liquefaction-induced deformation, and rainfall-earthquake coupled slope instability. Corrosion tests and cyclic loading tests are first conducted to quantify the time-dependent degradation of strength, stiffness and ductility of pipeline materials under different soil chemical conditions. Simplified analytical models, three-dimensional finite element simulations and large-scale shaking table tests are then employed to examine the nonlinear soil-pipeline interaction and the resulting strain concentration, joint opening, local buckling and functional loss of continuous and jointed pipelines. Particular attention is paid to the role of shear localisation, pore-pressure accumulation, liquefaction-induced ground deformation and rainfall-induced slope degradation in controlling pipeline damage patterns. Based on physical damage indicators and seismic fragility analysis, a functional loss assessment framework is further developed to link geomaterial degradation, pipeline damage states and post-earthquake serviceability. The results indicate that strength degradation, excess pore-pressure build-up and deformation localisation in geomaterials are critical factors governing the transition from local physical damage to system-level functional failure. The proposed framework provides a mechanistic basis for seismic performance assessment, post-disaster functionality evaluation and resilience enhancement of buried lifeline pipelines in complex geotechnical environments.

Mechanical behavior of sedimented clay in relation to their initial microstructure

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This study focuses on the impact of initial microstructures of clayey soils formed during sedimentation under the effect of one-dimensional compression. During the sedimentation process, kaolinite particles form distinct configurations dictated by the surface charge induced electrostatic forces and the pH of their environment. In low-pH conditions, edge-to-face arrangements dominate, while high-pH conditions favor face-to-face stacking [1]. Kaolinite samples with these two different initial microstructures were produced through sedimentation tests. Scanning Electron Microscopy (SEM) has proven to be an effective technique for visualizing clay microstructure [2], but particular attention is required during sample preparation. In this work, a specific sample preparation method was developed to enable observation of the fabric of clay slurries. SEM photographs revealed clear distinctions in the microstructure of flocculated and dispersed clay slurries. The flocculated samples displayed a card-house-like fabric with larger pores, while dispersed samples exhibited parallel particle orientation and smaller interparticle pores. Under increasing one-dimensional compression, initially flocculated samples showed a higher compressibility due to their larger pores and the collapse of the clay aggregates. However, as loading progressed, SEM observations showed that these distinct microstructures gradually converge, becoming indistinguishable at high stress levels, and the mechanical behaviors of both samples became similar, particularly during the unloading path. Quantitative analysis of the pore size distribution (PSD) based on SEM observations and image processing was conducted, highlighting the distinct initial clay fabrics and their evolution under mechanical loading [3]. These results emphasize the interplay between initial particle arrangement, stress conditions, and clay behavior, offering insights into the mechanical response of sedimented kaolinite under different environmental conditions.

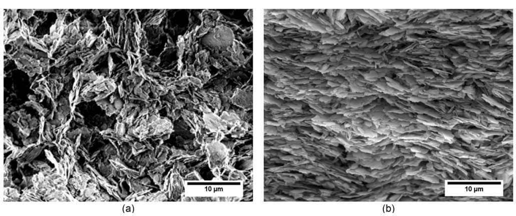

Figure 1. SEM images of (a) initially flocculated slurry; and (b) initially dispersed slurry

References

[1] Rand, B.; Melton, I. E. (1977). Particle interactions in aqueous kaolinite suspensions. Journal of Colloid and Interface Science 60(2), 308-320.

[2] Ding, Y.; Bennai, F.; Jrad, M.; Guyon, J.; Hattab, M. (2024). Three-dimensional pore network of kaolin using FIB-SEM imaging. Particulate Science and Technology 42(5), 815-831.

[3] Ma, M.; Bennai, F.; Hattab, M.; Hicher, P. Y.; Nicot, F. (2025). Influence of the initial clay fabric on the progressive destructuring process under one-dimensional compression. Journal of Engineering Mechanics 151(11), 04025065.

Numerical investigation of the influence of material heterogeneity on strain localisation development

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The work focuses on the influence of material heterogeneities in geomaterials over their localised response, seeking to extract quantitative informations. We consider a second-gradient continuum, which involves an internal length allowing for strain regularisation. The finite element method is employed to simulate laboratory tests in plane strain. The material follows a softening elastoplastic strain-stress relationship. Material heterogeneity is modelled by random field realisations of an initial parameter controlling the size of the elastic domain. The spatial variability of this random field is controlled by mean of a Gaussian covariance model, characterised by its variance and its practical range (correlation distance). A sequential analysis of the strain field development during the loading suggests to identify three stages of strain localisation: the nucleation stage, characterised by formation of isolated clusters of Gauss points in plastic regime; the diffuse localisation stage, characterised by the growth of a network of numerous small shear bands; and finally the mature localisation stage, characterised by the remaining of one or a few active final shear bands and the desactivation of others. The study highlights that the internal length of the model controls the width of the bands in both the diffuse and mature localisation stages, whilst the practical range influences the number and the distance between bands in the diffuse localisation stage. From different random field realisations, it is observed that the spatial distribution of material heterogeneity influences the localisation patterns in the three identified stages. Furthermore, introducing indicators of shear band criticality, the sequential analysis of the strain fields reveals that the mature band can be detected as early as the diffuse localisation stage in most cases. Finally, the methodology will be applied to a cavity problem involving non uniform far-field stresses.

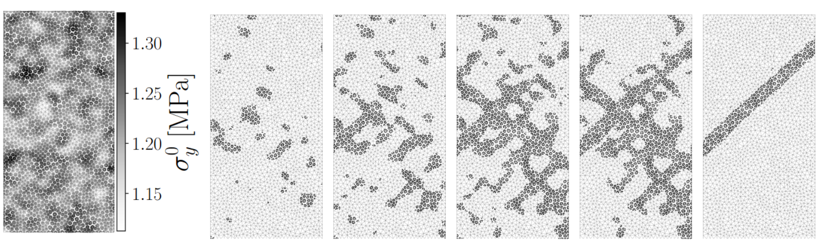

Figure 1. Map of the initial elastic limit σy^0 (initial material heterogeneity), followed by spatial distribution of yielding Gauss points (dark area) for different loading steps, illustrating the three strain localisation stages.

On the definition of the tensor A in hypoplastic constitutive models for sand

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In the framework of hypoplastic constitutive modeling of clays, the fourth-order tensor A is a fundamental component that defines the mathematical structure and the asymptotic stiffness of the material. The clay model according to Mašín (2013) is likely the most prominent model in this regard. While the role of A in describing asymptotic states is well-established for cohesive soils (clays), a consistent definition and application for non-cohesive materials, such as sand, has been notably absent in the literature. This contribution addresses this open question by proposing a tensor A specifically for sand. By modifying the compression relation of the reference hypoplastic model by von Wolffersdorff (1996), we demonstrate how the A-based mathematical framework can be successfully adapted for granular materials. This modification allows for the explicit formulation of an Asymptotic State Boundary Surface (ASBS) within the hypoplastic framework for sand and provides a solution for further constitutive model developments.

Multiscale bifurcation analysis in granular materials: discrete-continuum duality

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We develop a multiscale framework for investigating material instability and localization phenomena in plastic granular materials with a goal to establish a discrete-continuum duality. In continuum mechanics, bifurcation and stability analyses typically require the material tangent (stiffness) operator whose computation requires special treatment when using micromechanical approaches such as the Discrete Element Method (DEM). To bridge the discrete and continuum descriptions, we propose a new computational strategy that incorporates strain probing to reconstruct the elastoplastic constitutive tensor and its spectral characteristics directly from DEM simulations. The probing technique enables the evaluation of a tangent operator that inherits microstructural information from the discrete system, thereby allowing bifurcation analyses to be performed at the macroscopic scale. An incrementally linear constitutive tensor is obtained for each probing direction within a given tensorial zone or sector of incremental stress or strain space, rendering the overall response directionally nonlinear. Using this approach, material instability can be assessed from the spectral properties of the tangent constitutive tensor associated with a specific tensorial zone identified through DEM probing.

Finally, a mesoscale analysis is presented to detect shear band localization using Rice's classical criterion, extended here from its continuum origins to a micromechanical discrete modelling framework. The numerical results demonstrate that the proposed multiscale methodology, which allows access to microstructural information, yields predictions consistent with continuum analyses, including accurate estimation of localization angles during shear band formation in DEM-simulated granular specimens.

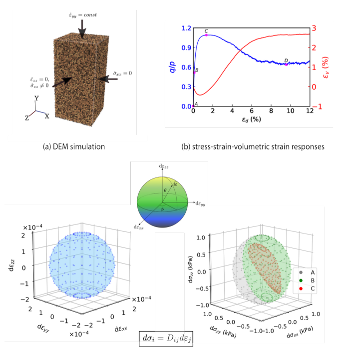

Figure 1. Strain probing on DEM sample to obtain continuum consistent operator: (a) DEM sample upon which a plane-strain loading is applied, (b) global stress-strain-volumetric strain responses, (c) global strain probe size of 2.0 E-4 applied to DEM sample, (d) global stress response envelopes at points A, B, C, D on master curve in (b)-local response envelopes can also be computed at each designated cell in the DEM sample.

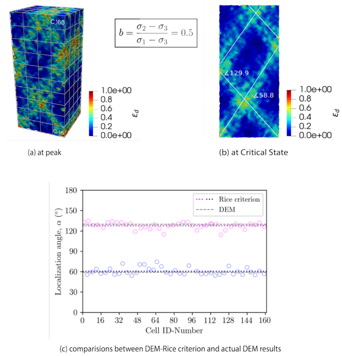

Figure 2. A generalized 3D loading case with b-parameter = 0.5: (a) localization pattern at peak, (b) fully developed shear band localization at critical state, (c) continuum tangent operator reconstructed as per method described in Fig. 1, and Rice's criterion applied to detect localization angles-good agreement between DEM-based Rice's criterion predictions and observed shear localization angles.

Beyond the bifurcation in geomaterials: controlling snapback response and strain rate inside the localisation zone

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Bifurcation and localisation of deformation in geomaterials are widely observed in both lab and field conditions. In such cases, inelastic behaviour inside the localisation zone dominates the deformation and dissipation characteristics. Given this dominance, strain rate inside the localisation band can be a few orders of magnitude higher than the macro counterparts (Fig. 1), potentially leading to unwanted dynamic effects that can alter the macro behaviour and hence obtained properties. Therefore, controlling the strain rates inside the localisation zone is essential to obtain intrinsic properties in quasi-static conditions. This control is also linked with stabilising the tests to capture snapback behaviour and maintain quasi-static conditions for the whole duration of failure. Snapback is the reversal of both load and displacement in quasi-static conditions (Fig. 1), which happens when strain energy stored in the specimen exceeds the dissipation capacity of a localisation band. We present techniques based on PID (Proportional-Integral-Derivative) control to allow successfully controlling snapback and strain rate inside the localisation zone in testing and simulating failure of rocks and other similar quasi-brittle materials. Differences with uncontrollable tests, in terms of responses and obtained properties, are also used to demonstrate the effectiveness of the proposed approach.

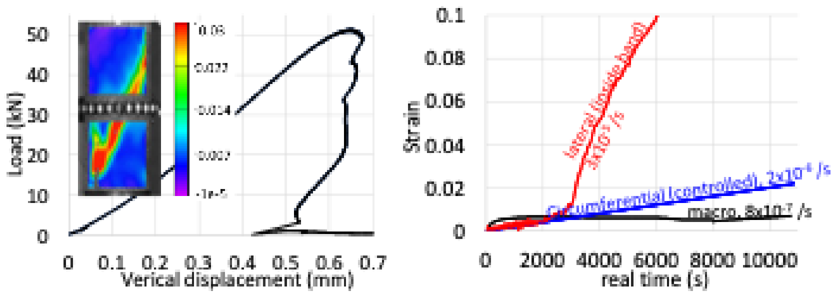

Figure 1. Localised failure, snapback behaviour and strain rates.

Granular materials and thermodynamics: the missing link

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Granular materials are known to be an illustration of complex materials as they display emergent macroscopic properties when loaded. An initially homogenous response can bifurcate into a heterogeneous one with the appearance of a rich variety of structured kinematical patterns. The shear banding that ensues illustrates a symmetry-breaking transition with multiple choices of macroscopic behaviours, a common feature of dynamical complex systems (Fig. 1). Even though the phenomenon has been studied for decades, this regime transition remains mostly mysterious in geomaterials, with no convincing arguments that could link it to the underlying microscopic mechanisms. This contribution revisits this issue by invoking fundamental extremal entropy production principles, in the context of a two-scale thermodynamics framework, to seek any connection with the second-order work theory in the mechanics of failure [1]. Our findings are verified through discrete element simulations that highlight the fundamental role played by the elastic energy stored within a granular material before a bifurcation occurs (Fig. 2, [2]), which also corresponds to a minimization of the entropy production (Fig. 3). By developing a multiscale thermodynamic which introduces the configurational mechanics from rational arguments, we suggest a new interpretation of the intriguing shear banding phenomenon as a bifurcation with the emergence of optimal dissipative microstructures germane to nonequilibrium thermodynamics of open systems [3].

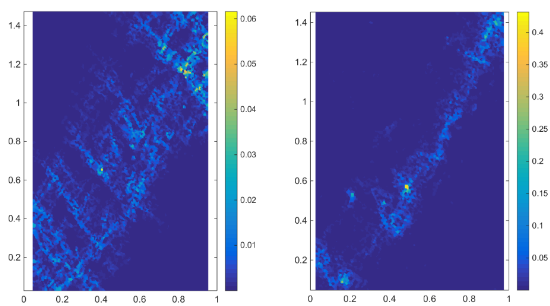

Figure 1. Distribution of incremental deviatoric strain ratio ($\delta\varepsilon_d/\delta\varepsilon_1$) within the granular assembly at the peak stress (left) and at the beginning of the critical state regime (right).

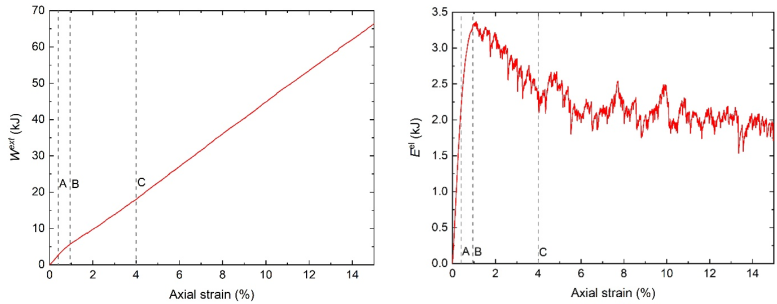

Figure 2. Evolution of both: (a) the external work, and (b) the elastic energy stored within the system along an axial compression path under constant lateral stress.

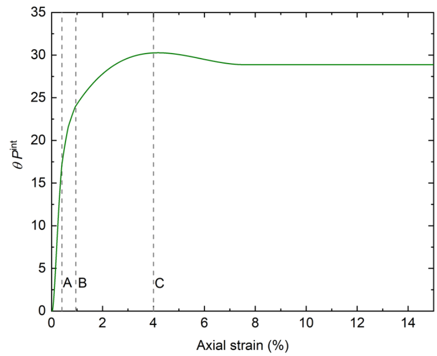

Figure 3. Evolution of the entropy production (times the thermodynamic temperature considered constant) along an axial compression path under constant lateral stress. The dashed line B corresponds to the deviatoric stress peak, and the dashed line C corresponds to the beginning of the critical state regime.

References

[1] Nicot, F.; Wang, X.; Wautier, A.; Wan, R.; Darve, F. (2023). Shear banding as a dissipative structure from a thermodynamic viewpoint. Journal of the Mechanics and Physics of Solids 179, 105394.

[2] Wang, X.; Liu, Y.; Nicot, F. (2024). Energy processes and phase transition in granular assemblies. Int. Journal of Solids and Structures 289, 112634.

[3] Nicot, F.; Lin, M.; Wautier, A.; Wan, R.; Darve, F. (2024). Configurational mechanics in granular media. Granular Matter 26(3). DOI: 10.1007/s10035-024-01443-1.

Fractures with constricted opening across the scales

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Traces of Mode I fractures in rocks across the scales are usually not straight; they exhibit interruptions and overlappings [1]. These features are usually observed on the surface which is one of 2D cross-sections. Obviously, these sections are far from being identical such that in 3D these interruptions and overlappings represent local bridges connecting the opposite sides of the fracture. These bridges are distributed all over the fracture constricting its opening and reducing the values of the stress intensity factor. The dimensions, the number and the geometry of the bridges depend upon the rock structure (at the scale microscopic with respect to the fracture length). Therefore, understanding the effect of bridges on the stress intensity factor can shed light on the rock microstructure. The combined effect of uniformly distributed bridges is accounted for by the introduction of constriction length [1]. As a result, under the given load the stress intensity factor depends on both the fracture length and the ratio of fracture length to the constriction length.

Fracture propagation is controlled by fracture toughness, which is usually determined by measuring/estimating the fracture length and the load at which fracture propagates. This is achieved using conventional models neglecting the effect of bridges. This approach produces a scale effect, the increase of fracture toughness with fracture length, which is believed to be exhibited by cracks in rock samples, hydraulic fractures, magmatic dikes, Mis-Ocean Ridges. The paper presents a modified model of constricted fracture propagation. The results confirm that for each scale there exists a constriction length such that the scale effect of fracture toughness disappears and the fracture toughness remains constant.

Determination of constriction length allows more realistic monitoring of fracture growth and provides insight into the rock structure. The suggested approach will also allow developing a more realistic scaling of fracture growth in strain rock burst and thermal spallation.

Acknowledgements: *The authors acknowledge financial support from of the Australian Research Council through project DP250103594.*

References

[1] Dyskin, A. V.; Pasternak, E.; Shapiro, S.; Bunger, A. (2025). Scaling laws for hydraulic fractures with constricted opening. Engineering Fracture Mechanics 327, 111464.

Insights into the potential of ALE and CEL analyses for large deformations in geomechanics

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The Coupled Eulerian-Lagrangian (CEL) approach can effectively model geotechnical boundary value problems including soil-structure interaction and large deformations. As a numerical tool for analyzing geotechnical problems with significant soil deformations, like pile installation, that methodology has become widely accepted. Two numerical meshes, one Lagrangian and the other Eulerian, overlap at least partially in the model. The Lagrangian part is the structure, and the Eulerian part is often the soil domain. Since there is just the material of the structure in reality and no other material at the same location, the material within the Eulerian region of the mesh overlap may be referred to as ”virtual” or ”ghost” material.

It is worthwhile to look at how much the numerical findings are impacted by the presence of ”ghost” material in CEL simulations. Two distinct instances of soil-structure interaction are used in this investigation: (i) a laterally loaded pile in undrained soil, and (ii) a numerical simulation of the installation of a single pile. The Arbitrary Lagrangian Eulerian (ALE) technique, which does not call for a ”ghost” material formulation, is also used to model both situations. A comparison of the modeling and outcomes from these two distinct approaches - CEL and ALE - provides insights into the analytical errors. The specification of void material on top of the free ground surface and the contact models in the numerical simulations present additional issues that will also be discussed here.

Chemo-mechanical bifurcation and deformation band formation in low-permeability granite

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Deformation bands in crystalline rocks are increasingly recognised as critical localisation features that control fluid flow, mineral alteration, and resource formation in the deep crust. In the Cooper Basin (Australia), Li-rich geothermal fluids (>200 ppm Li) coexist with unusually low salinity. This geochemical anomaly challenges conventional hydrothermal models. We propose that this signature originates from a chemo-mechanical bifurcation during the tectonic reactivation of basement granite, where stress-induced micro-dilatancy triggers fluid-generating mineral reactions (e.g., sheet silicate hydrolysis and Feldspar dissolution) in a low-permeability matrix.

We relax the classical effective stress principles and formulate a reaction-cross-diffusion model coupling solid deformation and internal fluid generation, analogous to classical bifurcation frameworks but extended to include fluid source terms from chemical feedback as additional coupled partial-differential equation. The system exhibits instability when fluid generation outpaces drainage. This condition leads to an excitation phenomenon of pore pressure buildup and mechanical compaction, triggering strain localisation into deformation bands. This mechanism explains both the preservation of early low-salinity fluids (generated during uplift ~300 Ma ago) and their reactivation under recent high-temperature conditions (<10 Ma, T >230°C), enabling sustained Li enrichment.

Unified Peridynamic modeling of THM coupled fracturing problems in geomechanics

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Peridynamics offers distinct advantages for modeling discontinuities in solid mechanics, but its application to fluid dynamics remains underdeveloped. To address this, we propose a unified peridynamics framework capable of solving coupled solid-fluid multiphysics problems within a single computational scheme. This framework employs a total Lagrangian formulation for solids and introduces a novel semi-Lagrangian approach for fluids and the temperature field, enabling the solution of the Navier-Stokes equations under large deformations via non-local operators. It integrates thermo-hydro-mechanical coupling mechanisms based on the principle of energy conservation and proposes a bidirectional virtual point method for accurate thermal coupling at moving interfaces. A key innovation of the framework is a multi-scale strategy that assigns independent interaction domains for thermal, mechanical, and fluid fields, effectively resolving challenges related to non-local operator discretization and particle mapping ambiguity. The framework is validated through simulations of natural/mixed convection, quenching processes, and cold water injection into dry hot rock. The results demonstrate its robustness in simulating evolving discontinuities, moving interfaces, and complex coupled phenomena, thereby advancing the application of peridynamics to cross-domain solid-fluid problems.

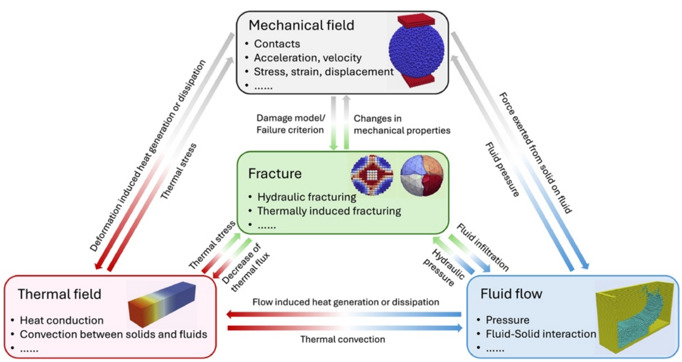

Figure 1. Unified Peridynamics framework for coupled thermo-hydro-mechanical multiphysics problems with evolving fracture

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A numerical study of the role of water phase change in the propagation of catastrophic landslides with reference to Vaiont landslide (Italy, 1963)

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We will show that the formation of the vapour cushion inside the shear band of the Vaiont landslide (Hedron and Patton 1985) is consistent with the kinematics of the landslide once the hydro-thermo-mechanical material parameters of the Vaiont clays are considered and using a very general non-isothermal elasto-plastic multiphase porous media model in dynamics.

Catastrophic landslides may occur after a transition from creep to high-velocity propagation and usually involve multiphase materials and multiphysics couplings. The Vaiont landslide occurred on October 9th, 1963, mobilizing more than 250 million m3 with the final slip of about 450 m at 25-30 m/s, is recorded as one of the most catastrophic landslides in literature. The soil failure mechanisms that led to the magnitude of the incident are still an area of active interest and research in the academic community, with an open question on the possible impact of thermal effects on the multiphase and multiphysics behaviour of the soil material and on the kinematics of the landslide. The temperature increase in the shearing failure zone due to friction during the sliding, if slow to dissipate, leads to thermal pressurization and may induce the vaporization of the liquid water in the pores, with detrimental effects on the hydro-mechanical behaviour of the soil. In this contribution, a fully coupled thermo-hydro-mechanical model for non-isothermal elasto-plastic multiphase porous media in dynamics is used to numerically examine the mechanisms that led to the extreme Vaiont rapid motion. It is shown that the formation of the vapour cushion inside the shear band of the landslide (Hedron and Patton 1985) is consistent with the kinematics of the landslide.

3D centrifuge model tests and numerical simulations of bearing capacity problems

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Experimental studies and FEM analyses have been conducted on the bearing capacity and deformation characteristics of shallow foundations under plane strain conditions. However, few studies have examined these issues in a fully three-dimensional setting, especially for embedded shallow foundations. This study aims to clarify the bearing capacity and deformation characteristics of embedded shallow foundations in three-dimensional conditions by conducting centrifuge model tests and corresponding elastoplastic FEM analyses using Subloading tij model. Centrifuge model test and FEM analyses of bearing capacity problems were conducted not only on level ground but also on ground including slopes. The results indicate that FEM analyses incorporating appropriate soil material properties can effectively explain the load-displacement behavior of foundations in both two-dimensional and three-dimensional conditions. Furthermore, the analyses successfully capture the differences in deformation modes between two-dimensional and three-dimensional cases. The study highlights the necessity of properly considering not only the influence of intermediate principal stress but also the effects of confining stress and dilatancy when analyzing bearing capacity problems in geotechnical engineering to obtain realistic results.

Hydraulic hysteresis as a degradation mechanism promoting localisation in unsaturated slopes under intermittent rainfall

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Strain localisation in geomaterials is commonly associated with degradation processes that progressively reduce stiffness and strength and concentrate deformation into narrow shear zones. In unsaturated slopes, intermittent rainfall imposes repeated hydraulic loading-unloading cycles; for soils exhibiting wetting-drying hysteresis, these cycles introduce a history-dependent degradation mechanism through incomplete hydraulic recovery between pulses. This study investigates how retention hysteresis, when present, acts as a hydraulic memory that promotes progressive weakening and strain localisation in unsaturated slopes subjected to rainfall pulses. A thermodynamically consistent hydro-mechanical constitutive framework is developed in which hysteresis is represented by a non-equilibrium internal variable within a unified free-energy and convex dissipation potential formulation, capturing irreversible wetting-drying processes and the associated hydraulic dissipation. The constitutive model is implemented within a coupled large-deformation Smoothed Particle Hydrodynamics (SPH) formulation to simulate infiltration-drainage and slope deformation, enabling the spatio-temporal characterisation of localisation initiation and evolution under successive rainfall pulses (onset location, rate of strain concentration, band continuity versus fragmentation, depth migration, and potential re-intensification under later pulses). Numerical simulations reveal that in hysteretic cases suction recovery is suppressed during rainfall cessations, leading to cumulative hydraulic preconditioning of the near-surface soil. This progressive degradation accelerates suction reduction and mean effective stress loss, induces stiffness/strength softening, and increases plastic strain accumulation, thereby promoting earlier and more connected localisation patterns under repeated rainfall pulses. Consequently, slopes subjected to intermittent rainfall can exhibit progressive failure evolution and potential reactivation behaviour that is not reproduced by non-hysteretic retention models under identical rainfall histories. The results highlight the critical role of hydraulic hysteresis (where it exists) as a degradation mechanism controlling localisation development and failure evolution in unsaturated geomaterials.

Particle size effect in gap-graded soil-rock mixture: a large-scale triaxial test investigation

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Rock size is a critical factor influencing the macro-meso mechanical properties of soil-rock mixtures (SRM). To investigate the particle size effect, this study conducted large-scale triaxial shear tests on SRM using the GDS apparatus, controlling the relative density as constant. Tests were performed on SRM with six rock sizes under three confining pressures. The results indicate that the stress-strain behavior of SRM primarily exhibits strain softening. The variation of shear strength and initial elastic modulus with Rd (the ratio of specimen diameter to the maximum particle size) all can be described by a power function. Rd=10 is established as the critical ratio. When Rd $\geq$10.0, the shear strength and strength parameters stabilize. The failure mode of SRM is jointly influenced by the Rd and confining pressure. Under a confining pressure of 100 kPa, the failure mode is characterized by shear failure. At 200 kPa, the failure mode transitions from shear failure to bulging failure as Rd increases. Under a confining pressure of 400 kPa, the failure mode manifests as bulging failure. Under the same confining pressure, particle breakage ratio follows a decreasing power-law trend with rising Rd.

Keywords: soil-rock mixture; the ratio of specimen diameter to particle size; large-scale triaxial test; fragmentation of particles

Controllability criteria for bridging bifurcation and progressive localization in geomaterials

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Traditional bifurcation theory is not applicable to analyzing strain localization in rate-dependent solids, as no explicit elastoplastic tangent tensor can be defined. Moreover, it fails to inform the modeling of the progressive development of localized bands through regularized numerical strategies, such as nonlocal theories. In this context, we investigate the kinematics characteristics within localized deformation bands and presents closed-form strain localization criteria for viscoplastic geomaterials based on controllability theory, combined with a strain-hardening constitutive model calibrated against Berea sandstone data. Analytical precursors of instability are derived from systems of ordinary differential equations (ODEs), and both integration-point and full-field results show that the proposed criteria capture quasi-instantaneous (load-induced) and delayed (creep-induced) strain localization bifurcations. The criteria are further used to interpret 2D/3D simulations of boreholes in porous rocks under dry and hydro-mechanical conditions, linking heterogeneous deformation patterns to far-field stress and pore-pressure states. The framework also provides a closed-form expression for localization zone thickness under multidimensional conditions with nonlocal gradient regularization, quantifying the interplay between material softening and plastic non-normality and identifying admissible bounds for parameters governing nonlocal regularization. Using the scale-independence of this expression, the adopted nonlocal model quantifies scale effects associated with the ratio of system size to shear zone thickness. Simulations of plane strain compression, miniaturized plate anchors, and shallow footings show that reduced system size leads to increased load capacity, reduced strength degradation, and systematic thickening and diffusion of localization zones. Supported by DEM, 1g, and centrifuge data, these results motivate correction factors based on the shear band thickness-to-structure size ratio to predict and rescale pullout and bearing capacity in reduced-scale or non-standard systems.

Keywords: controllability; bifurcation; progressive failure; viscoplasticity; nonlocal theory

Synergistic mechanism and failure evolution process of pile-anchor structure reinforced rock slope based on centrifuge shaking table tests

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In recent years, the frequency of earthquake-triggered landslides has increased. highlighting the urgent need for effective strategies in landslide prevention and mitigation. The pile-anchor structure, which combines the benefits of both anti-slide piles and anchors, offers a solution to the limitations of excessive pile bending moments and restricted slope support, facilitating a more efficient stress distribution compared to standalone anti-slide piles or anchors. This study investigates the dynamic response and synergistic behaviour of rock slopes reinforced by pile-anchor composite structures under seismic loading through a series of dynamic centrifuge model tests. The research examines the seismic behaviour of slopes subjected to both non-pulse and pulse-like ground motions, focusing on the amplification effects and structural responses, including pile bending moments, pile top displacements, and anchor tension. Additionally, parameter studies on the anchor elastic modulus, pile bending stiffness, and pile embedding depth are conducted to observe the dynamic response and failure mechanisms of the reinforced slope. The results demonstrate that increasing pile bending stiffness and embedding depth improves load-bearing capacity, reduces displacement, and mitigates failure. The synergy between the pile, anchor, and slope plays a crucial role in resisting earthquake-induced landslide thrust, with pulse-like ground motions, particularly low-frequency components, significantly amplifying the pile head response and influencing the overall seismic behaviour. These findings provide valuable insights into optimizing the seismic design of pile-anchor systems for landslide-prone regions, and thus effectively protect the safety of people's lives and property.

Keywords: Pile-anchor structure; Dynamic centrifuge test; Synergistic mechanism; Failure evolution process; Seismic performance

How subtle changes in microstructure can mitigate the liquefaction susceptibility of granular materials: from experimental and numerical evidences to multi-scale modeling

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Granular materials are complex in the sense that their constitutive behavior stems from the coupling between the local physical interactions between grains and geometrical effects. Grains self-organize into mesoscale structures, whose topology significantly influences macroscopic behavior, particularly failure modes. Thus, modifying local grain organization can effectively control macroscopic responses. Building upon the results of Wang et al. (2021), Wautier et al. (2019), who demonstrated how weakly loaded fine grains influence the non-associated plastic behavior of granular materials, this work synthetizes experimental, numerical and modeling evidences showing that the potential for static liquefaction can be mitigated through subtle microstructural changes. Introducing fine grains into the pore space of granular materials sensitive to static liquefaction may eliminate the occurrence of liquefaction on undrained triaxial loading paths. This effect requires only a small amount of fine grains (a few percent by mass), provided they are clogged at the contacts between coarser grains (Chen et al.). In such configurations, fine grains provide support to force chains. Conversely, if fine grains remain floating in the pore space or become trapped between coarse grains, the static liquefaction potential remains unchanged or may even increase. Complementing experiments and discrete element simulations, multi-scale modelling, based on the extension of the particular H-model (Nicot and Darve, 2011) further elucidates the relationship between mesostructure topology and static liquefaction potential.

References

[1] Chen, F.; Hegde, A.; Benahmed, N.; Philippe, P.; Nicot, F.; Wautier, A. Controlling static liquefaction of granular mixtures through subtle changes in fine-coarse grain local arrangements. Géotechnique. Submitted.

[2] Nicot, F.; Darve, F. (2011). The h-microdirectional model: accounting for a mesoscopic scale. Mechanics of Materials 43(12), 918-929.

[3] Wang, T.; Wautier, A.; Liu, S.; Nicot, F. (2021). How fines content affects granular plasticity of under-filled binary mixtures. Acta Geotechnica, pages 1-15. DOI: 10.1007/s11440-021-01430-3.

[4] Wautier, A.; Bonelli, S.; Nicot, F. (2019). Rattlers' contribution to granular plasticity and mechanical stability. International Journal of Plasticity 112, 172-193. DOI: 10.1016/j.ijplas.2018.08.012.

Friction and dilatancy of geomaterials: Another look

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The complexity of the constitutive behaviour of geomaterials including instability and strain localization mainly originates from their particulate nature. Friction and dilatancy are two saliant features of geomaterials when subjected to shear, and they are the controlling factors for the formation and orientation of shear bands. While a profound understanding has been established for each of them over the past decades, some aspects remain puzzling, as evidenced by the divergent views in the literature. Here we present a second look at the subject matter, with an attempt to address several intriguing questions. In the framework of micromechanics and based on specifically-designed laboratory experiments, we show that intergranular friction may not, as commonly conceived, be essential for dilatancy, but the fabric anisotropy associated with intergranular contacts plays a pivotal role. Theoretically, an assembly of frictionless particles can have a well-defined constitutive relation and exhibit dilatancy; only for the perfectly isotropic case, granular assemblies have vanishing dilatancy. Practically, it is however impossible for geomaterials because of their inherent anisotropy. We also discuss the implications of these alternative perspectives for the critical state theory.

Keywords: Anisotropy, Dilatancy, Friction, Granular materials, Micromechanics.

Mesoscopic mechanism of enhanced liquefaction resistance of fiber reinforced sand

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Soil liquefaction is a major geological disaster associated with earthquakes. A substantial corpus of researches has demonstrated the efficacy of fiber addition to sand in enhancing liquefaction strength. However, the majority of current researches on the liquefaction characteristics of fiber reinforced sand are conducted through experimental methods and concentrates on the macroscopic mechanical properties of fiber-reinforced sand. Research on the mesoscopic level of liquefaction resistance for fiber-reinforced sand is still lacking.

In this study, a series of undrained cyclic triaxial tests on clean Toyoura sand and fiber-reinforced sand were simulated employing 3D-DEM to investigate the macro-mesoscopic cyclic mechanical behaviors of fiber-reinforced sand. The mesoscopic contact parameters used in the DEM model were calibrated against laboratory monotonic triaxial test results under drained and undrained conditions.

The simulation results demonstrate that fiber incorporation can substantially augment the liquefaction resistance of sand, with the effect being more pronounced at higher fiber contents within a specific range. Concurrently, at lower fiber contents, although the number of cycles experienced by the specimen to reach the liquefied state does not increase significantly compared to the clean sand specimen, the deformation inhibition effect of fibers on the specimen is particularly pronounced. At the mesoscopic level, the presence of fibers increased the mechanical coordination number of strong contact in the soil. As the fiber content increased, the mechanical coordination number increased concomitantly, and the slower the tendency of mechanical coordination number decreasing. During the cyclic loading process, strong contact transforms into weak contact, and when the specimen reaches liquefaction, the mechanical coordination number of strong contact decreases to zero. The degree of contact anisotropy inside the specimen becomes increasingly evident during the loading process. Concurrently, the specimen structure tends to become more loosened, resulting in a continuous decrease in the contact force between the sand particles.

The Reinforcing Mechanism of Disposable Face Mask Chips in Sand: Insights from Numerical Analysis and Experiments

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This study presents experimental and numerical investigations into the use of waste face mask chips (FMCs) as reinforcement materials for granular soils in geotechnical engineering. In experimental aspects, the stress-strain relationships and shear band evolution of Fujian sand reinforced with FMCs under plane strain conditions were examined. The results indicate that FMCs significantly enhance the shear strength of the sand while reducing its initial stiffness. In numerical analysis, both the Discrete Element Method (DEM) and the Finite Element Method (FEM) were employed to investigate the micro- and macro-mechanical behaviors of FMC-reinforced sand, respectively. By using DEM, we conducted a series of triaxial and hollow cylinder torsional tests under various loading conditions. The result demonstrates that the micromechanical interactions between FMCs and sand particles, including separation, bridging, and enwrapping, enhance the internal force transmission network, resulting in increased peak strength but lower initial stiffness. Furthermore, we developed a micropolar hypoplastic constitutive model to accurately reproduce the stress-strain relationships of FMC-reinforced sand and implemented the model in a finite element code to study localized deformation under biaxial conditions. The results from both DEM and FEM closely match experimental observations, highlighting the potential of using FMCs for soil reinforcement and advancing sustainable practices in waste management and geotechnical applications.

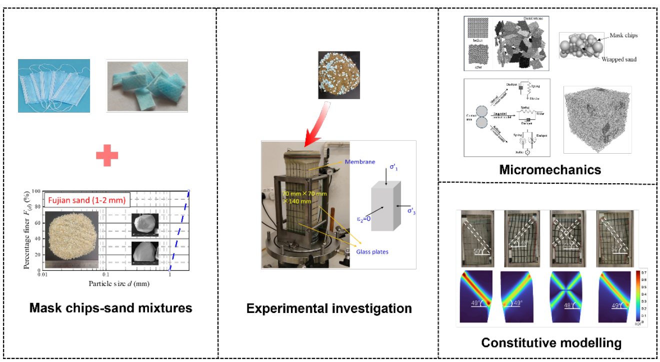

Figure 1. Experimental and numerical investigations into the use of waste face mask chips as reinforcement materials for granular soils

Micromechanical insights into the influence of cementation on shear localisation in cemented sands

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Bio-cementation by microbially (or enzymatically) induced carbonate precipitation can markedly increase the stiffness and peak strength of granular soils. Yet, experiments also report a counterintuitive trend: some treated sands exhibit lower residual strength than the uncemented material at large strains. In many geosystems and earth structures, stability is governed by the residual state that emerges once deformation localises onto shear surfaces. Pinning down the conditions under which residual weakening occurs therefore requires linking macroscopic post-peak response to the evolving mesoscale organisation of contacts, force chains, and kinematics.

We use discrete element method (DEM) simulations in which sand grains and calcium carbonate particles are modelled explicitly, enabling cement to occupy pore space rather than being reduced to contact “virtual bonds.” We focus on a grain-bridging precipitation pattern (carbonates connecting grains that were not initially in contact) and perform drained biaxial tests in 2D, supported by companion 3D results. A parametric campaign varies carbonate content, sand-carbonate cohesive strength, the stiffness contrast between carbonate and sand, and confining pressure. The results show that grain bridging does not impose a unique residual outcome: the residual state may be weaker or stronger than the uncemented reference depending on the competition between localisation-driven degradation and bond-supported load transfer. Residual strength is governed primarily by the cohesive strength at sand-carbonate contacts and by the stiffness contrast between carbonate and sand, while carbonate content (within the studied range) and confining pressure play secondary roles. Kinematic fields reveal a transition from diffuse deformation in uncemented (and low stiffness contrast) cases to early strain localisation and mature shear bands when bridging contacts are prone to instability, for example in weakly cemented packings combined with relatively stiff carbonate. Grain-scale stability analyses and bond-breakage mapping indicate that bridging carbonates modify the contact structure and can introduce metastable configurations that promote relative sliding and rolling, concentrating damage within the band. Inside the band, stress rotation and reduced mean stress accompany intensive bond breakage, rationalising the macroscopic softening and potential residual weakening.

Overall, residual behaviour in bio-cemented granular media emerges from a mesoscale competition: bond-induced stabilisation through retained cohesive bridges versus instability-driven localisation and restructuring. This framework helps reconcile disparate experimental trends and points to precipitation pattern as a key control, with combined patterns, especially contact cementation, offering a route to retain peak gains without residual weakening.

Fractional Derivative Modeling Approaches to Rock Mechanics

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Within the framework of the Intergovernmental Cooperation in Scientific and Technological Innovation of National Key Research and Development Program, the paper presents fractional derivative modeling approaches to time-dependent behavior of rocks, fractional derivative modeling approaches to non-Darcian flow in porous media, and the multi-physical coupling permeability model in rock mechanics. The future challenges of fractional-order derivatives are discussed.

Assessing and anticipating the potential for static liquefaction at the structure scale: application to tailing dams

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Static liquefaction is a critical failure mechanism in loosely compacted soils, potentially occurring before the material reaches its ultimate strength. The formulation of the second-order work criterion (Nicot et al., 2009, Wan et al., 2017) has formally demonstrated the existence of a bifurcation domain corresponding to a set of material states where conditional failure may arise, even away from the plastic limit failure surface. As a result, traditional approaches based on critical state characteristics are insufficient for predicting the onset of liquefaction in engineering practice. To overcome this limitation, this study establishes a numerical framework to map, at the structural scale, the set of points within the bifurcation domain. Material instability is first characterized at the material point scale through undrained triaxial numerical simulations, linking the slope η IL of the instability line (IL) to the material's state parameter (or void ratio). A stress-ratio-based liquefaction potential index (LPI) is then introduced to analyze stress fields derived from structural-scale computations. For practical application, the bifurcation domain is approximated by the stress states lying between the instability line (IL) and the critical state line (CSL) in the (p′, q) plane. Therefore, regions with LPI > 1 correspond to zones where static liquefaction can be triggered by specific perturbations in boundary conditions (conditional stability). The proposed methodology is implemented in FLAC3D using the NorSand constitutive model and applied to an idealized tailings dam. This application investigates the initiation, spatial distribution, and evolution of static liquefaction. The results reveal that the extent and location of liquefaction-prone zones are highly sensitive to the initial material state. The effective onset of static liquefaction is further analyzed under specific boundary condition perturbations, such as surcharge loading and drainage system clogging. This instability-based assessment framework offers a physically consistent and practical tool for identifying the initiation of static liquefaction in tailings dams before large strains develop in engineering computations. It complements traditional strength-based assessment approaches, enhancing the predictive capability for geotechnical engineers.

References

[1] Nicot, F.; Sibille, L.; Darve, F. (2009). Bifurcation in granular materials: an attempt for a unified framework. International Journal of Solids and Structures 46(22-23), 3938-3947.
[2] Wan, R.; Nicot, F.; Darve, F. (2017). Failure in geomaterials: a contemporary treatise. Elsevier.

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