

SCHEDULE

Venue: Kaisa Group Lecture Theater (IAS LT), Lo Ka Chung Building, Lee Shau Kee Campus, The Hong Kong University of Science & Technology, Clear Water Bay, Kowloon, Hong Kong

MARCH 2, 2024 – SATURDAY (WELCOME RECEPTION)	
18:00 – 20:30	**Welcome Reception** (For Speakers and Invited Participants Only; Venue: UniQue, Conference Lodge)
20:40	Return to Nina Hotel Kowloon East by coach (Boarding point: Conference Lodge)

MARCH 3, 2024 – SUNDAY (DAY 1)	
07:30	Pick-up at Nina Hotel Kowloon East by coach (Boarding point: Outside Nina Hotel Kowloon East)
08:00 – 08:30	**Registration**
08:30 – 08:45	**Welcoming and Opening Remarks** **Hong K. LO** (Dean of Engineering, HKUST) & **Jidong ZHAO** (HKUST)
Session 1:	**Granular Flow and Phase Transition** **Session Chair: Ha BUI (Monash University)**
08:45 – 09:15	*#1*: **The Big Role of Tiny Fluctuations in Granular Flow Modeling** **Ken KAMRIN** (Massachusetts Institute of Technology)
09:15 – 09:45	*#2*: **Heterarchical Modelling of Internal Comminution within Rotary Mills** **Itai EINAV** (The University of Sydney)
09:45 – 10:15	*#3*: **Granular Flow in a Rotating Drum from Dry, Partially Saturated to Submerged Conditions** **Yixiang GAN** (The University of Sydney)
10:15 – 10:45	**Coffee Break** (Venue: Lobby, G/F)

Session 2:	**Climate Resilient Geotechnics** **Session Chair: Limin ZHANG (HKUST)**
10:45 – 11:15	#***4***: **Preventing Human-Induced Seismicity to Fight Climate Change** **Ioannis STEFANOU** (École Centrale de Nantes)
11:15 – 11:45	#***5***: **Climate Resilient Geotechnical Infrastructure: Developing Computational Tools and Methodologies for Soil-Atmosphere Interaction** **Aikaterini TSIAMPOUSI** (Imperial College London)
11:45 – 12:15	#***6***: **Discrete Element Modelling of Soil Desiccation Cracking Behavior** **Chao-Sheng TANG** (Nanjing University)
12:15 – 12:45	#***7***: **Environmental Geomechanics: Towards a Minimised Chemical Footprint in Geo-Energy Engineering** **Manman HU** (The University of Hong Kong)
12:45 – 14:00	**Lunch** (For Speakers and Invited Participants Only; Venue: UniQue, Conference Lodge)
Session 3:	**Unsaturated Soil Mechanics** **Session Chair: Ken KAMRIN (Massachusetts Institute of Technology)**
14:00 – 14:30	#***8***: **Fundamental Concepts of Soil Water Potential and Effective Stress for Computational Geomechanics** **Ning LU** (Colorado School of Mines)
14:30 – 15:00	#***9***: **Does Effective Stress Concept Apply to Unsaturated Soil?** **Changfu WEI** (Institute of Rock and Soil Mechanics, Chinese Academy of Sciences)
15:00 – 15:30	#***10***: **Computational Modeling of Unsaturated Granular Media Transitions across All Liquid Saturation Regimes** **Richard WAN** (University of Calgary)
15:30 – 16:00	#***11***: **Modelling Suction Effect on Shear Behaviour of Unsaturated Soil Based on X-Ray Micro-CT Observations** **Yosuke HIGO** (Kyoto University)
16:00 – 16:25	#***12***: **Effective Stress and Poroelasticity Theory for Soil Incorporating Adsorption and Capillarity** **Chao ZHANG** (Hunan University)
16:25 – 16:45	**Coffee Break** (Venue: Lobby, G/F)
Session 4:	**Constitutive Modeling** **Session Chair: Yu WANG (City University of Hong Kong)**
16:45 – 17:15	#***13***: **Constitutive Behavior of Coral Sand from Element Tests and Numerical Simulations** **Huabei LIU** (Huazhong University of Science and Technology)

17:15 – 17:45	#***14***: **Formulating a State-Dependent Constitutive Model for Soil Based on Stress Probing Analysis** **Zhongxuan YANG** (Zhejiang University)
17:45 – 18:15	#***15***: **Combined Fabric Evolution Model for Granular Media: Validation via Particle-Scale X-Ray Measurements and Application for Cyclic Loading** **Rui WANG** (Tsinghua University)
18:15 – 18:45	#***16***: **DEM Investigations on the Multi-Directional Wave Velocities and Fabric Anisotropy of Granular Materials** **Xiaoqiang GU** (Tongji University)
18:45 – 19:10	**Day 1 Panel Discussion** – Open issues on session topics **Itai EINAV** (The University of Sydney) & **Ning GUO** (Zhejiang University)
19:10 – 21:30	**Dinner** (For Speakers & Invited Participants Only; Venue: China Garden Restaurant)

END OF DAY 1 (MARCH 3, 2024 - SUNDAY)

MARCH 4, 2024 – MONDAY (DAY 2)	
Session 5:	**Bio-Inspired Geotechnics** **Session Chair: Gang WANG (HKUST)**
08:30 – 09:00	#***17***: **Biomimetic Design of a Granular Intruder** **Matt EVANS** (Oregon State University)
09:00 – 09:30	#***18***: **Understanding Bio-inspired Soil Penetration Processes through DEM Modeling** **Alejandro MARTINEZ** (University of California, Davis)
09:30 – 10:00	#***19***: **When Nature Meets Technology: AI-Informed Discovery of Root–Soil Physical Interactions** **Anthony Kwan LEUNG** (HKUST)
10:00 – 10:30	**Group Photo Taking & Coffee Break** (Venue: Lobby, G/F)
Session 6:	**Offshore and Coastal Geotechnics** **Session Chair: Jun YANG (The University of Hong Kong)**
10:30 – 11:00	#***20***: **Modelling Offshore Foundations under Extreme Loading Conditions** **Stavroula KONTOE** (University of Patras)
11:00 – 11:30	#***21***: **CFD-DEM Coupling Simulation and Structuralized Cementing Technology for Wave Erosion Protection of Coastal Structures** **Gang WANG** (HKUST)
11:30 – 12:00	#***22***: **Risk Evaluation on the Installation of Offshore Spudcan Foundations** **Jinhui LI** (Harbin Institute of Technology (Shenzhen))
12:00 – 12:30	#***23***: **Frontiers of Geotechnics for Deep-Sea Mining** **Xuguang CHEN** (Ocean University of China)
12:30 – 13:00	#***24***: **Multi-Mechanics Process of Silty Seabed Responses to Progressive Waves** **Fuping GAO** (Institute of Mechanics, Chinese Academy of Sciences)
13:00 – 14:00	**Lunch** (For Speakers and Invited Participants Only; Venue: UniQue, Conference Lodge)
Session 7:	**Fracturing in Geomaterials** **Session Chair: Jianfu SHAO (Université de Lille)**
14:00 – 14:30	#***25***: **Phase-Field Modeling and Investigation of Mixed-Mode Fracture in Rocks** **Jinhyun CHOO** (Korea Advanced Institute of Science and Technology (KAIST))
14:30 – 15:00	#***26***: **Interpreting Chemically Assisted Crack Growth through a Surface Force-Based Fracture Theory** **Yida ZHANG** (University of Colorado Boulder)

15:00 – 15:25	#***27***: **Assumed Enhanced Strain Method for Fracture Propagation in Porous Media** **Fushen LIU** (Zhejiang University)
15:25 – 15:50	#***28:*** **Coupled Total- and Semi-Lagrangian Peridynamic Modeling of Hydraulic Fracturing in Solids** **Fan ZHU** (Kyoto University)
15:50 – 16:10	**Coffee Break** (Venue: Lobby, G/F)
Session 8:	**Discrete Element Method** **Session Chair: Zhongxuan YANG (Zhejiang University)**
16:10 – 16:40	#***29***: **Exploring the Macroscopic Stiffness of Sands via Grain-scale Experiments and DEM** **Kostas SENTAKIS** (City University of Hong Kong)
16:40 – 17:10	#***30***: **Dynamic Behaviors of Smoothed Polyhedral Materials with Deformable Discrete Elements** **Shunying JI** (Dalian University of Technology)
17:10 – 17:40	#***31***: **Bonded-Particle Discrete Element Method for Modeling Deformable Granular Materials** **Qiushi CHEN** (Clemson University)
17:40 – 18:10	#***32***: **Generation and DEM Investigation of Physical and Mechanical Properties of Morphological Controllable Particles** **Dong SU** (Shenzhen University)
18:10 – 18:35	#***33***: **Predicting Engineering Properties of Lunar Regolith Based on Chang'e-5 Lunar Samples Using Non-Destructive Microscopic Tests and DEM Simulations** **Yifei CUI** (Tsinghua University)
18:35 – 19:00	#***34***: **Ray Tracing Discrete Element Method** **Shiwei ZHAO** (HKUST)
19:00 – 19:20	**Day 2 Panel Discussion** – Open issues on the session topics **Ning LU** (Colorado School of Mines) & **Manman HU** (The University of Hong Kong)
19:20 – 21:30	**Dinner** (For Speakers & Invited Participants Only; Venue: UniBistro)

END OF DAY 2 (MARCH 4, 2024 - MONDAY)

MARCH 5, 2024 – TUESDAY (DAY 3)

Session 9:	**Data-Driven and Machine Learning** **Session Chair: Richard WAN (University of Calgary)**
08:30 – 09:00	*#35*: **Estimation of Mechanical Strength of Heterogenous Geomaterials Using Multiscale Homogenization and Machine Learning** **Jianfu SHAO** (Université de Lille)
09:00 – 09:30	*#36*: **Data-Driven and Physics-Informed Bayesian Learning of Spatiotemporally Varying Consolidation Settlement** **Yu WANG** (City University of Hong Kong)
09:30 – 10:00	*#37*: **Solving Inverse Problems in Granular Mechanics with Differentiable Simulators** **Krishna KUMAR** (The University of Texas at Austin)
10:00 – 10:25	*#38*: **An Integrated Data-Driven and Physics-Based Approach for Bayesian Inference of Geomechanical Models** **Hongyang CHENG** (University of Twente)
10:25 – 10:50	*#39*: **Machine Learning-Assisted Multiscale Modelling of Granular Media** **Tongming QU** (HKUST)
10:50 – 11:10	**Coffee Break** (Venue: Lobby, G/F)
Session 10:	**Internal Erosion and Gap-Graded Soil** **Session Chair: Stavroula KONTOE (University of Patras)**
11:10 – 11:40	*#40*: **Internal Erosion: Micromechanics, Constitutive Modelling and Mathematical Model** **Ha BUI** (Monash University)
11:40 – 12:10	*#41*: **Modelling of Fine Particles Transport in Granular Soils and Application** **Zhenyu YIN** (The Hong Kong Polytechnic University)
12:10 – 12:40	*#42*: **A Micro-CT Investigation of Internal Erosion Behavior of Gap Graded Soils** **Jianfeng Jeff WANG** (City University of Hong Kong)
12:40 – 13:05	*#43*: **A Simplified Homogenization Equation for Gap-Graded Soils with Applications to Elastoplastic Modelling of Sandy Clays** **Xiusong SHI** (Hohai University)
13:05 – 14:00	**Lunch** (For Speakers and Invited Participants Only; Venue: UniQue, Conference Lodge)

Session 11:	**Multiscale, Multiphysics Modeling** **Session Chair: Francois NICOT (Université Savoie Mont Blanc)**
14:00 – 14:30	*#44*: **Bridging Nanoindentation and Triaxial Creep Tests on a Shale** **Ronaldo I. BORJA** (Stanford University)
14:30 – 15:00	*#45*: **Numerical Upscaling of the Behaviour of Geomaterials** **Jean-Michel PEREIRA** (École des Ponts ParisTech)
15:00 – 15:30	*#46*: **Discrete-Continuum Coupling for Earthquake Rock Mechanics Science** **Guilhem MOLLON** (The Institut National des Sciences Appliquées de Lyon (INSA Lyon))
15:30 – 16:00	*#47*: **A Unified Nonlocal Theory for Discontinuous, Multiphysical and Multiscale Behaviors of Geomaterials** **Haitao YU** (Tongji University)
16:00 – 16:25	*#48*: **GeoTaichi: A Taichi-Powered High-Performance Simulator for Modeling Multiscale and Multifield Geophysical Problems** **Ning GUO** (Zhejiang University)
16:25 – 16:50	*#49*: **Continuum Models for Granular Materials at Various Scales** **Chuanqi LIU** (Institute of Mechanics, Chinese Academy of Sciences)
16:50 – 17:10	**Coffee Break** (Venue: Lobby, G/F)
Session 12:	**Large Deformation & Shear Banding** **Session Chair: Shunying JI (Dalian University of Technology)**
17:10 – 17:40	*#50*: **Shear Banding as an Optimal Dissipative Structure from a Thermodynamic Viewpoint** **Francois NICOT** (Université Savoie Mont Blanc)
17:40 – 18:10	*#51*: **Numerical Interpretations of Cone and Ball Penetration Tests under Partially Drained Conditions** **Dong WANG** (Ocean University of China)
18:10 – 18:35	*#52*: **PFEM and Its Application to the Post-Failure Analysis of Geotechnical Problems with Large Deformation** **Xue ZHANG** (University of Liverpool)
18:35 – 19:00	**Day 3 Panel Discussion** – Open issues on the session topics **Ronaldo I. BORJA** (Stanford University) & **Qiushi CHEN (**Clemson University)
19:00 – 21:30	**Banquet** (For Speakers and Invited Participants Only; Venue: Sai Kung) * Coach departs from Lo Ka Chung Building at 19:00 and returns at 21:30

END OF DAY 3 (MARCH 5, 2024 – TUESDAY)

MARCH 6, 2024 – WEDNESDAY (DAY 4)	
Session 13:	**Snow Avalanche & Debris Flow** **Session Chair: Matt EVANS (Oregon State University)**
08:30 – 09:00	#***53***: **Modeling Snow Slab Avalanches: From 3D to Depth-averaged MPM Simulations** **Johan GAUME** (ETH Zürich)
09:00 – 09:30	#***54***: **Modelling Phase Transition in Granular Materials** **Wei WU** (University of Natural Resources and Life Sciences, Vienna (BOKU))
09:30 – 10:00	#***55***: **Modeling Fluid-Particle-Structure Interactions in Debris Flow** **Jidong ZHAO** (HKUST)
10:00 – 10:30	#***56***: **Multi-Scale Analysis of the Rheology of Dense Suspensions** **Sergio Andres GALINDO-TORRES** (Westlake University)
10:30 – 11:00	#***57***: **Numerical Investigation on Waves and Their Transitions in Snow Avalanches Using the Material Point Method** **Xingyue LI** (Tongji University)
11:00 – 11:20	**Coffee Break** (Venue: Lobby, G/F)
Session 14:	**Predicting Slope Stability** **Session Chair: Johan GAUME (ETH Zürich)**
11:20 – 11:50	#***58***: **Application of Random Finite Element and Material Point Methods to Slope Stability** **Michael HICKS** (Delft University of Technology)
11:50 – 12:20	#***59***: **Global Analysis of Slope Stability and Location of 3-Dimensional Critical Slip Surfaces** **Hong ZHENG** (Beijing University of Technology)
12:20 – 12:50	#***60***: **DEM Analysis on Diffuse Failure of a Soil Slope Triggered by Earthquakes** **Yu HUANG** (Tongji University)
12:50 – 14:00	**Lunch** (For Speakers and Invited Participants Only; Venue: UniQue, Conference Lodge)
Session 15:	**Environmental Geotechnics** **Session Chair: Michael HICKS (Delft University of Technology)**
14:00 – 14:30	#***61***: **Analysing Thermo-Hydro-Mechanical Coupled Problems Using the Material Point Method** **Chao ZHOU** (The Hong Kong Polytechnic University)

14:30 – 15:00	#***62***: **Mechanisms of Landfill Liner Leakage: Mathematical Models and Detection Technology** **Haijian XIE** (Zhejiang University)
15:00 – 15:30	**Special Event –** Award Ceremony for Computers and Geotechnics 2022 Scott Sloan Best Paper Awards and 2022 Outstanding Reviewer Awards
15:30 – 16:00	**Coffee Break** (Venue: Lobby, G/F)
Session 16:	**Predicting Soil Properties** **Session Chair: Zhenyu YIN (The Hong Kong Polytechnic University)**
16:00 – 16:30	#***63***: **Small is Beautiful: Some New Insights into Small Strain Stiffness of Granular Soils** **Jun YANG** (The University of Hong Kong)
16:30 – 17:00	#***64***: **Estimation of Spatial Distribution of Surface Soil Properties on the Moon** **Takashi MATSUSHIMA** (University of Tsukuba)
17:00 – 17:30	#***65***: **Probabilistic Characterisation of Critical State Model Parameters for Saprolitic Soil in Hong Kong** **Andy Y. F. LEUNG** (The Hong Kong Polytechnic University)
17:30 – 18:00	**Day 4 Panel Discussion** – Open issues on the session topics **Jidong ZHAO** (HKUST) & **Chao ZHOU** (The Hong Kong Polytechnic University)
18:00 – 21:00	**Dinner** (For Speakers & Invited Participants Only; Venue: China Garden Restaurant) **& Closing Remarks**
END OF EVENT	

Sponsorships

The symposium is proudly supported by HKUST Jockey Club Institute for Advanced Study, K.C. Wong Education Foundation, HKUST Department of Civil and Environmental Engineering Distinguished Workshop Fund, and Global Engagement and Communications Office of HKUST. The symposium is co-organized by ISSMGE TC105 Geomechanics from Micro to Macro and TC103 Numerical Methods in Geomechanics.

Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Bridging Nanoindentation and Triaxial Creep Tests on a Shale

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Shale is known to exhibit significant creep across spatiotemporal scales. In this work, we perform indentation and triaxial creep tests on organic-rich Woodford shale and show that the measured creep responses at the nanometer and millimeter scales are statistically correlated in the sense that the indentation creep tests can be used to predict the triaxial creep response. The link between the two extreme scales is facilitated by an elasto-viscoplastic constitutive model based on critical state theory. Even though this constitutive model contains several material parameters, only the elastic modulus and viscosity play a major role in statistically correlating the creep responses at the two scales. Given that shale is commonly represented as a transversely isotropic material, we conduct indentation and triaxial creep tests in both bed-normal (BN) and bed-parallel (BP) directions on the rock samples. For the shale that was tested, the creep responses at the nanometer and millimeter scales are statistically correlated in the BN direction where the rock is weaker. However, the creep deformations at the two scales in the BP direction, where the rock is stronger, are significantly smaller than in the BN direction, and are not as strongly correlated. Nevertheless, the results of this study suggest that in addition to its inherent heterogeneity, shale can also exhibit strongly anisotropic creep responses.

Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Internal Erosion: Micromechanics, Constitutive Modelling and Mathematical Model

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In this talk, we share our latest findings and advancements in simulating and predicting the complex responses of granular soils subjected to internal erosion. This intricate process demands a profound understanding of grain-scale processes, where the loss of fines induces changes in the mechanical and physical properties of soils. A robust constitutive model capable of accommodating these micromechanical insights to predict the mechanical consequences of eroded soils, an advanced mathematical framework capable of predicting the multi-phase, multi-physical processes associated with internal erosion, and a reliable computational method to simulate the entire process—from onset to post-failure responses of granular soils caused by internal erosion—are essential. To address these critical needs, we employ the Discrete Element Method (DEM) to investigate the mechanical consequences of internal erosion at the grain-scale [1]. This approach unveils several interesting fundamental laws that help formulate a new constitutive model capable of capturing both the onset (suffosion) and post-onset (suffusion) stages of internal erosion. Furthermore, we develop a new five-phase continuum mathematical model to enable simulation of field-scale applications and solve this mathematical model using the latest advances in developing meshfree particle methods (SPH) [2]. We demonstrate that our proposed computational model can effectively capture complex responses and is approaching realistic predictions for lab and field-scale applications.

References:

[1] T. V. Nguyen, H. H. Bui, K. M. Tran, G. D. Nguyen, and A. Haque, Comp. and Geotech., 166, 105991 (2024.

[2]. G. Ma, H.H. Bui, Y. Lian, K. M. Tran and G. D. Nguyen, Comp. Meth. Appl. Mech. Eng. Vol.401, 115641 (2022).

Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Bonded-particle Discrete Element Method for Modeling Deformable Granular Materials

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Granular materials, such as geomaterials (e.g., sands, gravels, extraterrestrial regolith) and biomass feedstocks (e.g., wood chips, switchgrass), are ubiquitous in nature and in engineering applications. In this presentation, we would like to present our recent research efforts on modeling the behavior of deformable granular materials using the discrete element method (DEM). The materials of interest are biomass feedstocks used for renewable energy applications. We will discuss the development and use of bonded-sphere DEM for irregular-shaped flexible particles, the theory and implementation of contact and bond models, as well as the application to simulate the flow behavior of deformable granular materials in relevant processing equipment [1-3]. While the materials we focus on are not geomaterials, the methodologies and DEM models developed in these efforts could be adapted for geomechanics problems involving irregular-shaped particles, flexible particles, and particle breakage.

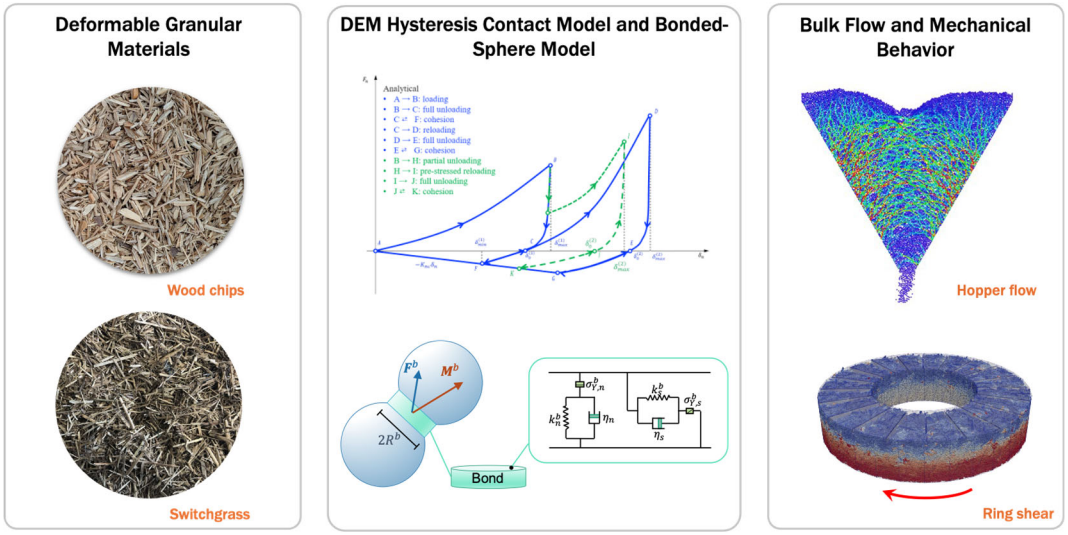


Figure 1. Research efforts on DEM modeling of deformable granular materials (images adopted from [1-3]).

References:

[1]. Guo, Y., Chen, Q., Xia, Y., Westover, T., Eksioglu, S., & Roni, M. (2020). Discrete element modeling of switchgrass particles under compression and rotational shear. *Biomass and Bioenergy*, *141*, 105649.

[2]. Chen, F., Xia, Y., Klinger, J. L., & Chen, Q. (2022). A set of hysteretic nonlinear contact models for DEM: Theory, formulation, and application for lignocellulosic biomass. *Powder Technology*, 399, 117100.

[3]. Lai, Z., Xia, Y., & Chen, Q. (2023). Discrete element modeling of granular hopper flow of irregular-shaped deformable particles. *Advanced Powder Technology*, 34(9), 104106.

Frontiers of Geotechnics for Deep-Sea Mining

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In the process of deep-sea mining, due to the special nature of deep-sea soil, the deep-sea mining vehicle easily suffers from skidding, sinking and attitude instability. As for mining collection, foreign equipment (e.g. Canada) has obvious advantages over Chinese mining vehicles in terms of mining efficiency and other aspects. As for the environment, the existing deep-sea mining methods have become a focus of international controversy, as they disturb the seabed drastically and produce huge plume hazards. Thus, research has been carried out on mining vehicle track-soil, jet-soil and deep-sea mining plume suppression methods, respectively.

1.1 Track-soil dynamic interactions and stable travel

A track-soil dynamic interaction model was established (Fig. 1), and a three-dimensional stress distribution expression under dual track dynamic walking was derived by applying the triple Fourier transform approach [1]. A multi-body dynamic motion model with a ratio of 1:1 was created using the tracked vehicle's intended walking structure and a number of simulation experiments were conducted.

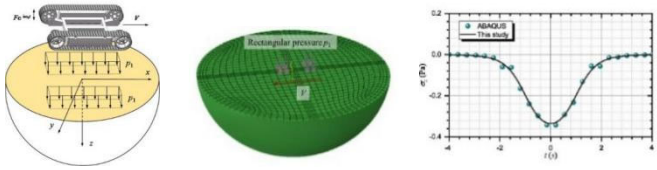


Figure 1. Numerical analysis and results of track-soil interaction

1.2 Jet-soil coupling interaction and efficient jet collection

The peak upper jet pressure and center stagnation pressure values under various nozzle jet characteristics were examined using the numerical simulation program FLUENT [2]. The movement of nodules under the influence of double row impinging jets was simulated using the bi-directional fluid structure coupling calculation method.

1.3 Low disturbance and plume suppression methods for deep-sea mining

In the laboratory, research was conducted on the plume generated by in-situ sediment disturbance. The mechanism of plume emergence under hydraulic disturbance was revealed, and the inhibitory effect of intergranular cementation on plume emergence was clarified. A new type of flocculant was developed to shorten the plume settling time by 90%.

References:

[1] Luan L., Chen X*., Kouretzis G., et al., Computers and Geotechnics, 2023, 157: 105356.
[2] Liu X., Chen X.*, Wei J., et al., Ocean Engineering, 2023, 285 (2023): 115220.

Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

An Integrated Data-Driven and Physics-Based Approach for Bayesian Inference of Geomechanical Models

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Model parameter inference is crucial for all computational science and engineering disciplines. It establishes a link between computational models and real-world observations. Geomaterials can be modeled at the microscale using the discrete element method, at the mesoscale with constitutive laws, or at the macroscale using the finite element method. A unified approach is lacking not only in integrating data, whether computational or experimental, from various scales for model inference but also in achieving a cross-scale understanding of the mechanical behavior embedded in the model parameters.

The bottleneck in the inference of geomechanical models is twofold: (1) the computational cost when running these models and (2) the model complexity reflected by parameter correlations. Reduced-order modeling techniques, such as neural networks, and clustering algorithms offer the possibility to emulate what the computational models can do and to learn how uncertainties are distributed in a reduced parameter space.

In this presentation, we will introduce probabilistic and data-driven techniques that enable the efficient inference of geomechanical model parameters. We will illustrate how data-driven and physics-based models are combined for the inference of model parameters at the micro [1], meso [2], and macro scales. Furthermore, we will address the question of which neural networks are best suited as model surrogates for problems at a given scale. Examples of the implications of this method for geotechnical practices will be provided in the context of dike safety.

References:

[1] H. Cheng, T. Shuku, K. Thoeni, P. Tempone, S. Luding, V. Magnanimo. An iterative Bayesian filtering framework for fast and automated calibration of dem models. Comput. Methods Appl. Mech. Eng., 350 (2019), pp. 268-294

[2] H. Cheng, V. Magnanimo, T. Shuku, S. Luding, T. Weinhart. Bayesian Uncertainty Quantification for Geomechanical Models at Micro and Macro Scales. In Proceedings of the 16th International Conference of IACMAG - Volume 1 (2021), pp. 837-845

Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Phase-field Modeling and Investigation of Mixed-mode Fracture in Rocks

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Rocks under compression often fail by mixed-mode fracture in which tensile and shear cracks are interwoven. Such mixed-mode fracture in compressed rocks exhibits a rich variety of patterns, which depend on rock properties, flaw geometry, and loading conditions. Numerical modeling of this variety of mixed-mode cracking patterns has been a fascinating subject in the computational geomechanics community. In recent years, phase-field modeling has become a popular method for this purpose, because it can capture complex crack morphology without any surface-tracking algorithms. However, the existing phase-field models of mixed-mode rock fracture overlook several critical features including quasi-brittleness and frictional contact. This talk introduces a double-phase-field model [1] that incorporates these features by combining two phase-field formulations for cohesive tensile fracture [2] and frictional shear fracture [3]. The double-phase-field model is well-validated against various experimental data in the literature. The double-phase-field model is also leveraged to investigate size effects [4] and intermediate principal stress effects [5] in mixed-mode fracture in rocks, which are challenging to investigate experimentally.

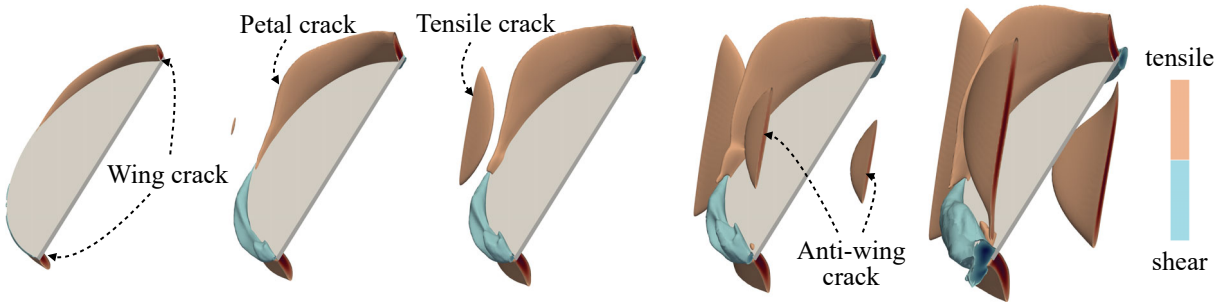


Figure 1. Phase-field simulation of 3D mixed-mode fracture in rock (Source: [5])

References:

[1] F. Fei and J. Choo, Comp. Methods Appl. Mech. Engrg. 362 112742 (2020)
[2] J.-Y. Wu, J. Mech. Phys. Solids 103 72-99 (2017)
[3] F. Fei and J. Choo, Comp. Methods Appl. Mech. Engrg. 376 113655 (2021)
[4] J. Choo, Y. Sun and F. Fei, Acta Geotech. 18 3451-3468 (2023)
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Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Predicting Engineering Properties of Lunar Regolith Based on Chang'e-5 Lunar Samples Using Non-destructive Microscopic Tests and DEM Simulations

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With the rapid development of human lunar exploration projects, the lunar base establishment and resource utilization are on the way, and hence it is urgent and significant to reasonably predict engineering properties of the lunar regolith, which remains to be unclear due to limited lunar samples currently accessible for geotechnical tests. In this research, we aim to address this challenge from the perspective of granular material mechanics. To this end, the 3D multi-aspect geometrical characteristics and mechanical properties of Chang'e-5 lunar samples are for the first time evaluated with a series of non-destructive microscopic tests. Based on the measured particle surface roughness and Young's modulus, the interparticle friction coefficients of lunar regolith particles are well predicted through an experimental fitting approach using previously published data on terrestrial geomaterials or engineering materials. Then the residual friction angle of the lunar regolith under low confining pressure is predicted using DEM simulations according to the particle overall regularity and interparticle coefficient of Chang'e-5 lunar samples. The presented results provide a cross-scale method to predict engineering properties of lunar regolith from particle scale information to serve for the future lunar surface engineering construction.

Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Heterarchical Modelling of Internal Comminution within Rotary Mills

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Rotary mills aim to effectively reduce the size of particles through a process called comminution. Modelling comminution in rotary mills is a challenging task due to substantial material deformation and the intricate interplay of particle kinematics of segregation, mixing, crushing, and abrasion. Existing particle-based simulations tend to provide predictions that cannot cope with the large number of particles within rotary mills, their wide range of sizes, and the physics dictating the crushing of individual particles. Similarly, there is currently no deterministic modelling means to determine the evolving population of particle sizes at any point in time and space within the mill. The aim of this contribution is to address these gaps by advancing a framework for a novel comminution model for rotary mills, which integrates heterarchical stochastic physics [1,2] along streamlines [3]. Although stochastic, the heterarchical approach has a well-defined deterministic continuum limit and can cope with arbitrarily large numbers of particles. The new model sheds light on previously obscured dynamics within industrial mills, as well as enables the field to predict the time evolution of the particle size distribution at any point in the mill domain. This modelling capability opens the doors to new developments for estimating and improving milling efficiencies, as well as other systems that involve continuous sorting by particle size and density, such as internal erosion in geotechnical embankment and coupled segregation and crushing in pneumatic conveyors.

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Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Biomimetic Design of a Granular Intruder

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The penetration of granular materials with a guided intruder is often necessary as part of many mining, geoconstruction, and subsurface exploration activities. The geometric characteristics of the intruder influence its wear rate, required penetration force, and steerability. Can we take lessons from nature to inform our design on these penetrators? We consider two biological inspirations for design of better intruders: a woodpecker and an earthworm. Woodpeckers are remarkably efficient at burrowing into wood to find insects, build nests, and mark their territory. One may strike a surface 12,000 times per day at a frequency of approximately 20 Hz with each impact capable of causing a deceleration of over 1,200*g* – all without sustaining any apparent brain injury. Alternatively, earthworms rely upon a different mechanism for locomotion through granular media: inflation-deflation cycles of their bodies. The expansion serves to relieve the geostatic stresses in the immediate vicinity of the worm upon contraction, thus allow it to move through materials that might otherwise prove intractable. We use discrete element method (DEM) simulations to investigate the potential for woodpecker beak-inspired intruder tip designs with wedge offsets and earthworm-inspired geoprobes (Figure 1) to influence the force regimes during penetration into a granular medium. Our simulation results show that these biomimetic designs provide benefits in performance relative to traditional designs.

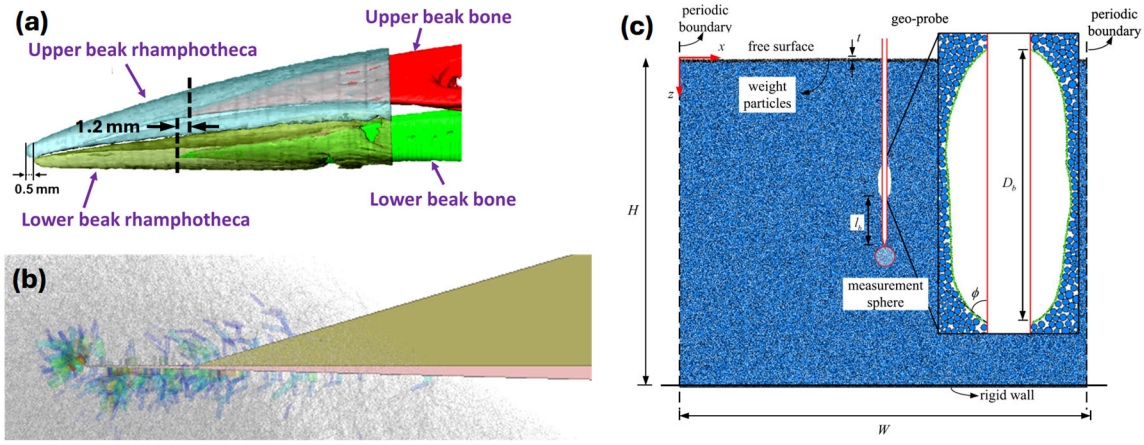


Figure 1. (a) Reconstructed image of a woodpecker beak [1]; (b) the force regime near the penetrator tip [2]; and (c) geometry of the earthworm-inspired geoprobe [3].

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Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Multi-Scale Analysis of the Rheology of Dense Suspensions

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In this presentation, we will introduce a micro-mechanical model for suspensions. The model considers each particle as a rigid body, with its movement governed by Newton's second law. Particle contacts are modeled using spring dashpot systems to account for dissipation caused by inelastic collisions. The fluid is modeled using the Navier-Stokes equations, which are solved numerically using the Lattice Boltzmann Method. The model accurately captures the momentum exchange between the fluid and particles at the particle surfaces. Experimental validations are provided using a rheometer, where data on suspension viscosity under different scenarios (such as suspension density, fluid viscosity, particle size, etc.) are obtained. The numerical simulation model is based on independently measurable parameters, without any curve fitting involved. Despite this, there is a perfect match between the experiments and simulations. Once validated, the numerical tool is used to investigate how the rheology, characterized by the friction coefficient of the suspension, changes with various parameters, including shearing rate, confining pressure, and even particle shape. Dimensionless numbers are proposed to combine all the results into universal curves, which can be used for upscaling models and large-scale predictions. An application of this upscaling effort is demonstrated through a submarine landslide, where both experimental and simulation results show a perfect match. Detailed simulation data reveals how the universal laws obtained from the previous stage still hold in the more complex case of a granular avalanche, further justifying the universal nature of the rheology description obtained from this work. The numerical tool and upscaling analysis have broad implications in several areas involving the interaction of fluids with solid particles.

Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Granular Flow in a Rotating Drum from Dry, Partially Saturated to Submerged Conditions

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Granular flows are common in various natural and industrial processes, such as landslides, mineral handling, and food processing. We investigated rheological and segregation behaviour of granular media in a rotating drum, which exhibits dependency on interstitial fluids. From dry, partially saturated to submerged conditions, we conduct experiments and numerical simulations to study granular flows in rotating drums. For modelling the granular systems, we employed the discrete element method (DEM), volume of fluids (VOF) and CFD-DEM methods for respective conditions. For fully dry or wet (submerged) conditions, VOF and CFD-DEM results show excellent match with experimental observations from mono- and binary systems, whilst revealing the internal dynamics, such as shear zones and pore pressure. In partially saturated conditions, we focus on varying the strength of cohesion (surface tension) and rotation rate within the modes of rolling flow and cascading flow. We extract statistical information on the formation of clusters within the flow and find a power law relation between the cluster size distribution and its probability, which indicates that stronger cohesion can promote the formation of larger clusters. Finally, we will discuss how intestinal fluids impact on the flow and segregation of granular media and its implications on industrial processes.

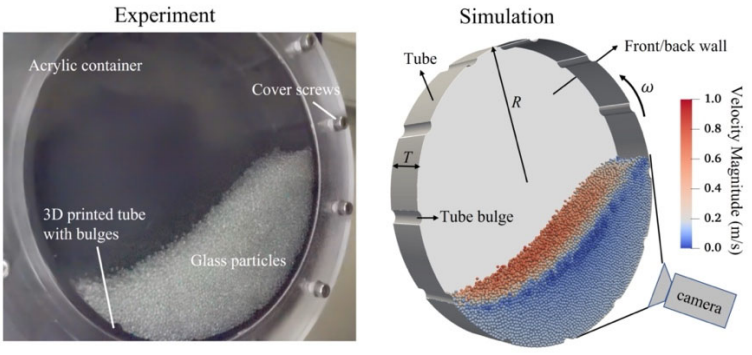


Figure 1

Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Multi-Mechanics Process of Silty Seabed Responses to Progressive Waves

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Liquefaction is the act or process of transforming any substance into a liquid. While ocean waves are propagating over a porous seabed, the amplitude of excess pore pressure would attenuate within the seabed (termed as “amplitude-attenuation”), which is always accompanied by “phase-lag”. Explicit expressions for the amplitude-attenuation and the phase-lag of transient pore-pressures were derived for a sandy seabed and further verified with the flume observations [1]. Such amplitude-attenuation and phase-lag responses can be spatiotemporally correlated for the sandy seabed. Nevertheless, the wave-induced liquefaction of a silt bed was found to be a complicated multi-mechanics process. Three typical stages were identified in the process of silt liquefaction via flume observations, including quasi-elastic, intensive build-up of residual pore pressure, and continuous liquefaction stages (see Figure 1(a)). The phenomenon of significant amplification of transient pore-pressure fluctuation was observed during the buildup of residual pore-pressures; meanwhile, the interfacial waves were detected at the mudline [2]. A volcano-shaped topography can then be formed at the surface of the post-liquefied silt bed (see Figure 1(b)). It is noted that once the residual liquefaction of a silty seabed is triggered, the conventional poro-elastic theory would be invalid for describing the transient pore-pressure fluctuations. A theoretical model is thereby proposed to describe the phenomenon of significant amplification of transient pore-pressures within the silt bed under the action of progressive waves.

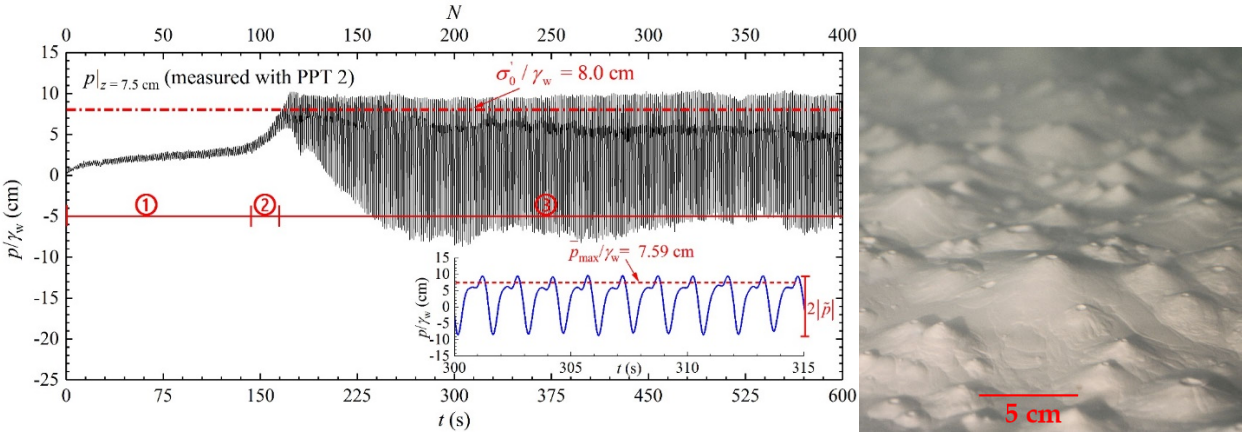


Figure 1. (a) Three typical stages in the process of silt liquefaction; (b) Snapshot of the volcano-shaped topography for the post-liquefied silt bed.

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Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Modeling Snow Slab Avalanches: From 3D to Depth-averaged MPM Simulations

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Snow exhibits a remarkable duality, capable of withstanding stresses akin to a solid or yielding fluid-like behavior depending on external forces and strain rates. The solid-fluid transition in snow can have dramatic consequences such as snow slab avalanches which are responsible for most of the damage and fatalities related to avalanches. These avalanches, characterized by a distinct, broad fracture line are released following anticrack propagation in highly porous weak snow layers buried below cohesive slabs. The anticrack mechanism is driven by the volumetric collapse of the weak layer, which leads to the closure of crack faces and to the onset of frictional contact. This complex mechanism explains why avalanches that release on steep slopes can be triggered from flat terrain.

Here, on the basis of MPM elasto-plastic numerical simulations, snow fracture experiments, full-scale avalanche measurements, we report the existence of a transition from sub-Rayleigh anticrack to supershear crack propagation. This transition follows the Burridge–Andrews mechanism, in which a supershear daughter crack nucleates ahead of the main fracture front and eventually propagates faster than the shear wave speed. Motivated by this new understanding and by the high computational cost of three-dimensional simulations, we developed a depth-averaged MPM (DAMPM) based on shallow water equations for the simulation of snow slab avalanches release with a shear failure model for the weak layer. This model extends the Savage-Hutter model to the case of elasto-plasticity for a curvilinear coordinate system.

Post-avalanche release and slab fragmentation, the snow behaves akin to granular materials, exhibiting flow characteristics. In that sense, snow can be viewed both as a porous, brittle solid and a granular fluid. To capture this behavior accurately, we introduce a novel elasto-viscoplastic constitutive model that combines critical state soil mechanics (describing granular solids) and the μ(I)-rheology (describing granular fluids). This model, validated against analytical calculations and previous experimental data, lays the groundwork for extensive practical applications in avalanche and alpine mass movements research. These applications include refined impact pressure calculations and advanced hazard mapping techniques on a large scale.

Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

DEM Investigations on the Multi-Directional Wave Velocities and Fabric Anisotropy of Granular Materials

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In this study, the discrete element method was employed to simulate multi-directional wave propagation within confined granular materials during bender element tests. A systematic analyses were conducted to investigate the influences of several critical factors, including particle size, confining pressure, void ratio, input frequency, and damping methods, on both the output frequency and calculated shear wave velocity. It was found that the output frequency experiences a progressive increase as the input frequency rises, eventually reaching a distinctive threshold value. Notably, this output frequency threshold exhibits a reduction as the wave travel distance extends, stabilizing at a constant level. Furthermore, this threshold shows a linear decrease with an increase in particle size.

Additionally, the examination of multi-directional wave velocities within specimens subjected to drained anisotropic loading conditions was investigated, coupled with an analysis of contact normal-based fabric. The results illuminate the relationship between fabric anisotropy and wave velocity anisotropy. Specifically, It was found that the stress-normalized wave velocity relies on contact normal densities in both wave propagation and particle oscillation directions. By representing the contact normal distribution using a density function, a robust linear correlation between microscopic fabric anisotropy and macroscopic wave velocity anisotropy was established. This compelling finding underscores the effectiveness of normalized wave velocity anisotropy as a macroscopic index for quantifying the fabric anisotropy in granular materials.

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Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

GeoTaichi: A Taichi-Powered High-Performance Simulator for Modeling Multiscale and Multifield Geophysical Problems

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This study introduces GeoTaichi, a high-performance numerical package designed for modeling multiscale and multifield problems in geotechnics based on the Taichi parallel programing language. It aims to provide a user-friendly, extensible, and accessible framework that can harness modern computer resources, including multicore CPUs and GPUs. While GeoTaichi is implemented in pure Python, it exhibits scalability and efficiency in solving large-scale problems.

The study primarily focuses on three modules currently available in GeoTaichi: the discrete element method (DEM), material point method (MPM), and the coupled method (MPDEM). The paper outlines the code structures and highlights the most significant features of GeoTaichi. Several benchmark tests are conducted to demonstrate the validity and robustness of the package. Furthermore, the performance of GeoTaichi is compared with similar codes in the field. The DEM simulation results reveal that GeoTaichi exhibits good scaling characteristics when the particle number exceeds 0.3 million on GPU. It is also shown that the DEM module in GeoTaichi offers approximately 70% speedup compared to similar tools utilizing GPU, while reducing memory usage by 350%. Moreover, the coupling scheme MPDEM in GeoTaichi proves to be significantly more efficient than other in-house codes with similar functionalities.

Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Application of Random Finite Element and Material Point Methods to Slope Stability

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This presentation focuses on the influence of soil spatially variability on the stability of slopes. In the first instance, it considers the 2D and 3D modelling of slopes for linear infrastructures such as flood defences and road and rail embankments. This is done by using, within a Monte Carlo framework, random fields to model the spatial variability of soil properties within layers and the finite element method to model the behaviour of the geotechnical structure, an approach often referred to as the Random Finite Element Method (RFEM). It is shown that the horizontal scale of fluctuation of soil shear strength has a big influence on the type of failure mechanism and on the computed slope reliability [1,2]. The presentation also considers slope stability problems involving large deformations, for which randoms fields may be combined with the material point method to form the Random Material Point Method (RMPM) [3]. RMPM has been used to investigate residual dyke resistance: the ability of a dyke to withstand flooding following an initial slope failure [4,5]. It has also been used to model the 3D evolution of retrogressive landslides in a sensitive clay [5].

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Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Modelling Suction Effect on Shear Behaviour of Unsaturated Soil Based on X-Ray Micro-CT Observations

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Based on a comprehensive exploration of the mechanical behaviours of unsaturated soils studied by X-ray micro-computed tomography (micro-CT), the effect of suction on the shear behaviour of unsaturated has been modelled and applied to a micromechanics model for demonstrating the performance.

The microscopic behavior of liquid bridges in unsaturated soils is investigated, focusing on their important role in strengthening microscopic inter-particle forces. Employing X-ray micro-CT and image analyses, the liquid bridges attached to the grain contacts in monodisperse granular media are extracted. Quantitative insight is provided through the introduction of the liquid bridge ratio (LBR), offering a measure of their contribution to shear behaviours of unsaturated soil. Evaluating the anisotropy of grain contact orientation by fabric tensor revealed that fabric transitions under a triaxial process for both grain contacts and that with liquid bridges are equivalent. This indicates that the orientation of the liquid bridge contribution does not have unique anisotropy [1].

A constitutive model on an experimental micromechanics basis for unsaturated soils was proposed by applying the liquid bridge contribution model as a combination of the LBR distribution model and the soil water characteristic curve model to a micromechanics model. The applicability of this model is spherical and monodisperse grains and the pendular saturation regime. The proposed model qualitatively reproduced the macroscopic suction effect on the shear behaviour in the biaxial compression test simulation.

The model is expanded by considering the additional influence of bulk water, particularly in higher saturation regimes, enhancing its applicability. The bulk water ratio (BWR) can be straightforwardly defined by the rest of LBR. The contribution of the bulk water is modelled as the increase in confining pressure with in the framework of Terzaghi's effective stress [2].

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Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Environmental Geomechanics: Towards a Minimised Chemical Footprint in Geo-energy Engineering

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Cracking is ubiquitous in a geomaterial when it is subject to an environmental perturbation. Controlling environmentally assisted subcritical crack growth is the key enabler to a safe and active geo-energy adaptation to Climate Change, particularly in the domain of e.g., unconventional shale hydrocarbon recovery, Carbon Capture Utilisation and Storage (CCUS) and enhanced geothermal systems (EGS). The aim of these applications is commonly to achieve an enhanced permeability and injectivity in the formation by the stimulation of hydraulic fracturing. In order to maximize the effectiveness of the technique and meanwhile limit the extent of chemical footprint, a sophisticated understanding of the feedback between the mechanics of a geomaterial and the surrounding environment it is subject to is required. In this talk, modelling approaches on the effect of chemical environment on subcritical cracking in a stressed geomaterial at multiple scales and an extension to less destructive alternatives incorporating shear instability will be presented.

DEM Analysis on Diffuse Failure of a Soil Slope Triggered by Earthquakes

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Earthquake-induced landslide can cause considerable casualties. However, the dynamic failure mechanisms, particularly at the particle level, are not well-understood. In this study, we investigate the micro-mechanics of landslide failure under dynamic seismic loading using discrete element modeling (DEM). Particularly, the DEM was firstly calibrated and verified by simulating a shaking table test. The dynamic response and failure surface of a slope from the simulation were benchmarked against experimental data from the literature. Subsequently, we delved into the failure behavior of the landslide under seismic loading from a microscopic viewpoint. To quantify the onset of the failure, we utilized second-order work, which proved effective in identifying critical moments throughout the failure progression. There is a discernible spatial correlation between the negative second-order work and the burst of kinetic energy, suggesting a potential way to ascertain the shape of failure surface. Additionally, we analyzed the frictional resistance of the slope under dynamic seismic loading to investigate the microscopic failure mechanisms. It is found that the evolution of the friction resistance exhibits unique characteristics at different stages of the seismic loading, namely the competing effects of frictional weakening and healing. A sudden increase in the amplitude of seismic acceleration weakens the frictional resistance, which can be related to the rearrangement of particles. In addition, the internal grain-contact microstates are profoundly influenced by the input vibration amplitude, leading to variations in friction resistance. The evolution of both the magnitude and anisotropy of the contact force are significantly affected by the input vibration amplitude, further resulting in the change of friction resistance.

Dynamic Behaviors of Smoothed Polyhedral Materials with Deformable Discrete Elements

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Granular materials, comprising numerous irregularly shaped particles, are prevalent in nature and industry, possessing unique mechanical properties and exhibiting solid-liquid transformation under external loads. Understanding the macroscopic mechanical behaviors of granular materials is pivotal in various engineering fields, and the discrete element method (DEM) has been instrumental in this regard for over four decades. Traditional DEM approaches, primarily using three-dimensional spheres, offer computational simplicity but fail to capture the complexities of non-spherical granular materials. These non-spherical granular materials exhibit distinct macroscopic mechanical properties due to factors like multiple collisions, low flowability, and particle interlocking, which are not adequately represented by spherical models.

In this study, a novel Minkowski sum contact algorithm is developed for simulating the dynamic properties of mixed granular systems with varied morphologies. This algorithm utilizes dilated super-ellipsoids, spherical harmonic functions, and polyhedrons to model particles of different shapes, enabling the simulation of particle interactions in both static and dynamic structures. The algorithm also includes automatic mesh simplification and GPU parallel methods, significantly improving the computational efficiency of DEM simulations. We validated the algorithm with four sets of numerical samples, demonstrating its robustness and applicability in simulating diverse granular systems. The numerical results, in alignment with theoretical results, confirm the algorithm's effectiveness in representing real granular systems involving elastic and inelastic collisions, particle packing, and mixed granular flows.

Moreover, the study extends the algorithm's application to large deformations in various structures and particles, employing a deformable DEM model. This model discretizes structures and particles into dilated triangular elements, using the Minkowski sum method for calculating contact forces. Internal forces within particles and structures are computed through a chain-link mesh method, accounting for tensile, shear, bending, and torsional stiffnesses. This approach enables the simulation of large deformations in chains, nets, thin shells, and solids, offering wide applicability in engineering. Overall, this research provides a more efficient tool for modeling granular materials with complex morphologies.

keywords: Granular materials, Discrete element method, Minkowski sum method, Arbitrarily shaped particles, Large deformation.

The Big Role of Tiny Fluctuations in Granular Flow Modeling

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This talk will discuss developments on grain-size-dependent constitutive modeling of granular flows. We begin with the notion of diffusing fluidization, which causes many of the well-observed departures from local plasticity in granular flows, such as the appearance of nonlocality in velocity profiles and grain-size-dependent flow-arrest relations in, for example, flow down a chute. By implementing one such diffusing fluidity model, the Nonlocal Granular Fluidity (NGF) model, using the Material Point Method, we can show that the same continuum model that accurately predicts steady 3D granular flow fields can also predict the grain-size-dependent clogging criterion in silos. Closer inspection of the fluidization field implicitly used in NGF reveals that this field is very closely connected to the particle velocity fluctuations, and thus the diffusion of fluidity calls directly to an analogy with diffusion of temperature. In fact, by directly relating flow-rate, stress, and velocity fluctuations, we can find a near-exact data collapse across many geometries taking the form of a thermal power-law correction to the so-called m(I) relation. This relation can be even further extended to account for second-order effects in the constitutive relation such as normal stress differences.

Modelling Offshore Foundations under Extreme Loading Conditions

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The growing demand for renewable energy has resulted in a rapid, worldwide expansion of offshore wind installations in deeper waters and in areas of medium to high seismicity (e.g. China, Japan, USA) with harsher ocean environmental conditions and with structures of higher energy capacity. The first generation of offshore wind farms was located in areas of low seismicity, mainly in northern Europe, and therefore there is limited experience worldwide on how this type of structures would respond to seismic loading or to combined environmental and seismic loading. In terms of methods of analysis which are available to estimate their response under such extreme loading conditions, the time domain fully integrated analysis approach, in which the entire structure of the rotor-nacelle assembly, tower sub-structure and foundation are simulated within one model, is the most comprehensive one, but also rather cumbersome computationally. The lecture will discuss the computational challenges encountered when simulating the entire soil-structure-interaction system in time domain (see Figure1), focusing on the modelling of monopile supported structures in liquefiable ground conditions using well-established and more recently developed constitutive models.

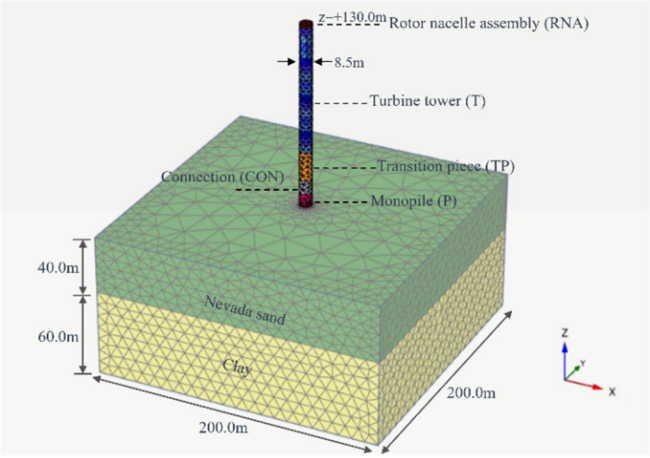


Figure 1: Example of simplified turbine substructure system: geometry, ground stratigraphy and finite element mesh.

Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Probabilistic Characterisation of Critical State Model Parameters for Saprolitic Soil in Hong Kong

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This talk reports the compilation of a database of multi-staged consolidated-undrained triaxial test results on a saprolitic soil in Hong Kong, and findings on the subsequent calibration of constitutive model parameters. The database contains over 700 sets of test results, which enable the probabilistic characterisation of shear strength and other parameters of different constitutive models, ranging from simple Mohr-Coulomb model to Nor-sand models based on the critical state concepts, with adjustments to simulate the dilatancy features of overconsolidated sandy soils. In particular, detailed comparisons of experimental and simulated stress paths of about 100 tests reveal the merits and limitations of the models, manifested as the discrepancies in stress paths throughout the entire multi-staged compression process, which can be interpreted as the model bias associated with the constitutive models. Based on the experimental results and the ensuing analyses, multivariate distributions of critical state model parameters are obtained, with the correlations among various aspects of material properties discussed in the context of copula fitting of model parameters. The impacts of these parameter characterisations are demonstrated through probabilistic analyses for a simplified engineering scenario.

When Nature Meets Technology: AI-Informed Discovery of Root–Soil Physical Interactions

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Nature-based solution using vegetation has been considered as sustainable and environmentally friendly approaches to improve slope performance. Vegetation can affect the stability of shallow soils not only through mechanical root reinforcement, but also through variations of soil matric suction associated with root–water uptake process. Upon plant growth, roots explore the soil pore space to search for nutrient and resources. Our recent work has demonstrated that the process of root exploration in soil pore space could significantly modify the water retention curve (WRC), which is a crucial soil hydraulic property that underpins many key unsaturated soil properties that affects the engineering design against slope stability. How fundamentally the soil pore morphology might change and evolve with time upon root growth dynamics including mortality and how this dynamic root–soil interaction at pore-level would modify the WRC remain unclear. The lack of knowledge has made the existing modelling of root-induced WRC mostly empirical or semi-empirical. Advanced non-invasive imaging techniques such as mX-ray computer tomography (CT) have been attempted to capture such interaction in-situ. However, challenges exist to reliably segmentate the many phases involved in an unsaturated rooted soil sample (soil, water, air, roots) from CT images because some of these phases have rather similar X-ray attenuation coefficients.

The presentation will share our latest development of using advanced technology including artificial intelligence (AI) to aid the discovery of physical interaction between two natural materials, unsaturated soil and vegetation, and the more correct characterisation of the engineering properties of their composite. The presentation will start by introducing how a new laboratory apparatus is designed to enable unsaturated rooted soil samples to be subject to in-situ hydromechanical loading and X-ray imaging simultaneously. An AI-informed image processing technique will then be introduced to explain how the reliability of phase segmentation of the CT images of an unsaturated rooted soil sample can be significantly enhanced, making the detailed quantification of 3-D morphologies of soil pore and roots and the spatiotemporal distributions of pore air and water possible. Some new discoveries of how roots physically interact with the soil pore space including the dynamic changes in the distribution, orientation and connectivity of soil pore size and how this pore-level information can be used to explain the water retention properties will be discussed in the presentation.

Risk Evaluation on the Installation of Offshore Spudcan Foundations

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Spudcan foundation is widely used to support jack-up drilling platform for offshore oil and gas exploration and wind turbine installation. However, the installation of the foundations is often hampered by the complex distribution of marine soils and harsh offshore loads. This talk focuses on risk assessment methods for installation of spudcan foundations. Firstly, through large-scale model tests and random large deformation numerical method, the interaction between the foundation and the spatially varied seabed soil during the installation is presented. Then, the failure mechanism between "complex sea-bed and spudcan foundation" is revealed. The influence of soil spatial variation characteristics is clarified. A risk assessment method for spudcan foundation installation integrating monitored data is proposed, which provides a systematic method for risk assessment of jack-up platform in offshore projects. Finally, the risk evaluation of several field cases are introduced.

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Numerical Investigation on Waves and Their Transitions in Snow Avalanches Using the Material Point Method

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Waves happen in numerous geological hazards, including debris flows, submarine turbidity currents, and snow avalanches. As the local flow height and velocity of waves could be high, they can cause more hazardous effects compared to uniform steady flows. Although field investigations show that the pressure maxima of snow avalanches coincide with the passage of waves, the mechanisms and dynamic behaviours of snow avalanche waves remain unclear. In this study, we use the material point method and a large-strain elastoplastic constitutive model to simulate snow avalanche waves, considering both ideal terrain and complex real terrain. In particular, the waves in an avalanche on real complex terrain are modeled and the simulation results are compared to the field data. The processes involved in waves of snow avalanches, including erosion, deposition, and flow instability due to terrain irregularity, are naturally recovered. In a single simulated snow avalanche, roll-waves, erosion-deposition waves and their transitions are captured. The behaviors of the simulated avalanche waves are consistent with the field data, in terms of the wave velocity and height. According to a dimensionless analysis, the wave mechanics is controlled by Froude number, slope angle, and wave mass. With further consideration of ideal terrain modeled as an inclined plane, the effect of slope angle and depth of erodible zone on the wave behavior is investigated. Clear correlation between wave features and the influencing factors are established. Two types of waves separately located at the front and the remaining part of the avalanches are identified. This study helps to understand the wave behaviors and reveal the mechanisms of different types of waves in snow avalanches.

Continuum Models for Granular Materials at Various Scales

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Granular materials can behave like solids and fluids. Their macroscopic behaviors are determined by the contacts between particles, which are directly linked to the geometries of individual particles. The most widely employed method for modeling granular materials is the discrete element method, which assumes that the particles are rigid. In this talk, we will introduce our work on the modeling of granular materials using continuum models. At the microscopic scale, we define a level set function to model the geometry of a particle. Since the boundary of the particle does not coincide with the vertices of the background grid, the function is noisy. We introduce a noise elimination algorithm and an approach to apply boundary conditions on surrogate edges of the grid. At the mesoscopic scale, we introduce a contact algorithm using level sets, an algorithm for particle segregation, and a contact algorithm using the virtual element method. At the macroscopic scale, we focus on granular flow, considering the coupling of fluid and solid, especially for the simulations of erosion.

Assumed Enhanced Strain Method for Fracture Propagation in Porous Media

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In this presentation, we introduce the Assumed Enhanced Strain (AES) finite element method designed to simulate fracture deformation and propagation in porous media. Our approach holds significance in unraveling complexities within subsurface processes, including fault reactivation, geothermal energy extraction, CO2 storage, hydraulic fracturing, and wastewater injection. The method enhances discontinuous functions in the strain field, enabling the accurate simulation of strong discontinuities, such as fractures and faults, within elements. Notably, this method maintains computational efficiency by not increasing the total number of global equations, as enriched degrees of freedom can be efficiently removed using standard static condensation. Our focus extends to addressing fracture propagation issues in subsurface environments, necessitating the consideration of coupled phenomena such as solid deformation, fluid flows, heat transportation, and frictional contact. We validate our numerical framework by comparing it with previously-published solutions and subsequently apply it to predict fracture propagation and frictional fault slip in porous media.

Constitutive Behavior of Coral Sand from Element Tests and Numerical Simulations

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Due to the irregular shape and fragility of coral sand particles, its engineering mechanical properties differ significantly from those of ordinary terrestrial sand. This study used element tests and discrete element simulation methods to investigate the particle breakage and constitutive behavior of coral sand. The study mainly focused on the particle scale and specimen scale, with a particular emphasis on the constitutive behavior related to the initial anisotropy and time-dependency caused by particle breakage and irregular shape.

CT scanning analysis and single particle compression tests were firstly conducted on coral sand particles. Extensive confined compression tests, triaxial tests, as well as direct simple shear tests, were then conducted on two different gradations of coral sand to investigate its monotonic, cyclic and time-dependent mechanical properties. The test results indicate that coral sand exhibits stronger compressive properties than ordinary quartz sand. With the increase of the sample's depositional angle, the effective internal friction angle of the coral sand decreases while the dilation increases. This is different from common quartz sand, where both the effective internal friction angle and dilation decrease with the increase of the depositional angle. Coral sand exhibits significant creep and relaxation phenomena, and the initial anisotropy has a significant influence on the creep and relaxation behavior. The main mechanical mechanism of creep and relaxation in coral sand is particle breakage, which results in a change of the force chains and particle size distributions with time.

Using discrete element method, the microscopic mechanism of the anisotropic responses of coral sand was numerically investigated. The simulation results indicate that the stress-contact force-fabric relationship can well explain the connection between the macroscopic shear strength of coral sand and its microscopic anisotropy. The initial anisotropy behavior of coral sand and the phenomenon of strength reduction due to particle breakage are microscopically attributed to the changes in four anisotropy invariants. Additionally, the evolution analysis of the sample particle's long axis direction reveals that the fabric evolution related to the unbreakable sample's particle long axis is closely related to the input energy of the sample, while the biased fabric reduction caused by particle breakage is closely related to the degree of sample breakage.

Finally, detailed analysis was conducted on the evolution of particle size and shape of coral sand samples before and after experiments and discrete element simulations. The results indicate that, despite of different experimental conditions, there is a specific relationship between the relative breakage rate Br and input energy E for the same particle size distribution of coral sand. However, the Br-E relationship of coral sand is influenced by the sample particle size and deposition angle. Additionally, there is an approximate hyperbolic relationship between the shape change factor Sr and the relative breakage rate Br, suggesting that the evolution of coral sand particle shape may be controlled by particle breakage.

Fundamental Concepts of Soil Water Potential and Effective Stress for Computational Geomechanics

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I will summarize the breakthrough advances in recent years in the cornerstones of soil mechanics: soil water potential and effective stress. The general soil water potential definition established under the thermodynamics second law explicitly includes capillary potential and sorption potential. The former is the result of the internal (mechanical) soil water interaction whereas the latter is the consequence of the external (electromagnetic-mechanical) soil water interaction. The general effective stress definition established under the force equilibrium principle explicitly includes capillary suction stress and adsorptive suction stress components. Two recently established experimental techniques: soil water isotherm for soil water potential and drying cake for suction stress characteristic curve will be briefly surveyed.

Understanding Bio-Inspired Soil Penetration Processes through DEM Modeling

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Soil penetration and excavation are ubiquitous processes in civil engineering activities, from the installation of foundations to the construction of tunnels and deployment of sensors. These activities are energy intensive, requiring the use of heavy equipment. In the last decade, engineers and scientists have investigated the strategies that organisms such as worms, clams, lizards, moles, and plants use to burrow in various ground conditions with the goal of developing more efficient penetration and excavation processes. This presentation will focus on understanding the geomechanical aspects of the penetration processes involved in bio-inspired burrowing strategies. Discrete element modeling simulations show the role of fundamental aspects of soil behavior, such as arching, rotation of principal stresses, and dilatancy, on the burrowing behaviors and performance. The results corroborate that it is possible to generate the required anchorage force within the drill string of a probe to overcome the penetration resistance to develop so-called 'self-burrowing' technology. This work also explores how altering the state of stresses around the tip of the penetrating object can produce significant reductions in penetration resistance. This work provides guidance on the development of self-burrowing tools for geotechnical applications and highlights challenges in its implementation.

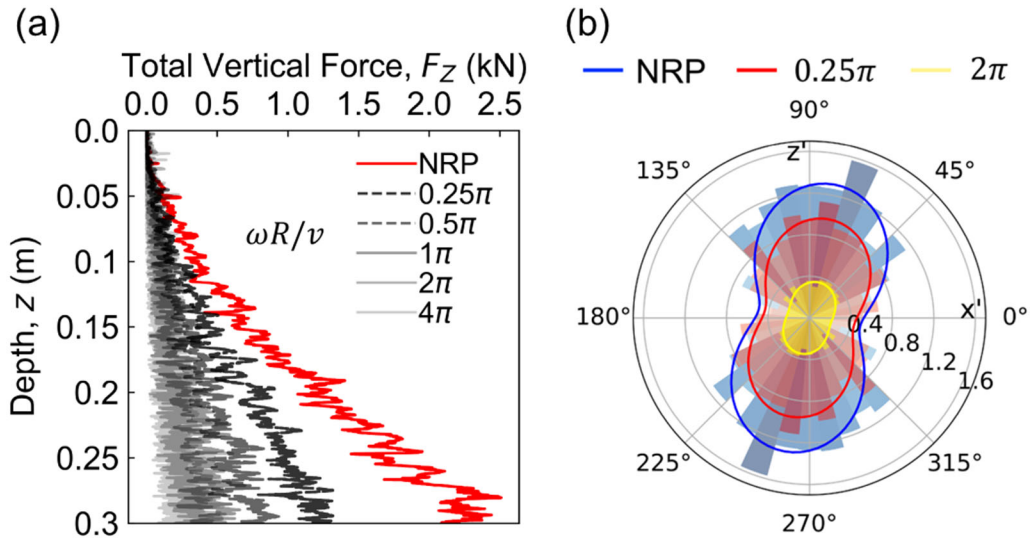


Figure 1. DEM simulations of circumnutation-inspired soil penetration. (a) Vertical penetration resistance as a function of the ratio of tangential to vertical penetration velocity (i.e., relative velocity) and (b) polar histogram showing the reduction in contact forces as the relative velocity is increased.

Estimation of Spatial Distribution of Surface Soil Properties on The Moon

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Lunar exploration has intensified in recent years, with various countries sending probes to the Moon to gather foundational information for the development of future lunar bases. Given the enormous cost of transporting materials from Earth to the Moon, it is imperative to develop technologies capable of producing various materials using lunar surface soil as the raw material. This technology, known as In-Situ Resource Utilization (ISRU), includes how to design optimal tools and facilities to collect, transport, sort, and process lunar surface soil. Therefore, it cannot be developed without the contribution of geomechanics.

A unique challenge in this endeavor, which goes beyond terrestrial geomechanics, involves predicting the physical and mechanical properties of the lunar surface soil with the very limited information currently available. In this presentation, we propose a methodology for roughly estimating the properties of the surface soil across the entire Moon from our previous research [1-3] and the recent unified geologic map of the Moon by USGS [4].

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Discrete-Continuum Coupling for Earthquake Science

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Earthquakes are frictional instability that occur in the lithosphere at a wide range of scales. They consist in the sudden release of the elastic energy stored in the country rock through a dynamic sliding event along a preexisting fault. Laboratory earthquakes are analogous events reproduced at small scale under controlled conditions in the lab, using a wide variety of experimental systems (e.g. sawcut triaxial tests, direct shear tests, high-velocity rotational tests, pin-on-disc sliding, etc.). In this communication, I will present the numerical twin of such an experiment. The numerical model consists in the direct coupling between continuum elastic regions (in order to represent the intact rock surrounding the lab fault, and its ability to store elastic energy and to transmit and damp acoustic seismic waves) and discrete regions (in order to represent the close vicinity of the fault plane, where rock can damage, break, and eventually form a continuous layer of powdery rock trapped in the interface and modifying its frictional response). I will show to what extend such a model can spontaneously reproduce a large number of seismic cycles, how it compares with experimental results, and what it teaches us about the role of the granular gouge layer, about the kinetics of wear of the fault rock, about the process of nucleation, triggering, and arrest of seismic events, and about the emergence and structure of fault heterogeneity.

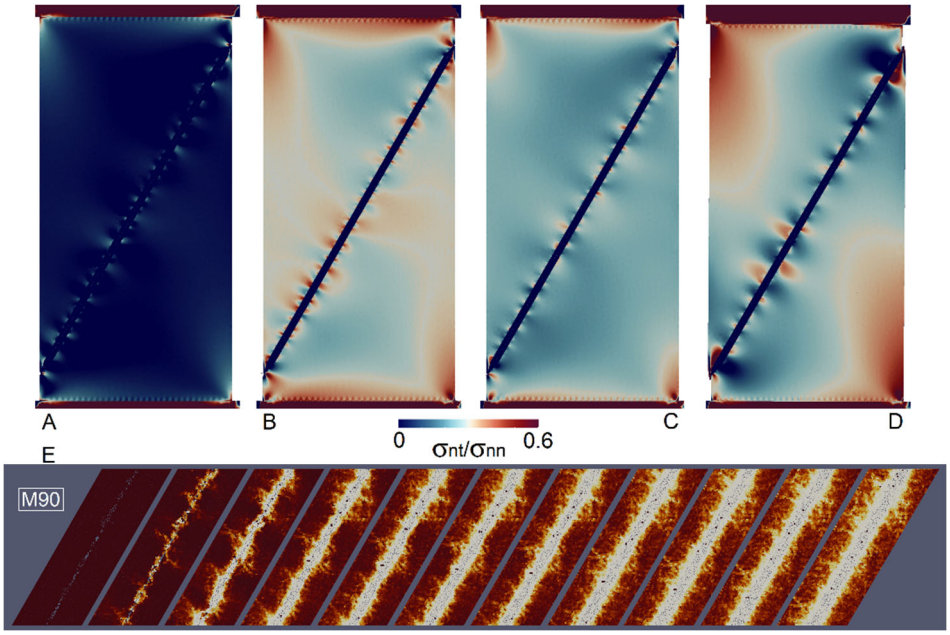


Figure 1. Top: Evolution of the stress field around the fault along numerous seismic cycles; Bottom: Progressive degradation of the discrete region and build-up of a granular layer.

Shear Banding as an Optimal Dissipative Structure from a Thermodynamic Viewpoint

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Granular materials are now 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. 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. The lecture investigates this issue by invoking the extremal entropy production theorems to seek any connection with the second-order work theory in the mechanics of failure. A general equation linking the derivatives of the entropy of a mechanical system to the second-order work is thus inferred, which leads to a thermodynamic interpretation of bifurcations in the failure behaviour of granular materials under a given loading. This is verified through discrete element simulations that highlight the fundamental role played by the elastic energy stored within a granular material before a bifurcation occurs, which also corresponds to a minimization of the entropy production. The analysis suggests a new interpretation of the intriguing shear banding phenomenon as a bifurcation with the emergence of ordered dissipative structures germane to nonequilibrium thermodynamics of open systems.

Numerical Upscalling of the Behaviour Geomaterials

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Microstructural features of geomaterials play a key role on their macroscopic behavior. Enriching macroscopic models with the physics arising from the microstructure constitutes an interesting approach to obtain constitutive relationships from physics that might be simpler to characterize at the microscale. Historically, analytical upscaling methods have been derived considering ideal microstructures, often quite simplified and sometimes far from realistic microstructures of geomaterials. Such methods are easy to use and provide useful bound values of the macroscopic behavior. Meanwhile, recent advances in imaging techniques allow a well-resolved determination of the microstructure of geomaterials. However, upscaling these detailed microstructures require the use of numerical techniques.

At the scale of the continuum medium, the upscaled behavior can then be used to predict the behavior of geostructures. Such a process involves multiscale simulations, from the microscale to the structure scale through the continuum scale. Two applications of such multiscale simulations will be presented.

In the first application, FFT-based numerical upscaling of real microstructures obtained from x-ray tomography images of hydrate bearing sediments will be presented [1]. This approach benefits from the direct use of tomographic images and does not require any meshing process, while presenting a computational cost smaller than the finite element method.

The second application presents the hydromechanical modelling of fractured reservoirs [2]. At the reservoir scale, simulations are performed using the box method, a hybrid finite element/finite volume method. No constitutive law is defined that the material point level. Instead, fractures at the microscale are accounted for and upscaled using a second (micro) level of the box method.

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Machine Learning-Assisted Multiscale Modelling of Granular Media

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Multiscale modelling can reproduce engineering-scale boundary value problems (BVPs) with consideration of particle-scale physics but suffers from substantial computational costs. Data-driven multiscale modelling (DDMM) is a potential strategy to accelerate computations. Model and data are two key components that enable the development of DDMM. From the perspective of models, we will discuss leveraging the frame-indifference principle and incorporating the evolution of microstructures into stress-strain modelling for sheared granular media, without explicitly using fabric information as direct inputs [1]. From the data's perspective, we explore using deep active learning to prioritize labelling the most informative data for the model and to quantify the uncertainty of surrogate predictions [2]. Additionally, we will demonstrate how to utilize existing phenomenological, numerical, and experimental models to facilitate cross-paradigm knowledge transfer. We will also touch upon utilizing data from similar materials to achieve cross-material knowledge sharing [3]. These data-driven modelling strategies will not be validated based on the representative volume element (RVE) of materials but also be embedded into finite element modelling (FEM) of BVPs (see Fig. 1). Lastly, we will discuss the current challenges of data-driven multiscale modelling and its potential future directions.

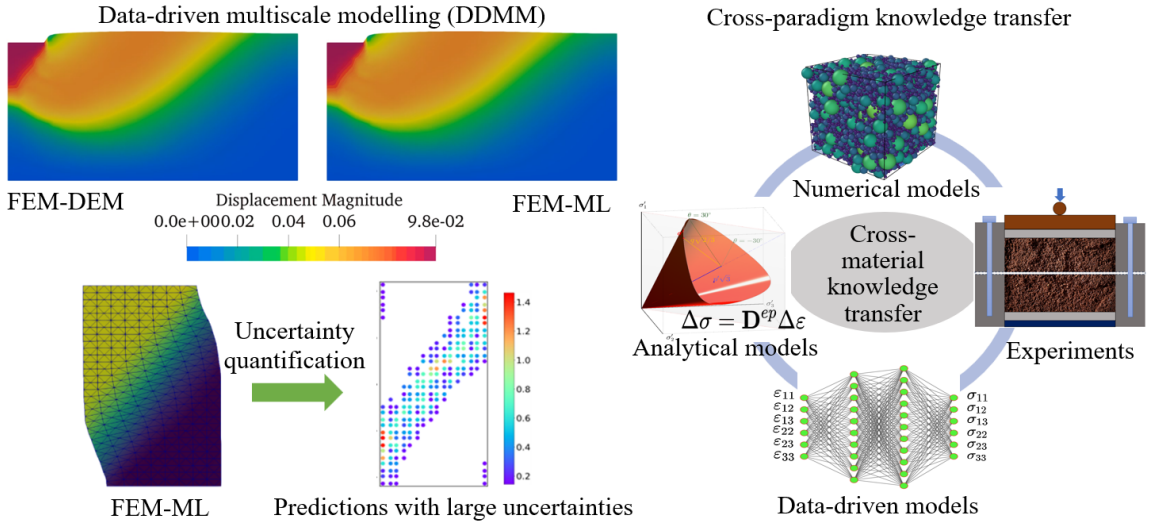


Fig. 1 Data-driven multiscale modelling with uncertainty quantification and knowledge transfer

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Abstract for IAS Symposium on Computational Geomechanics (March 3-6, 2024)

Exploring the Macroscopic Stiffness of Sands via Grain-Scale Experiments and DEM

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This presentation will discuss on the multi-scale analysis of stiffness at small strains in granular materials. In particular, the step-by-step approach to develop grain-scale experimental data will be first introduced with emphasis on grain-to-grain contact properties, followed by an approach to implement these data into a calibration process in DEM code[1,2]. Thereafter, the observed multi-scale trends from the numerical simulations will be linked with published macroscopic experimental data, predominantly from dynamic element testing, to provide insights into the stiffness of granular materials.

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Estimation of Mechanical Strength of Heterogenous Geomaterials Using Multiscale Homogenization and Machine Learning

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Most geomaterials, such as rocks and concrete, are characterized by multiscale complex microstructures. Their macroscopic mechanical properties are inherently affected by microstructural components and their evolution. The prediction of short and long terms mechanical strength is a key issue for stability and durability of engineering structures.

In this work, we consider a class of materials containing pores and inclusions are different scales. Analytical strength criteria issued from nonlinear homogenization techniques are first evaluated and their limitations are analyzed, in particular regarding the description of effects of spatial distribution and size of pores and inclusions. A numerical homogenization method based on Fast Fourier Transform is then presented. A large series of direct numerical simulations are performed for different classes of materials such as porous media, inclusion-reinforced composites, and materials with pores and inclusions at the same scale. The obtained results allow a comprehensive analysis of influences of pores and inclusions, as well as their interactions on the macroscopic mechanical properties.

Based on the direct numerical simulations, an Artificial Neural Network model is constructed for the prediction of macroscopic failure strength by using porosity and inclusion volume fraction as input parameters. This model is trained and tested by using a dataset based on the results obtained from the numerical simulations. The accuracy of the ANN-based model is demonstrated through different statistic error indicators. The good performance of this model is finally shown through the comparisons between its predictions and the references solutions from the direct numerical simulations for different classes of heterogeneous materials.

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A Simplified Homogenization Equation for Gap-Graded Soils with Application to Elastoplastic Modelling of Sandy Clays

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Naturally sedimentary clays and the clayey soils produced from engineering activities usually contain certain extents of sand aggregates, termed as sandy clays. This type of soils has a clay dominated structure, and their mechanical properties, such as stiffness and shear strength, are affected by the sand fraction. A structure variable is introduced to correlate with the evolution of inter-aggregates structure. This variable varies with the particle shape, and particle size distribution of sand aggregates, and is found to increase with the volume fraction of coarse aggregates but is rather independent of the confining stress and the initial void state of the fine matrix. The homogenization equation is further implemented into the elasto-plastic theory, and a constitutive relationship is then established to capture the deformation behavior of sandy clays. Compared with the modified Cam-clay model, only one additional structural parameter is required for the proposed model, and it can be readily determined from the data of an oedometer or triaxial shear test. Validation has been done by comparing the model predictions with test results from literature. It shows that our model is versatile to reproduce the reinforcement effect of sand aggregate on both compressibility and shear response of sand/gravel-clay mixtures with a wide range of coarse content.

Solving Inverse Problems in Granular Mechanics with Differentiable Simulators

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Solving optimization and inverse problems are critical for engineering design and analysis. Despite the computational power, calculating derivatives, i.e., evaluating the forward simulation multiple times with small perturbations, is computationally very expensive and is prone to numerical instability. Traditional forward simulations cannot be used in machine learning models for optimization, as they cannot compute gradients for the input parameters (reverse mode). We propose a novel Differentiable Programming simulator that combines automatic reverse differentiation with a second-order gradient-based optimization algorithm, such as L-BFGS, to develop a fully-differentiable MPM simulator. Using the differentiable simulator, we can identify the input material properties by iteratively updating the input parameters by minimizing a loss function. Typically the loss function is the norm of the difference to the target observation. We then minimize this gradient (loss corresponding to the input parameters) using a second-order optimization algorithm. We compare our differentiable simulator results with the state-of-the-art Proximal Policy Optimization (PPO) algorithm in Reinforcement Learning. Differentiable MPM solves the exact PDE and can approximate the dynamics of its environment better than model-agnostic reinforcement learning methods. The differentiable MPM simulator is written in Google JAX and exploits Tensor Processing Units to accelerate the computational time. We successfully estimated the input parameters for a collision of two deformable bodies. The differentiable MPM is a novel tool to provide gradients through a simulator, which can be coupled with existing machine learning algorithms to generate real-time decisions and optimization in robotics.

We exploit physics-embedded differentiable graph network simulators (GNS) to accelerate particulate and fluid simulations and solve challenging forward and inverse problems. GNS represents the domain as graphs with particles as nodes and learned interactions as edges. GNS allows learning localized physics compared to global dynamics, improving generalization. GNS achieves over 165x speedup for granular flow prediction compared to parallel CPU simulations. We propose a novel hybrid GNS/Material Point Method (MPM) to accelerate forward simulations by minimizing error on a pure surrogate model by interleaving GNS with MPM[1] to conserve momentum and minimize errors achieving 24x speedup compared to purely numerical simulations. The differentiable GNS enables solving inverse problems through automatic differentiation, identifying material parameters that result in target runout distances. Granular column collapse experiments demonstrate friction angle inversion based on final runout profiles. The physics-embedded and differentiable simulators open an exciting new paradigm for AI-accelerated design, control, and optimization.

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Preventing Human-Induced Seismicity to Fight Climate Change

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The Earth's underground presents a remarkable potential for renewable energy production and storage. For instance, geothermal resources are renewable and seem to be more than enough for covering the energy needs of humanity. Additionally to geothermal energy, solar and wind energy are vital for combating climate change, but their intermittent nature requires large-scale energy storage solutions like hydrogen production through electrolysis and storage in underground reservoirs to ensure consistent supply. Some other prominent options for fighting climate change involve carbon capture and underground storage.

Yet, all these prominent technologies involve the injection of large amounts of fluids in the Earth's crust, which causes significant earthquakes. The problem of induced seismicity due to fluids injections is challenging and remains unsolved.

In this talk, we will focus on recent progress [1-7] in order to prevent unwanted seismicity by leveraging tools from geomechanics and the mathematical theory. This new framework offers new insights and fresh perspectives for maximizing the production and storage of renewable energies, all while minimizing induced seismicity even under intermittent demand.

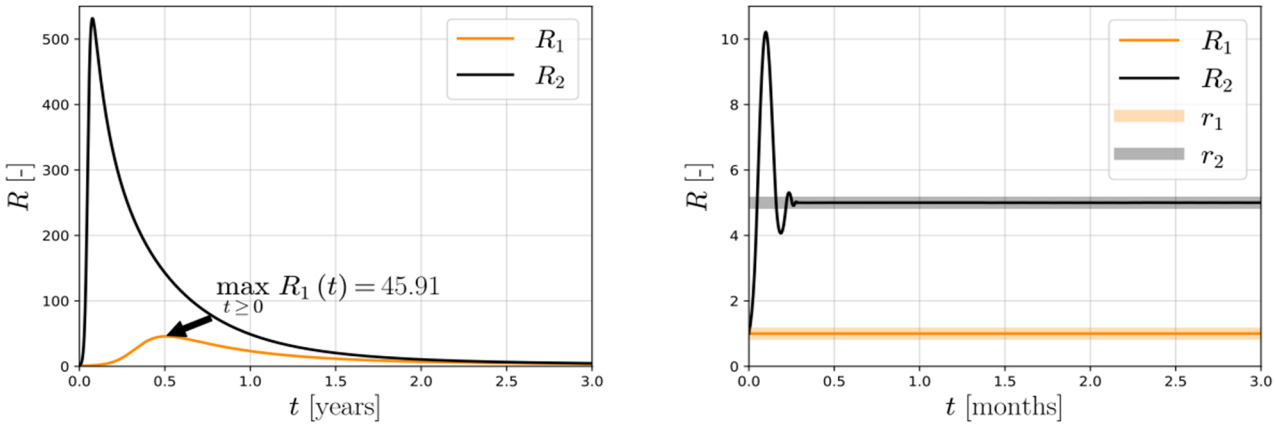


Figure 1. Evolution of the seismicity rate, R, in two sub-regions of a simulated geological reservoir due to the injection of fluids with (right) and without control (left).

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Generation and Dem Investigation of Physical and Mechanical Properties of Morphological Controllable Particles

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Granular materials are commonly encountered in nature, industry, and civil engineering practice, and their mechanical responses are intricately linked to the morphology of the individual particles. As a result, it holds significant theoretical and engineering value to systematically study the inherent connection between the geometric morphology at the particle scale and the macroscopic mechanical behavior characteristics. In this regard, the generation and DEM investigation of physical and mechanical properties of morphological controllable particles are introduced. Firstly, the theories and techniques of geometric reconstruction, and morphological characterization of irregular particles are presented. Secondly, methods for generating virtual particles with controllable multi-level morphological features, including form, angularity and roughness, are introduced. Building upon this, DEM investigations on the particle shape effects on the packing structures and shear behaviors of granular materials are further discussed. The relevant research was financially supported by the National Natural Science Foundation of China (No. 52278364).

Discrete Element Modelling of Soil Desiccation Cracking Behavior

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Soil desiccation cracking is a common natural phenomenon. The presence of desiccation cracks compromises the integrity of the soil mass and significantly influences the mechanical and hydraulic behavior of the soil. This study aims to investigate the effect of basal boundary conditions on the initiation and propagation of desiccation cracking along the vertical direction in thin clay layer using discrete element method (DEM). A two-dimensional discrete model was proposed considering shrinkage kinetics and property change during the drying process. Different basal boundary constraints were simulated by applying bond between the soil particles and the fixed base particles of difference sizes. The simulation results were compared with the laboratory experiments. The results showed that the model can reproduce the main trend of desiccation process. Larger base particles produced more cracks in the specimen. Both cracks initiated from the top surface and cracks initiated from the bottom soil-base interface were observed and discriminated in the simulation. The model revealed the development of bottom-initiated cracks and unpenetrated cracks beneath the surface that may be neglected in traditional cracking simulations. The study suggests that the different initiation position of cracks is associated with the change of force distribution inside the specimen. Moreover, the effects of different boundary properties (the geometrical roughness, the frictional coefficient and the bond strength), particle density change and evaporation gradient on model performance were investigated.

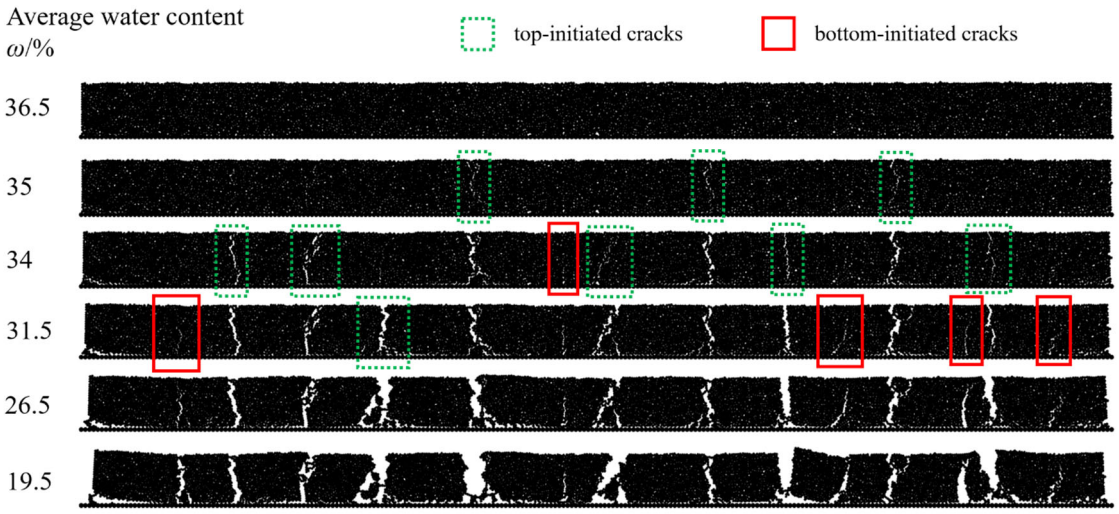


Figure 1. The initiation and propagation direction of desiccation cracks.

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Climate Resilient Geotechnical Infrastructure: Developing Computational Tools and Methodologies for Soil-Atmosphere Interaction

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Geotechnical infrastructure, such as railway and highway cut or embankment slopes, often becomes covered in dense vegetation, usually due to poor vegetation management. For example, there are hundreds of thousands of kilometers of vegetated slopes in the United Kingdom alone. As earthworks are known to demonstrate poor serviceability when interacting with vegetation, Engineers tend to perceive it as a liability rather than to appreciate it as an asset. Well-maintained vegetation, however, has the potential to enhance slope stability, e.g. under intense rainfall, and has undeniably positive environmental outcomes. Furthermore, vegetation may be main driver of stability in steep natural slopes and has the potential to be combined with engineered barriers proposed as means of flood protection in urban areas, by recharging their water holding capacity. As such, and under the prism of climate change, the dynamic interaction between the soil and the combined effect of vegetation and rainfall has acquired great significance. The numerical simulation of soil-atmosphere interaction requires numerical features beyond those traditionally used in coupled numerical analysis (e.g., appropriate boundary conditions for vegetation and rainfall, mechanical and hydraulic constitutive models), and collaboration across disciplines (e.g., to establish evapotranspiration and rainfall data). As comprehensive data sets that span long-term field measurements, atmospheric conditions and soil behavior are sparce, developing and validating numerical methodologies that can be used reasonably and reliably is challenging. The work presented explains the numerical tools that are required, assesses critically the assumptions that may be made, and presents the latest methodologies for accounting for soil-atmosphere interaction in geotechnical numerical analysis. Examples of the use of these methodologies with reference to cut and embankment slopes, natural slopes and engineered barriers are given, to highlight their potential, and pose new research questions.

Computational Modeling of Unsaturated Granular Media Transitions across All Liquid Saturation Regimes

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The talk tackles a major challenge in the modeling of multiphase flow in unsaturated soils where the solid skeleton deforms as water (liquid) and air (gas) occupy the pore space in various proportions. One can distinguish four water saturation regimes: (1) pendular state where particles are cohesively held by liquid bridges, (2) funicular state where the liquid engulfs only a few of particles with air largely occupying the remaining void space, (3) capillary state where liquid with some air occlusions invades the entire void space, and (4) the fully saturated condition with liquid exclusively in the void space. While the pendular regime is well-understood, the funicular and capillary regimes require particular attention. A major modeling hurdle is the complexity of the regime transitions that involve complicated dynamics of water and air clusters. Thus, there is a need for a novel approach to cover transitions across all capillary regimes. To address these challenges, we propose a numerical model coupling the Lattice Boltzmann Method (LBM) and the Discrete Element Method (DEM). The LBM simulates capillary bridge dynamics, solving Navier-Stokes and Allen-Cahn equations for multiphase flow in intricate pore geometries. On the other hand, DEM, based on an elastic-plastic contact law, handles the kinematics of solid particles. This coupled approach successfully captures features such as water or air invasion dynamics as well as the evolution of capillary-induced stresses during wetting or drying processes. The numerical simulations start with an initial assembly of particles subjected to drying and wetting. Hysteresis is observed in the mean capillary stress and suction (see Fig. 1), revealing the model's potential in predicting unsaturated soil behavior across the various saturation regimes.

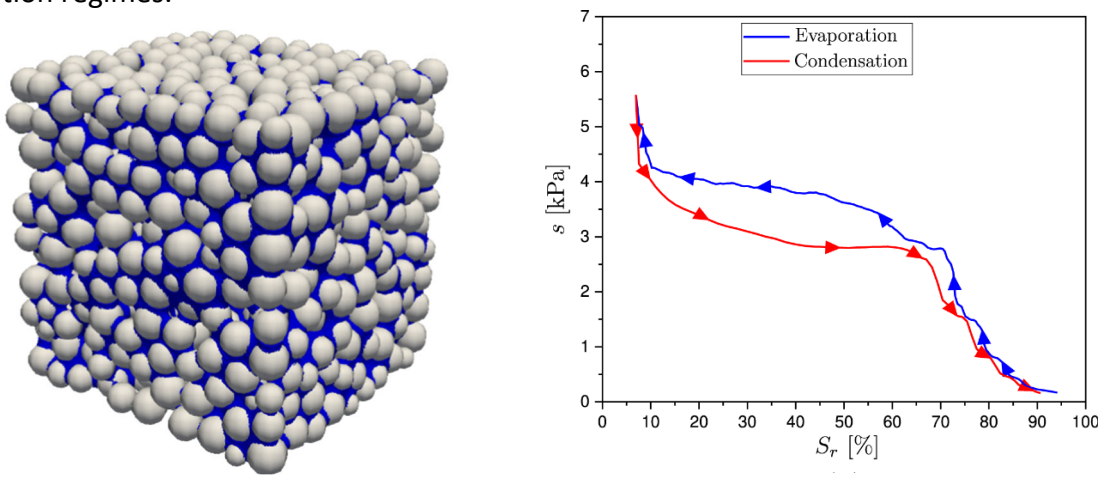


Figure 1. Coupled LBM-DEM computations and hysteresis of suction during a wetting and drying cycle.

Numerical Interpretations of Cone and Ball Penetration Tests under Partially Drained Conditions

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The cone and ball penetration tests are employed extensively to obtain the in-situ properties of soils. The soil responses caused by the penetrations may not under nearly undrained conditions, especially for silts, clayey silts or silty clays. Interpretations of the penetrations of conical and spherical probes and then the subsequent dissipations of pore pressures induced become complicated in intermediate soils, due to the partial drainage of soil around the probe during penetration. The influences of partial drainage on the cone and ball penetrometer tests are investigated, using a coupled pore fluid-effective stress large deformation finite-element approach incorporating the modified Cam-clay model. The displacement of penetrometer is divided into a sequence of incremental steps, whereby the excessive distortion of soil elements can be avoided by an allowable displacement in each step. The numerical approach is validated by extensive comparisons with model tests in centrifuge and in chamber, where the model probes were penetrated with a wide range of rates.

The large deformation results provide insights to explore the effects of drainage conditions, and our main findings are: (a) An approach estimating the effective internal friction angle via the penetration resistance is proposed, replacing the normalized pore pressure in the previous empirical equations with the normalized penetration rate. and (b) The distribution of pore pressures prior to dissipation and then the operative coefficient of consolidation, ch, against various penetration rates are quantified. The ratio between ch and the coefficient of consolidation can be described through a unique backbone curve.

CFD-DEM Coupling Simulation and Structuralized Cementing Technology for Wave Erosion Protection of Coastal Structures

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Coastal cities such as Hong Kong have been experiencing rapid development of coastal fronts in recent years. However, extreme weather conditions, such as typhoons and storm surges, have caused severe damage to offshore structures. To address these challenges, we develop structuralized cementing technology, which cements smaller-sized granular materials/rock amours to improve wave erosion protection of coastal structures.

In this study, a fully resolved CFD-DEM coupling method was developed to better understand the fundamental mechanism of the wave erosion process and fine-scale fluid-structure interaction. A mesoscopic-scale bond model is also developed to simulate a structurally cemented, irregularly shaped granular system. The numerical platform has important applications in wave erosion protection of coastal structures, as demonstrated by several examples, including scour protection of riprap systems and wind turbine foundations, the design of cemented rockfill dams, and floating offshore wind turbines.

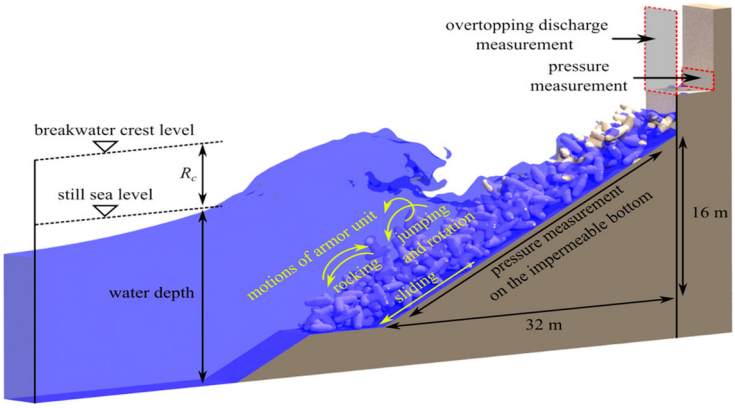


Figure 1. CFD-DEM simulation of wave erosion of a riprap system.

Acknowledgement:

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A Micro-CT Investigation of Internal Erosion Behavior of Gap Graded Soils

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This paper investigates the internal erosion behavior of gap-graded granular soils subject to triaxial shearing under constant hydraulic gradient conditions using a specially designed apparatus and X-ray CT scans. Two gap-graded soil samples with different fines content are tested and scanned multiple times to characterize sample- and pore-scale volume change and fines content using image processing techniques [1]. The CT experimental results show that internal erosion increases gradually with axial strain and has a complex impact on permeability increase due to the spatial variation of fines content. Triaxial shearing induces both pore contraction and dilation, destabilises the clogging of fine particles, and promotes internal erosion. Also, the erosion of force-supporting fine particles at a high fines content facilitates pore contraction. The progressive internal erosion due to mechanical disturbance leads to the formation of a flow channel from the upstream loading platen throughout the sample, resulting in a dramatical increase in permeability. Overall, this study provides novel insights into the interplay between the hydro-mechanical processes during shearing under constant seepage.

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Combined Fabric Evolution Model for Granular Media: Validation via Particle-Scale X-Ray Measurements and Application for Cyclic Loading

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Fabric influences the macro scale mechanical properties and behavior of granular materials as a continuum and can be represented by an appropriately defined evolving fabric tensor entering the constitutive equations. A theoretical formulation for contact normal fabric evolution was proposed by Wang et al. (2020) incorporating the influence of particle orientation fabric, referred to as the Combined Fabric Evolution (CFE) model, which was motivated and validated by observations from numerical DEM monotonic shear tests. Here, CFE is evaluated for the first time using grain-scale experimental measurements from physical tests on a strongly anisometric granular material. This new advance allows for such theoretical developments to make a step forward into the real world, from previously being only able to be assessed using numerical tools such as DEM or indirectly assessed via macro-scale experimental measurements. Furthermore, CFE is extended to the simulation of fabric evolution under cyclic loading. The comparison with DEM results highlight the capability of the CFE equation in simulating fabric evolution under cyclic loading for different anisotropy, density, and loading conditions. Such simulations are significantly more accurate in comparison with those obtained by with a basic fabric evolution equation without considering the influence of particle orientation fabric.

Keywords: Fabric evolution, fabric anisotropy, cyclic loading, DEM, granular materials

Data-driven and Physics-informed Bayesian Learning of Spatiotemporally Varying Consolidation Settlement

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A digital twin of a geotechnical project (e.g., a reclamation or ground improvement project) is a virtual or computational model that aims to continuously learn from actual observations (e.g., site investigation and monitoring data) and improve model predictions (e.g., spatiotemporally varying consolidation settlement). However, real geotechnical observation data obtained from a site are often spatially sparse (e.g., site investigation data) and spatiotemporally varying (e.g., settlement monitoring data). The sparse and spatiotemporally varying data pose great challenges for continuous learning of data and dynamic updating of the computational model. To address these challenges, this study proposes a novel data-driven and physics-informed Bayesian learning framework that automatically builds ground models from spatially sparse site investigation data, develops computational models based on the built ground models to incorporate geotechnical domain knowledge, and integrates the computational model results with limited, but spatiotemporally varying, settlement monitoring data to improve model prediction in a systematic and quantitative manner. The proposed method contains three key components: (1) data-driven ground modeling by Bayesian compressive sampling (BCS) using sparse site investigation data as input; (2) finite element modeling (FEM) of consolidation settlement that represents domain knowledge; and (3) Bayesian sparse dictionary learning of settlement monitoring data together with FEM results. The performance of the proposed method is illustrated using a real-world ground improvement project.

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Does Effective Stress Concept Apply to Unsaturated Soil?

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Presented here is a theoretical framework for modelling the constitutive behaviour of unsaturated soil. Central to the development is the formulation of a generalized effective stress tensor, which is work-conjugated to skeletal strain. The proposed effective stress incorporates the effect of soil-water interaction and transits smoothly between saturated and unsaturated regimes. Particularly, it ends up with Terzaghi's effective stress for fully-saturated, chemically inactive soils. It is shown that matric suction equals the derivative of the interfacial potential that accounts for soil-water interaction with respect to specific water content. In this context, the water content can be viewed as an internal state variable, the evolution of which describes hydraulic hysteresis or soil water retention characteristics. Using the modified Cam Clay model (MCCM) as a vehicle, we develop a constitutive model of unsaturated soil by introducing the degree of air saturation as a new hardening variable to account for the effect of collapsed pores. Comparisons between simulated and experimental results indicate that the proposed constitutive model captures well the main features of the constitutive behaviour of unsaturated soil under arbitrary hydro-chemo-mechanical loadings, while inherits the simplicity of the MCCM, showing that the concept of effective stress does apply to unsaturated soil.

Modelling Phase Transition in Granular Materials

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Granular materials are omnipresent in our daily life. The same granular material can behave like solid and fluid, which poses a formidable challenge to the constitutive models and numerical methods. Traditionally, constitutive models for the solid- and fluid-like behaviour have been developed for the respective flow regimes in different engineering/scientific disciplines with hardly any intersections. A single constitutive model capable of describing the transient behaviour during phase transitions in both solid-like and fluid-like regimes is a challenging task with enormous application potential.

We will take on this challenge with a simple yet efficient ansatz by decomposing the stress rate into a frictional and collisional part, which gives rise to an unconventional constitutive model with the 2nd order strain rate similar to the acceleration of motion. It serves as an excellent classifier for steady and transient motions. Based on the mixture theory, the field equations are established in rate form for the first time and discretised by a multi-layer SPH model. Advanced solution techniques are developed based on multi-GPU acceleration for high fidelity simulation of large-scale problems.

Mechanisms of Landfill Liner Leakage: Mathematical Models and Detection Technology

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The leakage of liners is a big environmental issue in the landfills in the mainland of China. The mechanisms of liner leakage will be discussed. The mathematical models for contaminant transport in the landfill liners will be presented. The breakthrough time based design method for the composite liners was then proposed. The leakage detection method based on tracer transport in landfills was proposed. The method was successfully used in the large-scale landfills in Hangzhou, China. A total of 9 types of fluorobenzoic acid was used as tracer. The dual-porosity model combined with the artificial neural network was proposed to analyze the breakthrough curves of the tracers. The leakage area of the landfills can then be determined. The proposed detection method is effective, economical and can be used for detection of deep leakage of landfills and contaminated sites.

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Small is Beautiful: Some New Insights into Small Strain Stiffness of Granular Soils

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Small strain shear modulus (G_0) or the associated shear wave velocity (V_s) is a basic soil property with clear physical meaning, and is required in various geotechnical applications. While it has been extensively studied in the past decades, some aspects of this property remain confusing or controversial. This is largely due to the particulate nature of soils. The characteristics of individual grains can significantly affect the packing pattern and the grain-to-grain interactions, and hence the overall mechanical properties. This talk will present selected results and findings from a long-term research program which was aimed at understanding the roles played by grain-scale properties in the small strain stiffness of granular soils. Focus will be placed on grain shape, surface roughness and inclusion of fines.

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Formulating a State-Dependent Constitutive Model for Soil Based on Stress Probing Analysis

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Nonlinearity, irreversibility, and state-dependency are fundamental characteristics of soil mechanics. To develop a constitutive model that accurately captures these features, a comprehensive understanding of the incremental stress-strain response is crucial. In this study, a numerical stress probing technique is employed in conjunction with the discrete element method to investigate the strain response of soil under stress increments along different directions. The impact of density and stress state on the incremental behavior is systematically analyzed. Leveraging the strain response envelopes obtained from the probing tests, explicit formulations of key components of the constitutive model are derived, including the yield surface, plastic potential surface, plastic modulus, and dilatancy function. Subsequently, a state-dependent constitutive model is established within the critical state framework. The predictive capability of the model is demonstrated through simulations of soil behavior in both discrete element tests and laboratory experiments under varying loading conditions. This research contributes to the development of a robust constitutive model for soil, facilitating improved predictions of soil behavior in geotechnical engineering applications.

Modelling of Fine Particles Transport in Granular Soils and Application

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This study attempts to formulate a coupled numerical model in the framework of continuum mechanics in order to investigate the phenomenon of fine particles transport in granular soils and its consequences on the mechanical behavior of soils. For this purpose, a four-constituent numerical approach has been developed to describe this process. The detachment and transport of the fine particles have been described by a mass exchange formulation between the solid and fluid phases. The stress-strain relationship of the soil is represented by a non-linear incremental model. Based on experimental data, this constitutive model has been enhanced by the introduction of a fines content dependent critical state, which allows accounting for the influence of fines on soil deformation and strength. The applicability of the numerical approach to capture the main features of this transport process and its impact on the mechanical behavior of the original soil has been validated by comparing numerical and experimental results of internal erosion tests on HK-CDG mixtures, which demonstrated that the model was able to reproduce with good accuracy the experimental data. Furthermore, the slurry infiltration and backfill grouting in TBM tunneling have been analyzed through numerical simulations.

A Unified Nonlocal Theory for Discontinuous, Multiphysical and Multiscale Behaviors of Geomaterials

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A unified nonlocal model is proposed to simulate discontinuous, multiphysical and multiscale dynamic behaviours in geomaterials. The mechanical behaviours of the material points are reformulated by incorporating the bond tension-rotation-shear coupling effects [1][2][4], which makes the proposed model suitable for complex discontinuous problems. A novel flux vector state and a non-local Darcy's law is proposed to illustrate non-local fluid transport effects in heterogeneous saturated porous media [3][5], as shown in Fig.1. For the simulation of multiscale behaviours of geomaterials, the PD model based on nonlocal theory is coupled with the finite element method (FEM) and the boundary element method (BEM) based on classical continuum mechanics, which can eliminate the boundary effects caused by nonlocal effects [6]. The proposed model is verified by comparing its results with those from experimental observations.

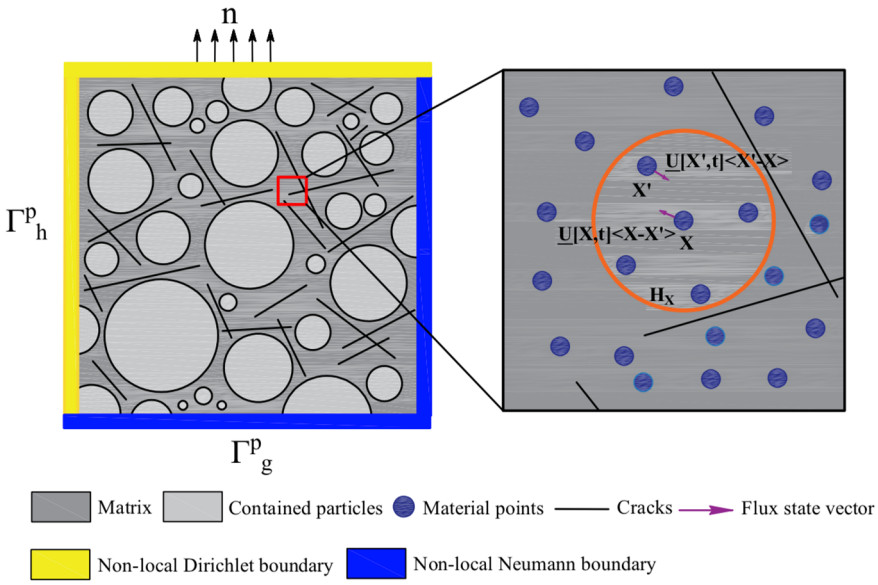


Figure 1. Heterogeneous saturated porous media in the proposed model.

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Effective Stress and Poroelasticity Theory for Soil Incorporating Adsorption and Capillarity

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Adsorption and capillarity, in the order of high free energy to low, are the two soil–water interaction mechanisms controlling the hydro-mechanical behavior of soils. Yet most of the poroelasticity theories of soil are based on capillarity only, leading to misrepresentations of hydro-mechanical behavior in the low free energy regime beyond vaporization. This inability is reasoned to be caused by two major limitations in the existing theories: missing interparticle attraction energy and incomplete definition of adsorption-induced pore-water pressure. A poroelasticity theory is formulated to incorporate the two soil–water interaction mechanisms, and the transition between them – that is, condensation/vaporization, by expanding the classical three-phase mixture system to a four-phase mixture system with adsorptive water as an additional phase. An interparticle attractive stress is identified as one of the key sources for deformation and strength of soils induced by adsorption and is implemented in the poroelasticity theory. A recent breakthrough concept of soil sorptive potential is utilized to establish the physical link between adsorption-induced pore-water pressure and matric suction. The proposed poroelasticity theory can be reduced to several previous theories when interparticle attractive stress is ignored. The new theory is used to derive the effective stress equation for variably saturated soil by identifying energy-conjugated pairs. The derived effective stress equation leads to Zhang and Lu's unified effective stress equation, and can be reduced to Bishop's effective stress equation when only the capillary mechanism is considered and to Terzaghi's effective stress equation when a saturated condition is imposed. The derived effective stress equation is experimentally validated for a variety of soil in the full matric suction range, substantiating the validity and accuracy of the poroelasticity theory for soil under variably saturated conditions.

PFEM and Its Application to Post-Failure Analysis of Geotechnical Problems with Large Deformation

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The realm of geotechnical engineering has undergone a profound transformation in numerical simulation techniques, progressing from the conventional Finite Element Method (FEM) to contemporary methodologies adept at addressing significant strains and deformations in post-failure analyses. This evolution is propelled by the imperative need for precision in analyses within complicated geotechnical scenarios marked by noteworthy changes in geometry, encompassing diverse applications such as cone penetration tests, pile/spudcan installations, landslides, debris flow, and more. The Particle Finite Element Method (PFEM), acknowledged as a robust continuum approach for managing large deformation problems, has experienced sustained development in geotechnical engineering over recent decades [1, 2]. This presentation introduces the PFEM, delineates its distinctions from other continuum approaches, and elucidates the associated challenges in handling geotechnical problems. Furthermore, it delves into the ongoing refinements in PFEM and its application to typical geotechnical challenges characterised by substantial changes in geometry (Figure 2).

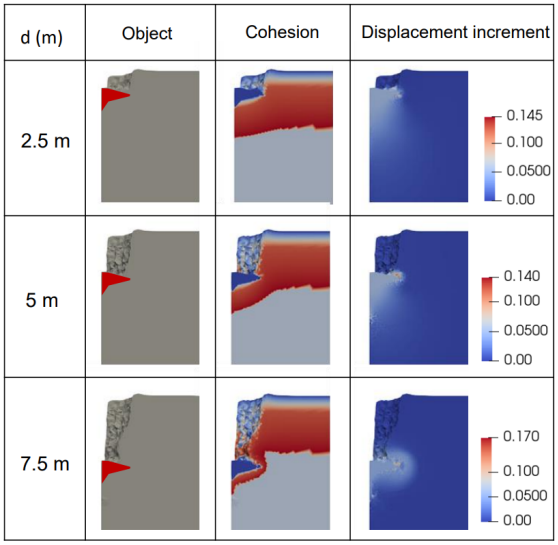


Figure 1. PFEM modelling of spudcan installation.

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Interpreting Chemically Assisted Crack Growth through a Surface Force-Based Fracture Theory

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Subcritical crack growth (SCG) plays a pivotal role in many geological processes, including delayed earth ruptures, weathering of surface rocks, and the relaxation of internal stresses within rock structures. Despite its significance, the mechanisms underpinning this chemically-driven cracking process—particularly the interactions at the nanoscale between crack walls and the transport of reactive species in the confined spaces near the crack tip—remain elusive.

In this talk, I will discuss a novel Surface-Force based Fracture Theory (SFFT) (Eskandari-Ghadi et al., 2022) for quantitatively analyzing the complex, multi-stage, non-linear SCG in brittle materials influenced by environmental agencies. In SFFT, crack growth is a result of thermally activated debonding at the crack tip driven by the effective stress intensity factor contributed by both external loading and surface forces along the crack walls. Differing from conventional cohesive crack theories (Barenblatt, 1962), we consider the variation of surface force-separation relation with respect to the local concentration of surface-reactive species. The species concentration profile is determined by Fickian diffusion and mole balance in the crack, thus is influenced by factors such as the relative velocity of the crack tip in comparison to its environment, the ambient concentration of reactive species, and the crack opening profile. The system of highly coupled equations is numerically solved via a partitioned implicit scheme for steady-state growth condition. We apply SFFT to investigate the impact of surface forces (such as DLVO and hydration forces) and species transport on the SCG behavior of glass in humid air and calcite crystals in NaCl solutions. We found that SFFT simulations naturally predict the chemistry-dependent cracking threshold as well as the multi-stage nonlinear SCG curves, without an assumed SCG shape a priori. Quantitative analysis showed that hydration force is much more influential than DLVO forces in determining the SCG curve of calcite at all NaCl molarities. Additionally, ion transport in nanoconfined fluids emerges as a critical factor influencing SCG behavior at higher crack propagation speeds. These important fracturing mechanisms revealed by SFFT simulations can assist the future engineering of carbonate reservoirs for safe and effective extraction and storage of resources (e.g. hydrocarbons, H_2) and wastes (e.g., CO_2).

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Modeling Fluid-Particle-Structure Interactions in Debris Flow

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In this talk, we introduce a novel, fully resolved coupled computational fluid dynamics (CFD) and discrete element method (DEM) for modeling complex fluid-particle-structure interactions involving arbitrarily shaped particles and stiff/flexible structures. We utilize a signed distance field (SDF)-based method and DEM to treat granular particles with arbitrary shapes and complex structural components. The volume of fluid (VOF) method is employed in the CFD to model multiphase fluids and fluid-particle interactions in the presence of non-spherical particles. SDF is further utilized to ensure consistent integration of DEM and CFD for the fully resolved coupling scheme, enabling accurate resolution of fluid-particle and fluid-structure interaction. Our approach demonstrates that the SDF method serves as a generic interface, empowering the new SDF-CFD-DEM framework for effective modeling of arbitrarily shaped particles interacting with multiphase fluids with desired resolutions. We benchmark the proposed SDF-CFD-DEM before applying it to simulate complex fluid-particle-structure interaction problems to showcase its predictive capability.

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Ray Tracing Discrete Element Method

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We introduce a novel, efficient and robust approach, the ray-tracing discrete element method (RTDEM), for direct numerical simulations of granular materials. To accelerate RTDEM simulations on graphics processing units (GPUs), advanced algorithms have been developed to leverage the specific ray-tracing cores equipped on RTX GPUs. RTDEM is composed of two variants: sphere-RTDEM and mesh-RTDEM, which respectively model spherical and arbitrarily shaped particles. Sphere-RTDEM is particularly useful for simulating large-scale geotechnical problems, such as landslides and debris flow. Our performance tests have shown that sphere-RTDEM can achieve a 1000x speedup for simulations of dry debris flow compared to commercial software particle flow codes (PFC). Mesh-RTDEM uses triangular meshes to represent arbitrary shapes and introduces energy-conserving contact models, such as vertex-potential and facet-potential models, to enable robust contact resolution. These contact models benefit from our novel discrete potential field functions. Moreover, we have proposed shape templates to efficiently tackle arbitrarily shaped particles with extreme size ratios. RTDEM is poised to be a next-generation tool for modeling large-scale granular systems with ease and efficiency, which has been implemented in our numerical computing platform SudoSim.

Keywords: disrete element method; arbitrary shape; large-scale simulation; GPU; ray tracing

Global Analysis of Slope Stability and Location of 3-Dimensional Critical Slip Surfaces

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Although there are many methods that can be used for slope stability analysis, the limit equilibrium method remains absolutely dominant in slope codes. The classical limit equilibrium method requires dividing the slope into slices, and is therefore also known as the method of slices. According to whether all the equilibrium conditions are satisfied, the limit equilibrium method can be divided into a rigorous method that satisfies all the equilibrium conditions and a simplified method that satisfies only some of the conditions. The rigorous method, which is considered to be more reliable, is always preferred for slope stability analysis. However, the rigorous method may not converge. In such a case, a less reliable simplified method has to be chosen. In addition, the 3D method of slices has been shown to satisfy at most 5 equilibrium conditions, so all the 3D methods of slices are simplified methods.

The global analysis that I will present in this talk takes the whole sliding body as the loading body instead of a single slice [1], and the 3D rigorous limit equilibrium method that satisfies all the equilibrium conditions can be realized very easily. Moreover, it can be proved that the solution of the safety factor can be reduced to an algebraic eigenvalue problem [2], thus completely solving the problem of non-convergence of the rigorous limit equilibrium method.

Compared with the solution of the safety factor, the location of the critical slip surface has stronger nonlinearity, and the automatic location of the 3D critical slip surface without specifying surface shape is still an open issue. In this talk, I will report our latest progress on this issue. Figure 1 demonstrates an example of a tunnel entrance slope.

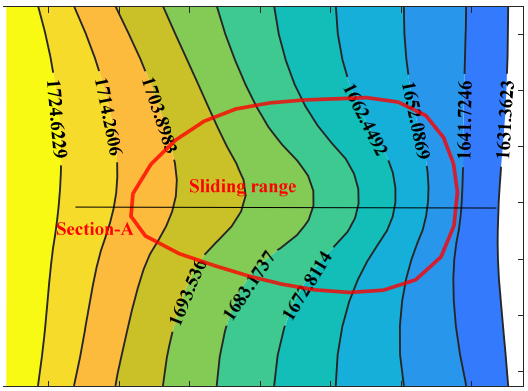


Fig 1(a) Slope contours

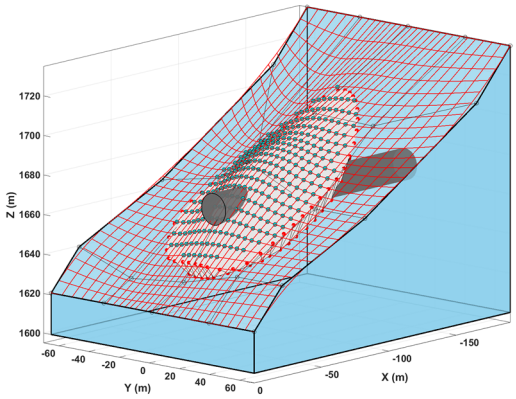


Fig 1(b) The tunnel and the 3D critical slip surface

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Analysing Thermo-Hydro-Mechanical Coupled Problems Using the Material Point Method

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The material point method (MPM) offers an effective approach for analysing large-deformation problems, such as landslides that often involve unsaturated soils[1]. Several MPM formulations for unsaturated soil have been reported in the literature, but they assumed that soil water retention ability and permeability function are independent of soil deformation. Furthermore, most studies assumed isothermal conditions, although friction-induced heating of the shear band could greatly affect the behaviour of saturated and unsaturated soils. To address these problems, a thermo-hydro-mechanical (T-H-M) coupled MPM formulation has been developed based on the two-phase two-point framework. The information of solid and liquid phases is carried by two individual sets of material points, assuming zero air pressure. The developed MPM formulations consider the effects of porosity and temperature on the water retention curve and permeability function of unsaturated soil. The elastoplastic mechanical behaviour is modelled by the Drucker-Prager model, which is modified to consider shearing-induced dilation/contraction, suction, and thermal effects. The MPM was validated using the results of physical model tests (for large-deformation problems) and finite element analysis (for small-deformation problems). Then, parametric studies of landslides were carried out using the T-H-M coupled MPM.

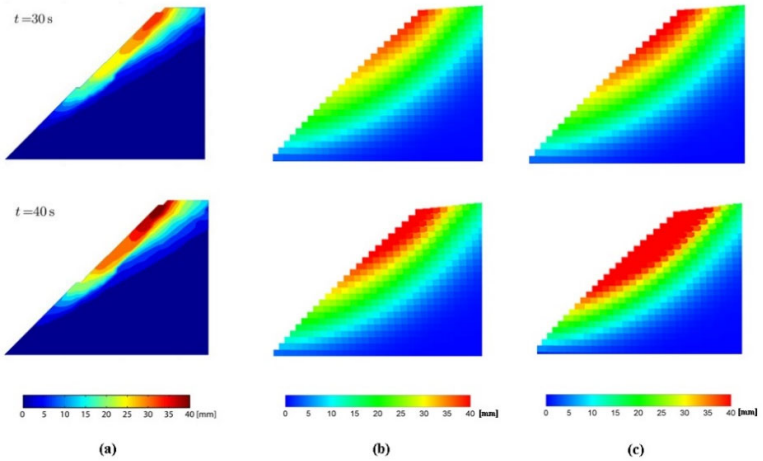


Figure 1. Displacement of an unsaturated sand slope is subjected to rainfall (a) measured in a centrifuge test (Wang et al., 2021); (b) MPM results considering porosity effects on SWRC and permeability function; and (c) MPM results with constant SWRC and permeability function.

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Coupled Total- and Semi-Lagrangian Peridynamic Modeling of Hydraulic Fracturing in Solids

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The peridynamics (PD) theory is often applied in modeling evolving discontinuities in solids. In reality, fracturing may often occur under a multi-physics context where fluid flow and even thermal field need to be considered simultaneously, examples include hydraulic fracking operation in petroleum exploitation. Numerical modeling of such processes remains challenging owing to the intricate interplays between solid deformation, fluid flow, and evolving fractures. In this study, we simulate the fluid-driven fracturing in solids with a coupled total- and semi-Lagrangian PD approach. The classical, total-Lagrangian PD is used for modeling brittle fracture in solid while the semi-Lagrangian PD is used for simulating fluid flow. A fluid-solid interface model is tailored for coupling the two formulations. The capacity of the semi-Lagrangian PD is demonstrated with simulations of water dam collapsing problems. The coupled computational scheme is then validated with the crack opening problem due to hydraulic pressure and the Kristianovich-Geertsma-De Klerk (KGD) problem (Fig. 1). We show that the coupled computational approach can reasonably capture the crack profile and growth subject to fluid pressure. We further consider the situation where the solid is a porous media and propose a computational approach which simulates porous flow during hydraulic fracturing. In such cases, the fracturing in the solid is accompanied by permeation of fluid into the porous media. Mass exchanging is modeled between the flow in fracture and porous flow, with two-way coupling between the mechanical field and porous flow. The model is validated with the classical one-dimensional consolidation problem, and the capacity of the computing scheme is illustrated with simulation of hydraulic fracturing in porous solid.

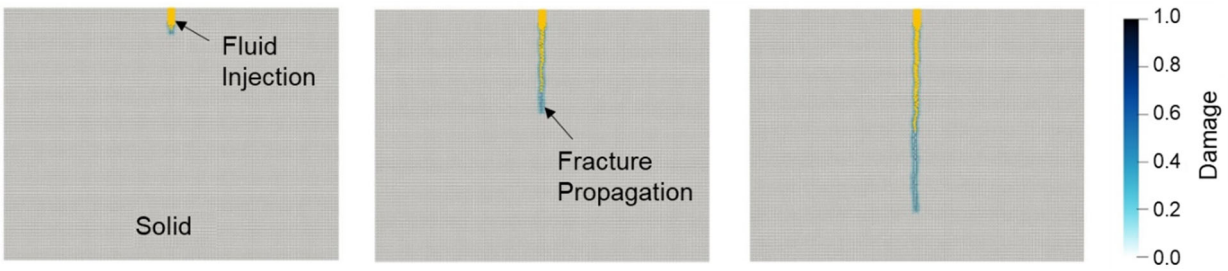


Figure 1. Simulation of fluid-driven fracturing in solid with coupled total- and semi-Lagrangian peridynamic approach.