ALERT Geomaterials

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33rd ALERT Workshop / POSTER SESSION

Booklet of abstracts

Editors: Nadia Benahmed
Antoine Wautier

(INRAE, France)

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The Alliance of Laboratories in Europe for Education, Research and Technology

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Poster Session

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Dear colleagues,

We are pleased to welcome you to Aussois and to our 33rd ALERT Workshop and School.

As always, it is an exciting time for us to continue to meet and bring together inspired people for fruitful days with interesting, stimulating discussions, exchange of knowledge and experience on Geomechanics. Presentations of recent advances offer the chance to get up-to-date and to remain at the cutting edge.

We would like to express our thanks to all of you who contributed to the success of this poster session!

We wish you a good workshop and school experience and a pleasant stay in Aussois (or elsewhere if you attend the workshop remotely)!

Kind regards,

Nadia Benahmed and Antoine Wautier.

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4-cell analogical model to describe plastic shear behavior of granular geomaterials

Takashi Matsushima[1], Yosuke Higo[2], Yu Otake[3]

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Keywords: Micromechanics constitutive model, uniform strain model.

Abstract

Constitutive modelling of quasistatic plastic shear behavior of granular solid is essential in geotechnical engineering problems. Various models describing complicated soil behaviors have been proposed mainly in the framework of phenomenological elastoplastic models as an extension of J2 flow theory in metals. Although another framework called micromechanics models have also been studied to describe the bulk behavior of granular assemblies in terms of grain scale mechanics, they are still under investigation. This study deals with the model of the latter type as a modification of the one proposed by Matsushima and Chang (2007). We introduce a 4-cell analogical model with which the orientational distribution of contact forces in the uniform strain model (Chang & Misra 1990) is modified to describe the plastic yielding toward critical state. The following figure shows an example of the response of the biaxial compression test under constant confining pressure in 2D granular assembly obtained by the proposed model. The transient behavior differs in different initial void ratio, and the stress ratio and the void ratio converges to the identical critical state. We also confirm that the response under constant volume test is similar to that of the undrained test of sandy soil.

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Figures

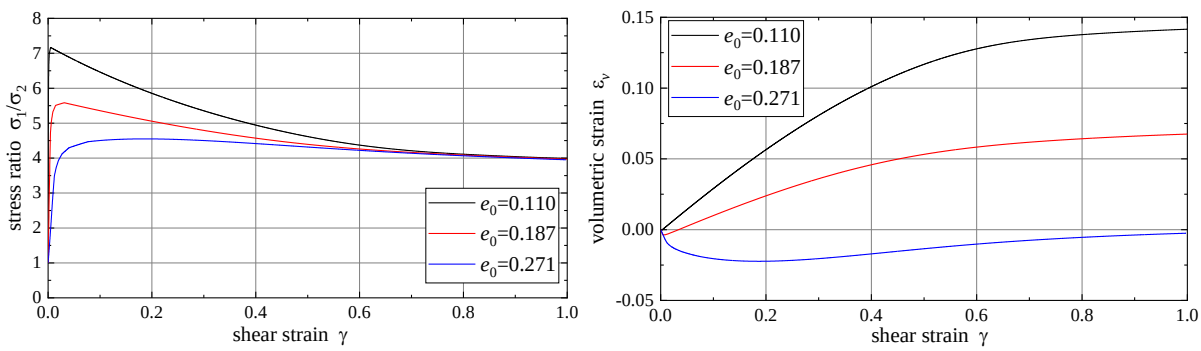

Figure 1 : *Biaxial compression response of the proposed model (stress ratio change (left) and volumetric strain change (right) in terms of shear strain*

The Resilience of Localisation in Brittle Porous Media

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Keywords: porous media, stress drops, localization, boundary conditions, constitutive model

Abstract

Brittle porous media subjected to confined compression experience compaction behaviour ranging from smooth stress-strain to one with recurrent abrupt drops in stress, which are often coincident with compaction bands. To study the persistence of the stress drops and compaction bands, we performed experiments with non-traditional experimental boundaries, ranging from embedded objects to non-flat boundaries. Our results show that localisation initiation and propagation endure despite non-conventional boundary conditions. Furthermore, we develop a novel model that qualitatively generates the different stress drop regimes observed. The key to the model's achievement is the meso-related temperature, which characterises the fluctuating velocities at the meso-scale and is general to all heterogeneous porous media. We assume that such temperature induces a loss of strength at the macro-scale and leads to a stress drop, where stress can recover because the meso-related temperature decays into micro-related (thermal) temperature. Our model provides insight into the physical mechanisms required to generate these compaction patterns and could generate compaction bands in boundary value problems for brittle porous media.

Figures

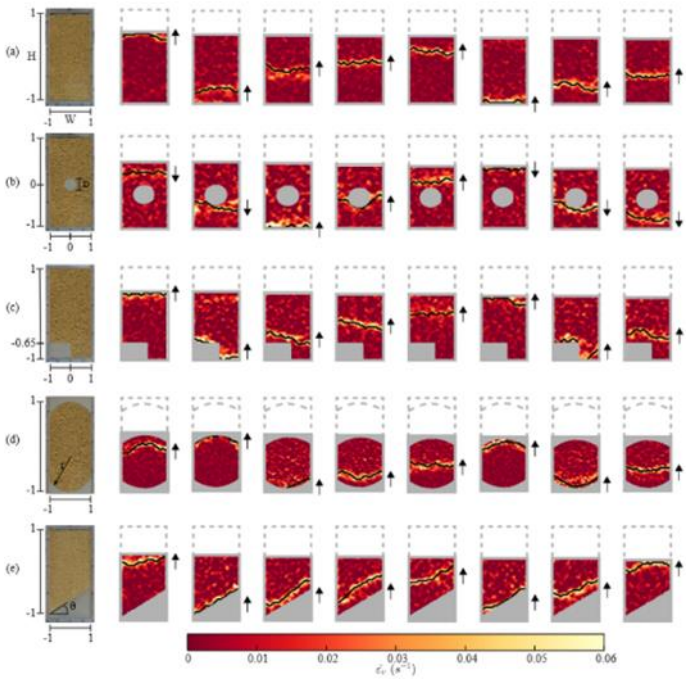

Figure 1: *Experimental geometries are shown in the left column with normalised height H and normalised width W and the corresponding volumetric Eulerian strain rate fields are shown to the right for: (a) rectangular domain, (b) free-floating cylinder with an initial normalised diameter D = 0.4, (c) embedded rectangle, (d) convex where the initial normalised inscribed circle radius r = 3, and (e) slanted bottom boundary that occurs at a non-normalised angle θ = 30°. Each snapshot of the strain rate field is separated by roughly 2 seconds. The black lines overlaying the colourmap denote the location of the compaction band. The black arrows denote the direction that the compaction band is travelling*

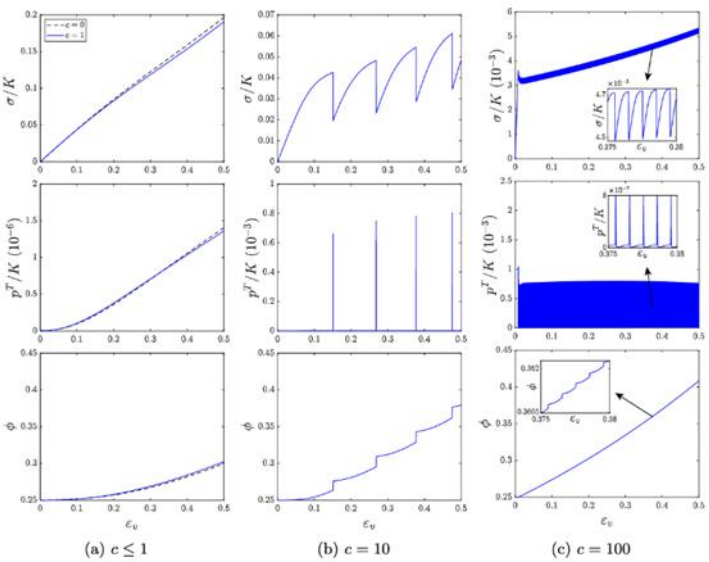

Figure 2 *: The effect of meso-related softening (kinetic softening) on the constitutive behaviour. Panels (a-c) show the response for three different values of a kinematic softening parameter c. Here, the effects are shown for the evolution of normalised axial stress σ/K (top), normalised thermodynamic pressure pT/K (middle), and solid fraction ϕ (bottom), all against volumetric strain εv. For reference, the black dashed line shows the compaction behaviour when c = 0. The inset plots in (c) show a zoomed view to identify the rapid oscillations. Note the different vertical axis between columns*

Creep-quake cycles in calcareous sand and rock salt

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Keywords: Calcareous sand, Dissolution, Acid, Quakes, Periodic

Abstract

Dissolution processes in porous media concern a vast number of industries and disciplines. In rocks and soils, this process can result in the formation of sinkholes, the sudden collapse of rock formations, and in the degradation of CO2 sequestration structures and tailing dams. Previous studies on puffed rice cereals show how partial degradation of a uniaxially compressed porous medium may result in the emergence of a collapse pattern characterised by cyclical localised collapse events, or quakes, followed by creep periods. In this study, we present a set of experiments to demonstrate how these creep-quake cycles can also emerge in hard soils (sand) and rock salt. Additionally, we describe the mechanism that underpins the collapse cycles with a general theoretical model, which we successfully implemented to qualitatively reproduce our experimental results. Our findings suggest that a non-uniform dissolution field and a compressive stress are the two main factors needed for creep-quake cycles to develop. Ultimately, we link the resembling collapse patterns of these seemingly different porous media under a single mechanistic umbrella responsible for its emergence.

Figures

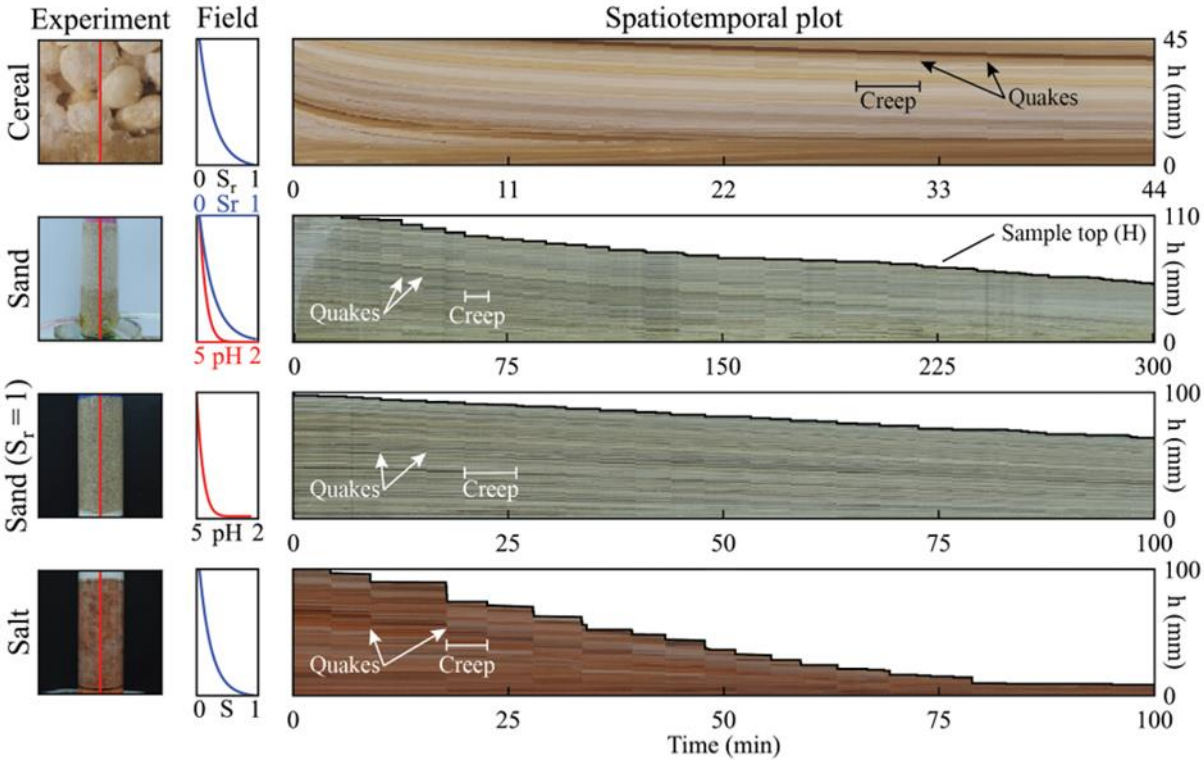

Figure 1: *Creep-quake cycles in: puffed rice under water saturation field (Sr, from Einav & Guillard 2018); calcareous sand partially saturated in acetic acid solution(Sr is saturation and pH = 2.4 is imposed at the bottom); calcareous sand fully saturated in acetic acid solution (pH = 2.4 at the bottom); and rock salt fully saturated in brine with a solubility field (S, achieved by injecting fresh water from the bottom). The columns from left to right show: photos of the experiments; their corresponding dissolution fields; and spatiotemporal plots of the pixels located under the red line on the left images, in which the creep-quake can be observed*

A consistent calibration process for the Matsuoka-Nakai friction angle under direct simple shear conditions for clay hypoplasticity

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Keywords: hypoplasticity, Matsuoka-Nakai, clay, direct simple shear, critical state barodesy

Abstract

In geotechnical engineering, direct simple shear (DSS) tests are used to determine strength and stiffness parameters of a material. DSS predictions of a constitutive model influence failure mechanisms in plane-strain, finite-element applications. We introduce a closed-form solution to determine the Matsuoka-Nakai equivalent critical friction angle from direct simple shear stress and normal stress data. In order to apply it to clay hypoplasticity (Mašín, 2013), we carry out DSS simulations to investigate rotations of principal stresses and the principal stress state at critical state for plane-strain conditions. Finally, we interpret DSS predictions of clay hypoplasticity for different overconsolidation ratios and demonstrate that the location of the CSL in the vertical stress - void ratio plane coincides with the location of the CSL in mean effective stress - void ratio plane, see Figure 1.

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Medicus G., Kwa K. & Cerfontaine B. (under review) A consistent calibration process for the Matsuoka-Nakai friction angle under direct simple shear conditions for clay hypoplasticity, revised and resubmitted to: Computers and Geotechnics

Figures

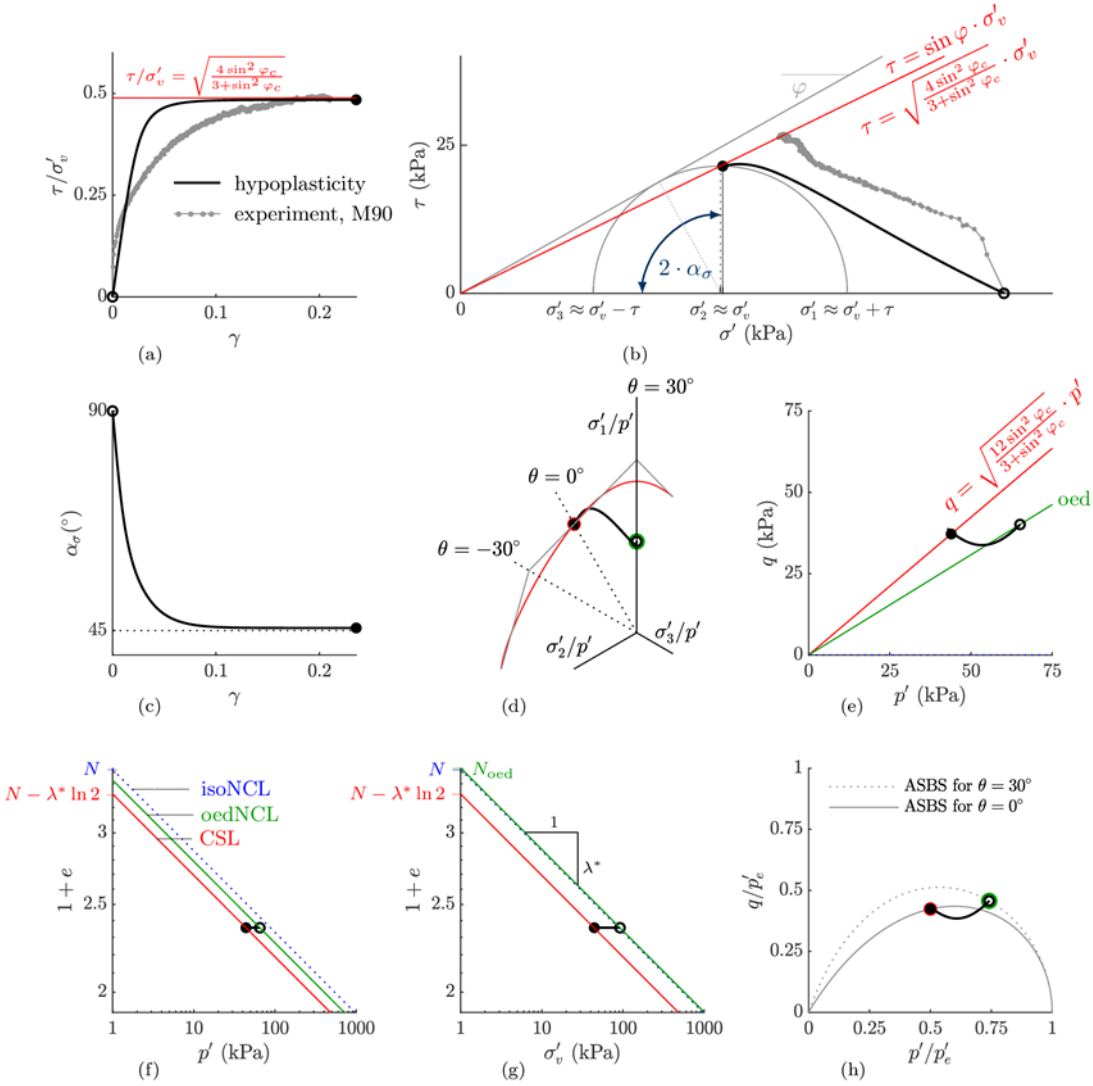

Figure 1: *Undrained DSS test starting at oedometric normally consolidated state. Simulations with clay hypoplasticity (Mašín, 2013), DSS test data (M90) from Laham et al. (2021))*

Remote and in-situ sensing of avalanche dynamics as part of a holistic model calibration

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Keywords: snow, radar, particle tracking, numerical modelling, open source code

Abstract

The flow behaviour of snow avalanches strongly depends on temperature and is therefore expected to be sensitive to climate induced changes [4]. Traditional avalanche models may be calibrated to cold and warm flow regimes. Although it is known that flow regime transitions exist, each regime is usually associated with a certain event, that allows to fit different parameter sets for the applied model, usually mimicking the observed runouts. When more information about the dynamics is available, such as frontal approach velocities or single particle velocities determined by field measurements, the optimized parameters are only in a reasonably small range for events associated with low temperatures. This clearly shows the need for more advanced models. However, the calibration of such models is more complex and cannot be performed with traditional observations like runout and deposition. We demonstrate ways to compare radar measurements with numerical results using synthetic radargrams [5,6] (Figure 1) and innovative methods for observing the internal flow dynamics [2,3] (Figure 2) of real-world events. The overall goal is to incorporate the results of these new field measurements along with traditional observations in a holistic manner into an automated calibration tool for an open-source avalanche modelling framework [1].

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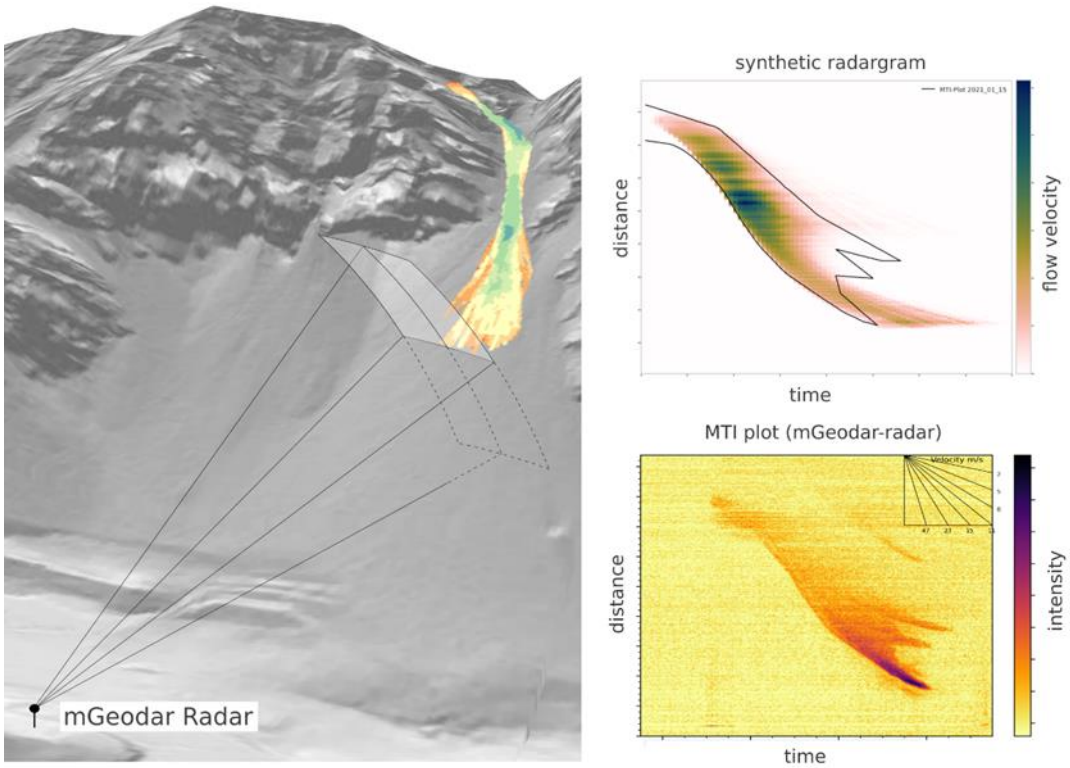

Figure 1: *AvaFrame simulation of an avalanche at the Nordkette by Innsbruck: synthetic radargram extracted from simulation, MTI plot from mGeodar radar measurement of real event. (based on [5])*

Figure 2: *AvaRange - multiple sensor device (AvaNode) moving with an avalanche on the Nordkette near Innsbruck, path of the AvaNode and excavated deposited AvaNode*

From 65 years of surface displacement towards modeling – A case study at a deep-seated gravitational slope deformation (Tyrol, Austria)

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Keywords: Natural hazard research, deep-seated gravitational slope deformation, point clouds, photogrammetry, multi-hazard, displacement time series.

Abstract

Deep-seated gravitational slope deformations (DSGSDs) pose serious threats to buildings and infrastructure in mountain regions. The understanding of past movement behavior is an essential requirement for enhancing process knowledge and potential mitigation measures. In this context historical aerial imagery provides a unique possibility to assess and reconstruct the deformation history of DSGSDs. Free and open-source (FOSS) photogrammetric tools have proven feasible for analyzing the long-term behavior of the Reissenschuh DSGSD (cf. Branke et al., 2020; Pfeiffer et al., 2018), in the Schmirn valley (Tyrol, Austria). The derived 3D point clouds also allow for analysis of related secondary processes as changes in creep velocity, rockfall or debris flows. For the photogrammetric analyses, scanned analogue and digital imagery of six acquisition flights, conducted in 1954, 1971/1973, 2007, 2010, and 2019, have been processed using the photogrammetric suite MicMac. An improved version of the image correlation approach (IMCORR) implemented in SAGA GIS was used for the area-wide assessment of slope deformation. For the georeferencing and scaling an airborne laser scanning (ALS) point cloud of 2008 provided by the Federal State of Tyrol (Austria) was used. In total five photogrammetric 3D point clouds covering the period from 1954 to 2019 were derived and analyzed in terms of displacement, velocity and acceleration. The accuracy assessment with computed Multiscale Model to Model Cloud Comparison (M3C2) distances between photogrammetric 3D point clouds and reference ALS 3D point cloud, showed an overall uncertainty of about ±1.2m (95% quantile) for all 3D point clouds produced with scanned analogue aerial images (1954, 1971/1973 and 2007), whereas 3D point clouds produced with digital aerial imagery (2010, 2019) showed a distinctly lower uncertainty of about ±0.3 m (95% quantile). Also, digital elevation models (DEM) of difference (DoD) for each epoch were calculated. IMCORR and DoD results indicate significant displacements up to 40 meters in 65 years for the central part of the landslide. The historical data sets further indicate a change of spatio-temporal patterns of movement rates (Figure 1) and a minor but overall acceleration of the landslide. The research enabled the characterization of the spatio-temporal movement patterns of the Reissenschuh DSGSD over more than six decades. Further research will incorporate the results as reference for numerical modeling the discussed multi-hazard

processes (cf. Kappes et al., 2012). For this approach field sampling of soil material was conducted and assessed in terms of friction angle and cohesion by triaxial shear tests within the geotechnical laboratory of the University of Innsbruck (cf. Schneider-Muntau et al., 2018).

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Figures

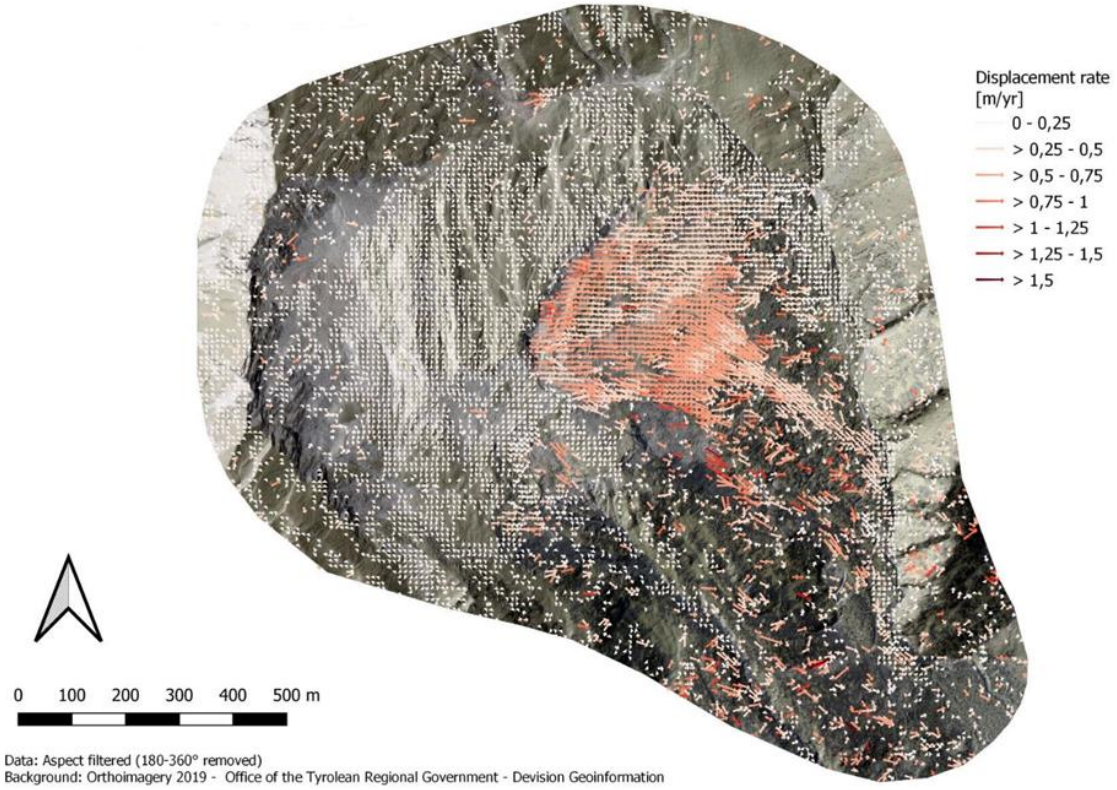

Figure 1 *: Displacement rate in meters per year derived from IMCORR feature tracking approach resulting from surface data acquired by photogrammetry (1954, 1973, 2007, 2010 and 2019) and the airborne laser scanning mission 2008 by the Federal State of Tyrol, combining 65 years of displacement information. Large gaps in debris covered areas and forest are due to rapidly changing surface and therefore no correlation could be found*

The geological and geotechnical analyses on the Ludoialm landslide (Tyrol, Austria)

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Keywords: Slope stability, Trigger factor, Snow melting, Seepage, Permeability, Geotechnical computation

Abstract

Landslides are common natural hazards worldwide. The Ludoialm landslide, which is located in the municipality of Münster in Tyrol, Austria, represents a large-scale landslide in the Alps [1, 2]. In past decades, there were two remarkable reactivation phases of this landslide - most probably due to intensive snow melting, which occurred once in early April 1967 and once in February 1999. The material loss is approximately 486,000 m^3 in volume by GIS analysis, with a length and width of about 550 m and 180 m, respectively. The basal sliding surface is gentle and roughly parallel to the slope surface with a dip angle of only about 12° according to the geological survey. The stratigraphy of the Ludoialm landslide is dominated by Cretaceous sediments of the Gosau Group which are overlaid with glacial deposits.

The failure mechanisms for the initial landslide formation and ongoing movement characteristics haven't been identified yet although a temporal coincidence between meteorological events and soil mass movements is shown. Our contribution adopts both geologic and geotechnical perspectives to provide a comprehensive analysis of the predisposition and initiating factors of this only slightly inclined landslide. A representative cross-section near the centerline along the direction of the landslide is selected for the 2D computations. The material parameters are based on the triaxial tests of soil samples taken from the landslide site and on field tests on site.

Limit equilibrium analysis (LEA), strength reduction finite element analysis (SRFEA) and finite element limit analysis (FELA) are employed and the computational results are compared, e.g. factor of safety (FoS) and the location of sliding zone. The location of calculated slip surface fits well with the one geologically assumed and obtained by field investigations.

This case study confirms that a high groundwater table due to intensive snow melting was an unfavorable factor for the Ludoialm landslide reactivations under consideration of different permeabilities for different soil layers. In this case study, considering different permeabilities in the stratified slope is essential to achieve a realistic sliding zone.

Acknowledgement

The research is funded by the University of Innsbruck in support of the doctoral program "Natural Hazards in Mountain Regions"(https://www.uibk.ac.at/alpinerraum/dps/dp-mountainhazards/). X. Dai has also received funding from the University of Innsbruck's "Exzellenzstipendien für Doktoratskollegs (DK)" fellowship programme (grant no. 2021/TECH-47). X. Dai is partially funded by Le Pôle interdisciplinaire d'études françaises de l'Université d'Innsbruck (Frankreich-Schwerpunkt der Universität Innsbruck).

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Figures

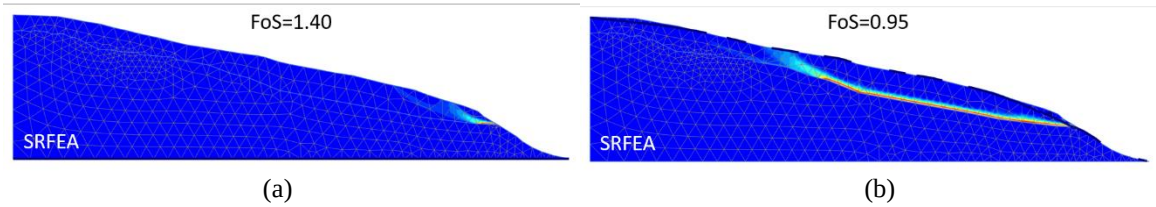

Figure 1 *: Safety analysis (a) without the consideration of seepage; (b) with the initial groundwater table of 1458 m (close to the slope surface)*

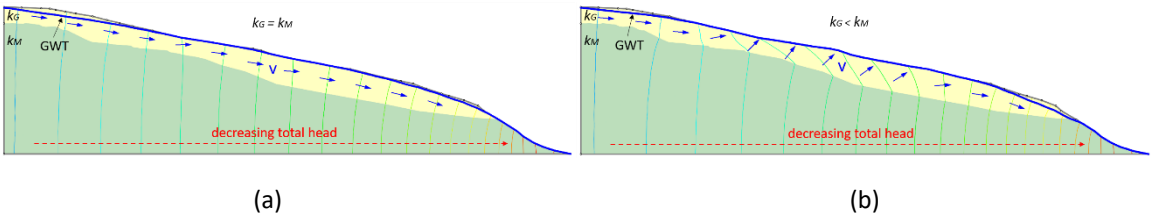

Figure 2 *: Directions of flow velocity (in upper glacial deposit layer). kG and kM represent the permeability coefficients in upper glacial deposit and lower marl layers, respectively. (a) in the case of equal permeability (kG = kM); (b) in the case of different permeabilities (kG < kM)*

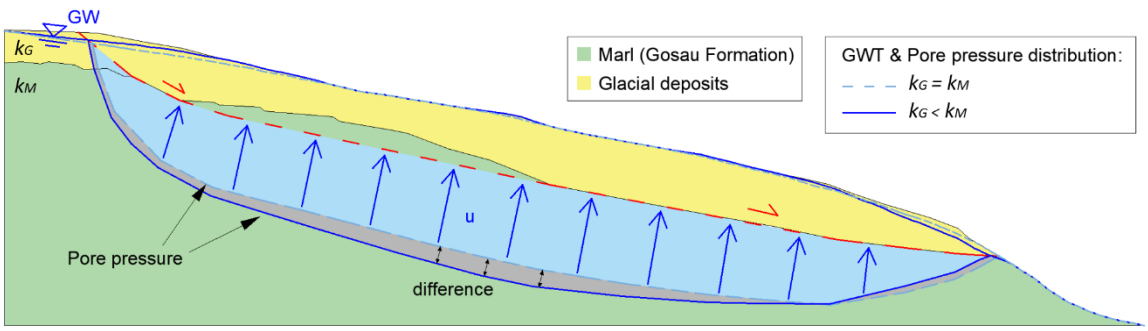

Figure 3 *: Schematic diagram of pore pressure distribution at the location of the basal shear zone (red dashed line) for cases with same and different permeabilities for both layers*

Permeable Structure for Mitigating the Effects of Debris Flows: A Two-phase Two-layer Depth-integrated SPH-FD Modeling

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Keywords: Permeable structure, SPH, Two-layer, Dewatering

Abstract

Permeable structures, such as flexible barriers and bottom drainage screens, are structural countermeasures designed to reduce the run-out distances of fast landslides. These energy dissipation structures consist of grids with a specified space between them to separate some amount of water from the solid skeleton, dissipate pore pressures, and increase friction between particles.

In this study, a depth-integrated model is used to reproduce the dynamic behavior of fast landslides propagating over a terrain equipped with a permeable structure. In the proposed computational model, there are two balance equations of mass and linear moment and one consolidation equation which are discretized with the numerical techniques of the smoothed particle hydrodynamics (SPH) and finite difference, respectively. It also has a two-phase formulation where the soil-water mixture is represented by two sets of particles, pore-water and soil skeleton, carrying all field variables. In this study, the previous model is developed into a two-layer model to enhance the description of the desaturated flowing mass with an upper desaturated layer and a lower saturated layer.

This so-called two-phase two-layer SPH-FD model will be applied to three types of cases where dewatering is the consequence of fluid particles (i) passing through two permeable walls located on both sides, (ii) passing through a permeable wall, and (iii) draining through a permeable basal screen.

Acknowledgement

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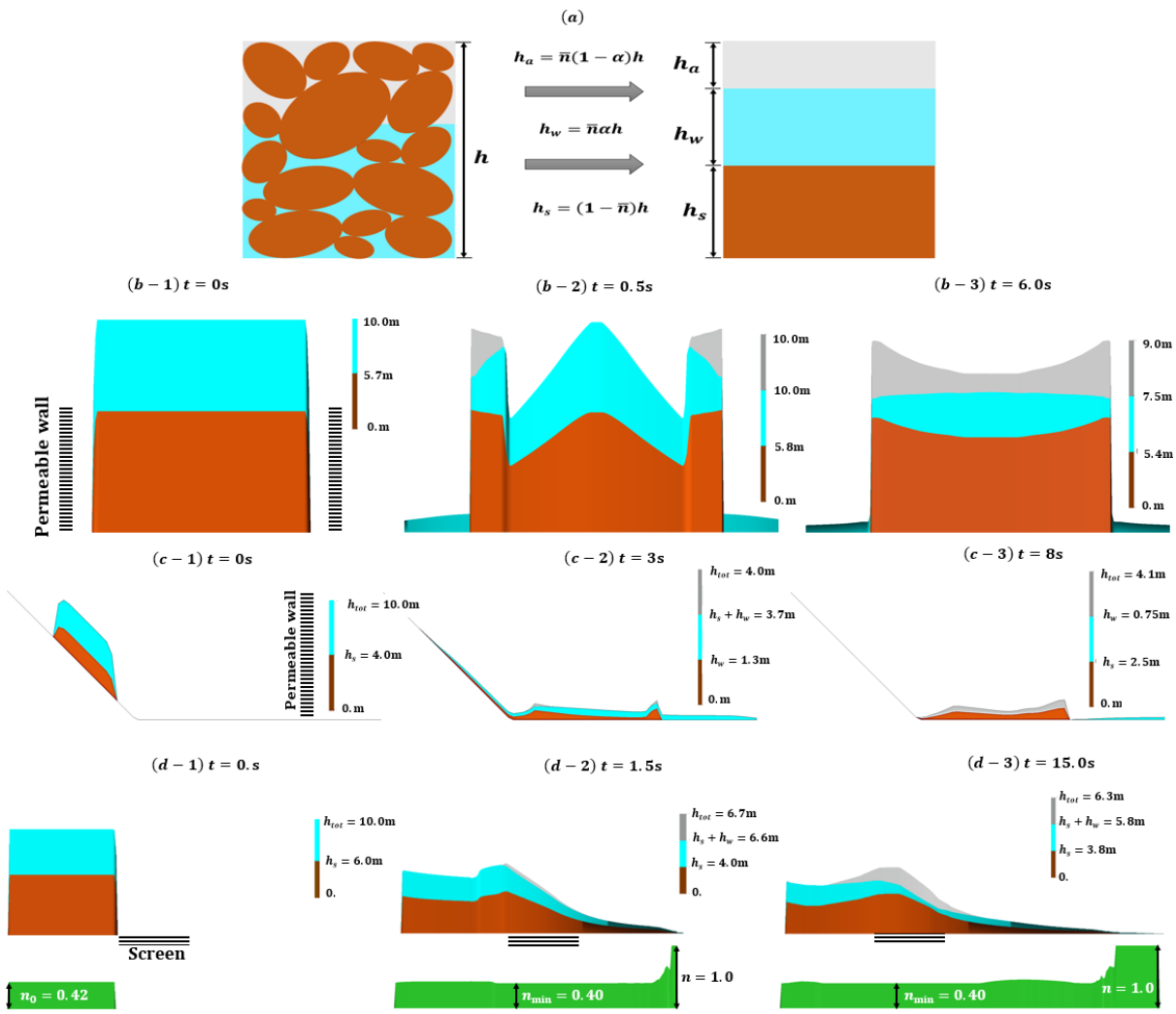

Figure 1: *(a) Magnitudes characterizing the partially saturated debris flow components. h_s, h_w and h_a are the partial heights corresponding to the solid, fluid and air phases. n is the porosity and α the relative height. Simulation of cases where dewatering is the consequence of fluid particles (b) passing through two permeable walls located on both sides, (c) passing through a permeable wall, and (d) draining through a permeable basal screen.ypical simplification of complex loading scenarios based on the Miner's rule postulate*

Stability of anchored walls

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Keywords: finite elements, limit analysis, design

Abstract

The stability of anchored walls is traditionally computed by limit equilibrium methods (LEM) employing appropriate failure mechanisms. Therefore, one has to choose in advance which failure is predominant, e.g. insufficient passive capacity, failure by overturning, rotational failure of ground mass. Advanced numerical methods like the strength reduction finite element method (SRFEM, Zienkiewicz et al. 1975, Tschuchnigg et al. 2015) or the finite element limit analysis (FELA, Sloan 2013, Tschuchnigg et al. 2015) are capable of identifying the dominant failure mode while computing the factor of safety. Such the failure mode is no longer an essential input. The computed values for the factor of safety for slopes are pretty similar to the values gained with LEM (e.g. Cheng et al. 2007) which opens the door for the practical application of these methods. Here we show the application to a specific example of an anchored wall, Figure 1. Using the SRFEM, the predominant failure mechanism can be unambiguously determined for different anchor lengths, Fig. 2. The factor of safety for the overturning failure (Fig. 2-b) computed by LEM according to design approach 2 (Fellin 2017) is FOS = 1,17. SRFEM yields FOS = 1,17 and FELA computes FOS = 1,17 $\pm$ 0,02. Thus, in our example the factors of safety are virtually equal, which means that a design based on these factors of safety has basically the same level of safety. This is a further evidence that advanced numerical methods can be recommended for practical design tasks.

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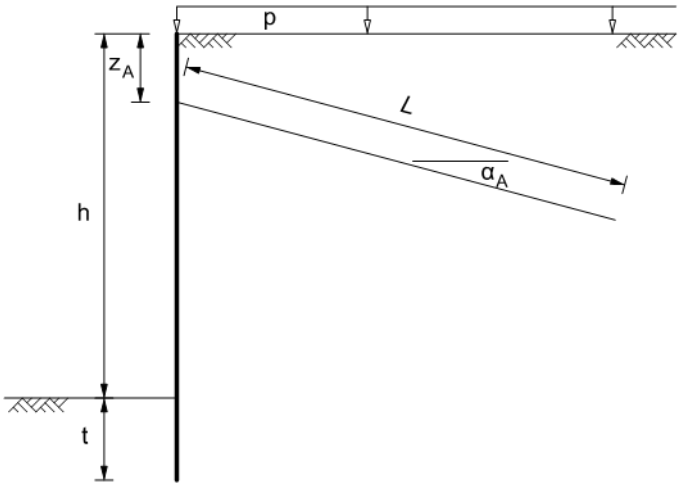
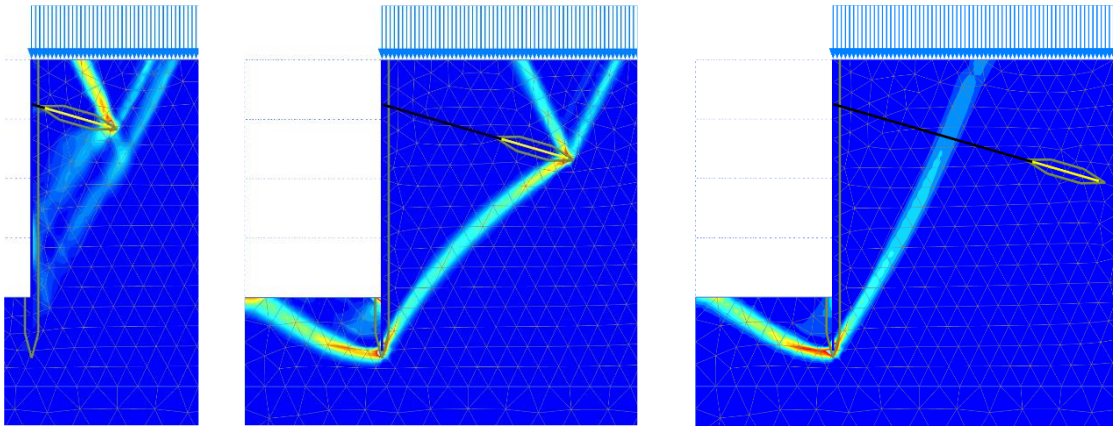


Figure 1: *Anchored wall: h = 8,0 m, t = 1,8 m, anchor z_A = 1,5 m, α_A = 15°, L = 8,75 m, soil γ = 17 kN/m^3, ϕ = 35°, c = 0, load p = 10 kN/m^2.*



a) L = 3 m
forward
rotation

b) L = 7 m
overturning, failure in the lower
sliding plane

c) L = 10 m
insufficient passive capacity

Figure 2 *: SRFEM - incremental deviatoric strain at failure for various anchor lengths*

Microstructures and micromechanisms of deformation in water-saturated gypsum

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Keywords: Gypsum, microcracking, kinking, dissolution, microstructures.

Abstract

The mechanical properties of evaporite rocks are rising increasing interest in the scientific community for the key role in tunnelling, mining and energy underground storage.

In particular, the excavation of underground infrastructures in natural formations containing sulphates (e.g. gypsum and anhydrite) have often registered technical problems, including swelling phenomena (Alonso et al., 2013), water weakening (Ramon et al., 2021), creep deformations (Hoxha et al., 2006; Ramon et al., 2021) and karst circulation (Caselle et al., 2020).

Nevertheless, there is a paucity of data about the effect of water on mechanical strength and time-dependent behavior of these rocks. The microstructures and micromechanisms generated during compression and creep in gypsum and anhydrite are to date not well known.

For this reason, the present study proposes an investigation of the mechanical response of a natural gypsum facies from Monferrato (NW Italy). The laboratory investigation includes uniaxial compression, uniaxial creep and triaxial compression experiments on nominally dry, oil-saturated, and water-saturated samples.

Results revealed significant water-weakening in Monferrato gypsum as well as a strong strain-rate dependence of uniaxial compressive strength. Moreover, uniaxial creep tests showed significant time-dependent deformation in wet samples, but not in dry and oil-saturated samples.

From the comparison between our new data and existing literature references for other rock types, we observed that typical micromechanisms (i.e. reduction of fracture toughness for water weakening and stress corrosion for creep), even if present in this rock, are insufficient to explain the deformations recorded in this case.

The Scanner Electron Microscope (SEM) analyses of post-test microstructures (Figure 1) suggested the key role of additional mechanisms related to the intra-crystalline anisotropy of gypsum. Exploiting the crystalline weakness layers, the deformation of the rock opens straight and parallel intracrystalline microcracks (well represented in all the tables of Figure 1). This mechanism is enhanced under the presence of water, since the solubility of gypsum is higher along the planes of the crystallographic layering (Fan and Teng, 2007).

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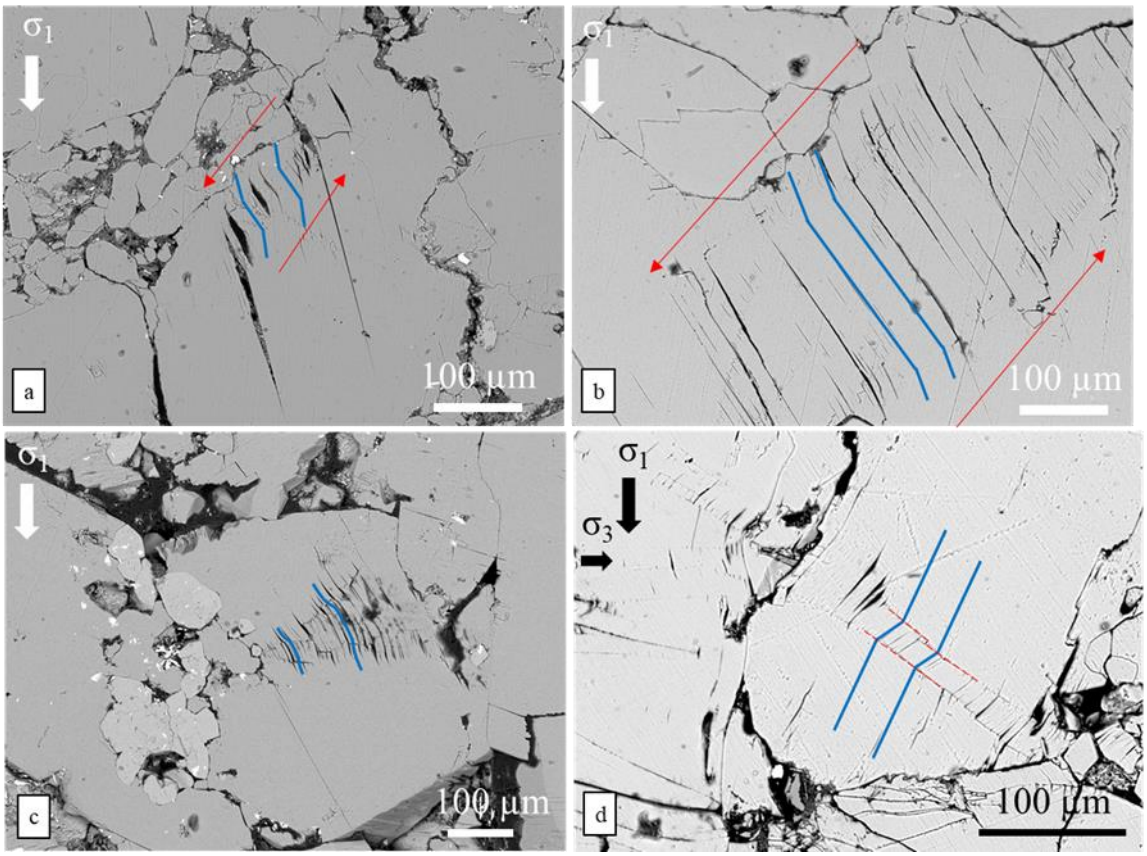

Figure 1 : *SEM microstructures of gypsum samples after mechanical tests (a. Dry uniaxial compression; b. Wet uniaxial compression; c. Wet uniaxial creep; d. Dry triaxial compression with confining pressure = 20 MPa). All the micrographs show straight and parallel intracrystalline microcracks that are consistent with the crystallographic layering of gypsum mineral. These cracks appear to be longer under wet conditions (b) than under dry conditions (a). Under creep (c) and triaxial compression (d), the opening of these microcracks drives the formation of plastic structures and kinking (red dashed lines in d)*

Unravelling the role of natural imperfections on the mechanical behaviour of cemented granular systems: insights from naturally weakly cemented sands

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Keywords: natural imprfections, shear localisation weakly cemented sands, x-ray CT, High Speed Neutron Tomography

Abstract

Weakly cemented sands can be classified as soft rocks; their difference from hard rocks (well-cemented sandstone equivalents) is their nature to disintegrate within a short time (from days to several years) when being exposed to water and climatic changes. This loss of strength is irreversible under normal conditions [Nickmann et al., 2006]. Understanding the mechanical behaviour of weakly cemented sands is crucial for several geotechnical engineering applications (e.g., shallow foundations, offshore construction, slope stability) because of the potential hazards posed by these materials. Previous work mainly focused on capturing how different cement types (i.e., concrete cement [Li et al., 2015], bio cement [Terzis & Laloui, 2019]) enhance the mechanical behaviour and durability of artificially cemented materials. This work has aimed to study the micromechanics of natural soft rocks exposed in a French outcrop, where numerous deformation bands have been observed locally.

Soriano's PhD thesis was carried out for this purpose focusing on a) the textural characterisation of the outcrop material (matrix and deformation bands); b) the mechanical behaviour of the natural weakly cemented material; and c) the manufacturing of an artificial material that mimics the mechanical behaviour of the natural one. The outcrop material has ~300 μm grain size and contains both quartz and clay cement. Several imperfections related to previous diagenetic and/or deformation processes captured in the tested material. In this presentation, we focus only on results from triaxial compression experiments conducted on natural weakly cemented sand samples containing a) regions of enhanced porosity; b) an elongated (greater than the sample's radius) pore, and c) a pre-existing dilation band [Figure 1]. Several non-destructive (x-ray CT, Digital Volume Correlation) and destructive (ESEM) methods were used to capture textural changes and strain fields due to lab-induced deformation. Our experimental results [Soriano, 2019] demonstrate that these imperfections locally trigger or halt laboratory-induced strain localisation. Samples with the elongated pore or with the deformation band are stiffer than those containing zones of enhanced porosity. The presence of local imperfections affects, thus, the system behaviour. However, their local position within the studied samples seems to leave unaffected the inclination of the (new) lab-induced deformation bands. Moreover, the pre-existing dilation band within one of the samples temporarily reactivates but then deactivates as new preferred orientation deformation bands develop.

To better understand fluid migration and flow patterns within weakly cemented sand samples containing dilation bands [Figure 1], we ran flow experiments coupled with High-Speed Neutron Tomography [Charalampidou et al., 2019]. To avoid total disintegration of the samples, we performed initially an oil injection (decane) followed by water (heavy water) injection. Time maps visualised complex flow patterns. Clay particles, aligned along the rims of a pre-existing dilation band, appear to retard oil saturation within the dilation band, while they promote matrix oil migration.

Our results show how complex the mechanical behaviour and the fluid-soft rock interaction can be in the presence of natural imperfections within the tested samples. An in-depth understanding of the local deformation processes and fluid migration pathways can facilitate the constitutive modelling of those materials.

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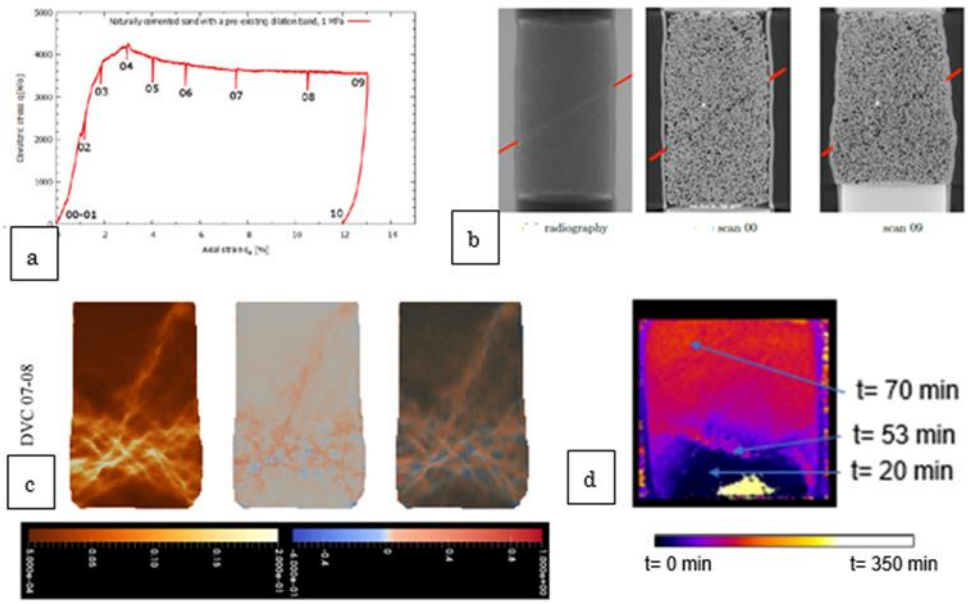

Figure 1 : *a) Deviatoric stress- axial strain in a weakly cemented sand sample (11 mm in diameter) containing a dilation band; b) x-ray radiography and CT vertical sections (red line shows the inclination of the dilation band) of sample in (a); c) vertical section showing shear, volumetric and superimposed shear and volumetric fields of sample in (a); d) vertical section of time map from a bigger sample (38 mm in diameter) containing a network of dilation bands (time maps were derived from high-speed neutron tomography images acquired during 2 phase flow experiments)*

The transition from soil to rock - A constitutive model for the physical characterization of the genesis of rock salt from crushed salt

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Keywords: crushed salt, rock salt, compaction, constitutive model, long-term compaction experiment

Abstract

The conceptual plans for the underground disposal of radioactive waste in salt rock formations are based on extensive backfilling of the residual cavities with crushed salt, taking into account cavity convergence and crushed salt compaction induced by the viscous creep properties of the rock salt mass. As evidenced by natural and engineered analogy, crushed salt becomes compacted in such a way that it assumes long-term material properties similar to those of the surrounding rock salt mass – impermeable to liquids and gases in its undamaged state. As part of the prognoses for the long-term safety of a repository in the rock salt mass, it must be quantitatively demonstrated by calculation that the progressive compaction of the crushed salt backfill (→ soil-like loose material) is suitable for generating a material (→ solid rock) corresponding to the undamaged rock salt mass, which heals the perforations in the geological barrier created during underground excavation of the cavity in the long term. From a physical point of view, this demands to describe the coupled thermal, mechanical and hydraulic processes in space and time that induce the "phase transition" from unconsolidated rock (→ crushed salt) to solid rock (→ rock salt).

In order to eliminate the currently existing deficits regarding the theoretical description of the compaction behaviour of crushed salt in the framework of the constitutive modelling, triaxial experiments on the compaction and permeability behaviour of crushed salt were and are being carried out by the Chair of Geomechanics and Multiphysics Systems and by the laboratories of the project partners within the framework of the joint research projects KOMPASS-I and KOMPASS-II funded by the BMWi. Based on the systematic analysis of the experimental database a constitutive model designated EXPO-COM is being newly developed, which is suitable to describe the compaction behaviour of crushed salt between the boundary states "loose material" and "solid rock" in space and time. Fig. 1 shows an exemplary test from the planed systematically lab program test TUC-V2, in which several influencing factors – porosity, mean stress, deviatoric stress and temperature – were investigated during a total test period of 750 days and valuable information was provided for the constitutive model construction. The poster gives a short overview of the methodology for the constitutive model related planning, evaluation and analysis of the tests as well as for the model development. In Fig. 2 the structure and main functional equations of the constitutive model EXPO-COM are presented.

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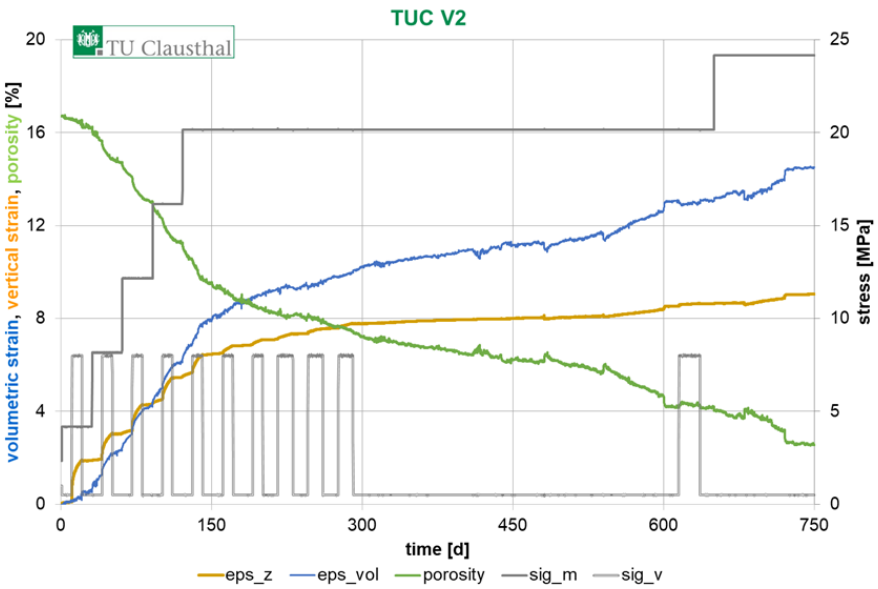

Figure 1: *Laboratory test TUC-V2 for the investigation of the long-term compaction of crushed salt (transition to rock salt)*

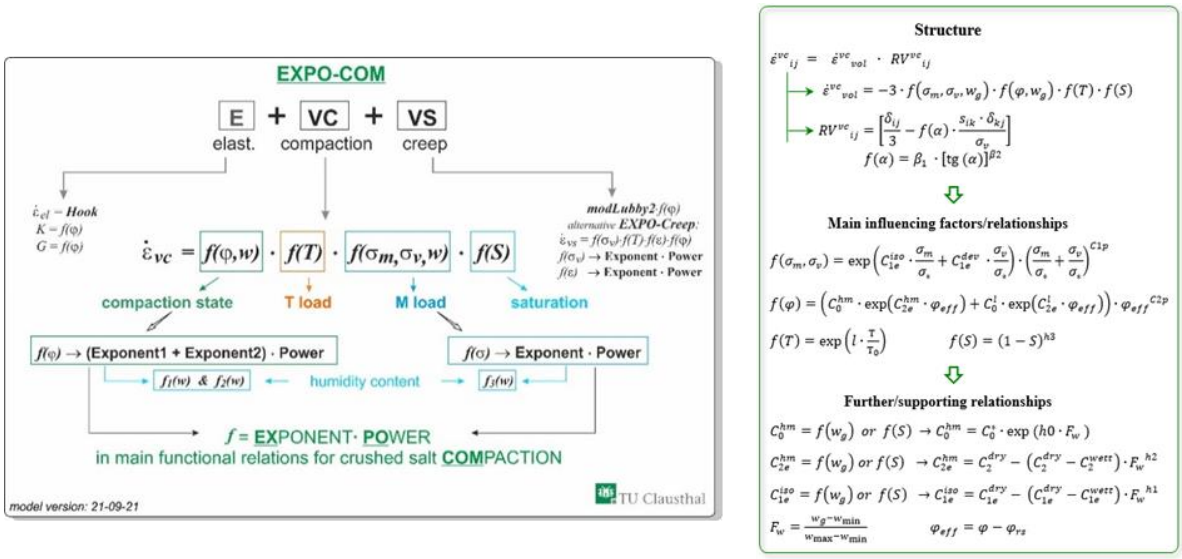

Figure 2*: Structure and functional equations for the constitutive model EXPO-COM*

Dynamic shear strength variations in compressed granular materials

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Keywords: Granular materials, Friction, Shear strength, Dynamic ruptures, Digital Image Correlation

Abstract

Natural faults contain fine granular material, called rock gouge, produced by comminution during sliding. Characterizing gouge rheology is of paramount importance as many large and damaging earthquakes on mature faults in the Earth's crust propagate along layers of rock gouge. The evolution of frictional strength plays a central role in controlling important aspects of earthquakes, including nucleation, shear stress drop, and magnitude [1], and consequently how destructive earthquakes can be. Understanding friction evolution is an active topic of research [1-6]. It is important to understand the velocity dependence of faults as velocity-strengthening faults increase their resistance as slip velocity increases and produce aseismic slip in response to slow tectonic loading, whereas velocity-weakening faults host frictional instabilities and dynamic earthquake ruptures [1, 2]. In this study, we discuss the rheology of compressed rock gouge layers based on our recent experimental findings [7].

To investigate the shear strength evolution of rock gouge layers, we produce spontaneously propagating dynamic ruptures in the laboratory and measure real-time friction variations during rupture propagation. In this study, we employ a novel hybrid configuration (Fig. 1a) featuring a quartz gouge fault embedded along the interface of a polymeric specimen made of Homalite-100 [7]. The laboratory setup mimics earthquakes by dynamic shear ruptures propagating along a quartz gouge interface loaded in compression and shear. This hybrid configuration enables us to initiate dynamic ruptures along the Homalite portion of the interface, due to the smaller instability length scales, and study their propagation along the quartz gouge layer. To quantify the rheology of the gouge layer, we employ our recently developed ultrahigh-speed imaging technique based on the digital image correlation (DIC) method [8-10], capable of capturing the full-field distributions of displacements, velocities, and stresses.

We observe intermittent rupture propagation within the gouge layer (Fig. 2b) associated with pronounced variations of the friction coefficient, obtained as the ratio of shear and normal stresses. The process is typically characterized by an incoming supershear rupture followed by a trailing-Rayleigh signature, both of which are arrested by the gouge layer. Later, various dynamic ruptures re-nucleate within the gouge interface due to dynamic stressing and re-loading of the interface (Fig. 2b). Friction initially exhibits a purely strengthening behavior increasing with accumulating slip but later displays weakening behavior over small slip scales, typically only 5 mm or so. Pronounced dynamic friction strengthening and weakening are associated with the re-nucleated rupture events (Fig. 3b). The marked strengthening displayed by the rock gouge interface with increasing slip rates resembles the velocity strengthening of the standard rate-and-state friction laws [2, 3]. However, the measured behavior is quantitatively different. Most importantly, the relatively mild logarithmic friction changes of the standard rate-and-state friction laws cannot explain the significant weakening and healing observed in our experiments. Rather, our measurements of marked friction reduction are consistent with the flash heating weakening mechanism [6].

A key finding of this work is that friction in rock gouge exhibits significant and repeated variations characterized by marked strengthening at lower slip velocities and pronounced dynamic weakening at higher slip velocities, followed by rapid re-strengthening. Notably, the weakening episodes result in a drop of 50%-75% of the frictional strength in just tens of microns of slip. Such patterns of marked and repeated friction variations explain the intermittent rupture propagation. The complex pattern of observed friction evolution is generally consistent with velocity-strengthening friction at lower slip velocities and significant dynamic weakening at higher slip velocities.

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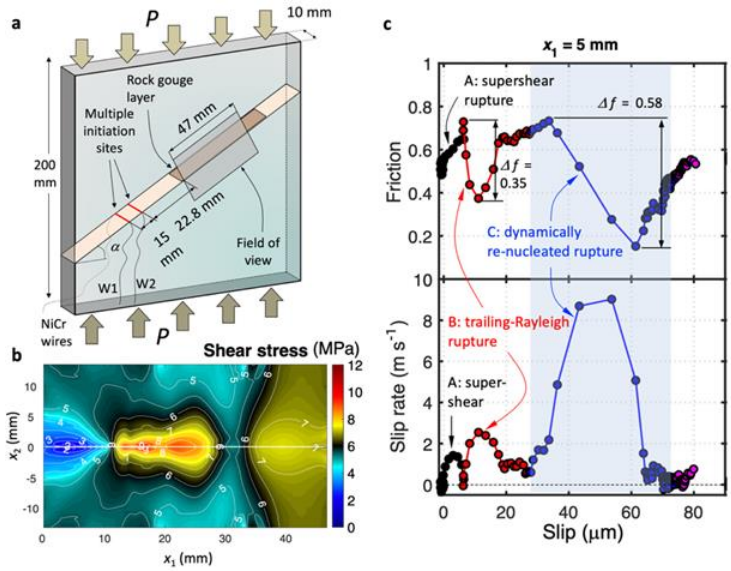

Figure 1 : *Dynamic shear strength variations in experiments with compressed granular materials. (a) Sketch of the experimental configuration featuring the Homalite sample with embedded rock gouge interface; (b) Shear stress variations associated with the remnant of a sub-Rayleigh rupture and a re-nucleated event; (c) Friction and slip rate vs. slip showing the pronounced shear strength variations due to dynamic weakening. Modified from [7].*

Effective parameters for the surface erosion of cohesive soils: An experimental study

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Keywords: Internal erosion, Hole erosion test, Erosion function apparatus, cohesive soils, erosion characteristics.

Abstract

Over the years, word-wide investigations have been focused on the erosion of hydraulic earthen structures, such as dams and dikes, and its disastrous consequences on the socio-economic level (1, 2). The susceptibility of these structures to surface erosion involves many parameters related to soil properties, with particular interest in the present study to clay mass fraction, coarse particles shape as well as degree of compaction based on experimental results with Hole Erosion Test (HET) and Erosion Function Apparatus (EFA). These two devices are widely used to assess the erodibility of cohesive soils. More specifically, erosion is analysed in terms of two intrinsic soil's parameters namely, critical shear stress τ_c and erosion coefficient K_{er} by means of two interpretation methods (3, 4). These parameters are introduced in the following equation that prescribes locally soil's erosion by a tangential flow:

$$\dot{m} = K_{er}\,(\tau - \tau_c),$$

where $\dot{m}$ is the mass rate of erosion (in $\mathrm{kg.m^{-2}.s^{-1}}$), K_{er} is the erosion kinetics coefficient (in $\mathrm{s.m^{-1}}$), τ is the applied shear stress to soil surface (in Pa), and τ_c is the critical shear stress for initiation of erosion (in Pa). A comprehensive campaign was carried out on seven different soil mixtures, composed of different fine contents, namely 20%, 30%, 40%, 50%, 70%, 90%, and 100%, as well as various soil textures. Armoricaine kaolinite (KA), classified as fine grain material with high plasticity (Plasticity Index PI>17%), as well as Hostun sand (HN0.4/0.8), Loire sand (TEN0.55), or glass beads (GB0.4/0.8), classified as coarse grain material, are used throughout this investigation. Five tests per mixture are performed using soil samples compacted at different compaction degrees, i.e. 88, 92, 95, 98 and 100% of maximum dry density (ρ_{dmax}), and at the optimum water content (W_{opt}) specific for each mixture. Experimental findings reveal the reproducibility of both HET and EFA under stationary test conditions. Results point out that the critical shear stress and erosion coefficient are strongly impacted for clay percentages lesser than 50% but then very little for percentages greater than 50%. Hence, it is very important to take into account the clay content when evaluating soil erodibility, since the increase in clay content increases the soil's resistance against erosion. Regarding the degree of compaction, the results show that by increasing soil's compaction degree the critical shear stress increases while the erosion coefficient decreases. Therefore, the

denser the soil, the less erodible it is. By the end, concerning particles shape, the experimental results point out two counterintuitive conclusions since, on the one hand, the highest τ_c value is found for the more rounded coarse particles. On the other hand, it is showed that K_{er} is higher for rounded particles mixtures, the latter being thus more erodible soil in comparison to angular particles mixtures. This fact might probably be attributed to the actual coating of the fines on the coarse particles as well as the lack of rotation resistance for spherical particles in comparison to the angular particles.

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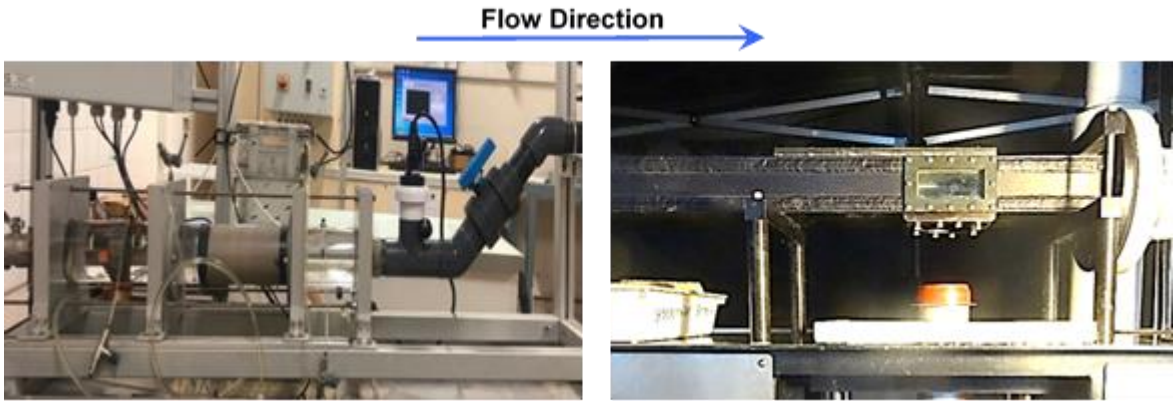
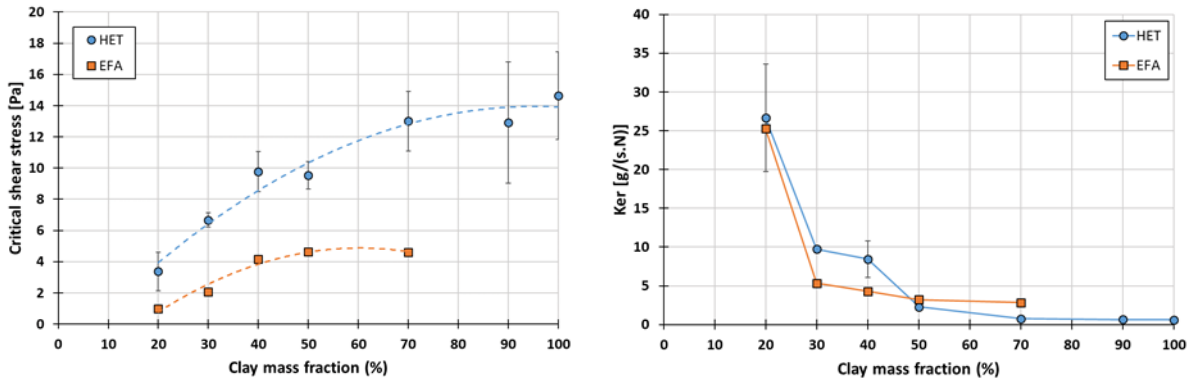


(a) (b)

Figure 1: *Experimental erosion devices: (a) Hole erosion test (HET); (b) Erosion function apparatus (EFA)*



(a) (b)

Figure 2 *: Effect of clay mass fraction on erosion parameters: (a) Critical shear stress τ_c; (b) Erosion coefficient K_er, using HET and EFA*

Compaction of mixtures of soft and rigid grains: a micro-mechanical model

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Keywords: Compaction, Soft matter, Sintering, Contact Dynamics

Abstract

Granular systems, in their most generic form, are composed of particles of different mechanical and elastic properties. By means of the Non-Smooth Contact Dynamics method (NSCD) coupled with Finite Element Methods (FEM), we analyze the isotropic compaction of mixtures composed of rigid and highly deformable particles. We characterize the evolution of the packing fraction and some microstructural parameters, such as the connectivity and the contact forces, as a function of the applied stresses when varying the mixture parameter and friction coefficient. We show that the packing fraction increases asymptotically to a maximum value φ_{max}, which depends on the mixture and the friction. At the microscopic scale, we first evidence a power-law tendency for the excess coordination number as a function of the excess packing fraction. Second, the force chains appear to be highly inhomogeneous close to the jammed state, where the strong forces lay on the rigid particles. Close to φ_{max}, the force distribution is more homogeneous in the case of only soft particles, while inhomogeneities persist for the high content of rigid particles. In the last case, the strong forces are still mainly supported by the rigid particles, a back-bone support (Fig. 1). We also present a micromechanical-based model to describe the compaction behavior as a function of the applied pressure, the Young modulus of the soft particles, and the mixture ratio. Such a model lies in the characterization of a single soft particle under compression together with the power-law relation between the connectivity and packing fraction.

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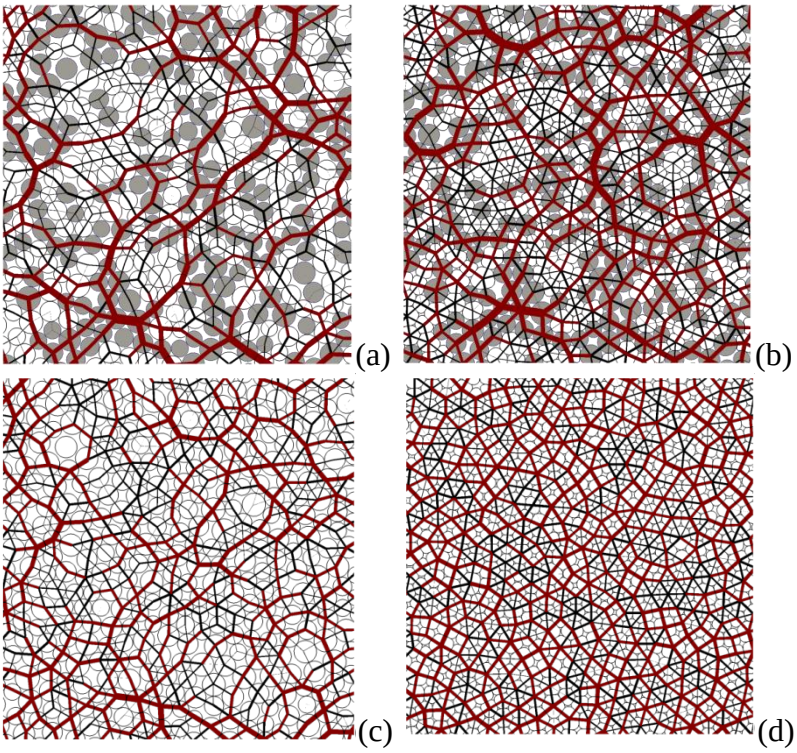

Figure 1 : *Close-up views of the force chains in frictionless assemblies of disks for 50% mixture soft/rigid particles (a,b) and only soft particles (c,d) at the jammed state (a,c) and for φmax (b,d). The magnitude of each normal force is represented by the thickness of the segment joining the centers of the particles in contact. The strong forces and weak forces are plotted in red and black, respectively. The rigid particles are colored in gray*

Dynamic properties evaluation of loose sand at low and high confining pressures, from low to high shear strains

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Keywords: Cyclic loading, dynamic properties, Dynamical Mechanical Analysis (DMA), rheometer, loose sand

Abstract

Cyclic and dynamic loading is the application of repeated or fluctuating stresses and strains to the soil, producing an accumulation of residual strains and changes in the soil strength (Hoeppner, 2013). Cyclic loads can generate different shear strain levels depending on the source. For example, Non- endogenous sources, like traffic, wind power plants, and mechanical compaction can produce low cumulative strain levels (<5%) while natural sources, like earthquakes, produce high cumulative strain levels (>5%) (Shankar, 2017). Consequently, in the whole-life infrastructure analysis, evaluating the soil's dynamic mechanical properties and their resultant long-term deformations is necessary. This research presents a new procedure for measuring the dynamic properties of loose sand using a Dynamical Mechanical Analysis (DMA) tester, which is commonly used in asphalt engineering but with limited use in geotechnical engineering. Compared to the traditional methods, like the Resonant Column and Cyclic Triaxial test, this methodology allows the evaluation of a wider range of strains (Villacreses, 2020). In this research, we evaluate the dynamical properties of loose fine sand ($D_r=0.105$) varying the input strain from $5x10^{-6}$ to $1x10^{-2}$, while applying confining pressures from 1kPa to 30kPa. The results validate the proposed procedure showing an increment of the shear modulus as the confining pressure increased and highlighting the advantages of the DMA for the study of the dynamic properties of soils.

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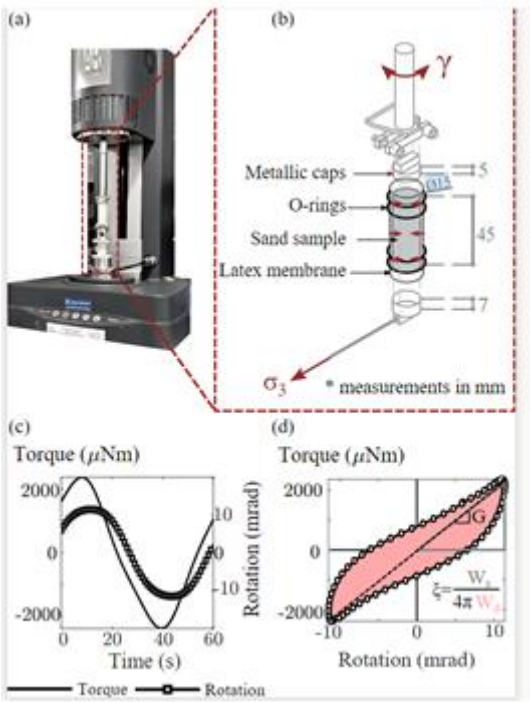

Figure 1 : *Soil specimen installed in the rheometer using a handmade latex membrane. The suction was applied by syringe through the bottom sample. Figure (b) presents the relationship between the Torque and displacement measured in the rheometer when the sample is subjected to a confining pressure of 30kPa and strain of 0.01%. Figure (c) shows the Hysteretic loop when the sample is subjected to a confining pressure of 30kPa, and strain of 0.01%.*

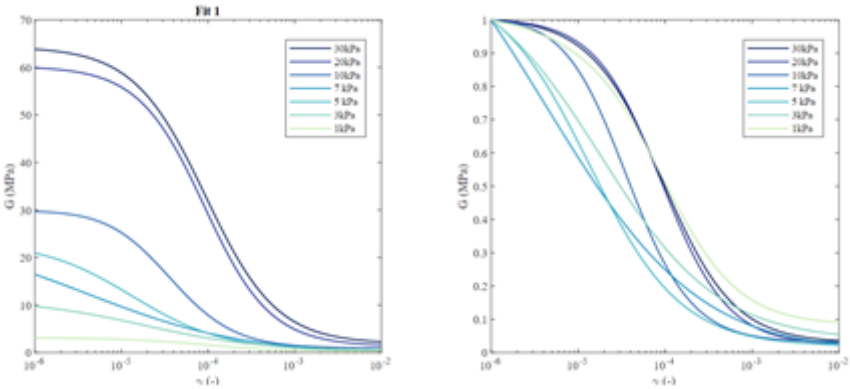

Figure 2 *: Dynamic modulus degradation for a confining presure range of σ3=[1-30] kPa*

A 2D state-dependent hyperelastic-plastic constitutive model considering shear-induced particle breakage in granular soils

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Keywords: Particle breakage; Crushable granular soils; Hyperelasticity; Elastoplasticity theory; Elastic-plastic coupling

Abstract

A two-dimensional elastic-plastic constitutive model considering particle breakage for the simulation of crushable granular soil behavior is proposed by Irani et al. (2022). In the model, elastic strain rates are derived from a modified Helmholtz free energy function and the influence of plastic shear work on the elastic properties of sand is considered as an elastic-plastic coupling mechanism. The hyperelastic description of the material is coupled with the bounding surface model proposed by Manzari and Dafalias (2004). To avoid the overestimation of particle breakage in loose sands, plastic shear work is employed to quantify the breakage extent. A direct comparison between the model simulations and laboratory data has been carried out for different series of drained/undrained monotonic and cyclic triaxial tests. For comparison purposes, simulations with the hypoplastic model proposed by Engin et al. (2014) for crushable soils are included as well. It is shown that the proposed model can provide reasonable predictions using a single set of parameters for each series of laboratory data.

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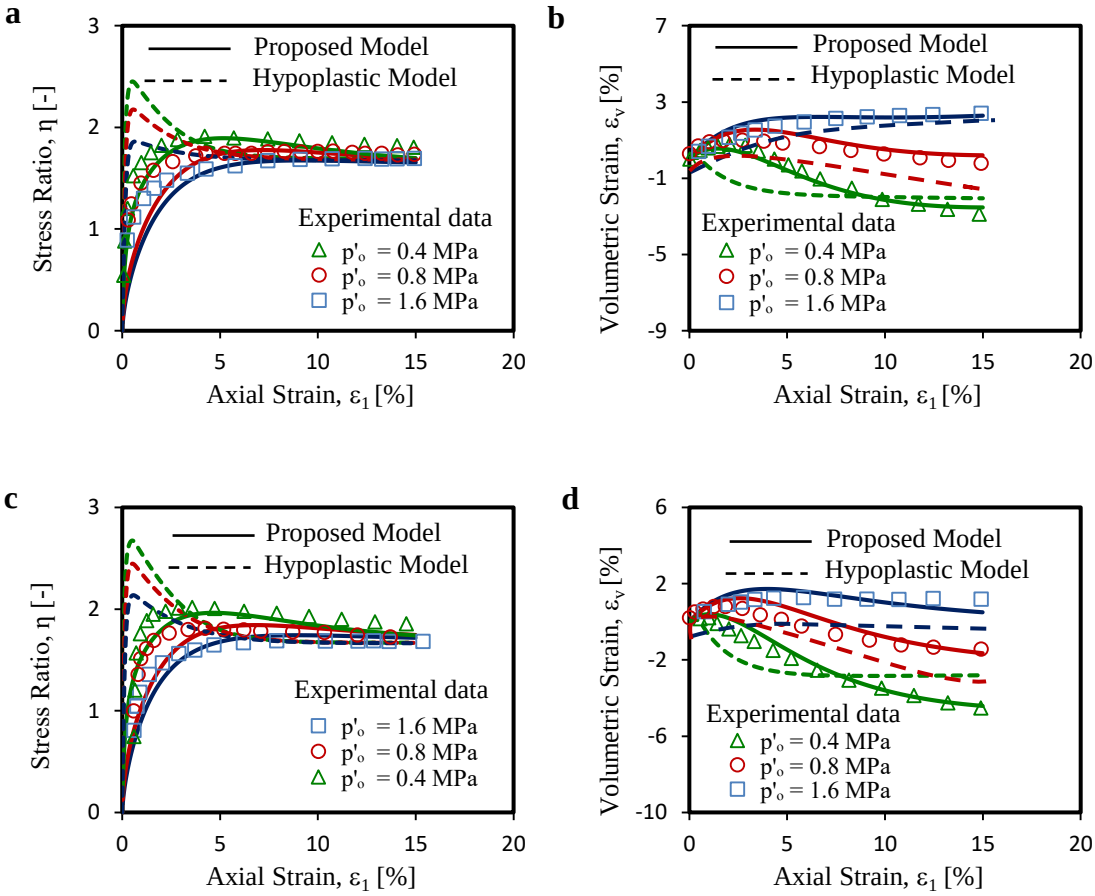

Figure 1 *: The proposed and hypoplastic model predictions for mobilization of stress ratio and volume change behavior of Tacheng rockfill specimens sheared under drained condition from p'0 = 0.4, 0.8 and 1.6 Mpa: (a) and (b) three specimens with e0 = 0.244; (c) and (d) three specimens with e0 = 0.189 [data from Xiao et al. (2016)]*

Homogenization of natural composites via Thermodynamics based Artificial Neural Network and dimensionality reduction techniques

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Keywords: Multiscale-modelling, Deep learning, Thermodynamics, Natural Composites

Abstract

Modelling natural composites requires facing their intrinsic multiscale nature. This is fundamental to account for any kind of multi-physics coupling happening at the microscale, which is reflected onto the macroscopic behavior. The modelling of natural composites is fundamental for many fields of science and engineering. Geotechnics is a clear example of the need of having reliable constitutive models of natural composites, such as soft and hard soils, to solve large-scale engineering problems.

During the last decades homogenization techniques have been used and developed to account for the influence of the microstructure of such heterogeneous materials at larger scales [4].

To capture in detail the effects of microscopic processes on the homogenized behaviour, many authors have developed multi-scale numerical schemes [5]. A common drawback of such methods is the high, if not prohibitive, computational cost needed to perform the numerical simulations.

Recently, Machine Learning based approaches have raised as promising alternatives to traditional methods and, in particular, Artificial Neural Networks – ANNs – have been used to predict the constitutive behaviour of complex, heterogeneous materials, with reduced calculation costs [1].

One of the most relevant weaknesses of such approaches is that they are not build on rigorous framework based on principles of physics. From that, it often follows a limited capability of extrapolate values ranging outside the training set and the need of large, high-quality datasets, on which performing the training.

This work focuses on the use of Thermodynamics-based Artificial Neural Networks [3] – TANNs – to predict the constitutive behaviour of natural composites. The collected information on the microscopic processes is compressed by means of dimensionality reduction techniques and utilized to characterize the state of the material at the macroscopic scale [4]. The use of such techniques into the workflow of TANNs guarantees accurate and always thermodynamically admissible material descriptions, requiring reduced computational costs.

An application to an heterogeneous model is presented, demonstrating the applicability of the method to multi-scale problems in which natural composites might be involved.

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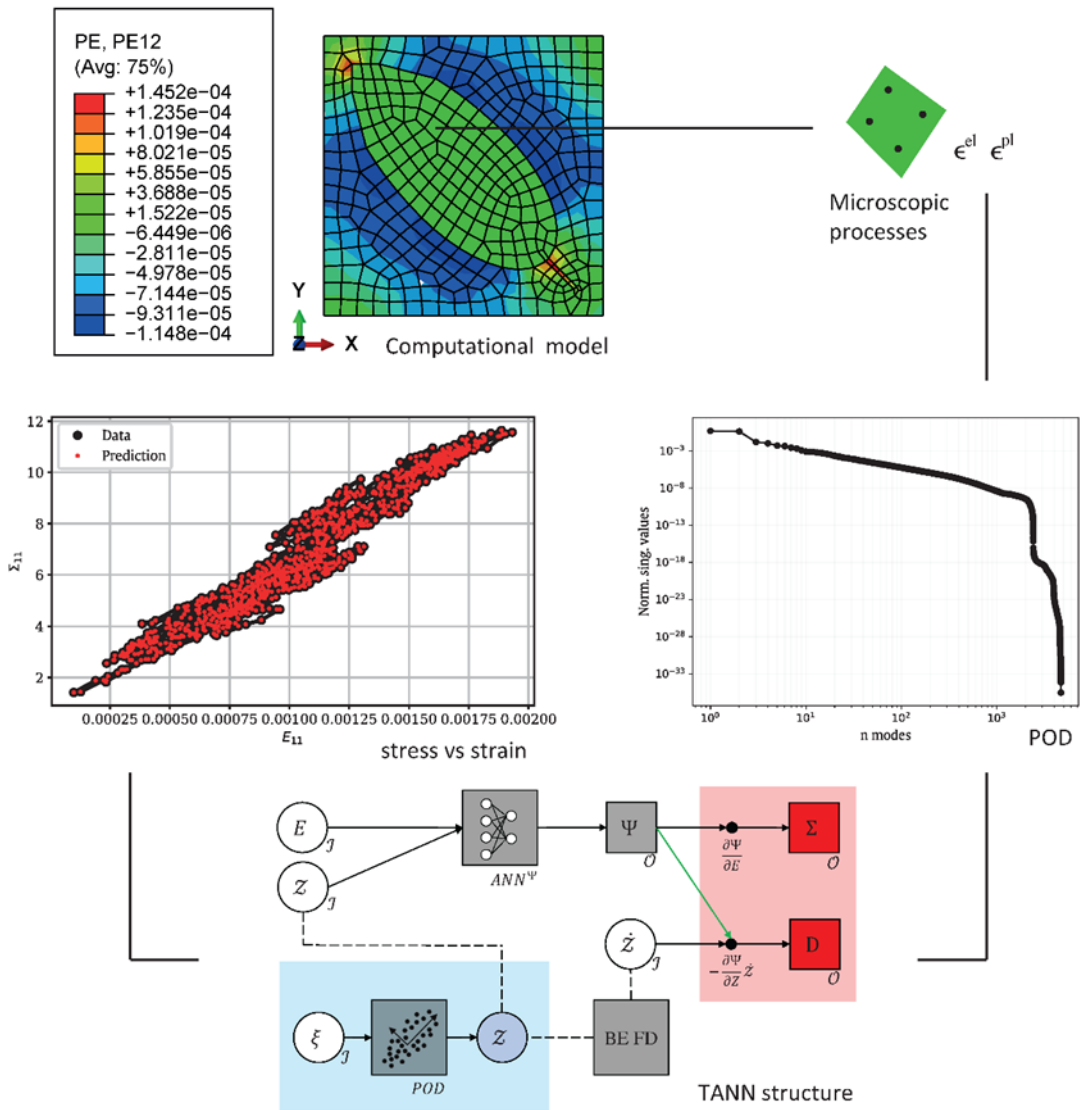

Figure 1 : *Workflow of the homogenization scheme: (a) solution of the computational model; (b) collection of information of the microscopic processes; (c) application of POD; (d) training of the TANN network; (e) use of TANN in inference mode.*

Design of reduced-scale experiments of masonry structures subjected to blast loads

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Keywords: Design, Reduced-scale, Explosions, Exploding aluminum wires

Abstract

In the last decades, the number of historical and ancient structures subjected to blast loads has steadily increased, due to either accidental or deliberate explosions, e.g. the archaeological site of Palmyra in 2015 and Beirut in 2020. The protection of such assets against blast loadings is essential. However, the response of structures to explosions cannot be investigated relying solely on numerical and analytical tools. Experimental tests are necessary to improve current understanding and validate existing models.

Large-scale experiments can be conducted only in special testing areas with restricted access, safety issues, and reduced repeatability.

An alternative solution to investigate the effects of a blast loads on structures is to rely on reduced-scale experiments in laboratory conditions. Reduced-scale experiments ensure a high degree of repeatability, moderate cost, and reduced hazards associated with environmental safety (equipment and personnel).

We present herein a new design setup, see **Figure 1**, to study masonry assets based on scaling laws for the rigid-body response of structures (see **Masi et al., 2019, 2022**). In particular, exploding wires allow to recreate loading conditions analogue to those in an explosion, with minimum costs and high reproducibility.

Preliminary results suggest that the proposed setup and methodology can be used to investigate, for the first time, the response of masonry structures under blast loads in a safe laboratory environment, **Figure 2**.

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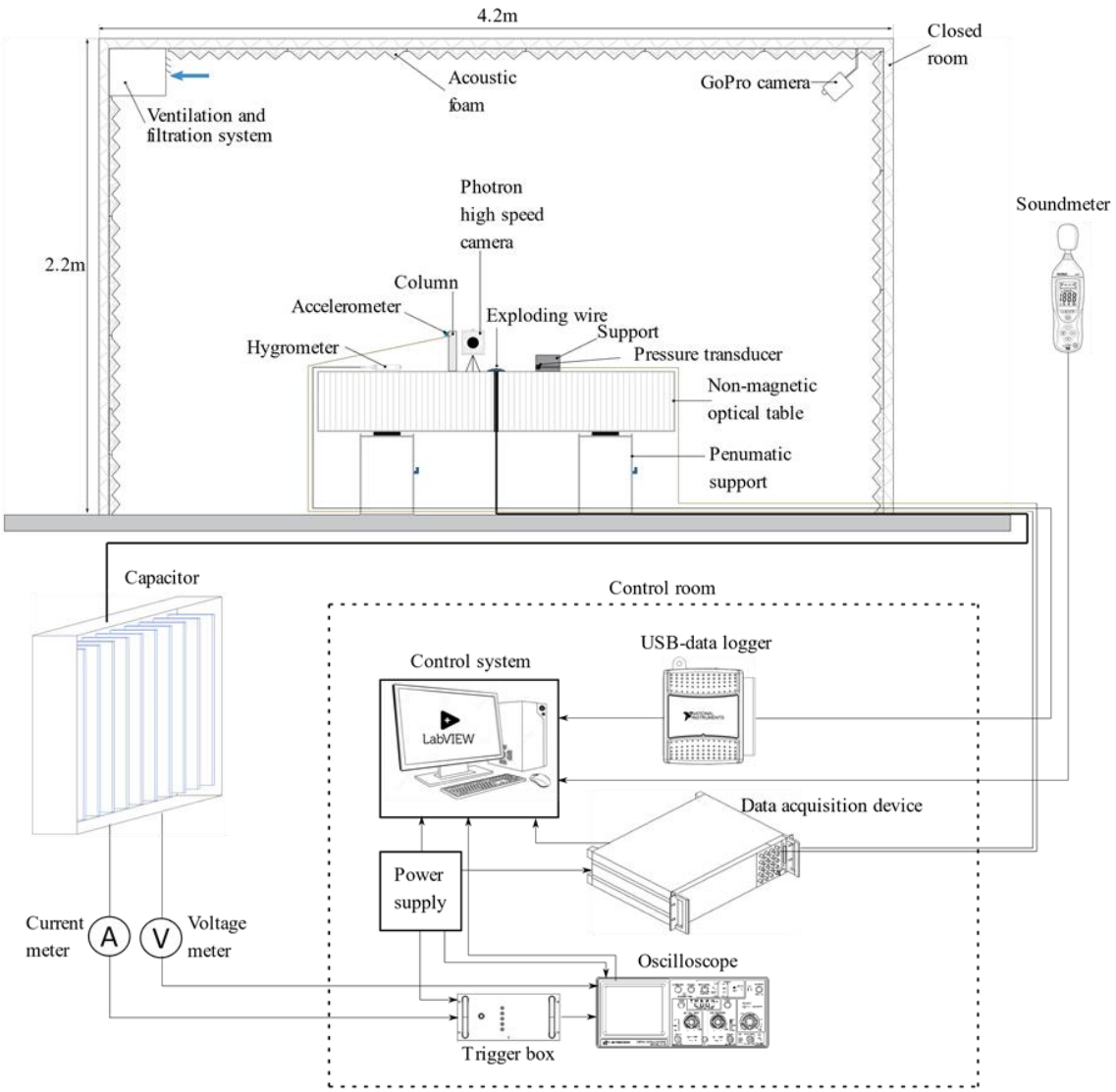

Figure 1: *Experimental setup of reduced scale experiments designed in the GeM research laboratory*

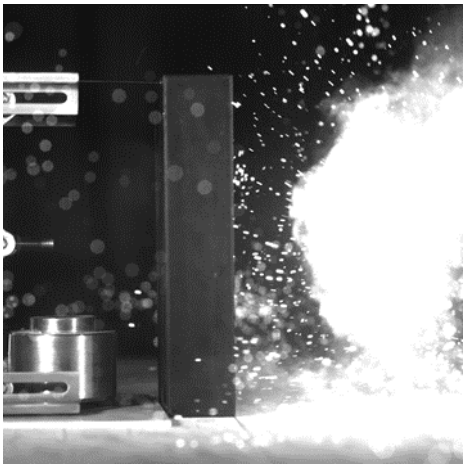

Figure 2*: Reduced-scale structure (column) subjected to blast load*

Can we tame scale bridging in complex materials?

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Keywords: Deep Learning; Thermodynamics; State variables; Microstructure; Multiscale modeling

Abstract

Accurate models for the behavior of materials are of fundamental importance in material science and mechanics. Traditionally, constitutive models are derived from underlying first principles (thermodynamics) and empirical approaches to ensure calibration over experiments. However, heuristic constitutive modeling may fail in describing the behavior of complex materials that display path-dependent behaviors and possess multiple inherent scales, e.g. metamaterials, geomaterials, and biomaterials.

In the last decades, data-driven and machine learning approaches have demonstrated to be able to overcome many of the issues encountered in heuristic constitutive modeling. Among these approaches, the Thermodynamics-based Artificial Neural Networks (Masi et al. 2021; Masi and Stefanou 2022a), based on the theory of internal variables, are able to discover constitutive equations from the laws of thermodynamics. The latter are hardwired directly within the structure of neural networks and allow predictions that are always thermodynamically consistent, by definition.

Yet, internal variables are hardly identifiable, in a general way, for the large spectrum of complex materials usually encountered in engineering problems. For this purpose, we develop new thermodynamics-based dimensionality reduction techniques allowing to discover admissible sets of internal variables from the knowledge of those quantities characterizing the microscopic material state.

Evolution laws of the internal variables are also needed to properly describe the material behavior. For this purpose, we develop a state-of-the-art methodology to discover the evolution equations from the microstructure dynamics and the enforcement of the first and second laws of thermodynamics (Masi and Stefanou 2022b).

The capabilities of the proposed method are demonstrated for the constitutive modeling of several complex, multiscale materials, displaying inelastic behavior, path- and rate-dependency.

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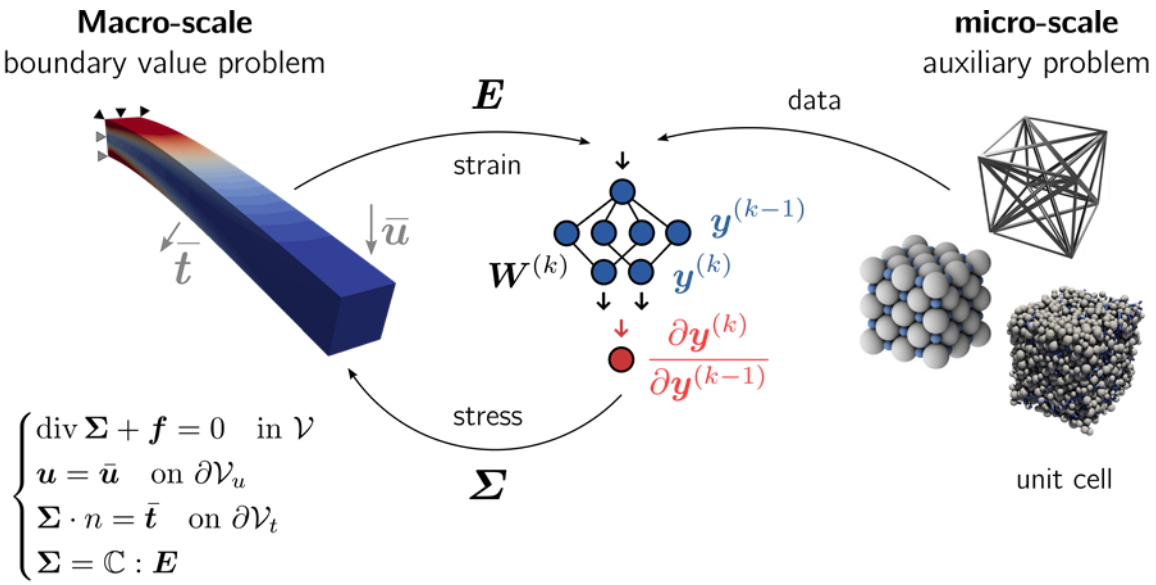

Figure 1 *: Scale bridging with Thermodynamics-based Artificial Neural Networks.*

Prediction of the Resilient Modulus (M_R) of soils using Artificial Neural Networks (ANNs): a case study of US soils

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Keywords: Artificial neural networks, resilient modulus; US soils

Abstract

A The Resilient Modulus (M_R) is one of the essential parameters to characterize the subgrades under cyclic loading for geotechnical and pavement applications [1]. **Figure 1** exhibits the classic definition of M_R. Remarkably, the experimental determination of the M_R requires sophisticated cyclic triaxial devices [2]. Thus, its execution is not feasible for many laboratories and projects with a limited budget. Therefore, multiple research efforts have been carried out in the literature to develop indirect methods for its estimation [3]. Nonetheless, these proposals are mainly mathematical models (i.e., correlations), which shows a significant gap in the literature because techniques of outstanding explanatory capabilities, such as Machine Learning (ML), are being left aside. In this research, a sub-branch of ML denominated Artificial Neural Networks (ANNs) is used to create computational models to predict the M_R of US soils. For this purpose, 64701 datasets from the Long-Term Pavement Performance (LTPP) program were analyzed. The vast amount of data allowed us to contemplate a comprehensive variety of soils, from A-1 (coarse-grained soils) to A-7 (fine-grained soils). Hence, it was possible to create computational models powerful enough to model a wide range of soils. For each dataset, the grain size distribution (percentage of soil that passes through the following sieves: 3 in, 2 in, 1.5 in, 1 in, 0.75 in, 0.5 in, 0.375 in, No.4, No .10, No.40, No.80, and No.200) and the stress conditions (i.e., bulk stress -θ- and octahedral shear stress -*T*-) were considered as input data. Meanwhile, the M_R was the only output data. **Equation 1** and **Equation 2** show the mathematical formulas to calculate θ and *T*, respectively.

Figure 2a (Model A) and **Figure 2b** (Model B) show the best ANN architectures obtained. Both computational models are Deep Neural Networks (DNNs). On the one hand, Model A was developed employing the Adadelta optimizer. On the other hand, Model B uses the RMSprop optimizer. **Figure 3** shows the performance measures addressed, i.e., Mean Absolute Error (MAE) and Mean Squared Error (MSE). Notably, the MAE was used as the loss function. Although both models are highly exact, Model A requires fewer epochs (training times) and is 23.3% faster than Model B. The main findings of this study are the creation of two computational models capable of predicting the M_R of US soils with a precision higher than 99%. Furthermore, it was demonstrated that the grain size distribution, θ and T are sufficient to accurately estimate the M_R of granular and fine-grained soils.

$$\theta = \sigma_1 + \sigma_2 + \sigma_3 \qquad (1)$$

$$T = (1/3)\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} \qquad (2)$$

Where: σ_1 = major principal stress; σ_2 = intermediate principal stress; σ_3 = confining pressure stress.

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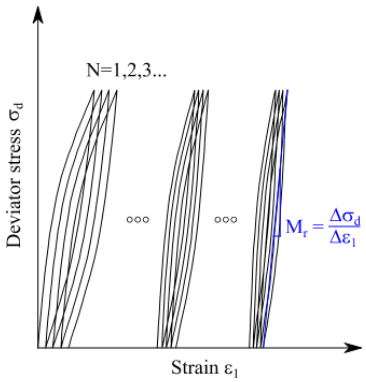
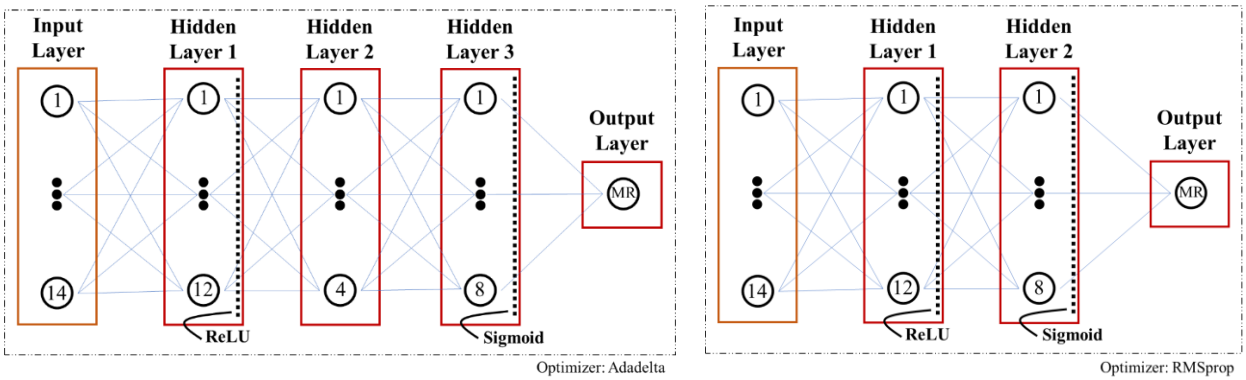
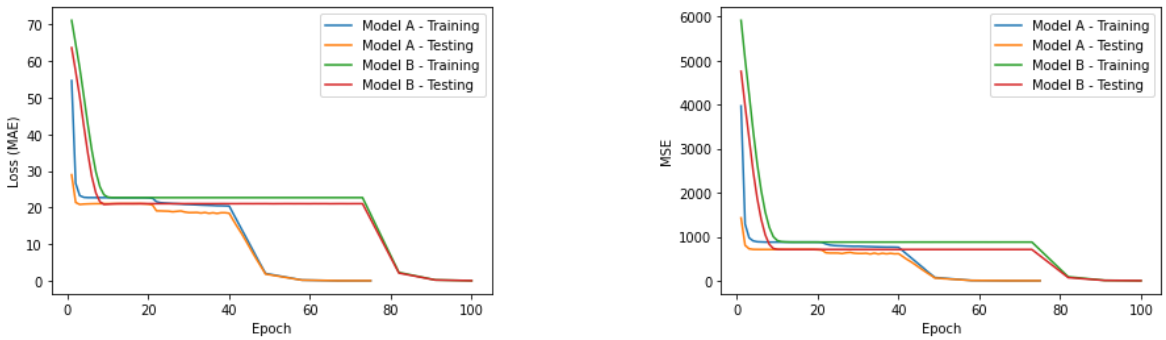


***Figure 1**: Definition of the MR*



a) Model A (employing the Adadelta optimizer) *b) Model B (employing the RMSprop optimizer)*

***Figure 2**: Proposed DNNs to predict the MR of US soils*



a) Loss (MAE) *b) MSE*

***Figure 3**: Statistical evaluation of the proposed DNNs.*

A micromechanical approach of wet soils behavior based on DEM-LBM coupling

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Keywords: Coupling DEM-LBM, partially saturated media, capillary forces, capillary bridges

Abstract

To illustrate the ambivalent impact of a change in water content on the mechanical properties of geomaterials, the geo-mechanical community usually refers to the example of a sandcastle. A small amount of water strengthens the specimen thanks to capillary bridges due to their forces that create an effective cohesion. Once the water content exceeds a certain threshold, capillary bridges start to disappear making the sandcastle weaker possibly leading to failure.

This work presents a coupling between the Lattice Boltzmann Method (LBM) with a Discrete Element Method (DEM) to investigate in detail the behavior of specimens under unsaturated conditions. Regarding the LBM, the phase-field-based model seems to be the best candidate to model capillary bridges which consists in coupling the Allen-Cahn equation with the two-phase Navier-Stokes equation via surface tension force term. Then, capillary forces are passed to DEM to update grain positions.

First, we demonstrate the capability of LBM by modeling capillary bridges between a doublet of particles. At equilibrium, the LBM capillary bridge profiles between two spherical grains and experimental ones appear to coincide accurately [1]. In addition to the shape of capillary bridges, capillary forces are also computed at equilibrium and compared to experimental data [2]. Furthermore, a triplet of particles is considered to show the possibility to handle implicitly the merging of two isolated capillary bridges, as shown in Figure 1. LBM capillary forces for triplet are also computed and compared with other numerical results reported in the literature [3]. A great agreement is found between these two methods [4].

These studies are further extended to a sample made of thousands of spherical particles under unsaturated conditions. The proposed coupling has proven its capability to model the capillary effect in wet sand whereby a cubical specimen can stand up when wet due to the attractive capillary forces, whereas it would collapse when dry, as illustrated in Figure 2. A quantitative computational of the capillary cohesion in terms of degrees of saturation is eventually done to identify the optimum degree of saturation.

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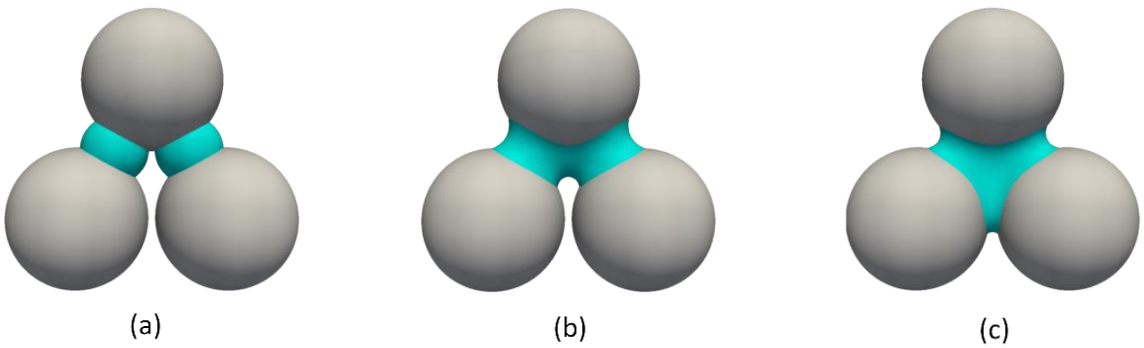

Figure 1: *(a) initialization phase, (b) transition phase, and (c) convergence*

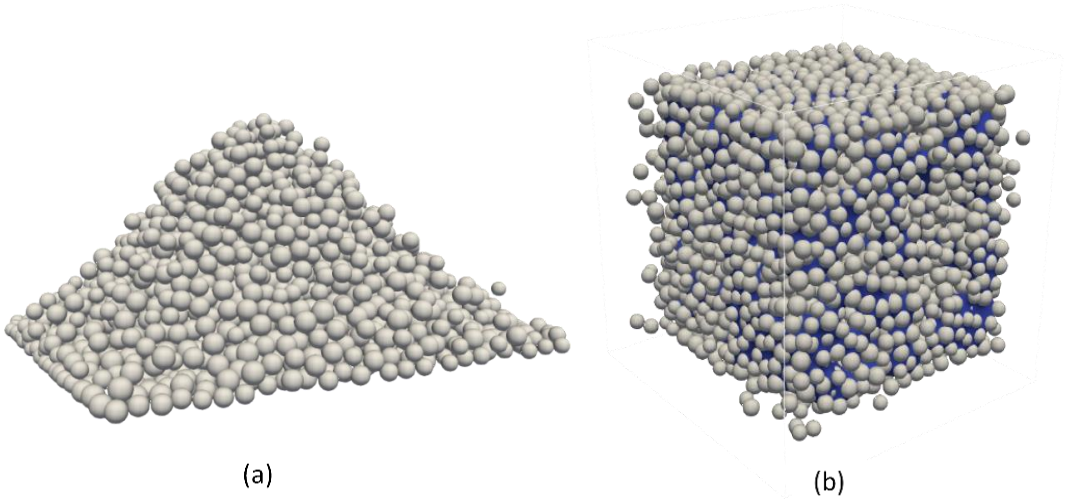

Figure 2*: (a) Collapse of a dry specimen without support, (b) apparent cohesion in a wet specimen without support*

Underground pumped hydroelectric energy storage (UPHS) in sand – Ongoing numerical simulations and field experiments

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Keywords: Energy storage, field experiment, numerical simulation, finite element method, cyclic loading, hypoplasticity with intergranular strain

Abstract

For the green transition, the share of renewable energy has to significantly increase from current levels. One of the most important challenges in the envisioned transformation of the energy sector is the natural fluctuation of renewable energy production (e.g. solar and wind sources). To tackle this, energy storage capability is needed, which stores excess energy and discharges it when the demand is greater than production.

Energy can be stored using chemical, electrical/electromagnetic, thermal or mechanical storage systems. Among these, pumped hydro storage power plants are a well-known method of gravitational energy storage. Recently developments have involved novel underground pumped hydroelectric energy storage (UPHS) systems, consisting of a bag-like and impermeable membrane and a sandy overburden: namely, energy can be stored/discharged by inflating/deflating the membrane and uplifting/lowering the overburden. The principle of an UPHS is shown in Figure 1. As a first approximation, stored energy corresponds to the potential energy of the uplifted overburden and inflated water [1, 2]. The storage density (capacity per unit square meter) and efficiency of UPHS systems are depending on the mechanical behaviour of the overburden (e.g. the development of arching or accumulative effects) [3, 4].

The presented work focuses on numerically modelling the mechanical response of the soil under cyclic operations of the geomembrane-lined bag and its impact on resulting storage capacity. The numerical study is inspired by small-scale field trials of UPHS in sand carried out in Foulum, Denmark, with a plan size of 20 m x 20 m and overburden cover of 2 m and 4 m (1:5 to 1:10 scale of a full prototype system). In the field experiments, during cyclic test series at varying maximum inflation volume, pressure-volume curves at the reservoir bag, total stress changes in the overburden and surface overburden displacements were measured. Finite Element analyses were carried out in axisymmetric conditions using ABAQUS and implementing a hypoplastic constitutive model with intergranular strain [5], whose parameters were calibrated using extensive laboratory tests of the Foulum sand. Within the limitations of the made assumptions, such as axial symmetry, the numerical model can qualitatively reproduce the deformation patterns of the overburden and variation in pressure with volume, as observed of the field test. Results shown that local and global arching effects, shown in Figure 2, influence the pressure-volume response and accumulation of irreversible strains of the overburden, with implications on long-term cyclic performance.

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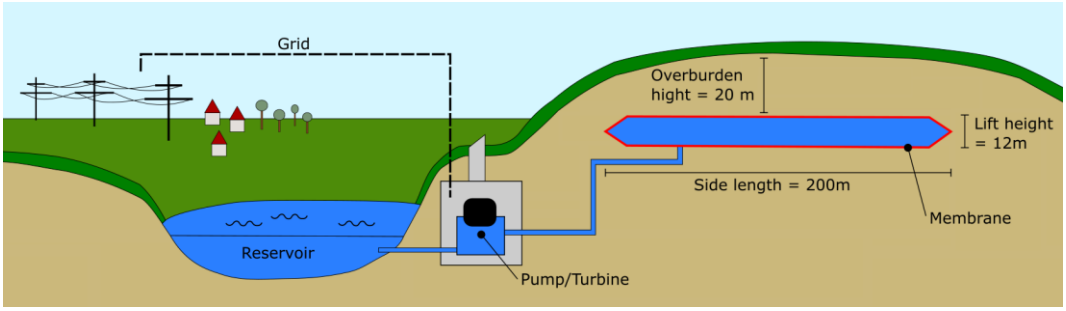

***Figure 1**: Functional principle of a full scale UPHS, modified from [1]*

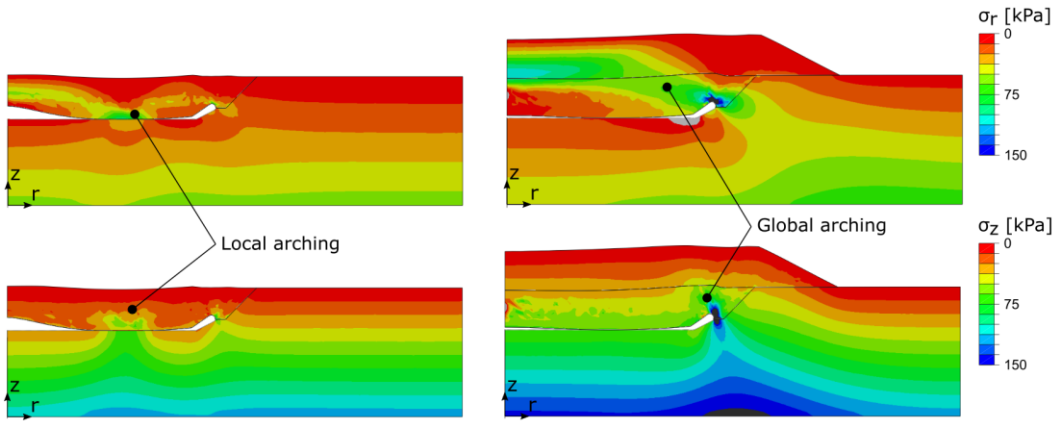

***Figure 2**: Results obtained from the numerical simulation of the field tests: Arching effects have a significant influence on the energy storage capacity of a UPHS, modified from [6]*

Cyclic thermal-mechanical behaviour of coarse granular material for thermal energy storage application

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Keywords: High thermal cyclic loading, Carnot battery, coarse grain material

Abstract

There is considerable interest in the behaviour of coarse granular materials under cyclic thermal loading in the context of thermal energy storage systems. These systems are frequently referred as Carnot Batteries and they store energy in the form of heat in a storage medium [1]. In addition to fluids and sand, granulates of coarse bulk material have been used [1]. Limited data is available in the literature [2,3] on how this porous media behave at high temperatures. The focus of these studies is mostly on geochemical and alteration effects of the grain itself and its thermo-physical properties. For example, the bulk material's chemical and mineralogical resistance to heating at up to 1000°C was studied [2].

However, there is a lack of understanding about the behaviour of the coarse granular material and the behaviour of the grain skeleton under cyclic thermal loading. Therefore, an experimental programme including thermal heat cycles was carried out on two different materials. A fractured material out of volcanic alkaline rocks and fluviatile pebbles from the rhine-area were studied. The grain size distributions of both sample materials consisted out of grains between 16 mm and 32 mm diameter and the specimen reached a comparable bulk density. The experimental investigations were realized in a test device with oedometric conditions and a heating chamber encapsulated the large-scale odeometer specimen (see Figure 1). The strain behaviour of the specimens was studied during six thermal cycles ranging from 50°C to 300°C and a constant vertical stress of 300 kPa. The test data of the experiment with the fractured volcanic material is shown in Figure 2.

Accumulated strains of the specimen resulting from the cycles were observed during the tests. These results are shown in the development of the void ratio over the number of completed thermal cycles (see Figure 3). This observation can be explained by rearrangement processes of the grain skeleton during thermal extension and contraction of the grains. Besides observable grain breakage was detected and a dust formation could be observed. From this small dataset using a large-scale high-temperature odeometer device it could be shown that the thermal accumulation effects are important to consider for new thermal energy storage systems. Nevertheless, in the future a larger data set and more influencing factors should be examined (e.g. higher number of thermal cycles, grain shape, grain size) as changes in the void ratio and the dust formation can negatively affect the efficiency and lifetime of the Carnot batteries.

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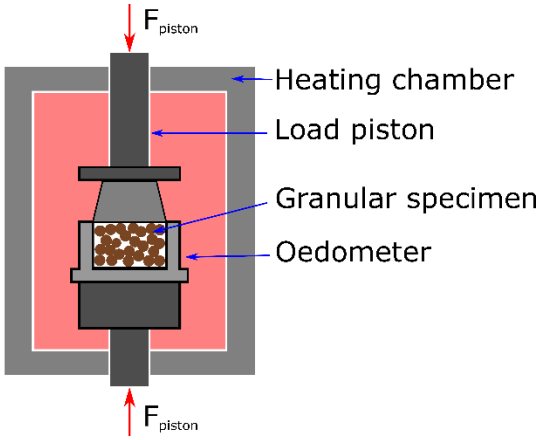

***Figure 1**: Oedometer device with heating chamber*

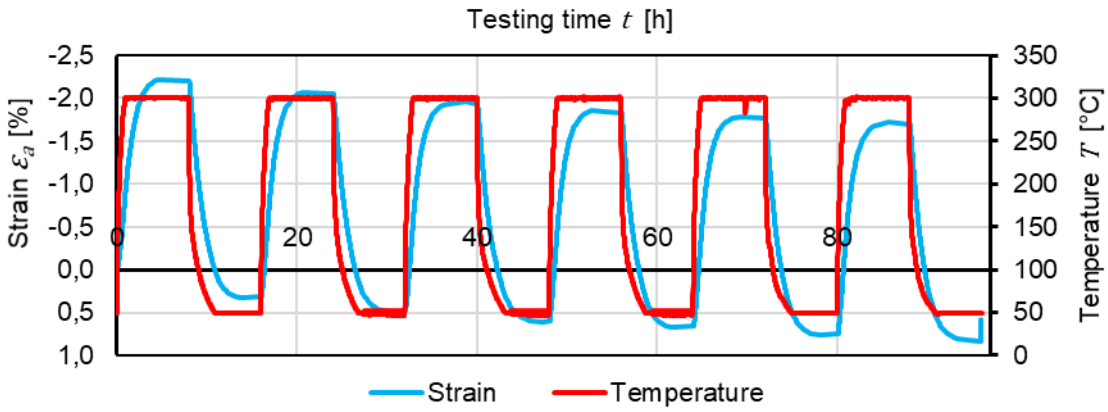

***Figure 2**: Test on the fractured material*

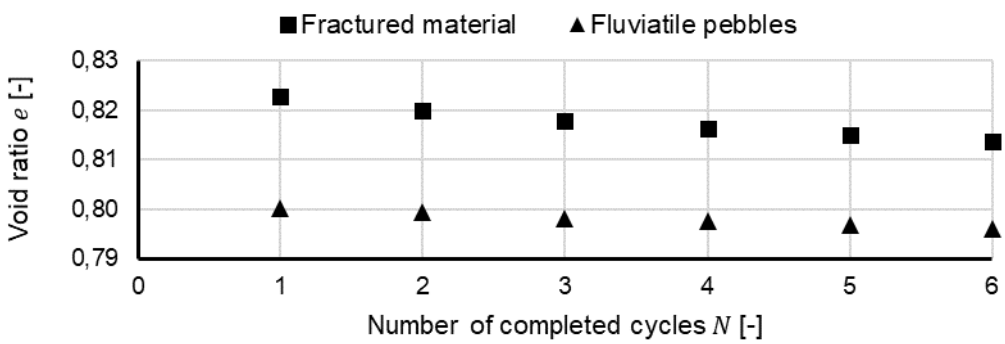

***Figure 3**: Development of the void ratio e over the number of thermal cycles N*

Design of new earthquake control experiment: numerical analysis

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Keywords: Earthquake-like events, numerical simulations, mathematical theory of control

Abstract

In this work, we present the preliminary design of a new apparatus to implement the existing mathematical for controlling earthquakes (Stefanou, 2019a; Stefanou and Tzortzopoulos, 2022; Tzortzopoulos, 2021; Gutiérrez-Oribio et al., 2022). The apparatus represents a real fault in a more realistic way than in previous experimental works (Gutiérrez-Oribio et al., 2022; Tzortzopoulos, 2021). With the new machine, it will be possible to monitor, study and better control the slip propagation along the analog seismic fault.

For this purpose, a new setup is proposed (Figure 1). The analog rock surrounding the fault is a soft triangular block with shear modulus G=7000Pa. The top face of the block is in frictional contact with a plate and constitutes the analog fault. The length of the analog fault is one meter. The material elasticity and the analog fault length were chosen using newly developed scaling laws.

Before constructing the new apparatus, a series of numerical simulations were performed in order to improve the design. Three different configurations that simulate earthquakes magnitude between 2 and 7 were studied. The stresses in the block and at the contact interface were evaluated. In addition, we studied the effects of the boundaries on the stresses.

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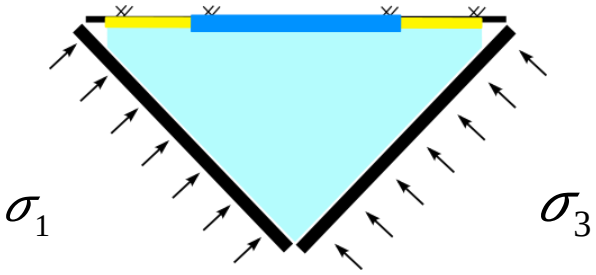

Figure 1 *: Configuration of the earthquake control experiment with the frictional contact at the top face. Stresses are applied on the lateral faces. Instability takes place in the blue part at the top face.*

The Numerical Geolab project: A fast and efficient suite for the solution of multiphysics problems in inelasticity and generalized continua

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Keywords: Finite Elements; Solid Mechanics; Inelasticity; Multiphysics; Open Source; FEniCS

Abstract

We present Numerical Geolab, an open source project focused on the fast and efficient solution of problems in material inelasticity, multiphysics and generalized continua. Numerical Geolab bases on the open source finite element project FeniCS [2], that allows for a fast and efficient symbolic formulation of the finite element model. Numerical Geolab uses the incremental from of the equilibrium and coupled diffusion equations of the problem using the Voight tensor to vector notation. This allows the users to be versatile and adapt the system of equations to their particular application. Moreover, Numerical Geolab provides access to the Gauss points of the finite element model, allowing the user to use any inelastic material library including thermodynamics-based neural networks (TANN) [4]. Geometric nonlinearity can also be taken into account with the use of an adaptive lagrangian eulerian (ALE) procedure. Numerical Geolab can model fairly general and complex behavior in solid mechanics, with emphasis in geomaterials. It allows for fast, intuitive and robust implementation of general systems of coupled partial differential equations describing multiphysical (e.g. Thermo- Hydro-Mechanical couplings) and (micro-) mechanical models (e.g. Cosserat model [7]) in inelasticity [1,3,5,6].

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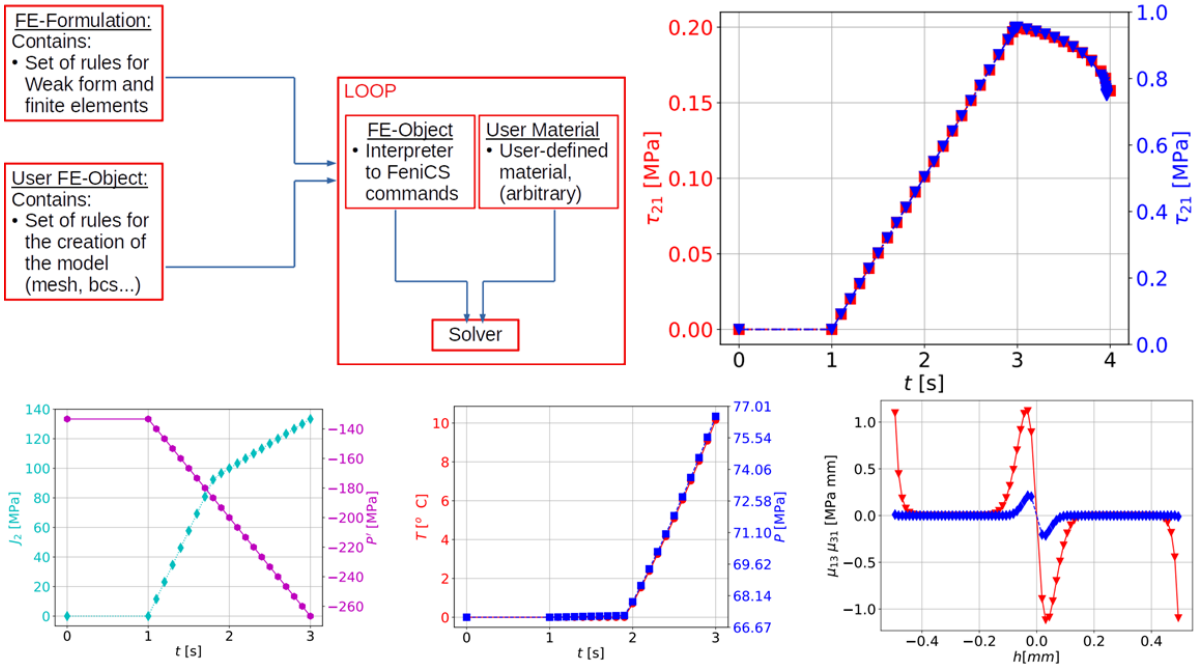

Figure 1 : *Structure of Numerical Geolab, example of an analysis of Cosserat Material and multtiphysical couplings*

A constitutive model, for Lightly Cemented Granular Materials, that predicts Dilatancy, grain Breakage and cement Damage

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Keywords: Thermo mechanical constitutive modeling, Micro-mechanics, Cemented granular materials, Breakage, Damage, Dilatancy

Abstract

Lightly Cemented Granular Materials both naturally occurring (e.g., sandstone) and artificial (e.g., grouted soil), are widely encountered, yet there is a certain lack of mathematical models describing them in a consistent and unified manner.

In this work we develop a micro-mechanics inspired constitutive models for Cemented Granular Materials whose internal variables have a clear physical physical interpretation. It builds on the work in Tengattini et al. (2014), which is able to predict several aspects of the behaviours of bonded geomaterials (e.g., stress strain responses, localisation patterns) but does not predict dilation at low confinements.

In the present development dilation emerges at low confinements by explicitly adding porosity as an internal variable, without the addition of further parameters; this extension is expired by a model for uncemented granular media undergoing crushing and dilation (Tengattini et al., 2016).

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Figures

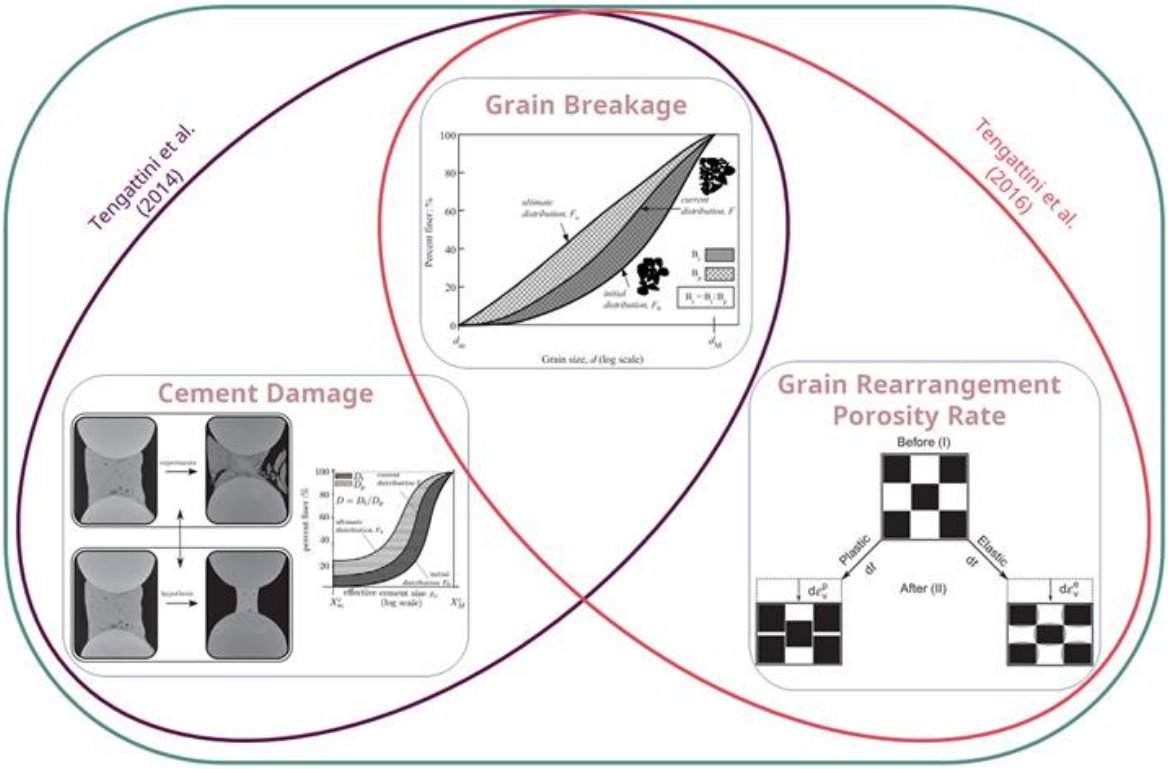

Figure 1 : *Schematic representation of the three Micro-mechanisms of inelasticity of the model*

On the influence of the loading frequency on the cyclic response of Malaysian kaolin

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Keywords: Cyclic loading, kaolin, triaxial testing, loading frequency

Abstract

This poster comprises some relevant results of an extensive experimental investigation on Malaysian kaolin (liquid limit $LL = 65\%$, plastic limit $PL = 40\%$, and therefore, a plasticity index $PI = 25\%$) under cyclic triaxial loading. Samples were prepared considered a moist compaction method and were further saturated in the triaxial device. The mechanical behavior of the compacted kaolin samples was evaluated considering an initial mean effective pressure of 200 kPa and different deviatoric stress amplitudes $\{60,70,80,90,100\}$ kPa and loading frequencies $\{0.01,0.05,0.1\}$ Hz.

Figure 1a summarizes some typical results of compacted kaolin samples considering an initial mean effective pressure of 200 kPa, a deviatoric stress amplitude of 60 kPa and different loading frequencies $\{0.01,0.05,0.1\}$ Hz. Interestingly, the results suggest that depending on the loading frequency different shapes of the mobilized effective stress loops are obtained. While larger loading frequencies lead to banana-shaped effective stress loops, small frequencies reproduced eight-shaped effective stress loops. In addition, larger loading frequencies lead to larger number of cycles to reach failure conditions (single-amplitude of axial strain of 10%). Apart from that, the qualitative responses on tests with different loading frequencies are essentially the same, see Figure 1b,c. Finally, Figure 2 presents the Cyclic Stress Ratio against the number of cycles to reach failure conditions. The results suggest a clear shifting in the curves with approximately unchanged inclination based on the loading frequency. The reason for the observed differences in the behaviour (rate-dependent material behaviour, dynamic effects or inhomogeneous fields of pore water pressure) is yet to be investigated, both experimentally and using numerical modelling.

Figures

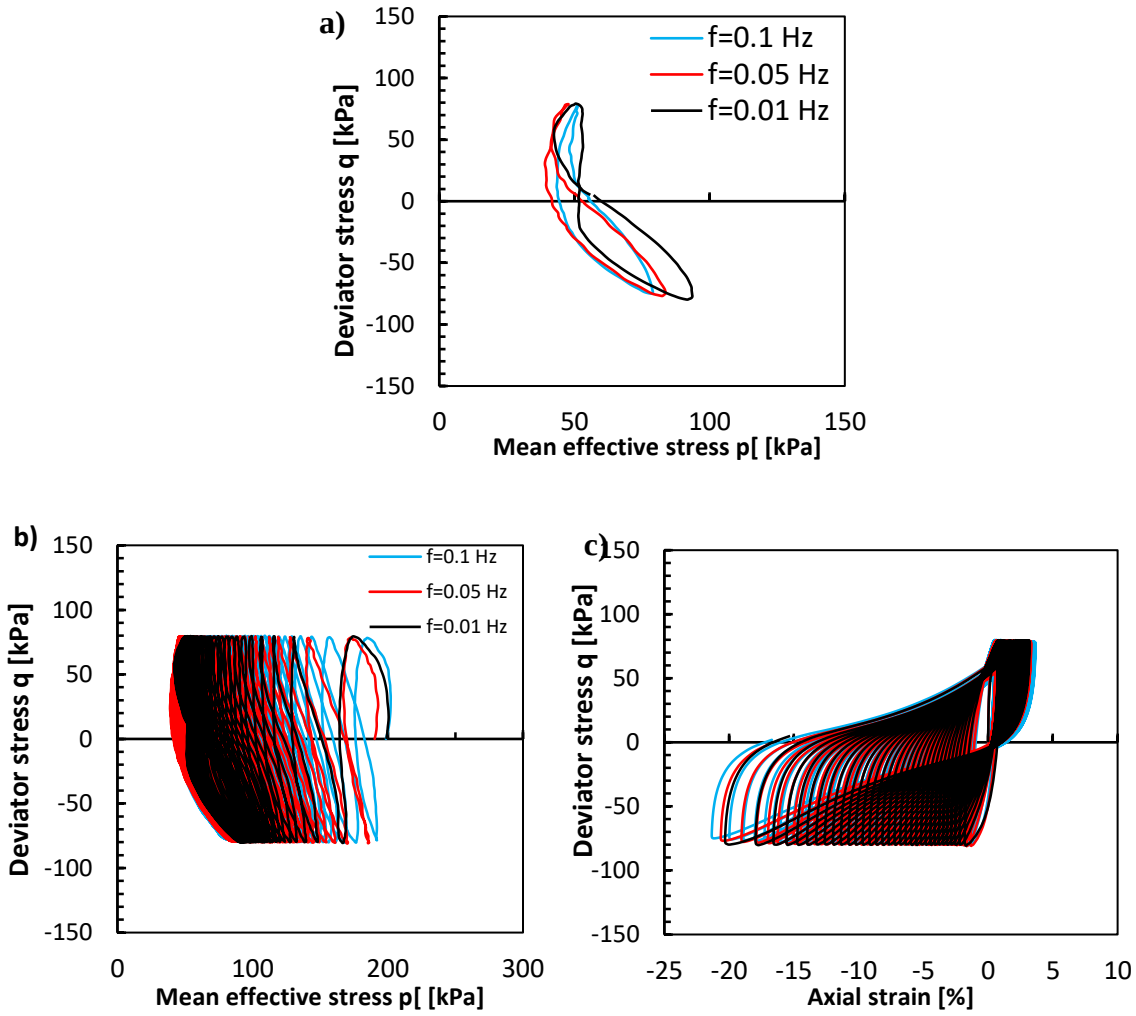

Figure 1*: Typical results of undrained cyclic triaxial tests with different loading frequencies*

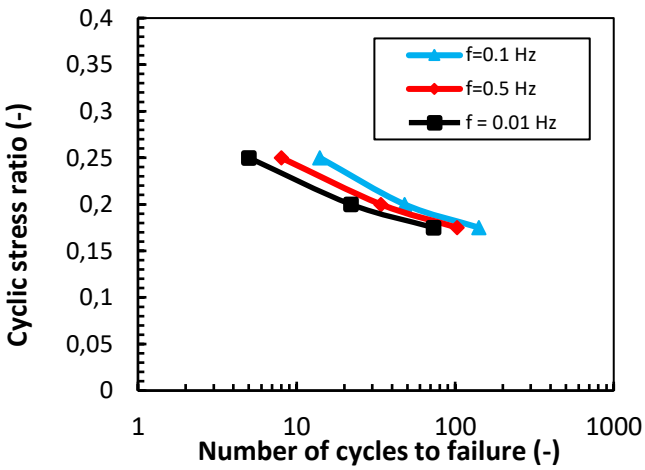

Figure 2*: Cyclic stress ratio vs Number of cycles to failure conditions on tests with different loading frequencies*

Compaction of cohesive granular materials

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Keywords: Compaction, cohesive, granular, simulation, DEM

Abstract

Cohesive granular materials play a major role in nature and industry. Cohesive interactions between particles have various physico-chemical origins such as capillary bonding, Van der Waals forces, and a cementing matrix [1]. Despite extensive experimental and numerical work on these materials, their mechanical behavior under the action of external loading is still poorly understood [2]. In this work, we use the Discrete Element Method (DEM) to perform an extensive parametric study of isotropic compaction of cohesive granular materials in which the cohesive action between two particles is modeled as a constant adhesion force.

We propose a compaction law expressing the relative void ratio as a generic function of a new dimensionless number η^* using parameters such as the cohesive force, the normal stiffness and the isotropic pressure. We also show that the finite size and wall effects can lead to deviations from this law as a result of stress concentration at the boundary of the system.

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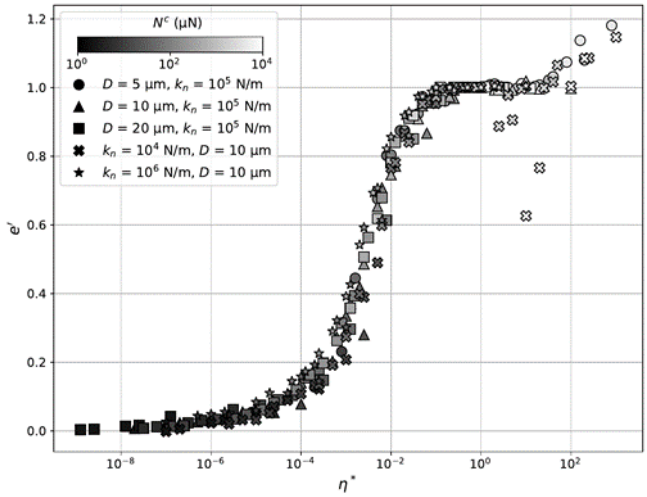

Figure 1 : *Relationship between the relative void ratio* ***e'*** *and the dimensionless number* ***η****

Porosity and permeability calculations in a biolithite using x-ray tomography images

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Keywords: Biolithite, Pore Network Model, Anisotropy, X-ray CT, moldic & interparticle porosity

Abstract

Successful characterization of carbonates starts from being able to properly describe them using globally defined classification standards such as (Folk, 1959; Dunham & Ham, 1962), etc. Key indices of rock quality and reservoir performance are usually directly or indirectly related to porosity and permeability which are reflections of the internal fabric of the rock. Carbonates are more susceptible to physicochemical reactions after deposition, albeit over a long period of time, these can alter the internal architecture of the rock creating complex pore networks and connectivity relationships. Anisotropy - the directional dependency on measurement of a property, e.g., permeability makes establishing a relationship with porosity even more complex – bearing in mind that anisotropy effect may also differ depending on the scale of measurement. The ability to reconstruct representative models of the pore network is a key factor in understanding the behaviour of any complex reservoir rock when subjected to flow/dynamic conditions. This work emphasizes on the importance of a consistent workflow, also discussed by (Aaron & Teng-Leong, 2021), during reservoir description, in addition to generating pore network models that have representative geometrical and topological characteristics at a microstructural scale. This enables better quantification of some reservoir parameters useful in solving problems related to fluid flow in porous media (Jiang, et al., 2010).

X-ray computed tomography (X-ray CT) technique is a non-destructive method which can be used for studying the internal architecture of core plug samples of complex rocks such as carbonates, unconventional tight sandstones/shales, etc. The technology and knowledge base for analyses of 3D digital images has also advanced significantly over the years making it easier to apply this methodology into workflows for evaluation of complex reservoirs (Mazurkiewicz & Mlynarczuk, 2013; Anselmetti, et al., 1998, etc). The ability to also process digital images at different scales enable better understanding of spatial continuity of porosity and permeability therefore producing different useful realizations of representative pore network models. However, the process of analysing digital images like many other processes also has its own uncertainties which can easily be obscured during evaluation and final interpretations can be significantly affected negatively. In this biolithite from an outcrop in Northern Greece, digital images of three test plugs with different orientations (B11, B23 & B33) taken from a core sample, including a high-resolution version, (B23HR) were given (Figure 1a). Porosity and permeability were calculated using pre-processed 3D digital images. Effective porosity was derived by binarization of these digital images and calculated as a fraction of the total area of objects to non-objects within a specified region of interest. Based on grey values, colour tables, and spatial-geometrical relationship of pore spaces, two major contributors to porosity have

been classified in this material (Figure 1b). The smaller percentage of total pores are attributed to moldic macroporosity while the larger percentage of pores are attributed to interparticle microporosity. Trends of porosity with x-ray parameters such as integrated density and mean intensity were generated for each plug sample to give insight to the distribution of pores and their spatial/vertical relationships with each other (Figure 1c). Permeability in three orthogonal directions was calculated using "Pore Analysis Tools" software application (Jiang, et al., 2010). Strong anisotropy, seen in B23 is controlled by preferential orientation of some pores (Figure 1d), the origin being under investigation. The K_z component had the highest magnitude in all three samples and the B33 sample generally had lower K_z compared to the other samples (Figure 1e). The unique fabric of this rock is such that the calculated vertical plug permeabilities, within a very small separation distance (in the same core) are different – hence heterogeneity and anisotropy is predicted.

Scope for further work exists by incorporating results from other techniques; mercury injection capillary pressure (MICP), nitrogen gas adsorption, scanning electron microscope (SEM) analysis and corresponding mineralogical interpretation from thin section analysis, etc.

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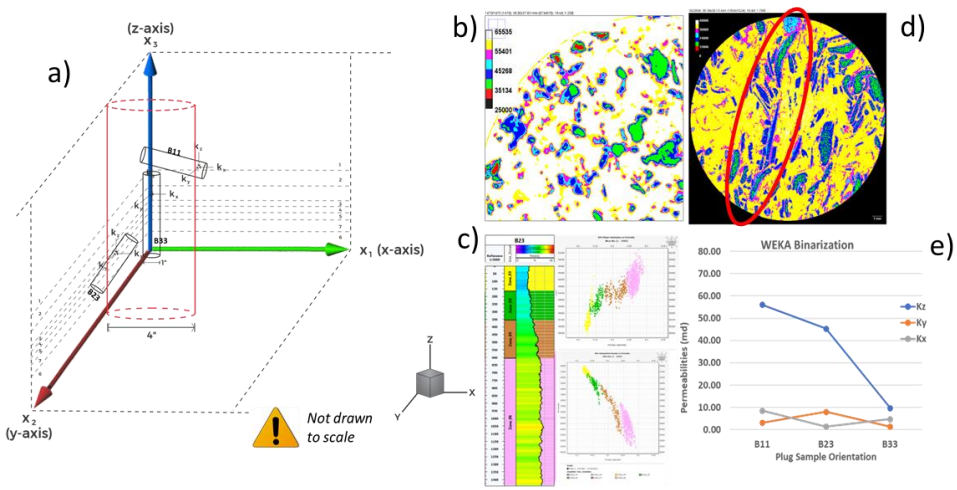

Figure 1: *a) Conceptual schematic of plug sample orientations from biolithite core b) Example of final conditioned sample used in classification of porosity c) Log view and crossplots of x-ray properties with porosity for B23. d) final conditioned display of Slice 90/894 of Sample B23HR. e) Permeability results from Pore Analysis Tools (PAT).*

Water retention properties of a bentonite/sand mixture by NMR characterization

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Keywords: Expansive clay, wetting-drying, pore distribution, NMR, suction-controlled

Abstract

Blocs of compacted bentonite/sand mixture, with a 40/60 proportion in dry mass, are being studied as engineered barrier in the French concept for high-level radioactive waste disposal. In the disposal, the barrier will be saturated by water infiltration from the host rock. The water retention properties of the bentonite/sand blocs are crucial to understand and predict the hydromechanical behaviour of the barrier. This poster presents first laboratory results which analyse water retention properties like water content and degree of saturation at different suction values. As bentonite is a highly expansive clay, all experiments were conducted at quasi-confined conditions to prevent swelling deformations and reproduce the in situ conditions. Results obtained on the wetting path are shown, corresponding to the saturation process.

In addition, results showing the porewater distribution at the microscopic scale during hydration is also presented. For this purpose, two different experimental techniques were used at different hydration states. Firstly, by Mercury Intrusion Porosimetry (MIP) we obtained the evolution of pore size distribution. Secondly, by Nuclear Magnetic Resonance (NMR) we searched to observe the evolution on molecular dynamics of the pore water populations. Longitudinal and transversal relaxation times (T1 and T2) of its hydrogen molecules were used to represent the molecular dynamics. In addition, we compare the relaxation time results with basal distance evolution in the interlayer of montmorillonite during hydration. The basal distance results are obtained from X-Ray Diffraction (XRD) experiments taken from the literature [1, 2]. This comparison provides a further interpretation of porewater evolution, given that MIP cannot estimate interlayer pores, creating a good synergy between experimental techniques.

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Calibration and evaluation of a hydro-mechanical hypoplastic model for unsaturated soils accounting small strain stiffness

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Keywords: Constitutive modeling, small strain stiffness, unsaturated, hypoplasticity

Abstract

Climate change is causing severe seasonal and daily moisture variations, which can induce cyclic coupled hydro-mechanical loads to the soil. Reproducing the aforementioned behavior is complex from a numerical point of view and requires robust constitutive models able to predict the coupling between the hydraulic and mechanical behavior of fine-grained soils, combined with predictions of history-dependent stiffness evolution at small strains. For this reason, Wong and Mašín [1] developed a hydro-mechanical hypoplastic model for partially saturated soils including small strain stiffness effects. The model incorporates a hysteretic void ratio dependent water retention model formulated in terms of degree of saturation and the intergranular strain concept modified for partially saturated conditions. In this work, a calibration of the model by Wong and Mašín [1] is presented to reproduce the behavior of a completely decomposed tuff from Hong Kong at different suctions. In addition, the new calibrated model is compared with the previous calibration under different stress paths. The results suggests that the model is able to reasonably describe the hydro-mechanical behavior of the decomposed tuff since the very small strain range up to the large-strain response, but some shortcomings have also been identified which will be corrected in future work.

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Degradation of Claystone under Freezing and Thawing Cycles

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Keywords: Freezing and thawing cycles, Clay, Degradation

Abstract

The degradation due to freezing-thawing (F-T) cycles is the major producer of erodible material in mountainous badlands (Regüés et al., 1995). This work aims to deepen the understanding of degradation processes in claystone due to cyclic F-T in such areas and quantify material degradation in relation to present F-T conditions (number of cycles, freezing temperature, degree of saturation, etc.). The work combines extensive field monitoring at a test site with experimental work in a laboratory.

The monitored site is a badland area in the Vallcebre basin located in the Eastern Pyrenees, Spain. The two slopes of the North-South oriented claystone ridge (Fig. 1a) are equipped with weather stations and sensors measuring temperature, water content, thermal properties, and suction (Fig. 1b). With proper calibration, the sensors provide enough data for ice content calculation. Figure 2 presents temperature data measured in a 5-minute interval on the northern slope. The data from winter 2021/2022 show a clear absence of freezing on the southern slope, whereas the northern slope is undergoing two freezing periods. Additional field tests and observations revealed a thicker layer of degradation on the northern slope in comparison with the southern one.

The studied material is a natural silty clay (71% of silt-sized and 25% of clay-sized particles) of relatively low plasticity (LL 40.3% and IP 20.6 %). The experimental work focuses primarily on cyclic F-T testing of natural, remolded, and recompacted, saturated and unsaturated samples of centimeters size. The experiments are performed using transparent plastic cells submerged in a freezing bath with a minimal vertical load. The temperature is recorded by thermocouples in the center and on side of the sample and in the freezing bath and by Micro-Electro-Mechanical System (MEMS). Figure 3 represents a typical course of the F-T test with 5 cycles applied.

Visual observations of freezing both in the field and in the laboratory showed a clear effect of frost heaving on the macrostructural changes, especially in soil with a high degree of saturation. Further research will focus on the effect of freezing on microstructural changes under various conditions using Mercury Intrusion Porosimetry.

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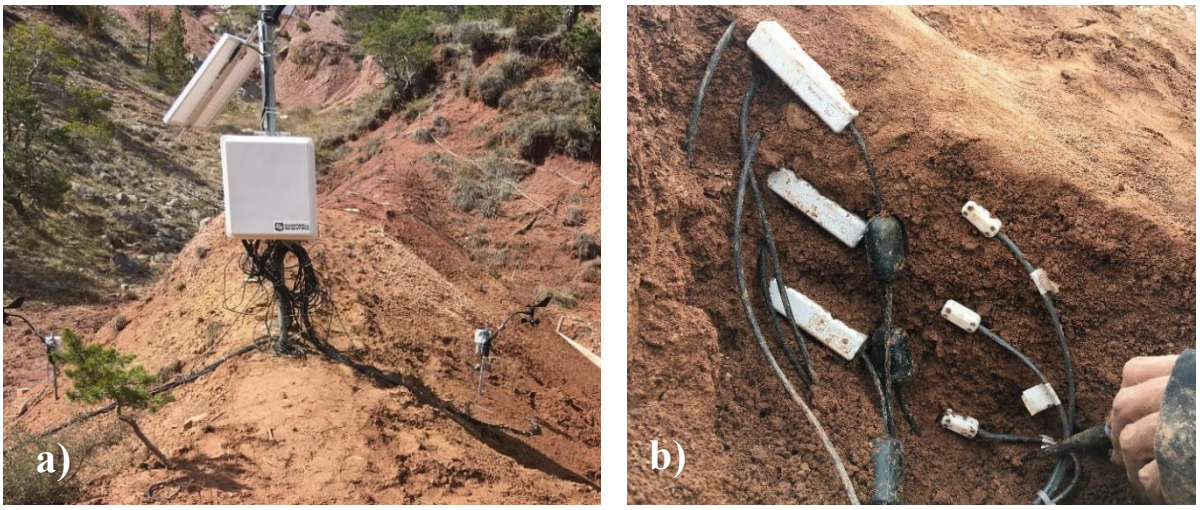

Figure 1 : *Monitoring setup at the site: a) Monitored ridge with a southern slope on the left side and northern slope on the right side. Both slopes are equipped with a weather station and sensors connected to data loggers and an IP modem on the top of the ridge. b) 40 cm deep sensor profile on the northern slope. From the left side 4 thermometers, 4 volumetric water content sensors (only the top 3 visible), 3 specific heat sensors, and a suction sensor (where the screwdriver points).*

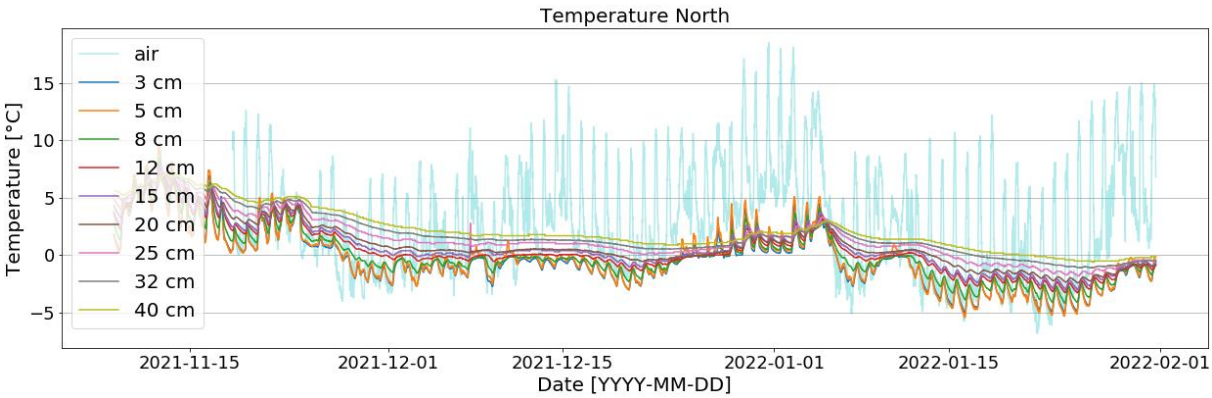

Figure 2 : *Temperature series measured at the northern slope by thermometers (at a depth of 3, 8, 12, and 20 cm), volumetric water content sensors (at 5, 15, 25, and 40 cm depth), and weather station (air).*

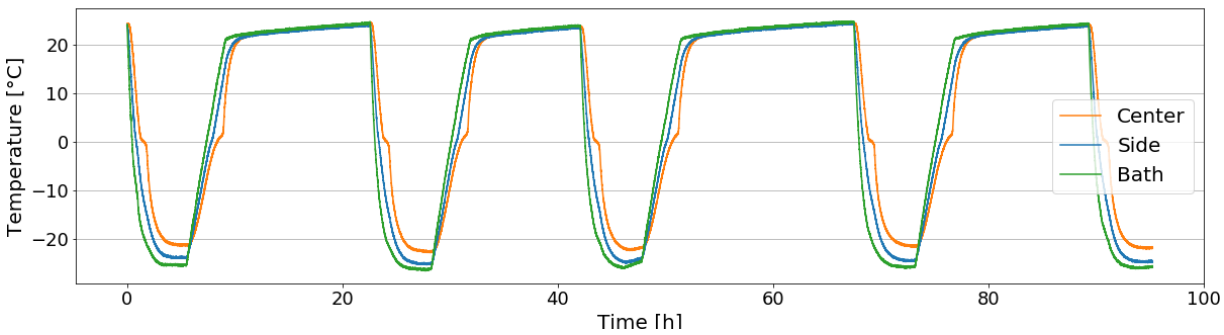

Figure 3 : *F-T test of unsaturated sample recompacted at w = 18 % and ρ_d = 1.2 g/cm^3. 5 cycles applied. Thermocouples are measuring the temperature in the center and side (5 mm from the cell wall) of the sample and in the freezing bath next to the cell.*

Elastic behavior of granular packings: effect of particle shape

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Keywords: Elastic moduli, particle shape, triaxial loading

Abstract

The elastic properties of granular assemblies and their relation to microstructure have been investigated by many researchers[1,2]. By means of particle dynamics simulations, we investigate the elastic moduli of dense packings of spherical and dodecahedral monodisperse particles. The samples are prepared by isotropic compaction under constant load and zero friction, leading to the densest isotropic state. Then, they are subjected to quasi-static triaxial compression using tri-periodic boundary conditions, thereby removing spurious wall effects, for different values of the interparticle friction coefficient (from 0.1 to 0.4). Axial symmetry leads to five independent moduli (Young modulus and shear modulus along and perpendicular to the loading axis together with bulk modulus), which we evaluate from the stress and strain data at several instances of loading by applying a small strain increment (10^{-7}) both along and opposite to the shear direction. We find that the elastic moduli are independent of the friction coefficient at very small shear strain due to the stability of the contact network at such dense states, but change significantly at larger strain when the topology of the contact network begins to evolve or slip events at persistent contacts occur. Notably, beyond this point the shear and bulk moduli decline with further shear deformation to a value all the smaller that the friction coefficient is large whereas the Poisson ratio increases. In all cases, the longitudinal, off-diagonal, and shear elastic moduli for polyhedra at each instant of shearing are above those for spheres. We show that this behavior reflects the continuous decrease in the contact density despite the increase of fabric anisotropy. Interestingly, we find that all the data points from different instants of shearing for different elastic moduli in each space direction nicely collapse on the same curve when plotted as a function of contact density in the same direction.

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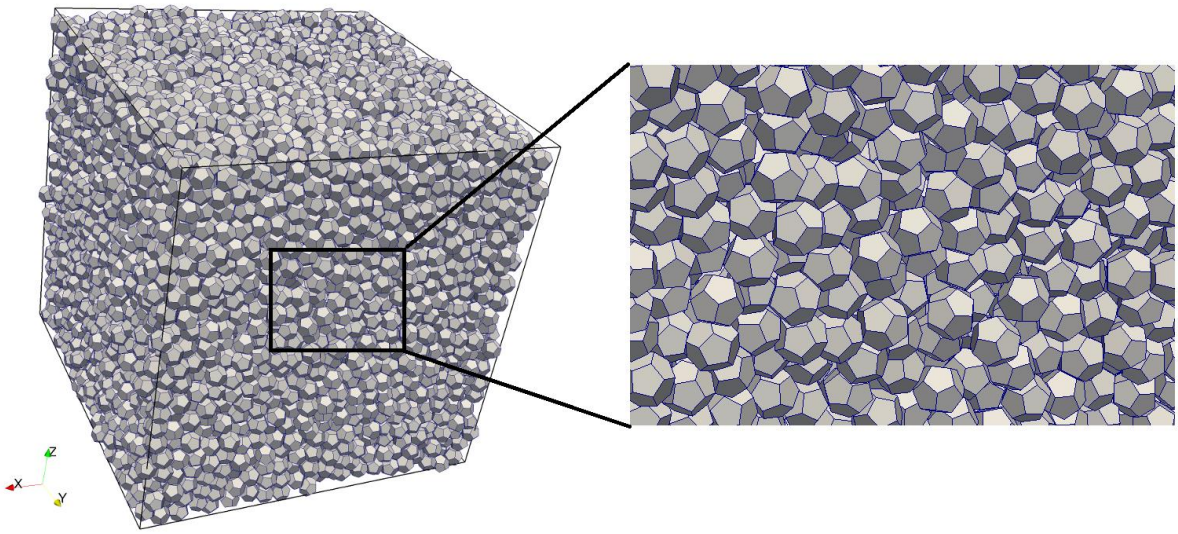

Figure 1: *Snapshot of the polyhedral packing with triperiodic boundary conditions*

A Phase-Field Discrete Element Model (PFDEM) applied to granular materials to consider irregular grain shapes and their heterogeneous evolution

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Keywords: Granular material, Micromechanics, Discrete Element Method, Phase-field Method, Microstructure evolution

Abstract

Discrete element method (DEM) was first developed by Cundall and Strack to model the micromechanical behavior of granular materials by reproducing more accurately the interactions in an assembly of grains. In the classical approach, grains are modelled as discs (2D) and spheres (3D), however, real particles can be highly irregular. These complex shapes of the grains influence greatly the macroscopic mechanical behavior of the material [Guevel, 2022] and accurate models should aim at capturing this complexity. To do so, different approaches have been developed in the frame of DEM like particles cluster, ellipsoids, polygonal (2D) or polyhedral (3D) particles [Nezami, 2004]. The latter is most accurate solution, but it tends to overestimate the roundness of the particles and show some limitations to reproduce experimental results [Lee, 2012]. Recently, a level-set discrete element model was developed and allowed to capture the complex shape of the grains and reproduce experimental results [Kawamoto, 2018].

Moreover, grain dissolution or precipitation are important phenomena in many applications involving granular media like diagenesis, fault mechanics, among others. To model these phenomena, discrete elements are often considered with a homogenous decrease or increase of the particle diameter. But in some cases, like pressure-solution, the dissolution and the precipitation are localized and depend on the local state of stress. Considering the granular material as a phase, the phase-field theory is a good candidate to model with physics-based laws an addition or reduction of the quantity of material locally.

In this study, an extension to the discrete element method is developed to simulate the irregular shapes of particles in a granular material and their heterogeneous change using the phase-field variable as a particle's geometrical descriptor. This method is applied to reproduce results from previous experiments and observations.

In a first step, the advantage of the method to model non-regular shapes is illustrated by a granular material tested under oedometric conditions during the injection of an acid to dissolve the grains [Shin, 2009], [Cha, 2014]. It has been highlighted that k_0 evolves during this dissolution. Polygonal particles can be used in the PFDEM framework to have realistic angularity and interlocking.

In a second step, the heterogeneous dissolution or precipitation capacity of the model is shown by investigating the pressure-solution phenomena at several grains level [Guevel, 2020]. The

dissolution at the contact is controlled by the introduction of energy into the Allen-Cahn formulation. Whereas the precipitation and the mass conservation are verified by the Cahn-Hillard formulation. The result is validated to previous phase-field discrete element model used to study sintering and grain growth [Shinagawa, 2014] and then applied to geomaterials.

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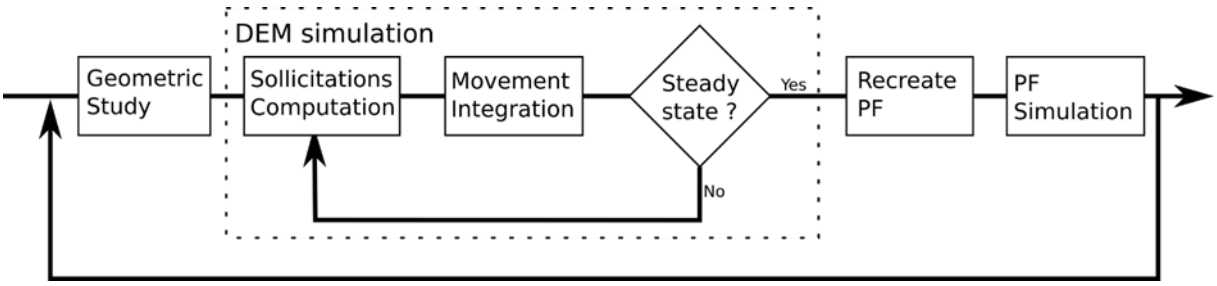

Figure 1: *General scheme of the collaboration between Phase-Field (PF) and Discrete Element Model (DEM)*

Experimental insight into the role of hydrothermal alteration on volcanic flank instabilities

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Keywords: Volcano; landslide; hydrothermal alteration; triaxial tests; microstructure

Abstract

The largest landslide in recorded history happened in Mount St. Helens in May 1980 and was the trigger of a major explosive eruption (Lipman & Mullineaux, 1981). This event drew attention on the instability of volcanic edifices, and their tendency to experience lateral collapse. Indeed, volcanic lateral collapses and their associated (volcanic) debris avalanche deposits are highly destructive because of their rapid onset and ability to cause destruction across large areas.

The growing structure of active volcanoes due to material addition can lead to oversteepening and overloading (McGuire, 2003). This situation can be worsened by seismic activity as most volcanoes are located in seismically active areas. Moreover, the materials forming volcanic edifices are subjected to extreme conditions in terms of temperature, pore pressure (consequence of several combined factors) and chemically aggressive fluids (very low pH for example) which can all destabilize volcanoes' flanks. Among these factors, hydrothermal activity is of particular interest as it enhances rock dissolution (and thus, increases rock porosity), promotes high pore pressures and leads to the creation of mechanically weaker materials (like clay-rich rocks) and promote the instability (Rattez and Veveakis, 2020). However, the effects that these processes have on volcano stability have been barely quantified (Heap and Violay, 2021).

To better understand the influence of different types of hydrothermal alteration on the hydraulic and mechanical properties of volcanic rocks, permeameter and triaxial experiments have been performed on samples retrieved by Detienne et al. (2016) from the Tutupaca volcano (17° 01′ S, 70° 21′ W). This volcano is a dacitic dome complex located at the southern end of the Peruvian arc. The study focuses on a remarkably well-preserved debris avalanche deposit emplaced to the northeast of the volcano (Figure 1a). The debris avalanche is sourced to Eastern Tutupaca; it left a horseshoe-shaped crater open to the northeast and was accompanied by a pyroclastic flow (volume: 6.5-7.5 x 10^7 m^3) (Samaniego et al., 2015). The mineralogy and the microstructure of the samples have been investigated using X-ray diffraction and micro-computed tomography respectively. Preliminary results exhibit a high variability of mineralogy, microstructures, and mechanical properties. It appears that the alteration degree may have more influence on the mechanical behavior of volcanic rocks than the porosity (Figure 1b). This dataset could be further used in numerical models of flank collapses to better constrain the role of hydrothermal alteration on the nucleation of those events.

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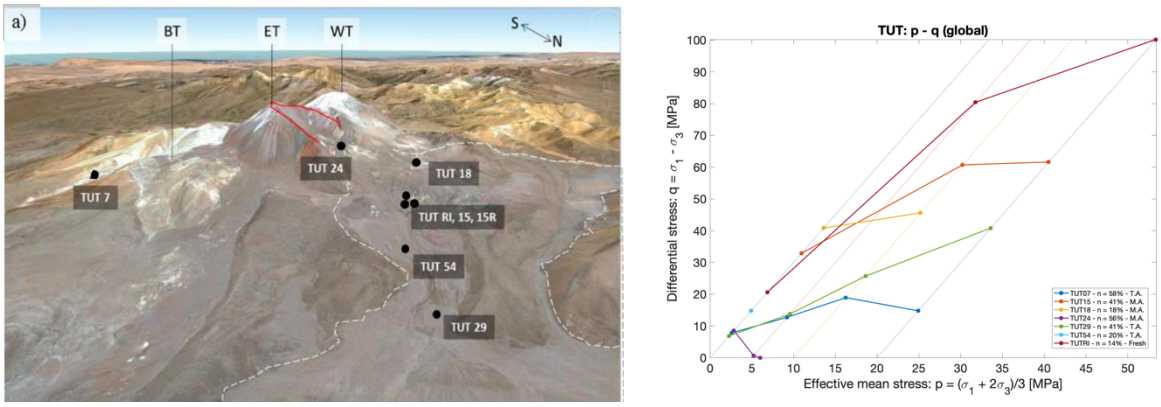

Figure 1 : *a) Google Earth image showing Tutupaca volcano, its debris avalanche deposits and the rock sample locations (From Detienne, 2016). The dotted lines delimit the debris avalanche deposit that resulted from collapse of Eastern Tutupaca ~200 years ago. The red contour indicates the scar left by the collapse. b) Differential stress as a function of effective mean pressure results from the triaxial tests performed on different samples from Tutupaca (T.A.= Totally altered, M.A.=Moderately aletered).*

Multiscale modelling of the thermo-hydromechanical behaviour of argillaceous rocks

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Keywords: Numerical homogenization, FEM2, thermo-hydromechanical behaviour of clayrock, multiscale modelling

Abstract

The study of argillaceous rocks experiences an increased interest from researchers due to its potential as host rock for nuclear waste storage facilities. Nevertheless, damage to the host rock during the life time of the repository arises from multi physics phenomena and smalled scales. As a result, a multiscale approach, based on a computational homogenization scheme [1][2], is proposed where a Representative Elementary Volume (REV) that considers the microstructure heterogeneities regarding mineral inclusions distribution and size, clay matrix content and pore space distribution (Fig. 1) is solved with a one-way coupled model (Fig 2.). At the macroscale, the model captures the main features of the thermo-hydromechanical behaviour of argillaceous rocks.

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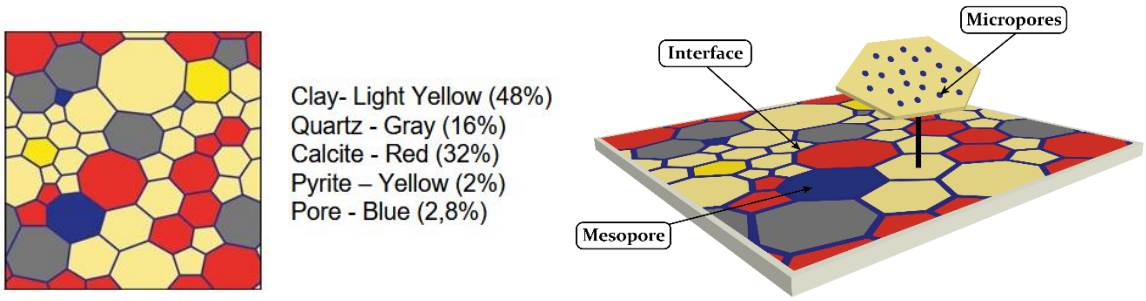

***Figure 1**: Representation of the REV with the mineral inclusions and pore space*

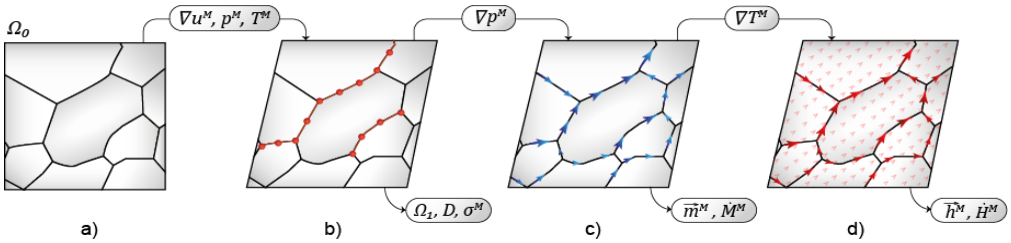

***Figure 2**: Scheme of the microscale solution algorithm at the; a) Initial configuration of the REV; b) Mechanical system; c) Hydraulic system and d) Thermal system solution.*

A Robotic Earthworm to Explore the Underground: Design, Fabrication and Testing

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Keywords: Bio-inspired engineering, Soft robotics, Soil investigation, In-situ testing

Abstract

In the last decade, important societal challenges, such as the fast climate change and energy transition, required of new, sustainable solutions for soil exploration, deployment and maintenance of utilities, tunnelling in areas inaccessible to conventional instruments. Nature provides a unique source of inspiration to design "innovative" and effective engineering technologies (bio-mimicking). For example, earthworms have adapted over time to burrow into soil. The soft body is able to exploit peristalsis locomotion to excavate and move in diverse conditions. An earthworm can anchor in soft ground, penetrate in stiff underground layers or loose sand. Pioneer works on artificial burrowing earthworms have been proposed in the robotic and geotechnical communities by Borela et al., 2021, Martinez at al., 2020, Sadeghi et al., 2013.

The current work proposes the development of a soft robotic earthworm to explore soil. The robot is made of a rigid conical tip mounted on three-chambers soft body. The movement is made possible by the alternate axial and radial inflation/deflation of the three chambers. Various soft elastic materials and tip shapes are tested to facilitate the process without yielding the body fabric and with limited disturbance of the soil microstructure. The prototype can hold high inflating pressure and horizontally advance in a granular soil at shallow depth. Preliminary results show that the selected design and material support an inner pressure of 2 bar, and a tip advancement of 12, 6, 2.5 cm for a depth of 3,5,7 cm, respectively.

Further quantitative analysis need to be conducted to assess the distance at which the prototype influence the soil and its relation with the prototype size.

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