# ALERT Geomaterials

*Alliance of laboratories in Europe for Research and Technology*

## 25th ALERT Workshop

*Aussois, 2014*

## POSTER SESSION

*Booklet of abstracts*

**Coordinator :**

*Donia Marzougui*

*(Grenoble Inst. of Tech., 3S-R Grenoble –France)*

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*Dear colleagues, welcome to Aussois!*

*We are extremely delighted to have you here with us for this this 25th Alert's Workshop, we hope it will be the perfect place for stimulating discussions on geomechanical issues and presentation of recent advances.*

*We have the honour to welcome you in a wonderful place and an authentic village of Savoie where tourism rhymes with quality of life and harmony.*

*We wish you will have good moments with us and get benefits of these exciting encounters.*

*Have a pleasant stay!*

***Donia Marzougui***

# Are FEM-DEM multi-scale computations too numerically intensive for real computations ? Tracks to overcome the CPU issue

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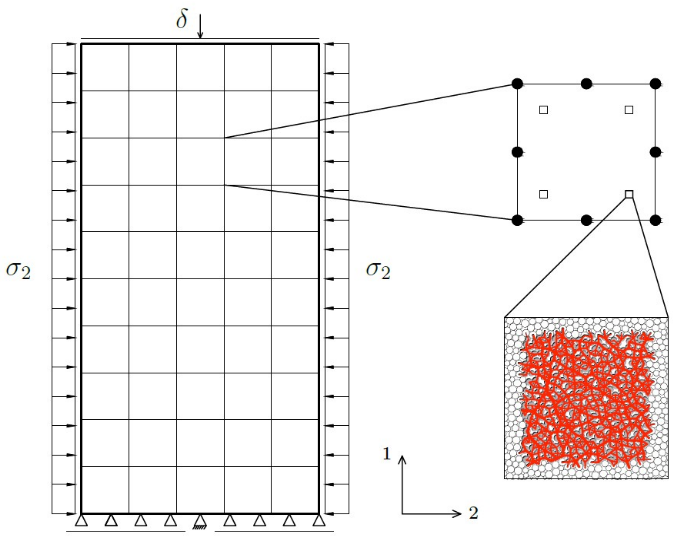
***Keywords:*** constitutive law, homogenisation, DEM Discrete Element Method

***Abstract***

Numerical approaches of the homogenisation of the microstructural behaviour of materials used in combination with macro-scale numerical methods, e.g. Finite Element Method, are an alternative to the well-known classical way that consist in formulating mathematically constitutive equations supposed to represent the behaviour of the material, and implementing these equations as local stress-strain rate laws where and when these laws are needed, i.e., for FEM, when updating update the local stresses in the iteration process of the Newton-Raphson (or else) algorithm [1-5].
Although very promising, these approaches called “Multiscale Numerical Analysis” are clearly more CPU- time demanding than the classical way, inducing some scepticism with respect to the perspectives of becoming practical modelling tools. In this presentation we propose to discuss this issue, and illustrate different perspectives of improvement of the numerical efficiency of the Multi scale approach, in the case of FEMxDEM method which associates Fem at the macro scale and Dem at the micro scale.



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# A numerical model for energy-efficient design of geothermal systems

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***Keywords:*** Numerical modelling, foundation piles, heat exchangers, geothermal energy.

***Abstract***

Geothermal systems have emerged in the last decades as an efficient and ecological way to provide heating/cooling to buildings. Traditional borehole heat exchangers (BHEs) have been the subject of extensive studies, aimed at improving their efficiency. More recently, energy piles (EPs), serving the double function of foundations and heat exchangers, have been proposed as a convenient alternative to BHEs, as they remove the requirement to make special purpose excavations and they can be expected to have a greater energy capacity per drilled metre. Currently, EP design tends to be carried out using simplified analytical or empirical methods developed for BHEs. However, EPs have a different aspect ratio than BHEs and their large diameter means they take longer time to reach steady state; hence, the transient heat transfer processes operating within the pile become more important. To increase our understanding of these processes and eventually lead to improved thermal design approaches for pile heat exchangers it is important to examine the heat transfer within the pile in detail. To this aim, an innovative numerical approach has been developed.

The transient heat convection-diffusion problem applied to EPs was solved by employing FE software ABAQUS to integrate 3D transient conduction through the solids, complemented by writing bespoke user subroutines to model the convective heat transfer at the fluid/solid interface and the temperature changes in the fluid along the heat exchanger pipes. To minimise computational time, the 3D FE mesh was created via manual input in an axisymmetric fashion (Fig. 1), representing a single energy pile with the possibility of selecting the position and number of embedded pipes and the type of hydraulic connection between the loops.

The model was validated by reproducing both the outlet fluid temperature (Fig.2) and the concrete temperature at selected locations along the pile during a multi-stage thermal response test (TRT) carried out on a test pile installed in London Clay (Loveridge et al., 2014). As an additional validation step, the performance of the 3D numerical model was also compared to calculations obtained using the 1D line heat source analytical solution (Carlslaw and Jaeger, 1959) (Fig.3).

In all cases, the numerical model was shown to provide realistic interpretation of the key aspects related to heat transfer in EPs. Hence, the model can be used in a number of applications, such as (i) aiding thermal parameter estimation during TRTs; (ii) assessing thermo-mechanical interactions, i.e. exploring any effects of the induced temperature variations in the pile's mechanical behaviour; (iii)

carrying out parametric analyses to produce recommendations aimed at improving EP design. The latter application is of particular practical interest, since our model can be employed to identify, among design factors that can be easily engineered, the most important ones to enhance energy efficiency, yet complying with geotechnical design. As an example, the influence of the number of pipes installed in a pile on the total energy exchanged between the fluid and the ground can be assessed (Fig. 4).
It is finally worth remarking that despite the focus of this work being on energy piles, the proposed numerical model can be promptly applied, upon modifying the mesh and the material properties, to the study of diverse geothermal systems, such as diaphragm walls and tunnel linings.

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## *Illustrations*

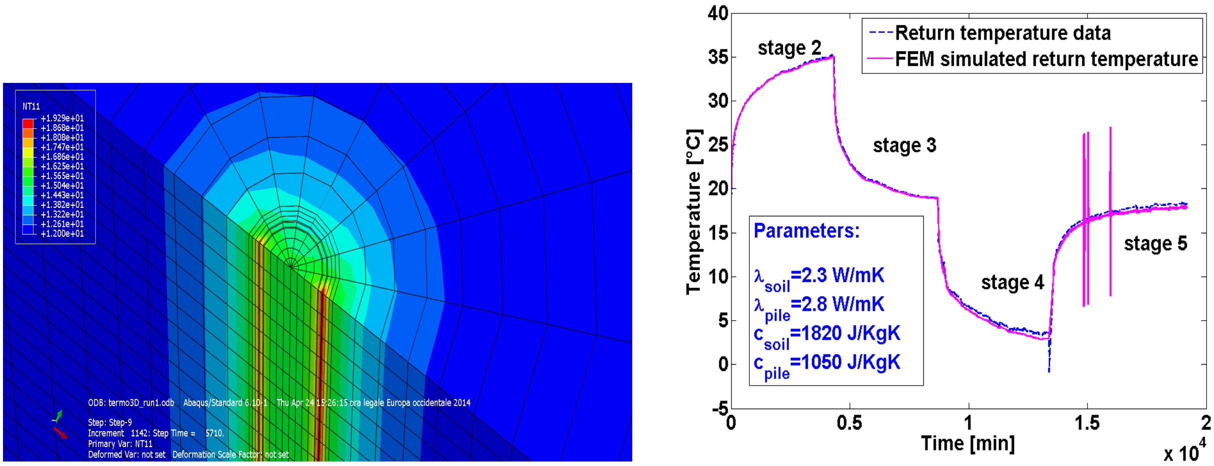


Fig.2. *Predicted outlet fluid temperature compared to measured outlet fluid temperature for TRT stages 2 through 5.*

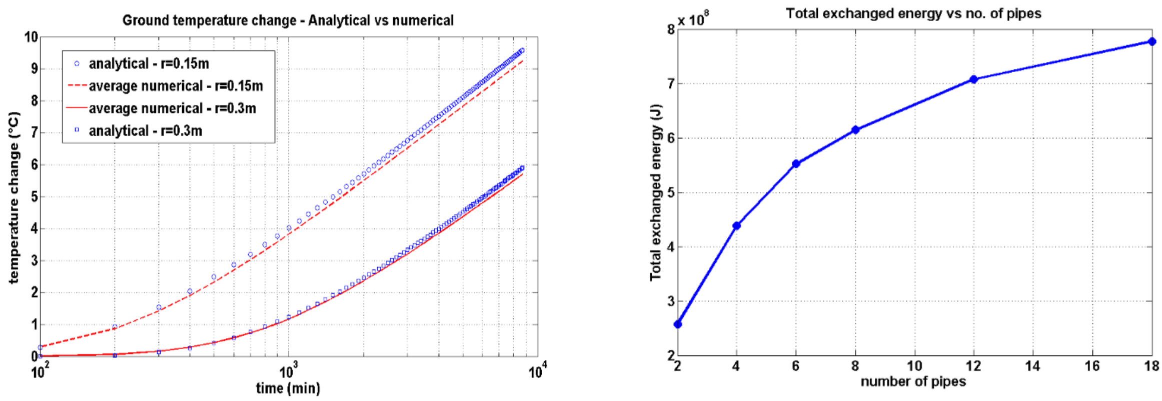


*Fig.3. Comparison between average numerical simulations and analytical calculations for the ground temperature change at radial distances of r=15 cm and r=30 cm from pile axis.*

# Implicit implementation of the Prevost model

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**Abstract**

The Prevost model for cohesionless soils [1] is currently used for the modelling of their cyclic behaviour, especially in earthquake engineering [2,3]. It's made of conical yield surfaces (Figure ) allowing plastic deformations in both loading and unloading. Its non-associated volumetric flow rule (Figure ) captures pore pressure build-up and cyclic mobility [4].

The method of implementation of a constitutive law is a crucial issue [5,6]. On one hand the accuracy of the solution must be ensured, especially when a large number of cycles are considered. But on the other hand, the cost of the computation must be minimised which implying step size as large as possible. An implicit implementation of the Prevost's model is proposed for the design of offshore foundations where a large number of cycles may be involved. This implicit formulation aims to imply a better accuracy of the results.

In this implicit algorithm, all the variables are written at the end of the step. Firstly, the hardening law proposed in the original paper has to be changed according to [7], in order to suit the implicit implementation. Secondly, all variables are expressed in terms on four primary implicit unknowns. A system of non-linear equations has then to be solved locally at an integration point in order to compute the final stress state. A Newton-Raphson process where derivatives are computed analytically is used. Thirdly, the elasto-plastic consistence operator is computed numerically.

This algorithm was implemented in the finite element code LAGAMINE that can carry out fully-coupled simulations. It was applied to the transient modelling of suction caissons in dense sand [8].

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### *Figures*

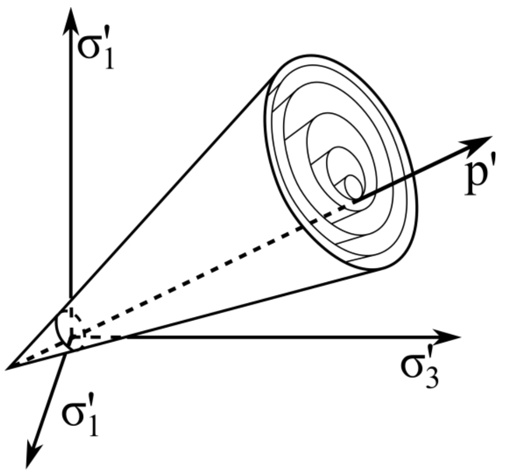


***Figure*** *Conical surfaces of the Prevost model*

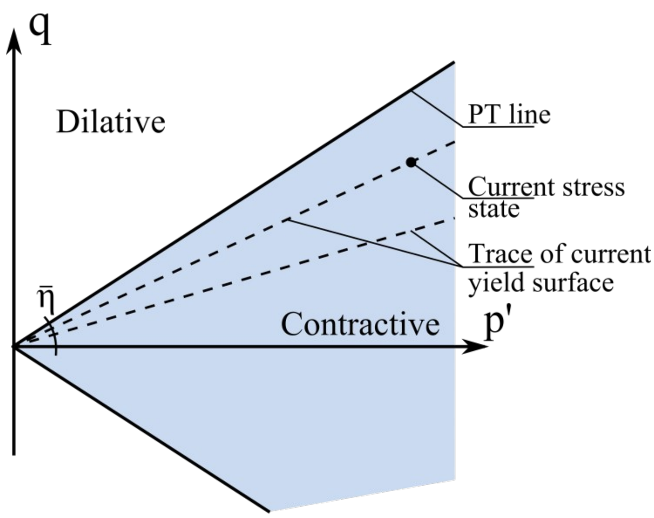


*Figure Sketch of the non-associated volumetric flow rule*

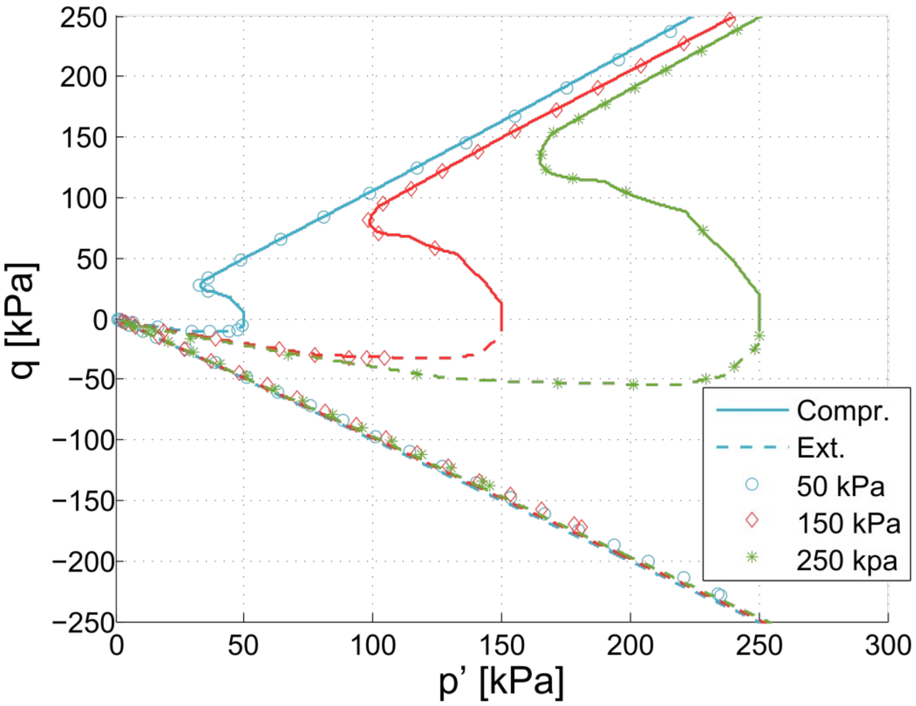


***Figure*** *Monotonic undrained simulations: comparison of analytical solutions (solid and dashed lines) with implicit results (markers) in compression and extension*

## *DEM Simulations of Unsaturated Soils Interpreted in Thermodynamic Framework*

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***Keywords***: unsaturated soils, DEM, interfaces, energy, roughness

***Abstract***

The interactions between the particles at grain scale in unsaturated granular materials have strong influence on their mechanical behavior. At low water content, a water bridge is formed between the grains, and additional forces due to the suction in the fluid add complexity to the study of such materials.
The main purpose of this study is to conduct numerical simulations of unsaturated materials and to analyze the results in a thermodynamic framework, ultimately enabling the derivation of constitutive laws that are energetically consistent. Issues raised in the recent years concerning the effective stress should also be elucidated.
Simulations are performed with discrete element method where the bridges are formed between spherical particles of different sizes in perfect wetting conditions (Scholtès et. al. 2009). The model of Scholtès et al. is enriched by introducing a new micro-mechanical variable accounting for the roughness of the grains (inspired from the work of Molenkamp et al. 2003). A new output of the model is the area of the interfaces that separate the different phases which is of primary importance from an energetic point of view (Nikooee et. al. 2012, Gray et. al. 2002 , Morrow 1969).
The state of the pendular bridges is determined by solving the Young-Laplace equation in its exact form. It relates the suction in the medium to the shape of the water bridge connecting the particles. At the micro scale, the energies of a system made of two spherical grains connected by a water meniscus are calculated, including the energy of the interfaces. For the same configuration, the work supplied to the system is calculated and divided into two parts: a) the work due to the change of the matric suction in the medium, and b) the work resulting from the relative displacement between the grains. At the macro scale, energies are determined for regular and random packings subjected to suction change or deformation. The first law of thermodynamics is verified at micro and macro scale and the effect that occurs at micro scale on the formulation of the energies at macro-scale is evaluated. The validity of some approximations made in thermodynamics is also tested.

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# *Pore-scale modeling of drainage for two-phase flow in porous media*

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**Keywords:** two-phase flow, drainage, pore-scale modeling, network models, discrete element method

## Abstract

We propose a pore-scale numerical model for the drainage process of initially saturated granular materials, as part of a wider project aiming at a fully coupled model combining two-phase flow and deformation in porous media. Although the model has similarities with previously developed pore-network models, important differences are also noticeable in the geometrical idealization of the pore space. These differences are mainly due to the spherical geometry of the solid particles and to the pore space decomposition technique. A requirement of this decomposition is that it must be able to reflect in a natural way the deformations of the porous material system. Such a flexibility is obtained by using regular triangulation, which is based on our previous research, the Pore-scale Finite Volume scheme (PFV).[1]

In this study, the method is applied to the quasi-static regime in dense random polydisperse sphere packings generated with the discrete element method (DEM [2]), aiming at simulating the primary drainage phenomenon of nonwetting-wetting (NW-W) system. The theoretical formulas for calculating the curvature of NW-W interface $r_c$ and entry capillary pressure $P_c$ at pore throats are based on the MS-P method[3-6], which are used for defining as local invasion criteria (Fig.1). The drainage process is represented by the invasion of the NW-phase when the threshold value is reached.

One key feature of the model is its capability to trap the receding W-phase(Fig.2). A dynamic search algorithm is applied to identify whether local disconnection causes large clusters of pore to get disconnected from the W-phase reservoir boundary. Another key feature is its optional side boundary condition. To accommodate different experimental situations, the pore throats of side boundary can be considered open or closed[7]. Since we assume the capillary number is quite small, the phenomenon of capillary fingering can be observed. Another trait of NW-W interface motion, which is related to the discontinuous changes of the W-phase content, i.e., Haines jumps, can also be simulated in this model.

A series of repeated simulations are performed on different sizes of random packings, from 200 to 40000 spheres, with the same particle size distribution and porosity, but different positional distribution. The capillary pressure-saturation ( $P_c - S_r$ ) relationship and the amount of trapped W-phase varies significantly (Fig.3). It suggests that the REV size for drainage process and residual saturation is much larger than what is usually considered in dry granular material problems. That

can be explained by the size of the patches of trapped W-phase which can be much larger than the diameter of the particles.
For validation purpose, we also compare some of the simulations with experiment test [8]. The simulated $P_c - S_r$ curve in primary drainage is in very good agreement with the experimental one (Fig.4).

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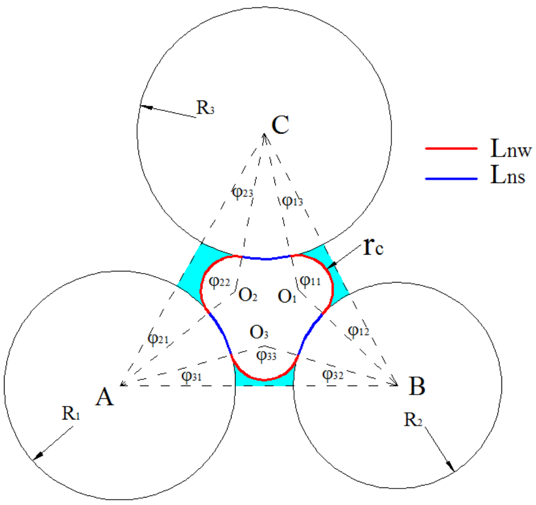


*Figure 1: Cross section geometry of pore throat, the pore throat radius is calculated based on the balance of forces for NW-W interfaces, after MS-P method.*

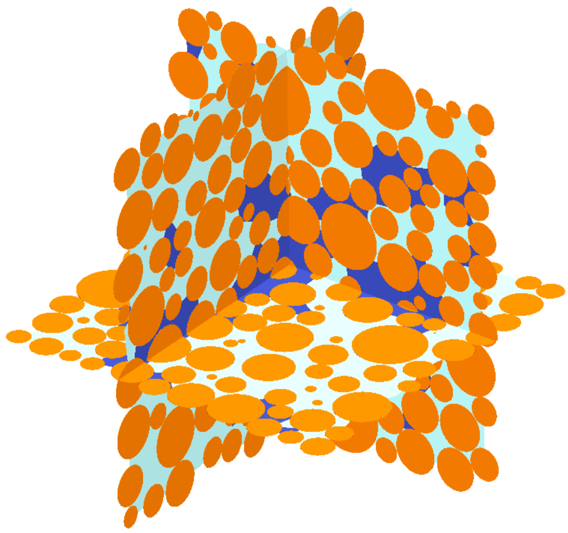

*Figure 2: W-phase trapped at the end of the simulated drainage; Solid is plotted in brown, W-phase is dark blue, and invading NW-phase is light green.*

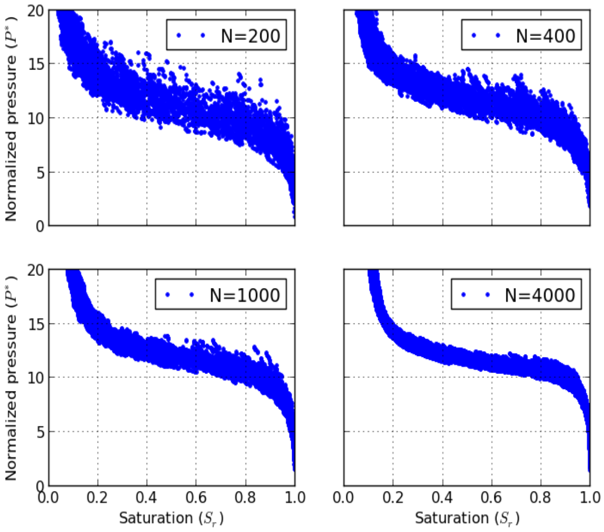


*Figure 3: Pc−Sr scattered points for different scales of samples (N is spheres number). For each scale, the No. of observations is 100.*

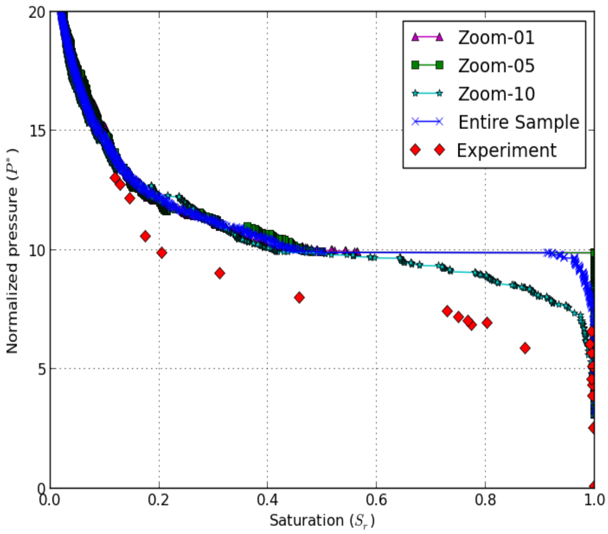


*Figure 4: Comparison between simulation model and experiments for primary drainage Pc−Sr curves. Zoom-01 connect with W-phase reservoir, Zoom-10 connect with NW-phase reservoir.*

# An efficient approach for large scale DEM modelling: application to a double-porosity crushable granular material

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***Keywords:*** DEM, crushable soils, particle failure, double porosity

***Abstract***

The discrete element method (DEM) is progressively gaining acceptance as a modelling tool for engineering problems of direct geotechnical relevance. One area for which the method seems naturally well adapted is that of crushable soils. Grain Crushing is generally modeled using the DEM via two alternative methods: replacing the breaking grains with new, smaller fragments [1-7]; or by using agglomerates [8-11]. The latter, despite being very helpful for the understanding of the micromechanics occurring in a single grain, becomes an unpractical tool for the modeling of larger scale problems. In fact, when considering those alternatives there is always a need to balance computational expediency, accuracy of results and soundness of principle. This work focuses on the encounter of those two last requirements, as exemplified in a series of simulation of high pressure one-dimensional and isotropic and triaxial compression of silica sand. A recently developed model for crushable soils [12] is briefly outlined. It is shown that the upscaling procedure adopted allows a considerable reduction of computational load without losing accuracy in terms of grain size distribution evolution and mechanical response [13]. The model is then modified in order to account for double porosity materials [14]. In particular the effect of grain crushing during one dimensional compression and triaxial compression tests of pumice sand is investigated. Experimental tests results from the literature [15] were simulated in 3-D using a large number of particles and without the use of agglomerates. The numerical simulations show the importance of incorporating internal porosity as a material characteristic. The variation of internal porosity with particle dimensions is of fundamental importance while describing the mechanical behavior of the material. The contact model parameters were calibrated using low confinement triaxial compression experimental tests while the particle failure criteria was calibrated using high pressure one dimensional compression

tests. Particle strength size effect was assumed equal to that observed in other porous geomaterials [16] and ultimately derived from the variation of internal porosity. The good fit to experimental macroscopic observations thus attained lends credibility to numerical inferences about the evolution under loading of porosity fractions (intergranular and intragranular).

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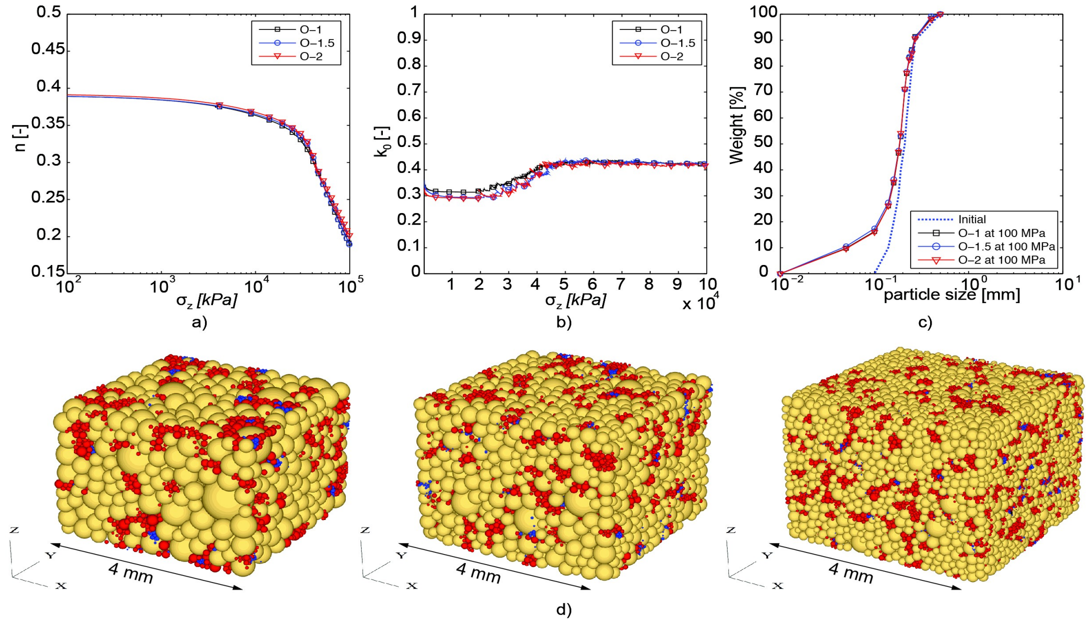


*Figure DEM-simulation of one dimensional compression: a) n-vertical stress b) k0-vertical stress c) grain size distribution at 100 MPa for the three numerical samples and d) scale 2, 1.5 and 1 samples at 100 MPa*

# Low inertial number discrete element modelling of the asymptotic behaviour of granular materials

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***Keywords:*** asymptotic behaviour, Discrete element method

***Abstract***

Mašín (2012) described the concept of the asymptotic behaviour of particulate materials, including its enhancement by considering asymptotic states in extension. A 3D discrete element model with elastic spherical particles and the granulometry of a real sand has been set up using DEM software Yade. The numerical sample has been stretched from different initial states, and the influence of the strain rate direction on the final state has been studied within the stress ratio, void ratio and mean stress space. Mašín (2012) observed the behaviour which well corresponded with the known behaviour of soils, apart from one difference - the asymptotic stress ratio (such as the critical state friction angle) depended on mean effective stress. Mašín (2012) argued that this dependency might have been caused by relatively high inertial numbers I adopted in his simulations. Mašín (2012) opinion that I is a likely cause of the dependency of the asymptotic stress ratio on mean stress has been based on results of several other researchers. They observed that the global coefficient of friction $\mu^*$ in simple shear tests increased with increasing I. For lower then the threshold values of I (approximately $I < 10^{-2}$), however, the friction coefficient did not depend on the shear rate.

Mašín (2012) could not run his simulations at sufficiently slow rates due to excessive computational demands. In this paper, we present new discrete element simulations. We slowed-down the stretching rate by several orders of magnitude and performed computationally highly demanding simulations. Consistently with the expectation of Mašín (2012) and in agreement with the standard assumptions of the critical state soil mechanics, asymptotic stress ratio at low inertial numbers was found not to depend on the mean stress level. In addition, we also investigated the influence of Lode angle on the asymptotic stress ratio.

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## ***Illustrations***

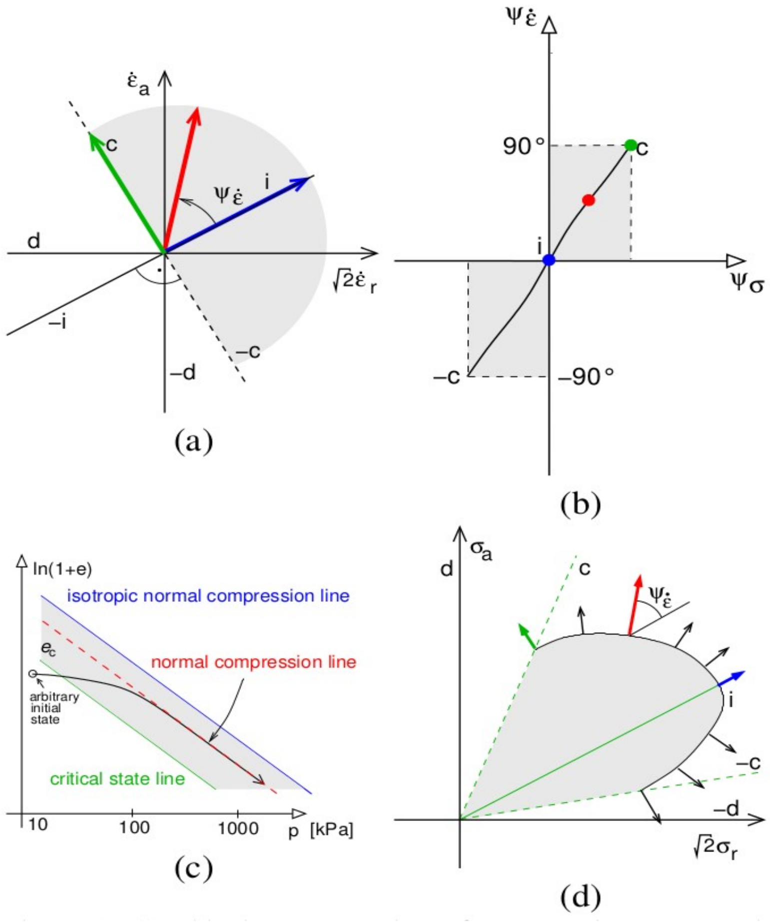


*Figure 1: Graphical representation of compression asymptotic states.*

# Critical state constitutive model for re-saturated structured soils

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***Keywords:*** Constitutive model, structured soils, conventional mechanical tests, structure degradation

## *Abstract*

Earth constructions are generally built by dynamic compaction that provides specific behaviour to fine-grained soils related to their microstructure. Compaction at the dry side of optimum provides an aggregated structure to the soil (*Delage et al. 1996*). At low stress states, the behavior is relatively rigid and governed by the inter-aggregate contacts. Then, when plasticity is reached, the deformation is first induced by the rearrangement of the aggregates. The large pores collapse first and the bi-modal pore size distribution moves to a uni-modal distribution that corresponds to a degradation of the microstructure. Finally, at large strain levels, the deformation is induced by the deformation of the aggregates themselves.

After an overview of existing experimental evidences on the link between soil structure and global mechanical behaviour, a constitutive model for saturated soils is developed to incorporate the effects of structure on the mechanical behaviour. The model is based on the ACMEG model developed for remoulded unsaturated soils (*Francois and Laloui 2008*) and extends it through the consideration of a structure parameter. Irreversible strains are considered through two inter-connected plastic mechanisms. The isotropic mechanism is activated upon hydrostatic loadings while deviatoric mechanism is mobilized upon deviatoric stress states (Figure 1). The apparent preconsolidation pressure ($p'_c$) is the link between the two mechanisms. In addition to the conventional strain hardening, the apparent preconsolidation pressure depends on the structure state which is affected by the condition of compaction and the subsequent degradation upon plastic strain. Finally, progressive mobilisation of plasticity can also be activated inside the bounding surface in order to control the smooth transition between elastic and plastic responses. This is particularly well-appropriated for soil with a dispersed structure. The proposed model follows the main concept of the models for structured soils as developed previously by various authors (*Kavvadas et Amorosi 2000, Nova et al. 2003, Liu et al. 2013*, among others) using a structure parameter. The new ingredients are related to the double mechanism of plasticity that distinguishes

structure degradation induced by deviatoric and isotropic loading.
A physical significance of the structure parameter is given by the tracking of the pore size distribution along different compression states (*Delage 2010*). The soil is considered as fully structured when it exhibits a fully developed bi-modal pore size distribution while this structure parameter vanishes when the pore size distribution shows a single mode of pore sizes.

This model is validated by comparison with experimental results (triaxial and oedometric compression tests (Figure 2)) obtained on re-saturated soils compacted at different moisture contents (in order to generate different microstructures). Triaxial test on heavily overconsolidated soils were carried out to highlight the deviatoric behaviour of isotropically-destructured soils. This framework can be extended towards other origins of the soil structure (compaction conditions, cementation, chemical treatment, natural clayey bondings). The physical significance is investigated through Mercury Intrusion Porosimetry on soils at different compaction conditions and different loading stages (Figure 3).

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## *Illustrations*

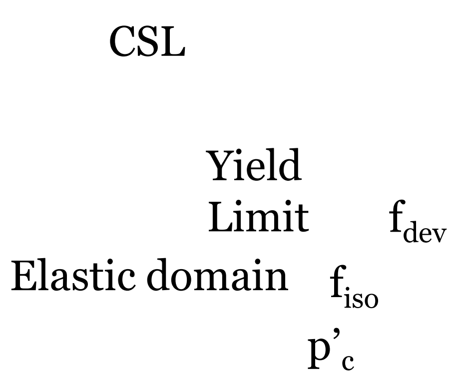


*Figure 1: Elastic domain delimited by deviatoric and isotropic Yield Limit*

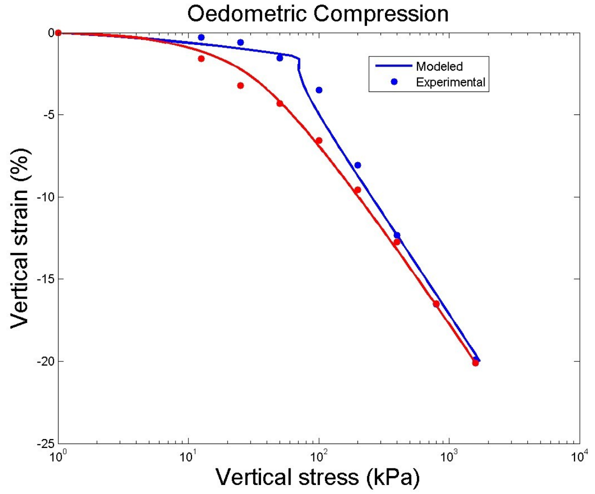


*Figure 2: Modeling (solid line) of oedometric compression tests carried on structured (blue) and unstructured (red) soils*

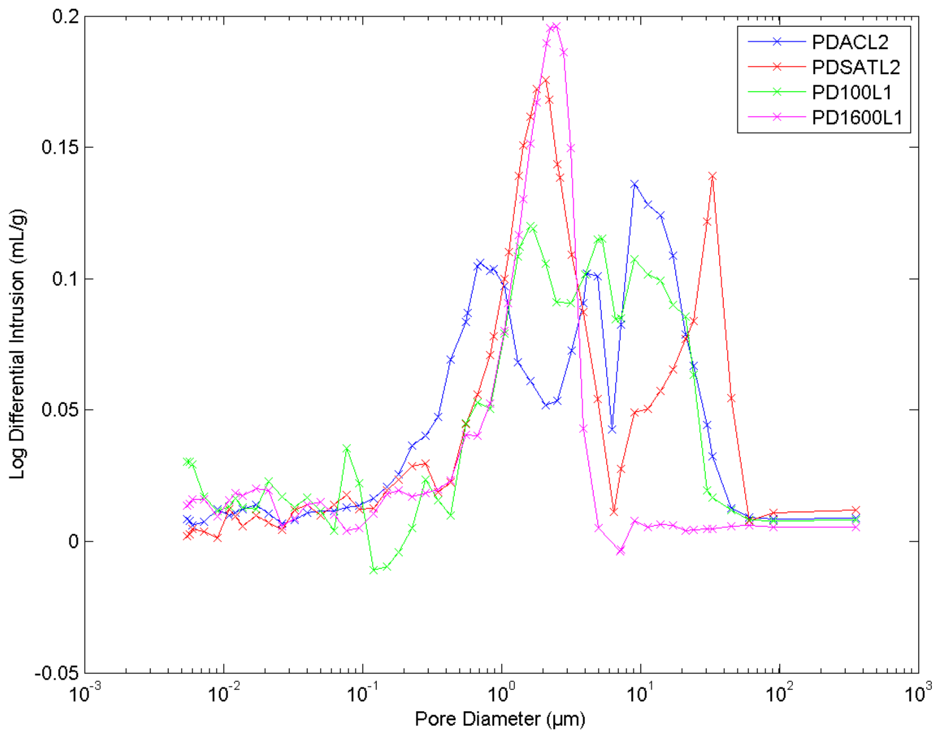


*Figure 3: Pore Size Distribution of a structured soil at acompacted state (blue), saturated (red) and loaded in an oedometer at 100 kPa (green) and 1600 kPa (magenta)*

# A viscoplastic approach to the behaviour of fluidized geomaterials: application to the case of Aberfan flowslide

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***Keywords:*** Landslide propagation modelling, coupled pore pressures, Perzyna viscoplasticity, SPH

### *Abstract*

Landslides can cause major economic damage and large number of casualties as it is possible to see from past events occurred all over the world. Being able to model these kind of hazards would then suppose the achievement of great benefits. Here a model that combines a depth integrated description of the soil-pore fluid mixture together with a set of 1D models dealing with pore pressure evolution within the soil mass is presented. In this way, pore pressure changes caused by vertical consolidation, changes of total stresses resulting from height variations and changes of basal surface permeability can be taken into account with more precision. Concerning the material behaviour, the approach used is the one suggested by the Perzyna viscoplasticity, which has been extensively used in the past to model solid behaviour prior to failure. Three different yield criterion are considered in the framework of Perzyna's model: a Von Mises, a Mohr Coulomb and a Cam Clay yield criterion. The obtained results lead to a good agreement with the results achieved using classical rheological models. Then, from Mohr Coulomb viscoplasticity, a simple shear rheological model is derived, providing the basal friction needed in depth integrated models. As an example that shows the performance of the proposed model, the case of the Aberfan flowslide, occurred in 1966, is presented.

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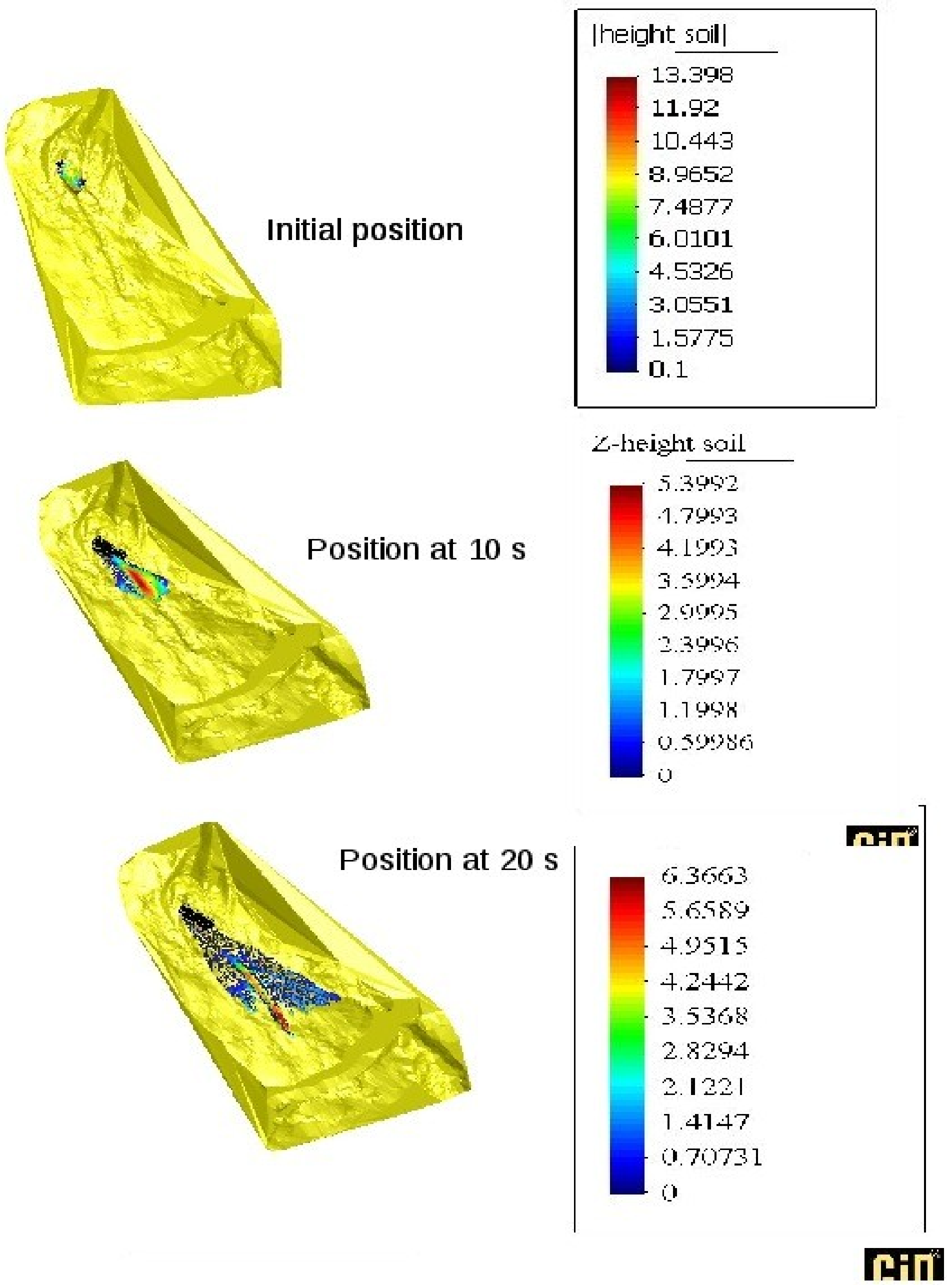
## *Illustrations*



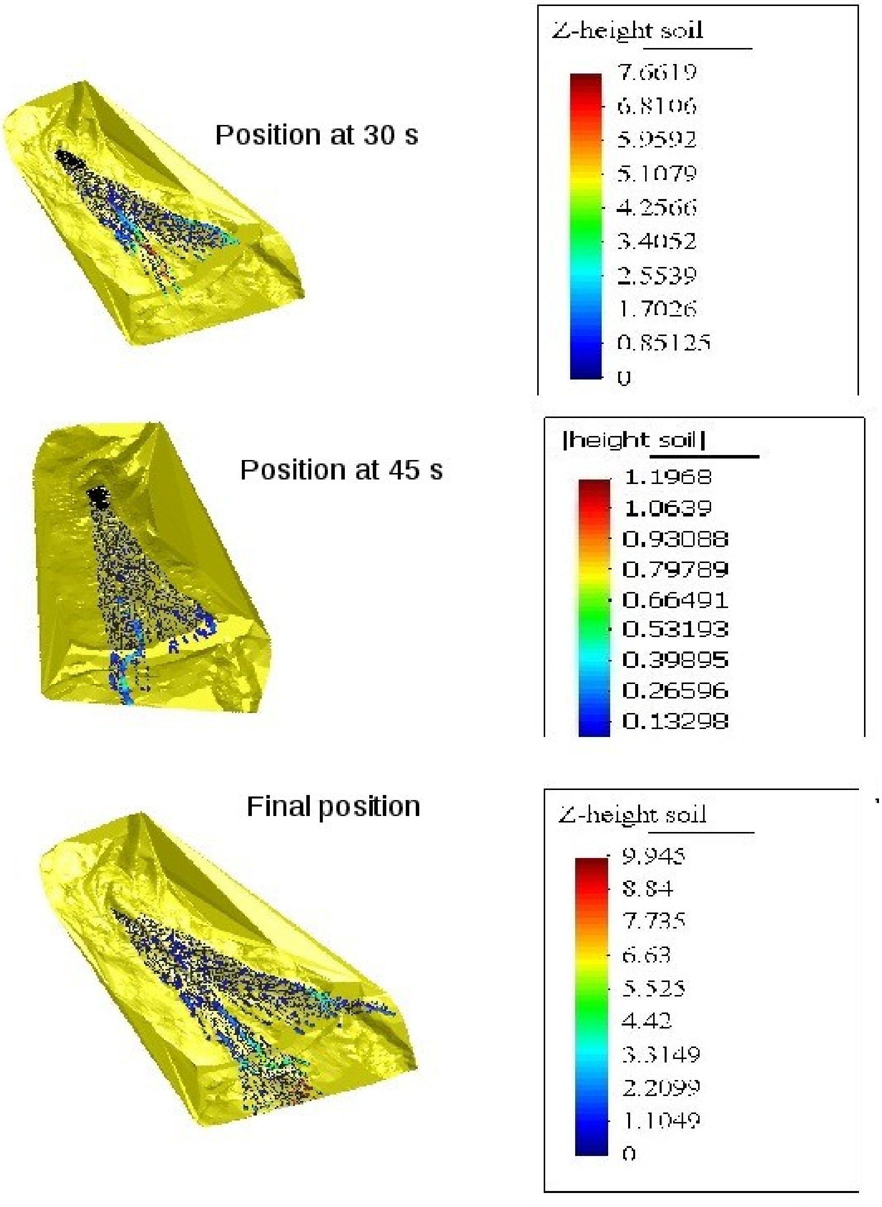



***Figure 1:*** *Results sequence of Aberfan flowslide simulation at 0, 10, 20, 30, 45 and 50 seconds*

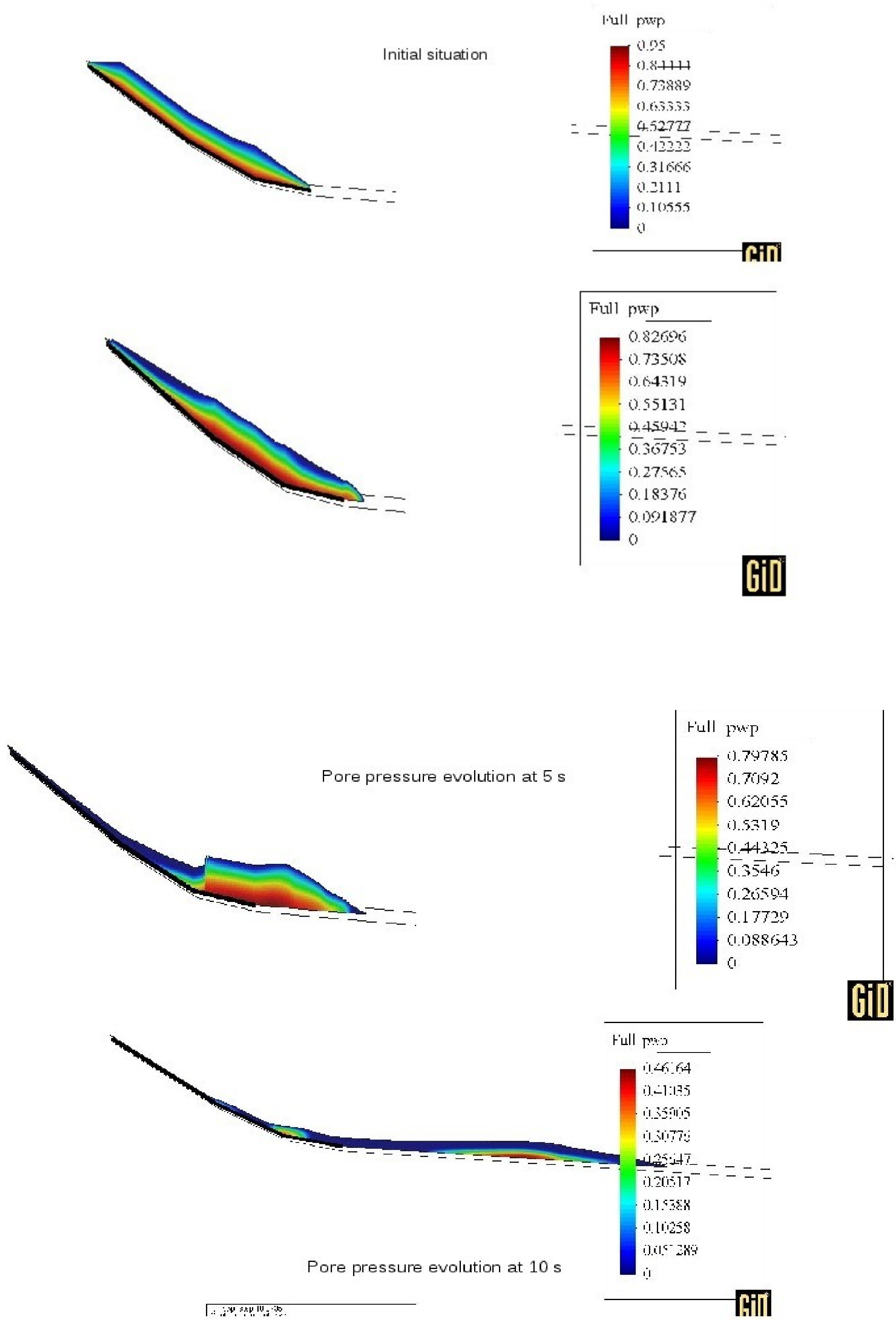



***Figure 2:*** *Results sequence of pore pressure contours evolution at 0, 2, 5 and 10 seconds*

# In situ characterisation of heterogeneous bedrock

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***Keywords:*** Bedrock characterisation, Ultrasonic borehole imager, Distributed Temperature Sensing technique

***Abstract***

In order to investigate the bedrock heterogeneity in situ and obtain information useful for its hydro-thermo-mechanical behaviour, four boreholes equipped with double-U geothermal pipes (Borehole Heat Exchangers, BHE) of 100 m long were installed on the campus of the University of Liege (Liege, Belgium) over a surface area of 32 m². During pipe installation fiber optic cables were attached along the pipe loops in the four boreholes. The bedrock, which starts at a depth approximately of 8 m, is quite fractured and consists mainly of siltstone and shale interbedded with sandstone.

An ultrasonic borehole imager (borehole televiewer) was lowered into the boreholes to obtain high-resolution, continuous images with 360° coverage of the local geology and fracturing (Fig.1). Moreover gamma-ray logs of the four boreholes were obtained and inclinometry was conducted. Fiber optics allow us to measure the temperature along the borehole length by applying the Distributed Temperature Sensing technique, which is based on Raman optical time domain reflectometry [1]. Temperature is measured during hardening of the grouting material (Fig. 2a) and at the undisturbed state, every three months for one year (Fig. 2b).

The applied procedure can provide detailed information on the rock mass, useful for the hydro-thermo-mechanical behaviour of the bedrock. Based on the borehole televiewer data and observation of the cuttings during drilling a detailed rock characterisation is obtained, including rock identification through depth, fractures characterisation (position, opening, orientation, dip angle) and layer dipping determination. The bedrock heterogeneity is indicated due to the uneven distribution of fractures in the four boreholes and with depth as well as due to the alternation of different rock types. Temperature measurements during hardening of the grouting material indicate extended fractured zones, probably filled with grouting material. Apart from the open fractures, the locally filled with grouting material fractures would affect the distribution of permeability, the mechanical strength and the effective thermal conductivity of the rock mass. The temperature variation through depth at the undisturbed state indicates heat loss through the foundation of buildings near the boreholes and/or ground water movement, parameters that affect the thermal behaviour of BHEs.

Distributed Thermal Response tests will be conducted in the four BHEs [2]. The measured data will allow us to correlate any anisotropic thermal behaviour to the geological characteristics. The available information could be used for a detailed numerical model.

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## *Illustrations*

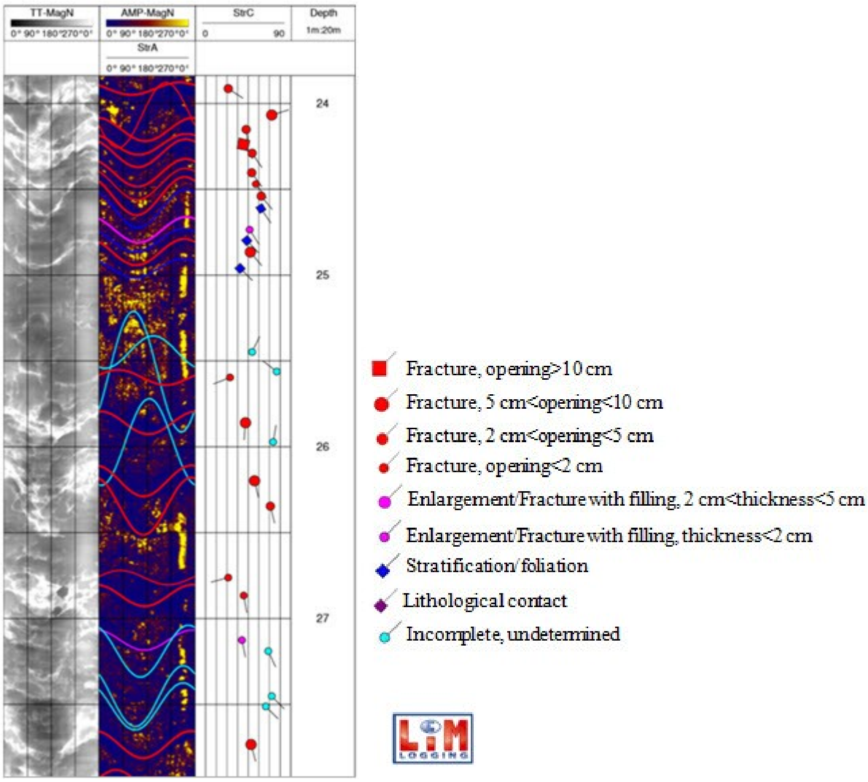


Figure 1: High-resolution images of an extended fractured zone
from left to right: acoustic travel time column, acoustic amplitude column, structural interpretation of each fracture (opening, orientation, dip angle) and corresponding depth values

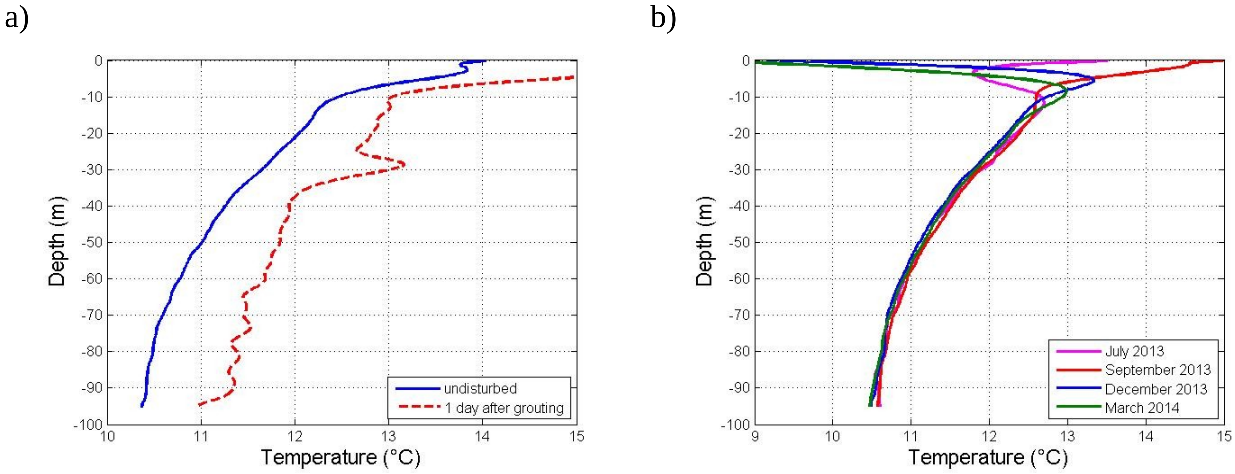


*Figure 2: a) Temperature during hardening of the grouting material and b) Undisturbed ground temperature*

# Some factors affecting the cyclic stiffness of rail-track foundation materials

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***Keywords:*** railway, suction, cyclic, stiffness.

## *Abstract*

The main serviceability criteria used for railway tracks require estimates of permanent deformations [1] and track stiffness [2]. Design methods for sub-ballast layers are predominantly empirical or semi-empirical [3]. The track foundation is regarded as a type of pavement structure [4]. The resilient modulus, $M_R$, is used in mechanistic-empirical pavement design as the main material input parameter for predictions of pavement response and performance [5].
The research has investigated the influence of matric suction, and principal stress rotation due to train induced stresses [4], on the cyclic stiffness ($M_R$) of unsaturated railway foundation material. Cyclic hollow cylinder tests (Figure 1) have been conducted on unsaturated railway foundation material compacted at a range of water contents. Resilient moduli of unsaturated samples have been found to be up to five times higher than for saturated samples. In contrast, PSR due to shear stress reversal reduced the measured MR on unsaturated formation material by only approximately 20%, comparable to results previously reported for saturated samples [6].
Interpretation of unsaturated soil behaviour using two stress state variables; net normal stress and matric suction [7] or suction stress [8] is part of ongoing analyses. The collapse potential of the compacted materials [9] has yet to be evaluated.

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## *Illustrations*

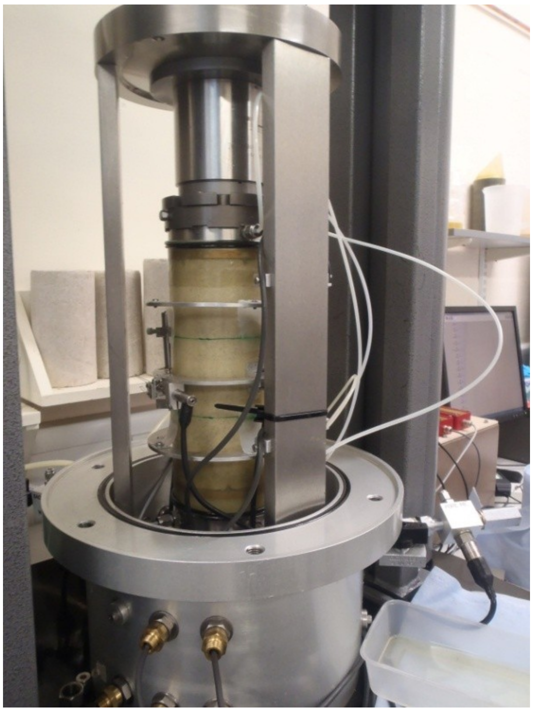

*Figure 1: Cyclic hollow cylinder test set-up with local displacement measurements*

# Back-analysis of $K_0$ in overconsolidated clay on the basis of convergence measurements of a circular cavity

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***Abstract***

In the poster, we present an investigation of the earth pressure coefficient at rest $K_0$ by means of back-analysis of deformation measurements in underground cavity constructed in overconsolidated Brno clay. The model has been setup within Plaxis 3D software. To represent the clay behaviour, we utilized recently developed hypoplastic model with small strain stiffness anisotropy. Soil anisotropy was shown to influence the back-analysis results significantly. We also demonstrated, that back-analysed $K_0$ is also influenced significantly by the neighboring exploratory gallery. The analyses indicated $K_0$ = 0.81 in the depth of 23 m. To verify the results, this value was subsequently used as initial condition in numerical 3D analysis of Královo Pole tunnel. The measurements of horizontal deformation by inclinometer and surface settlement trough agree well with the results obtained from the back-analysis.

# Laboratory investigation of two basic models for inhomogeneous soils

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***Keywords:*** *lumpy soils; series model; parallel model; failure mode; stress distribution*

***Abstract***

Lumpy soils are inhomogeneous materials which can be encountered in land reclamation and open pit mining. The lumps are randomly distributed in the reconstituted soil but on a mesoscale their configuration can be expressed by two simplified configurations of both constituents. For this purpose, isotropically consolidated drained triaxial shear tests were performed on artificially prepared specimens with parallel and series structures. The laboratory tests show that the series specimens have the same failure mode like the constituent with the lower strength; the parallel specimens have a failure plane which crosses both constituents. As a result, the shear strength of the series specimens is only slightly higher than that of the constituent with the lower strength and the strength of the parallel specimens lies between those of the constituents. Furthermore, the maximum volumetric strain of the series specimens is lower than that of its constitutes, which is significantly different from that of the parallel specimens. The stress ratio of parallel specimens, defined as the ratio of stress in the stiffer constituent to that of the weak one, increases with the consolidation stress; while, the strain ratio of the series specimens, defined as the ratio of strain in the stiffer constituent to that of the weak one, is not sensitive to the consolidation stress.

***Illustrations***

*Parallel and series specimens used for the triaxial test in this study*

# Numerical modeling and homogenization of soft granular media

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**Keywords**: *Contact Dynamic Method; Material Point Method; Deformable Particles*

## Abstract

Soft-particle materials include colloidal pastes, vesicles, many powders, microgels and suspensions, indicating their diversity and technological importance. These materials share the common feature of being composed of well-defined particles that can undergo large deformations without rupture. In this respect, they differ from hard-particle materials with their plastic behaviour mainly governed by particle rearrangements and frictional sliding. Soft particles can reach high packing fractions by particle shape change and still flow plastically. The compaction, volume change behaviour under shearing and the properties of the resulting complex textures in soft packings above the random close packing state have basically remained unexplored due to the lack of proper numerical and experimental tools.

The *Discrete Element Methods* (DEM) are widely used for modeling particle assemblies due to its ability to take into account different loading conditions, particle size distributions and physical properties of the particles. However, the DEM is not suitable for simulating realistic behaviour at the sub-particle scale, including large deformations. To model the mechanical properties of soft particles and their mutual interactions, a new methodology is proposed on an implicit formalism of *Material Point Method* (MPM) coupled with the *Contact Dynamics* (CD) [1]. In MPM, each particle is discretized by a collection of material points. The information carried by the material points is projected onto a background mesh, where equations of motion are solved. The mesh solution is then used to update the material points. The implicit formulation allows for unconditional numerical stability and efficient coupling with implicit modelling of unilateral contacts and friction between the particles. This implicit MPM-CD model is implemented in a manner that the contact variables (velocity, force...) can be computed simultaneously with bulk variables.

This technique MPM is compared with a simpler model in which deformable grains represent by an assembly of primary particles interacting by attractive forces and simulated by the CD method. We present an investigation of the compaction process of 2D soft-particle assemblies by means of these proposed models.

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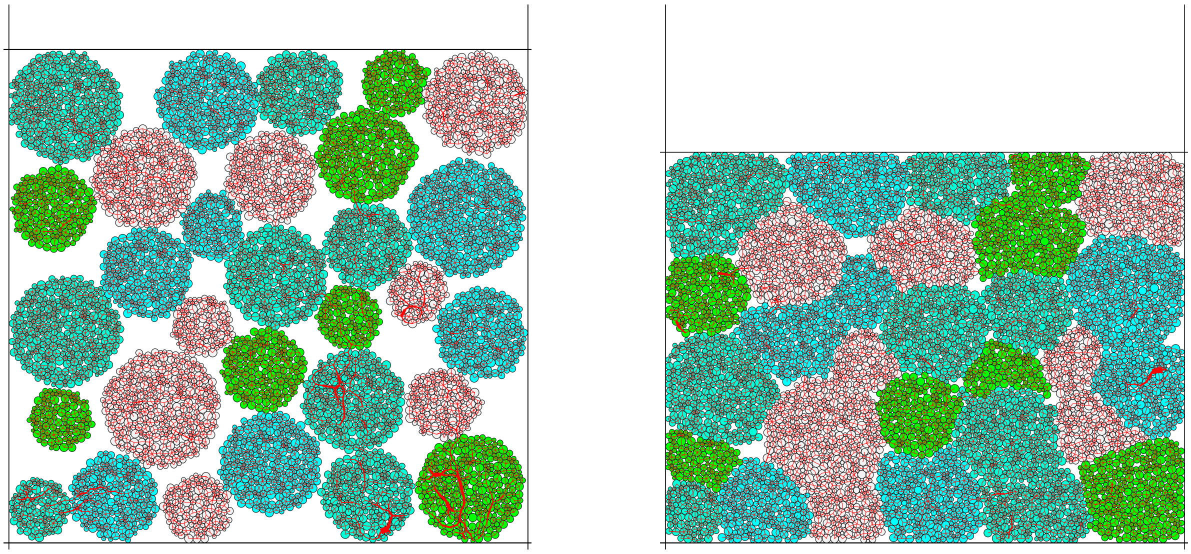
## Illustrations



(a) (b)

# Analysis of convergence measurements in drifts in Callovo-Oxfordian Claystone

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***Keywords:*** *convergence measurements, anisotropy, underground excavation, claystone.*

***Abstract***

The main purpose of this work is to analyze the anisotropic convergence observed in drifts of the Meuse/haute-Marne Underground Research Laboratory (M/HM URL). In 2000, the French National Radioactive Waste Management Agency (Andra) began the construction of the M/HM URL with the main goal of demonstrating the feasibility of geological repository in Callovo-Oxfordian claystone. Drifts have been constructed with different characteristics: excavation method, structure geometry, supports system and orientations with respect to the horizontal principal stress directions. In each drift different sections have been instrumented to monitor the convergence evolution and the rock deformation. Continuous monitoring of the excavated zone around the drifts revealed the development of a fractured zone (extensional and shear fractures) induced by the excavation. The fracture distribution depends on both the drift orientation and the in-situ stress field (Armand et al., 2014) and has an important influence on the drifts convergence.

The convergence measurements showed an anisotropic closure, which depends on the drifts' orientations. The drifts following the direction of the minor horizontal principal stress showed a vertical to horizontal convergence ratio of around 4.0, while this ratio was about 0.5 for the drifts with axis following the major principal stress (Armand et al., 2013). It should be noted that at the main level of the URL (i.e., -490 m) the minor principal horizontal total stress is very close to the vertical stress (≈ 12MPa), while the major principal horizontal stress is about 16MPa. Knowing that the initial stress state is quasi isotropic (in the plane of their section) for the drifts following the direction of the major principal horizontal stress, the anisotropic closure of drifts can be attributed to the anisotropic behavior of the rock mass.

In this work, the anisotropic character of the convergences is taken into account by assuming that the drift section evolves following an elliptical shape (Figure 1). The convergence measurement

data was analyzed on six different points around each drift in order to identify the main axes of the deformation ellipse, following the methodology proposed by Vu et al. (2013). Then, using the semi-empirical law proposed by Sulem et al. (1987), the convergence evolution is fitted independently for each axis of the ellipse. The convergence law parameters evaluated for different monitoring sections in each drift, permit to describe the evolution of each axis of the ellipse with time and with the distance to the front face (see Fig.2 and Fig.3). Moreover this method permits to distinguish two effects: the face advance effect and the time-dependent behavior of the ground.

The results for two drift orientations show close values for the parameters describing the time-dependent properties of the ground, the distance of influence of the face and the extension of the decompressed zone around the drift. Thus, these parameters can be assumed as constant values. Then, a good reproduction of convergences can be done by fitting a single parameter describing the instantaneous convergence (no time-dependent). It is observed that with a period of about 40 days of convergence monitoring, the model can give reliable predictions of the convergence evolution in the long-term. Moreover, the model can be generalized in different drifts geometries and different drifts supports.

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## *Illustrations*

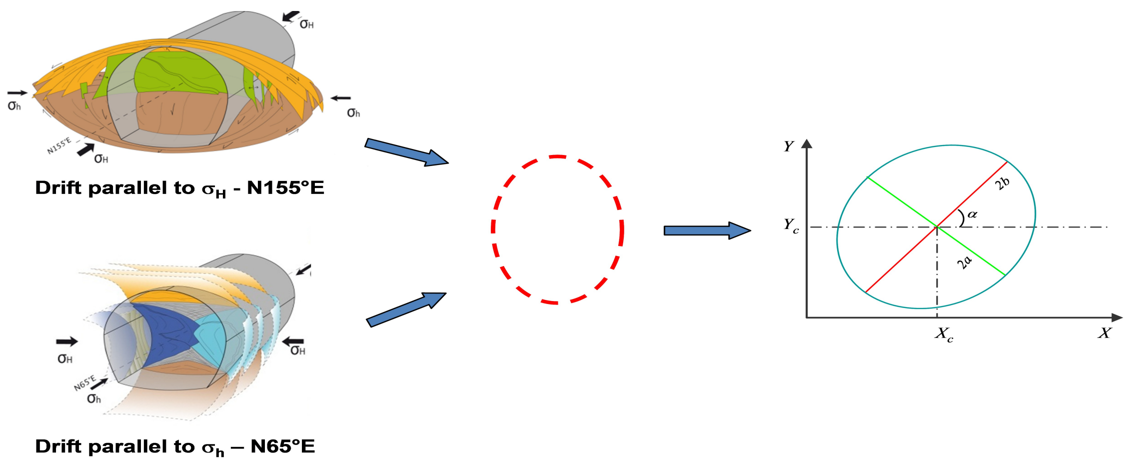


***Figure 1:*** *Identification of the main axes of deformation*

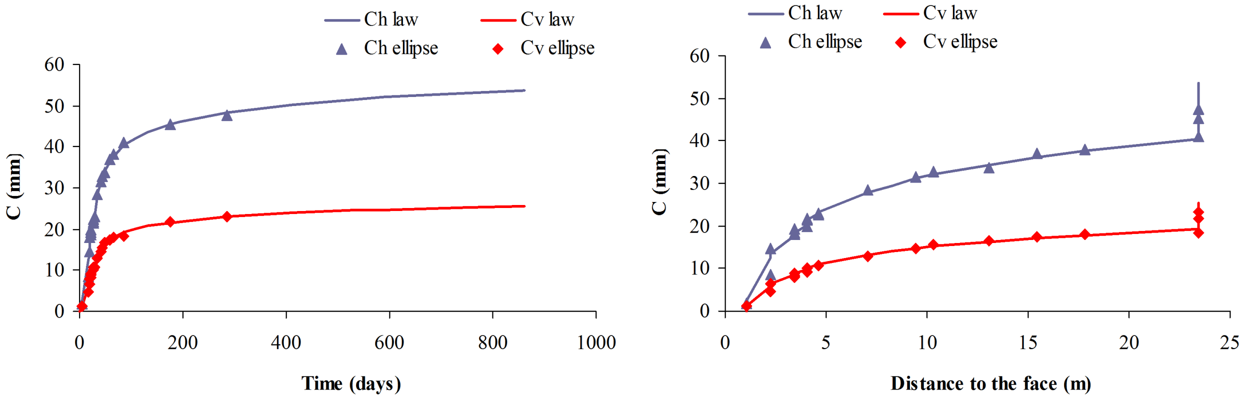


***Figure 2:*** *Convergence evolution in a drift section – Parallel to $\sigma_H$. ($C_h$ = horizontal convergence; $C_v$ = vertical convergence*

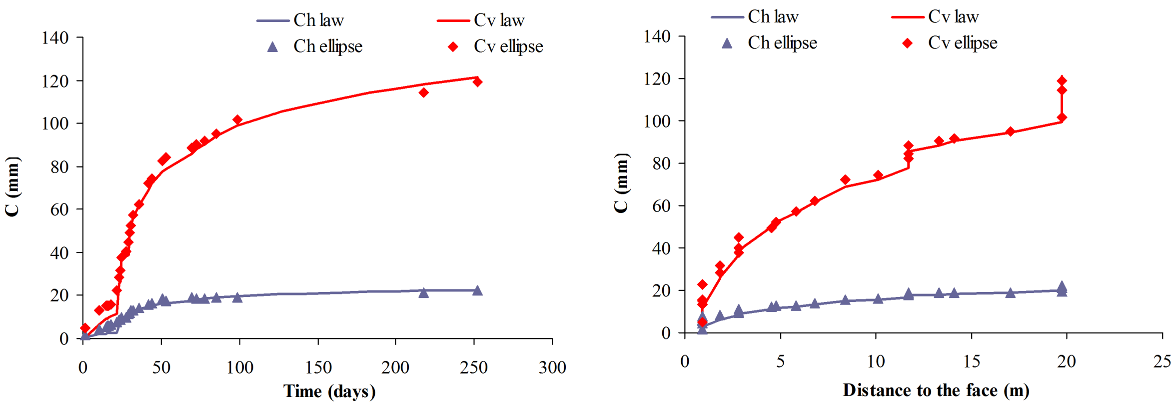


***Figure 3:*** *Convergence evolution in a drift section – Parallel to $\sigma_h$. ($C_h$ = horizontal convergence; $C_v$ = vertical convergence*

# Seismic wave attenuation associated with flow through thin fractures

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***Keywords:*** *wave-induce fluid flow, fracture flow, seismic attenuation, modeling*

***Abstract***

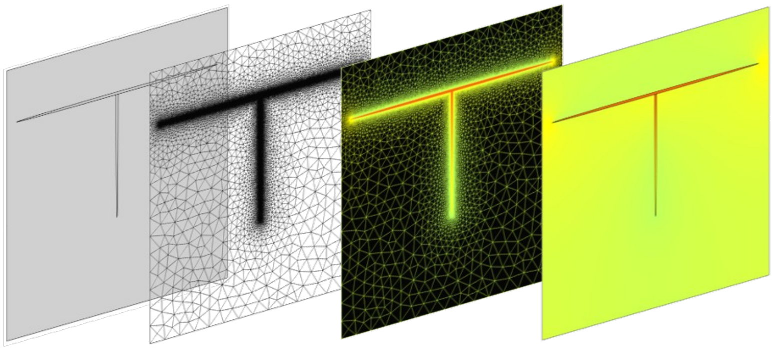
Heterogeneity of porous media induces a number of fluid-flow mechanisms causing attenuation of seismic waves. Inhomogeneous distributions of rock-matrix properties and hydraulic properties induce heterogeneous effective stresses and fluid pressure distributions, causing fluid flow on the length scale of the heterogeneities. In a fractured material, fluid flow may occur in a single conduit or between conduits when the material volume is stressed.

Attenuation induced by squirt-type mechanisms has previously been analyzed at the pore scale for aspect ratios smaller than $10^3$. Yet, natural or stimulated fractures in reservoirs exhibit high aspect ratios and resemble thin and elongated inclusions with aspect ratios > $10^3$. An improved understanding of the role of attenuation due to flow in fractures with realistic aspect ratios provides new directions for the interpretation of field data, for example estimation of fracture parameters from seismic data or analysis of fracture connectivity.

Using a hybrid-dimensional modeling approach, particularly apt for large-aspect-ratio conduits, we numerically simulated fluid flow induced by elastic deformation of fractures that are much larger than the average pore size of a porous rock, to investigate the physics of attenuation related to the interaction of fracture-induced fluid flow and to leak-off.

Attenuation related to fracture flow increases in magnitude with increasing geometrical aspect ratio of the fracture. The inherent time scales of both flow mechanisms do not influence each other, but the faster process is associated with stronger attenuation than the slower process. Models relying on simple diffusion equations have rather limited potential for approximation of pressure transients.

***Illustrations***



# Effect of carbon dioxide on fault friction and slip stability

***Hadrien Rattez[1], Jean Sulem[1], Siavash Ghabezloo[1]***

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***Keywords:*** *Carbon Storage, Rate and State friction laws, fault stability, friction experiments*

## *Abstract*

The Carbon Capture and Storage (CCS) is one of the technics considered to reduce the humans' emission of greenhouse gases. The principle is to capture the $CO_2$ and separate it from other gases in the combustion smoke of major plants like cement factories or coal-burning power plants. Once extracted, the gas is compressed and transported with a pipeline to injections sites. As this method would operate at massive scale to reach the expectation of experts, we have to anticipate all the potential risks and ensure the safekeeping of gas. The injection site is likely to present faults. Thus, the question whether CO2 can potentially reactivate pre-existing faults and induce seismic events is of importance. This kind of risk is not dangerous for human life and facilities, because the induced earthquakes would have a relative low magnitude of 3-4 compatible with the actual construction codes (Zoback & Gorelick, 2012). However, it is likely to alter the seal integrity and induce a leakage out of the reservoir.

In order to study possible fault reactivation and induced seismicity due to $CO_2$ injection, an experimental program has been performed on a carbonated sand as an analog of natural fault gouge. The objective is to evaluate if the presence of $CO_2$ in the pore fluid and the dissolution of the calcite sand by the acidic water can affect the friction properties of the artificial gouge. In particular, we are interested in measuring the friction rate parameter A-B as defined by the commonly used 'Rate and State' friction laws for assessing possible unstable slip. This parameter can be measured by conducting so-called "velocity stepping" tests in which a material is sheared to steady state and sliding velocity is instantaneously stepped up or down. Shear tests have been performed on carbonated sand composed of 99% calcite with a self-similar particle distribution and a fractal dimension of 2.6 in order to have a grain size distribution similar to a natural gouge. The upper fractal limit is 1mm.

In order to simulate the exposition of calcite to aqueous CO2, the sand is placed in an autoclave with water saturated in $CO_2$ at a pressure of 180 bars and a temperature of 60°C during different periods of time. The first samples are placed for 10 days without changing water. The second ones are placed for 5 days, then dried in a hoven, and placed again in the autoclave with renewed water saturated in $CO_2$ for 5 more days. These samples are then used for annular shear experiments with a special device developed in ENPC, and the so-called ACSA apparatus (Figure 1). This device can be used for the study of soil-structure interaction (Lerat, 1996) as well as for the friction properties of granular fault gouges submitted to large slip distances(Chambon, 2003). Velocity stepping shear experiments have been performed at different confining stresses (100, 200, 500 and 800 kPa) for 'intact' and 'degraded' sand.

Results show that the friction coefficient evolves with the slip distance and exhibits a peak value and a weakening branch before reaching a constant residual value (Figure 2a). Saturated samples exhibit a lower friction coefficient than dry ones. The experiments do not show any significant influence of the $CO_2$ on the friction coefficient. For evaluating the friction rate parameter A-B velocity steps are applied with the following path: 0.1 – 0.4 – 0.6 – 2 – 6 – 2 – 0.6 – 0.4- 0.1 mm/min.  Two types of tests have been performed (a) by applying the velocity steps at low slip distance (5mm) and (b) at larger slip distance (3cm). For low slip distance, positive values of the friction rate parameters are obtained whereas negative ones are obtained at large slip distance. However, no significant effect of CO2 is observed on this parameter. This observation is consistent with the ones obtained by (Samuelson & Spiers, 2012) for a different experimental set-up on artificial gouge materials made from claystone and sandstone extracted from a test site in the North Sea.

From these friction tests, we can conclude that, for the degradation process used here, no significant influence of carbon dioxide on the friction properties of the studied material is observed.

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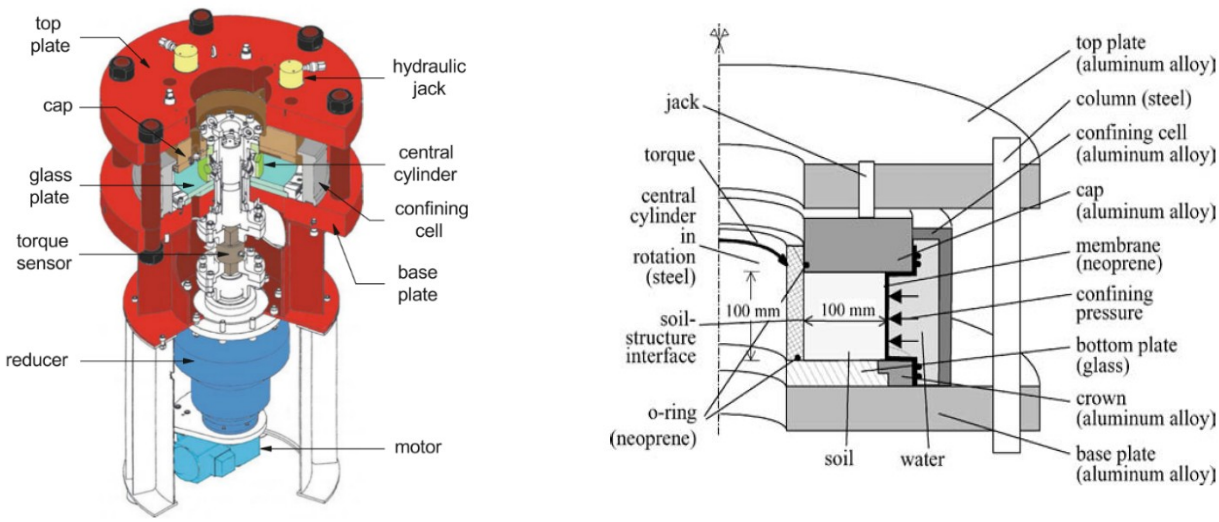


*Figure 1. Schematic view of ACSA*

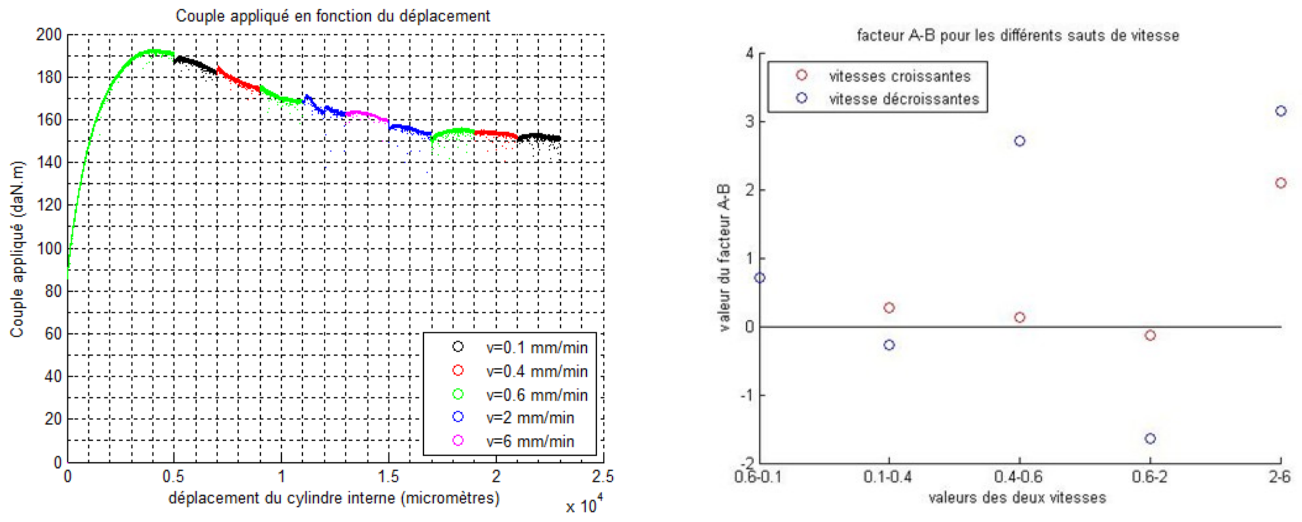


*Figure 2 . Typical results for the first method (intact sand, 500 kPa), couple applied as a function of the displacement (left), values of A-B for the different velocity changes (right)*

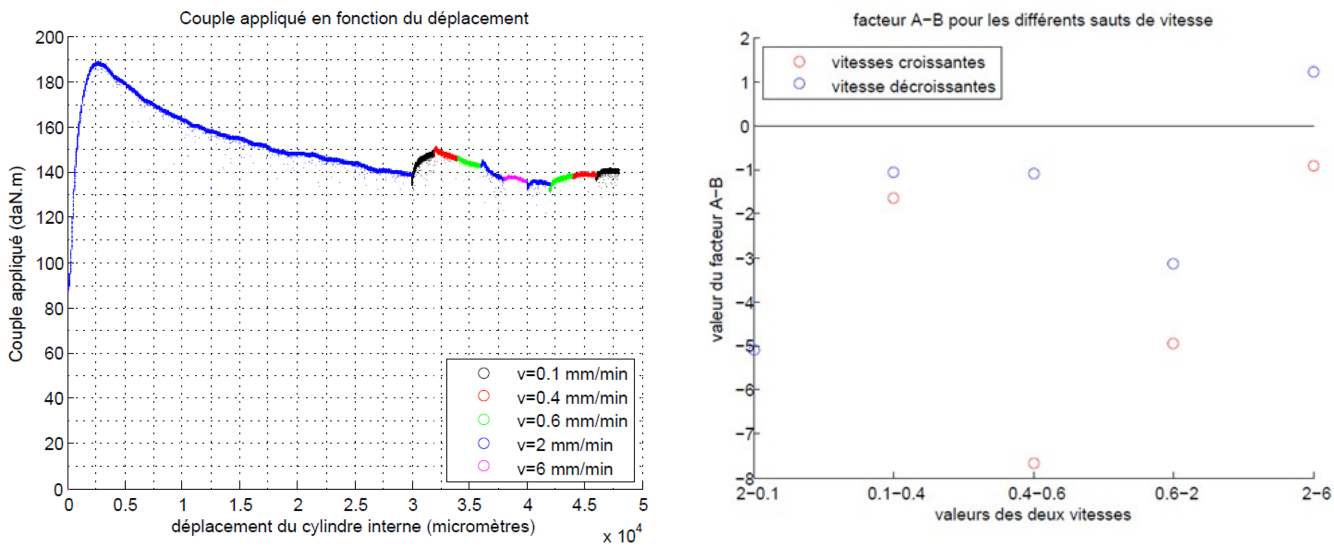


*Figure 3. Typical results for the second method (intact sand, 500 kPa), couple applied as a function of the displacement (left), values of A-B for the different velocity changes (right)*

# State variable analysis of cone penetration test in fine-grained soils

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***Keywords:*** *Cone Penetration Test, CPTU, spherical cavity expansion, shape factor*

***Abstract***

The cone penetration test with pore water pressure measuring (CPTU) is a commonly used method to investigate the subsoil. In most cases empirical relationships are used to analyse CPTU data. As an alternative, Cudmani (Cudmani and Osinov, 2001) presented a new method to evaluate the soil state in sand for cone penetration tests (CPTs). He developed a semi-empirical approach based on the comparison of the results of a spherical cavity expansion and the cone resistance from CPT using a calibration factor (here the factor is called shape factor).

Here a new approach is presented to evaluate the soil state (e.g. void ratio or soil consistency) in a fine-grained soil based on the method of Cudmani (Figure 1). Additionally the determination of shape factors is shown.

CPTUs were conducted at the laboratory in a CPTU calibration chamber (Uhlig, 2014). A miniature cone was pushed into an isotropically loaded soil while the sleeve friction, the cone resistance and the pore water pressure were measured. The tests were performed at different cell pressures.

The numerical analysis was performed with a simplified finite element model simulating a spherical cavity expansion using the hypoplastic model for fine-grained soils (Mašín, 2005).

The shape factors for two different soils (clay and silt) were determined (Figure 3) by comparing the results of the simulations with the laboratory tests performed in the CPTU calibration chamber. Figure 2 shows the net cone resistance ($q_t$-$p$) from CPTUs (triangle) and the limit pressure $p_{LS}$ (square). The limit pressure is the radial pressure on the surface of the expanding sphere.

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## *Illustrations*

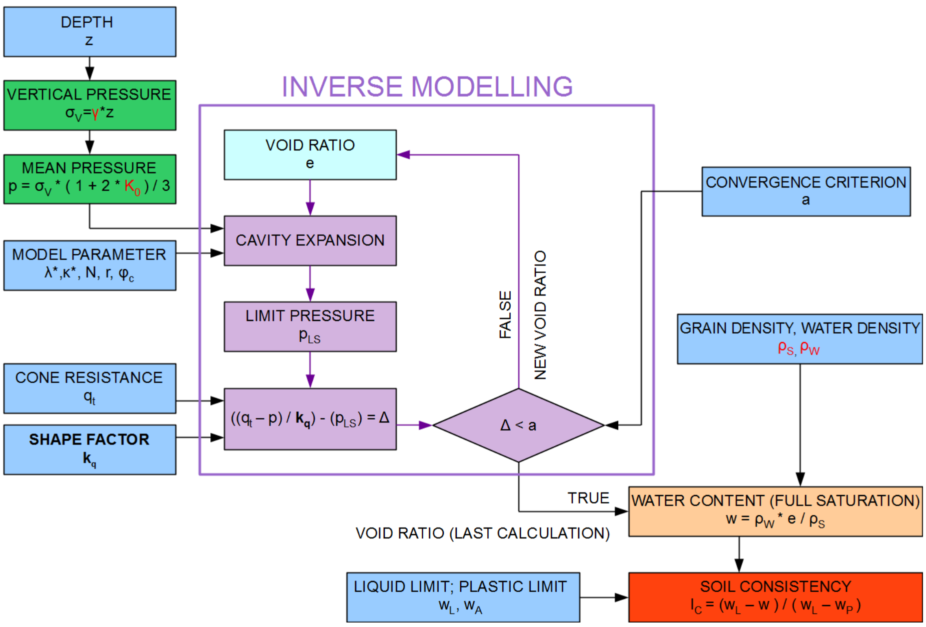


*Figure 1: Semi-empirical procedure for the determination of soil consistency from CPT*

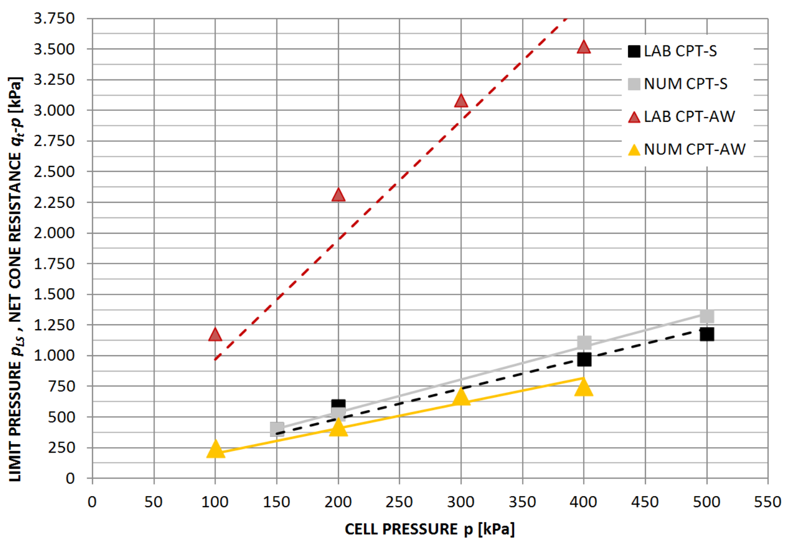


*Figure 2: Results of the CPTUs in the calibration chamber (LAB) and simulations (NUM)*

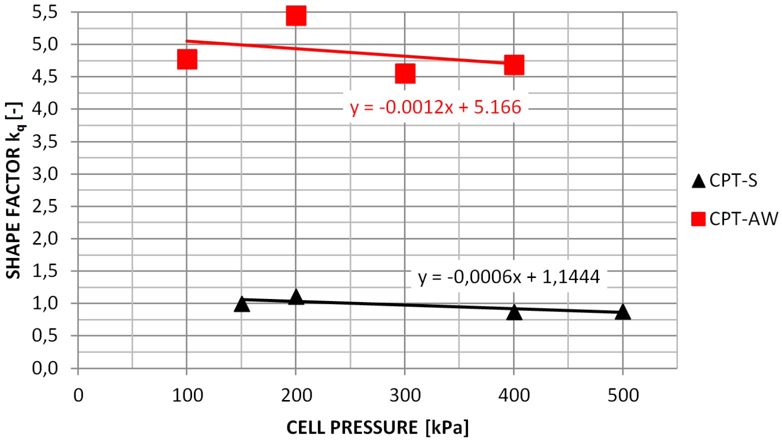


*Figure 3: Shape factors $k_q=(q_t - p)/p_{LS}$ for clay (CPT-S) and silt (CPT-AW)*

# Effect of water on granular matter mechanics, local scale: evaporation, extension and rupture of liquid bridges.

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***Keywords:*** *capillary force, capillary bridge, evaporation, rupture*

### *Abstract*

The mechanical strength and cohesion of granular matter depend strongly on water content (i.e. in soil). Water exists in different forms between the solid particles, due to surface tension generates internal stresses in granular material and develops mass exchange with the environment during the evaporation process. During evaporation the internal stress evolves, which may lead to the medium shrinkage, air entry and damage. The most sensitive is the final stage of evaporation, which corresponds to the rupture of capillary bridges (Péron et al., 2010).
In this study, the phenomenon of air entry, evolution of intergranular forces and behavior and rupture of capillary bridges are analyzed experimentally at the local scale, on the example of capillary bridges between two and three spherical grains.
Capillary bridges are made from distilled water and exposed to evaporation under constant atmospheric conditions, with constant separation between the grains. For comparison, the liquid bridges are also tested for mechanical extension at constant volume, with constant extension rate.
The evolution of the capillary bridge profile is recorded by still photo camera and high-speed camera (prior and at the moment of rupture), in correlation with direct measurements of evaporation rate and capillary force with the use of precision balance. Further image processing allows to measure several geometric parameters (Fig. 1), used then to trace the evolution of global and local variables, as surface area of evaporation, evaporation flux, Laplace pressure $\Delta p$, capillary force $F_C$ and its component forces, with use the solutions of Young-Laplace equation (Adamson, 1976).
Obtained results of experimental measurements are compared with calculated values based on the geometrical parameters. The behavior of liquid bridges depends strongly on the separation distance between the grains. Substantial differences are observed also between the evolution of capillary force due to evaporation and due to extension of the liquid bridges.
Negative Laplace pressure noted at small separations significantly decreases during evaporation, and becomes positive toward the end and prior to rupture. At larger separations the pressure is positive all the time, changing a little. Rupture of the bridge occurs at positive pressure; however,

the resultant total capillary forces are always tensile, and decreasing toward zero, in all cases. None of the dynamic variables characterizing capillary bridges i.e. Laplace pressure, capillary force qualify as state variables of volume and separation upon evaporation and/or extension, but rather depend on additional variables. In particular, the evolution (pinning/depinning) of the diameter of the three-phase contact line and the "apparent" contact angle at the solid/liquid/gas interface seem to control the capillary force evolution (Mielniczuk et al., 2014a).
The rupture of the bridge is accompanied by air entry and a decrease in cohesion of the material. Several rupture modes are observed, depending on the liquid bridge configuration: disjunction in the middle, creation of water-wire (Mielniczuk et al., 2014b), nucleation and growth of an air bubble or a movement of water volume. Water body instability generated by dynamic penetration of air may also provide an imperfection for the granular system, potentially leading to cracking.
The findings are of relevance to the mechanics of unsaturated granular media in the final phase of drying.

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Mielniczuk, B., M. S. El Youssoufi, L. Sabatier, T. Hueckel (2014b), Rupture of an evaporating liquid bridge between two grains, Acta Geophysica, 2014, DOI: 10.2478/s11600-014-0225-6

### *Illustrations*

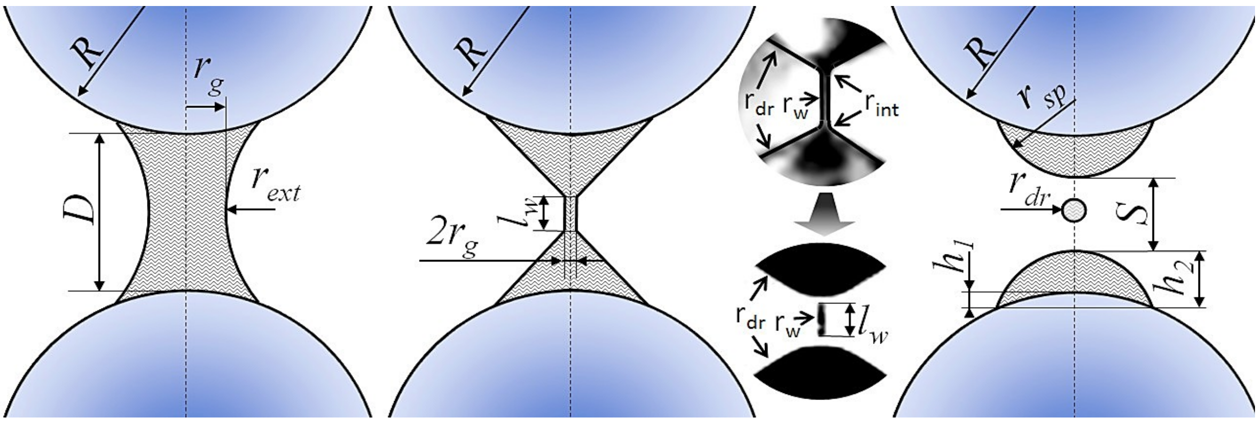


*Fig. 1. Scheme of capillary bridge between two spheres during evaporation/extension processes and at the moment of rupture.*

# Granular Matter at High Water Saturation Levels

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***Keywords:*** *granular matter, water bridges, water clusters, transport in granular matter*

***Abstract*:**

Rainfall induced slope failures are a common phenomenon in mountainous regions after long periods of rains. These failures might lead to landslides which are together with debris flows highly dangerous for both people and infrastructure. While the main macroscopic reason for these events is an increase of water saturation level in soil, only little is known about the initiation mechanisms of failures at the microscopic level. Our goal is to model triggering mechanisms of rainfall induced slope failures at the grain scale. In the first step we develop a model which allows to simulate higher saturation levels beyond the well-studied capillary bridge regime.

Granular material is simulated by a discrete model based on the contact dynamics approach (3D). To investigate the influence of increasing water content in granular material we extend an existing model for capillary bridges (Mani 2013) to account for larger liquid structures that can fill the space between grains. This geometrical model is developed in the spirit of the work by Cieplak (1988) and for the considered 3D case based on the work by Gladkikh (2005). The core feature of this approach is to approximate the shape of the water-air interface of liquid clusters as a spherical cap (meniscus) that is located between three grains in the pore throats of granular material. The corresponding Laplace pressure is then defined by the curvature of the interface and can be easily calculated. This is a purely geometrical model, the water is propagating due to deterministic events. Examples of such events are the instability of the interface that arises if a critical imbibition curvature for a given pore is reached or if two interfaces come into contact.

The main difference to the model of Gladkikh is that water is not pressed into the material but it is transported through the network of liquid structures due to the gradient in Laplace pressure. Thus, isolated water clusters can arise in the material when smaller liquid structures merge due to water inflow. We investigate the water transport through the material at the grain scale and report on the details of the creation mechanisms of several liquid structures like trimers and larger clusters in samples with different packing densities.

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# FULL-FIELD MEASUREMENTS OF STRAIN LOCALISATION IN SANDSTONE BY NEUTRON TOMOGRAPHY AND 3D-VOLUMETRIC DIGITAL IMAGE CORRELATION

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***Keywords:*** *neutron, tomography, DIC, sandstone*

***Abstract***

Recent studies have demonstrated that the combination of x-ray tomography during triaxial tests ("in-situ" tests) and 3D-volumetric Digital Image Correlation (DIC) can provide important insight into the mechanical behaviour and deformation processes of granular materials such as sand. The application of such tools to investigate the mechanisms of failure in rocks is also of obvious interest. However, the relevant confining pressures for triaxial testing on rocks are higher and therefore stronger pressure containment vessels are required. Therefore, pressure vessels for rock triaxial tests are typically made of steel or aluminium, which are not very transparent to x-rays, making in-situ imaging of triaxial tests on rocks a challenge. One possible solution to overcome this problem is to use neutron, instead of x-ray, imaging. The absorption of neutrons by materials is different to x-rays and many materials that are not so transparent to x-rays, such as aluminium, are quite transparent to neutrons. This means that fewer compromises should need to be made in designing pressure vessels for in-situ triaxial testing on rocks with neutron imaging. In this perspective, this work assesses the capability of neutron tomography with DIC to measure deformation fields in rock samples. Recent results of neutron tomography of sandstone samples before and after triaxial deformation tests (not in-situ) and corresponding DIC analysis (to provide full 3D displacement and strain fields) will be presented, *e.g.*, Figure 1. These results are also compared to equivalent analyses based on corresponding pre- and post-deformation x-ray tomography of the same samples.

***Illustrations***

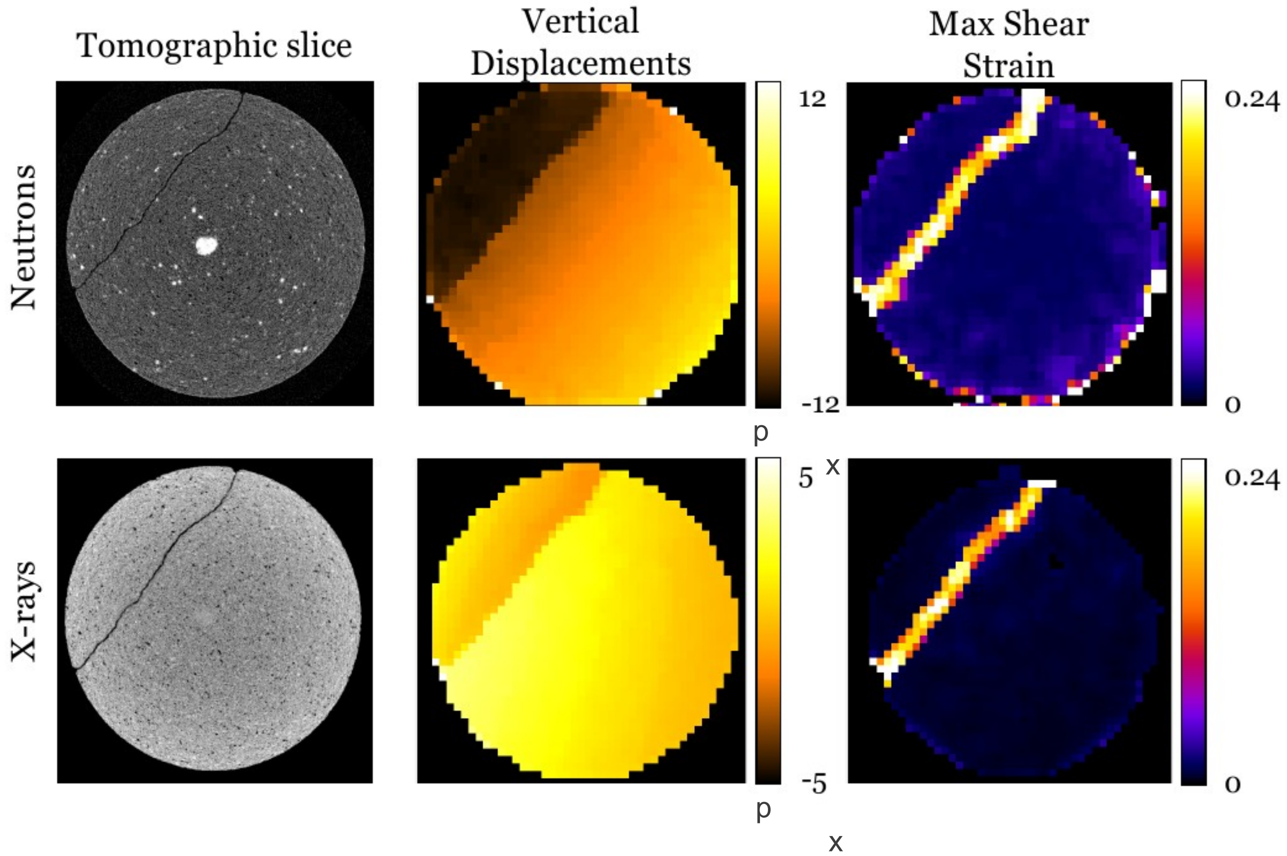


***Figure 1:*** *Example slice of neutron and x-ray tomography of a deformed sample with a diameter of 50 mm and corresponding DIC results in terms of vertical displacements and shear strain. The difference in displacement values is due to a change in the configuration of neutron image acquisition between the two measurements.*

# Multiscale modelling of cementitious materials subjected to multiple hazards

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***Keywords:*** *concrete, multiscale, high temperatures, nuclear radiation.*

***Abstract***

Although concrete in traditional engineering studies is considered as a homogeneous material idealized as an infinitesimal continuum medium with average properties (macroscopic approach), it is a highly heterogeneous material and its composite behaviour is exceedingly complex. For obtaining a deep understanding of the macroscopic constitutive behaviour of concrete, theoretical studies based on micromechanics analysis of the interaction between various components of concrete have been developed. However, the microstructure and properties of the individual components of concrete and their effects on the macroscopic material behaviour have not been generally taken into account. For such details to be included in the computational analysis, concrete needs to be analysed as a multi-scale composite material where the microstructure is realistically simulated.

Specifically, for the level of observation lower than the macroscopic one, i.e. the mesoscale, it provides a more realistic description of global behaviour; this could be expected, being the macroscopic behaviour a direct consequence of the phenomena taking place at the level of the material heterogeneities.

Concrete at mesolevel is a mixture of cement paste, aggregates of different size and a thin layer of matrix material between these two components called interfacial transition zone (ITZ).

A thorough knowledge of concrete at the mesoscale level is nowadays essential to better characterize and understand the mechanical behaviour, if subjected to multiple hazards such as fire, which can induce to a specific phenomenon called spalling, and nuclear radiation.

In this work, a 3D fully coupled thermo-hydro-mechanical finite element code [1,2] has been developed, in order to characterize the behaviour of concrete if subjected to the above described hazards.

In detail, as regards elevated temperatures, the effect of aggregates characterized by different porosities is investigated, to catch the damage scenarios related to the different inclusions types and hence to understand the role of aggregates porosity on spalling when concrete is exposed to fire [3].

To reduce the risk of spalling of a concrete material under fire condition, a low dosage of polypropylene fibres in the mix design of the concrete is included. This effect can be explained considering the increment of voids connectivity in the cement paste as well as the increment of porosity in the material due to the polypropylene evaporation above certain temperatures. Therefore, in this work the complex mechanism of polypropylene effects in the concrete material under thermal conditions has been also numerically evaluated [4].

Finally, as regards nuclear radiation, the effects at mesolevel on a concrete shielding have been investigated. This has been done for the specific neutron source of a study case in conjunction with a Monte Carlo code (Fluka), used to describe the radiation field in terms of neutron fluence and deposited energy that the mechanical field is dependent on. Complex irradiation cycles are accounted for both at a macroscale and a mesoscale level and the performances of the analyses at the two scales are discussed in view of the final shielding characteristics of concrete [5].

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## *Illustrations*

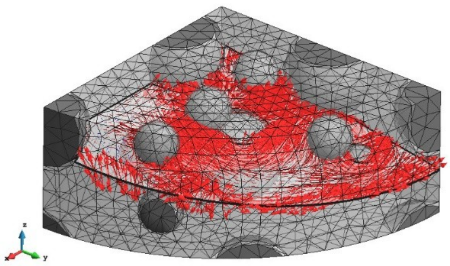

*Figure 1 : High temperature studies: Stress on a generic plane section into the mesoscale model.*

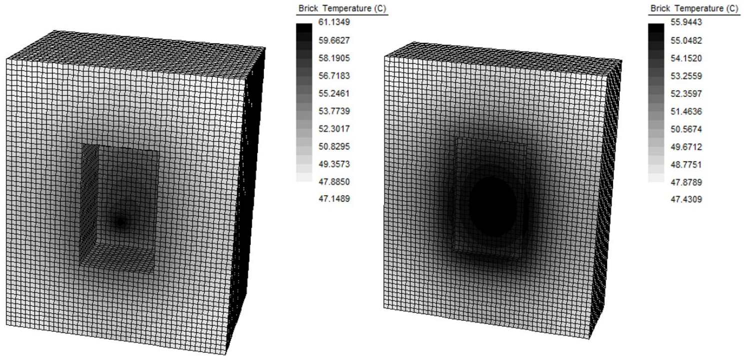


*Figure 2 : Nucelar Radiation investigations: Five years simulation – final temperatures.*

# Statistical Homogenization of granular plastic behavior

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***Keywords:*** *homogenization, plastic, granular, quasi-static*

## *Abstract*

The quasistatic flow of rigid frictional particles can be seen as a succession of *limit states* globally as well as locally. The internal parameters that characterize the state (be it local or global) have to be encoded in the geometry of the packing (compacity, coordination number, fabric tensor, and possibly higher order statistical moments …). The rheology, possibly including its statistical variability, consists of relating these limit states to the value of the internal parameters. In order to identify this rheology, it is proposed to follow a discrete element simulation in parallel to a continuum description slaved to the former through spatial averaging operators (for mass, velocity, momentum or geometric features). This intimate link from discrete to continuum description can be seen as a substitute to solving for the mechanical problem in the continuum description alone. Identification can thus be seen as the inverse problem than consists of "learning" the continuum rheology from the discrete one performed at various spatial or temporal scales. The relevance of statistical variability or on the contrary of a simple deterministic constitutive law is expected to lie in the averaging scale chosen either in space and/or time. Thus the same scheme is applied to arbitrary coarse-graining scales. The present study focuses on the methodological aspects of this approach.

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# Parametric analysis of fabric anisotropies' correlation using DEM

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***Keywords:*** *Fabric, Anisotropy, DEM*

### *Introduction*

In the here presented work two different kinds of fabric are correlated: inter-particle contact normal directions and orientations of void shapes. Considering existing literature which presents that experimental determination of contact normal directions is rather difficult compared to void vectors, following difficulties associated with measurement of tangent contact planes (Jaquet et al 2013), the authors present a comparison between fabric tensors obtained by identifying the unit vector along the directions of the fabric elements mentioned above. For this reason, an extensive 2D DEM analysis was conducted; focus is given on the effect of the correlation of particular mechanical and geometrical parameters of the tests, i.e. the initial confining pressure, the particle geometry, the interparticle friction and stiffness. The results are indicating a very strong linear correlation, which can be a motive for further -3D- analysis and possible implementation in constitutive models.

### *Fabric identification*

The contact normal fabric is identified as a fabric tensor based on the contact normal unit vector $\boldsymbol{n}_c$ which is defined by the normal to the tangent plane (Figure ). The fabric tensor is then defined as

$\mathbf{G}_c = \frac{1}{N_c} \sum_{k_c \in V} \boldsymbol{n}_c^{k_c} \otimes \boldsymbol{n}_c^{k_c}$ ,where $\mathbf{G}_c$ is the fabric tensor for contact normal vectors; the subscript "c" denotes that the fabric quantification considers the contact normal vectors. In addition, the symbol $\otimes$ is the tensor product of the vectors $\boldsymbol{n}_c$ and the Latin numbering of vectors implies i=1,2, j=1,2 in 2D. Also, $\sum$ implies the summation over all the contacts $k_c$ of the volume $V$ and $N_c$ is the total number of the contacts that exist between particles. The volume $V$ describes the area in 2D where the measurement of the fabric takes place. For the biaxial test that is used in this project the principal axis coincide with the x and y axis and the diagonal terms of the terms are zero. In this case the anisotropy of the tensor is easily defined as $\alpha_c = G_c^{I} - G_c^{II} = G_c^{11} - G_c^{22} = G_c^{yy} - G_c^{xx}$ .
The void fabric is calculated by using a void scan line approach similar to Ghedia & O'Sullivan (2012). Parallel scanning lines are used in order to identify the voids for several angles from -90$^0$ to

$90^0$ (Figure 2). At each inclination angle of the scanning lines a unit vector $\boldsymbol{n}_{vs}^{\theta}$ is defined and the total void scan line fabric tensor is

$$\mathbf{G}_{vs} = \frac{1}{\sum_{\theta=-90}^{90} \bar{l}^{\theta}} \sum_{\theta=-90}^{90} \bar{l}^{\theta} \boldsymbol{n}_{vs}^{\theta} \otimes \boldsymbol{n}_{vs}^{\theta}$$

where $\otimes$ is the tensor product, $\bar{l}^{\theta}$ is the mean void length for the inclination angle θ which varies from $-90^0$ to $90^0$. The fabric anisotropy can be defined in the same way as for the contact normal fabric tensor, i.e. $\alpha_{vs} = G_{vs}^{I} - G_{vs}^{II} = G_{vs}^{11} - G_{vs}^{22} = G_{vs}^{yy} - G_{vs}^{xx}$.

### *Correlation between contact normal fabric and void scan line fabric*

In order to examine the correlation between those two fabric anisotropies, a parametric 2D DEM analysis has been conducted using the PFC-2D© code. Several geometrical (shape of particles), micromechanical (interparticle friction and stiffness) and mechanical (isotropic pressure) parameters have been examined in this analysis; the results are presented in Figure 3 and Erreur : source de la référence non trouvée.
The names of the experiments on the legends are based on their properties; D2L500_0.3 means that the particles are disk shaped, mean isotropic pressure p=2*100kPa, micromechanical stiffness $k_n=k_s=500*10^6$ N/m and interparticle friction f=0.3.

### *Conclusions*

A relatively strong linear correlation is observed between the contact normal and the void scan-line fabric for both the pre-CS and the CS conditions. This strong correlation stands for all parameters considered in the current work.
The slope of the linear correlation between the two fabric types is dependent on the shape of the particles and the stiffness but independent of the mean isotropic pressure and of the interparticle friction.
At Critical State, the contact normal as well as the void scan line fabric tensors tend to maintain an almost fixed critical state value; the mean value of the scattering is constant. This is consistent with the Anisotropic Critical State Theory (CST) presented by Li & Dafalias (2012).
In any case, further analysis is needed for the quantitative and qualitative evaluation of the trend observed in the relevant graphs for all the parameters included in these kinds of tests. 3D analysis should then follow before using results in macromechanics, i.e. constitutive modeling.
The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Program FP7-ERC-IDEAS Advanced Grant Agreement n° 290963 (SOMEF).

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## *Ilustrations*

*Figure 1: Definition of unit contact normal vector*

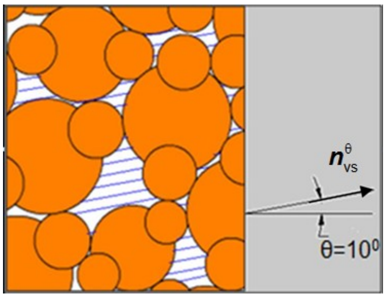


*Figure 2: Definition of unit void scan line vector*

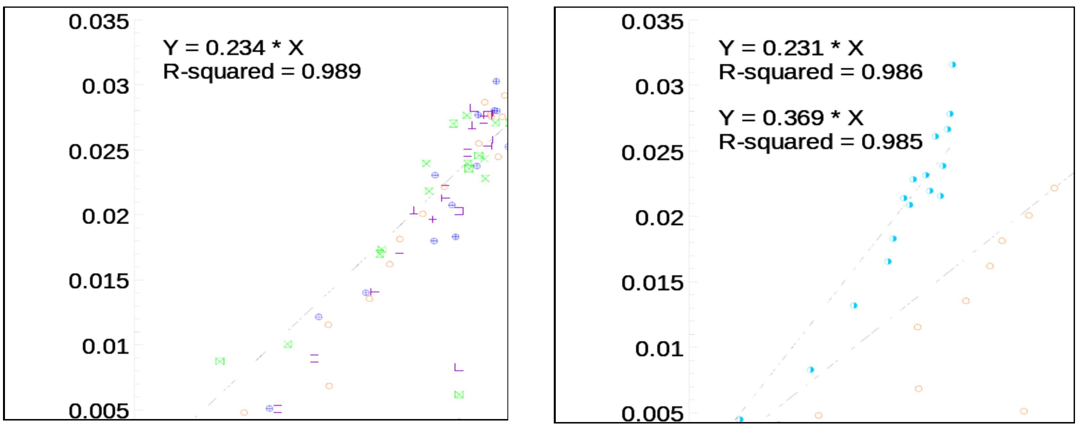


*Figure 3: Linear correlation of contact normal and void scan line fabric anisotropies for disk shaped particles*

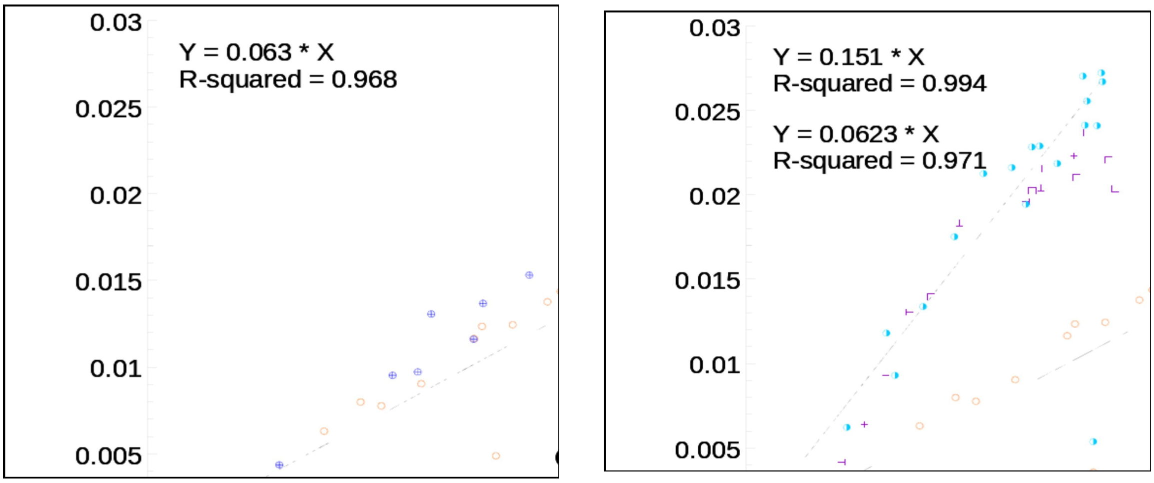


*Figure 4: Linear correlation of contact normal and void scan line fabric anisotropies for disk shaped particles*

# Nonlinear FEM analysis of a horizontal wellbore drilled through a porous rock formation

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***Keywords:*** *wellbore stability, porous rock, finite strain elastoplasticity, band localization***.**

## *Abstract*

The aim of this study is to quantify the stress field, plastic zones, and the possibility for localized deformation around a horizontal borehole drilled at great depth through a highly porous rock formation. Quantifying plastic deformation and localization band is fundamental for the prediction of instability and sand production [1, 2], but at the same time it is very challenging, mostly due to the complicated mechanical behaviour of porous rock [3]. In fact, as revealed by several laboratory tests, depending on the loading path, highly porous rocks are susceptible to different failure mechanisms. Most of these mechanisms are mainly due to shear-induced dilation and shear-enhanced compaction [4]. Plasticity models, in conjunction with bifurcation analysis, represent a useful framework for describing such detailed constitutive responses. This work presents first a new elasto-plastic constitutive model characterized by two yield surfaces intersecting smoothly: a linear yield surface for the dilatant side, and an elliptical yield surface for the compactant side, which can expand depending on the accumulated plastic volumetric strain (Fig. 1). This model is able to capture the different failure modes typical of porous rock, since it is characterized by a dilatant and a compactant plastic surface [5]. The model has been calibrated against experimental data for several different porous rocks, showing the capability of the model to reproduce both hydrostatic and triaxial experimental tests, as shown in Fig. 2. The calibrated model has been then used to determine the stress and strain distributions around a horizontal wellbore using nonlinear finite element analysis [6,7]. A nonlinear geometry approach has been used throughout the entire analysis, to take into account the finite deformation effects enhancing the strain localization. Particular interest has been devoted to predict the condition for the formation of a localized band of intense deformation, elucidating the factors that either prevent or enhance the band initiation. Results of simulations, as reported for example in Fig. 3 and Fig. 4, show that the stress condition and geometric imperfections play a key role in the development and propagation of plastic zone, as well as in the initiation of localization zone.

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## *Illustrations*

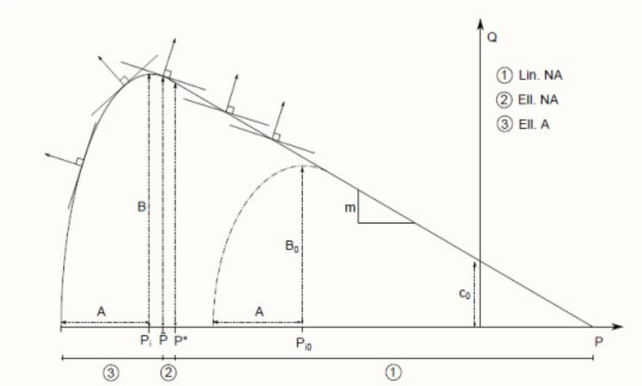


***Fig.1****: Graphical representation of the elastoplastic constitutive model.*

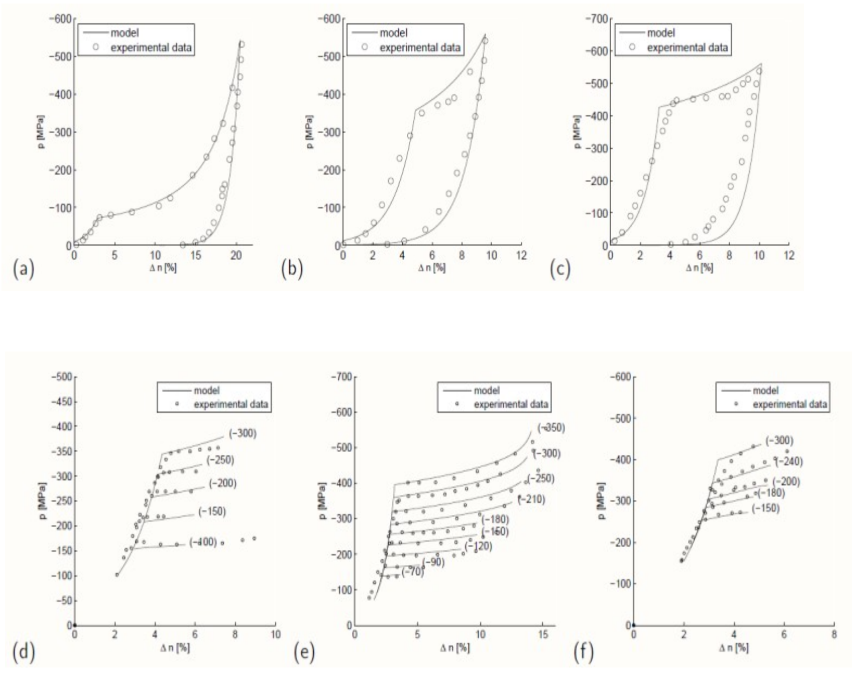


***Fig. 2*** *: Comparison between experimental data and model simulation of a hydrostatic test for (a) Boise, (b) Berea, (c) Bentheim and of a triaxial test for (d) Darley Dale, (e) Berea and (f) Bentheim sandstones.*

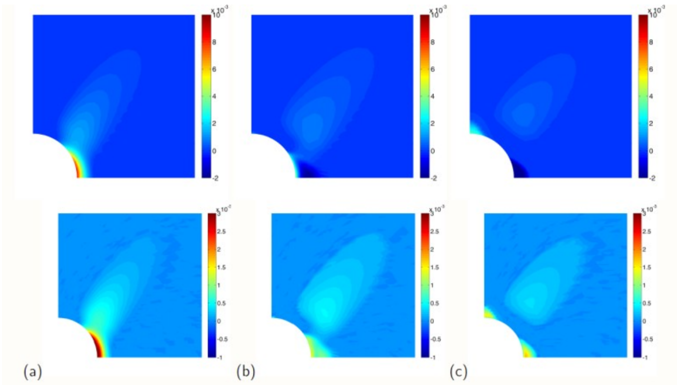

***Fig. 3**: Volumetric (top) and deviatoric (bottom) plastic strain for different value of pressure (a) ΔP = 0 (b) ΔP = 8 and (c) ΔP =16 MPa.*

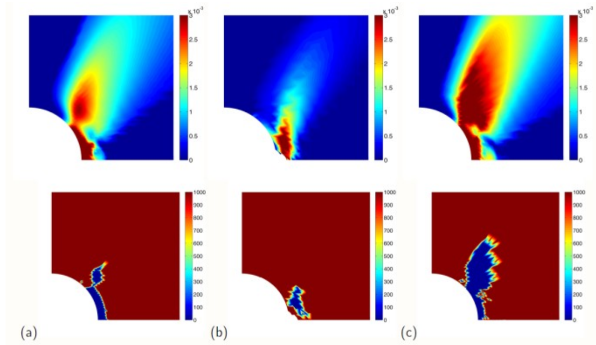

***Fig. 4:** Plastic deviatoric deformation (top) and localization function (bottom) for different value of the vertical in-situ stress (a) $\sigma_v$ = 39.0, (b) with imperfection ($\sigma_v$ = 32.1) and (c) $\sigma_v$ = 42.0 MPa with balanced drilling (ΔP = 0 Mpa).*

# Formation of compaction bands in a porous sandstone with high density inclusions

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***Abstract***

Compaction bands in porous sandstones have been described as tabular zones of localised deformation that accommodate pure compaction, with no macroscopic evidence of shear (e.g. Mollema and Antonellini, 1996). These deformation bands are formed normal or subnormal to the maximum principal stress direction and are accompanied by localised porosity loss (Holcomb et al., 2007). The involved micro-processes are mainly characterised by grain crushing and pore collapse. To better understand the onset and propagation of such deformation structures, a series of experimental studies has been carried out in porous sandstone specimens. In some experiments samples contained a notch acting as stress concentrator and thus, localising the onset of compaction band formation (Stanchits et al., 2009). Here we investigate the effect of high density inclusions in sandstone specimens on compaction band propagation.

Specimens of Bentheim sandstone (22% porosity) were used in this study, having a diameter of 50 mm, a length of 105 mm and a circumferential rounded notch of 4 mm depth and 0.8 mm height machined on their mid-height. Pre-deformation x-ray tomography (carried out in laboratory 3SR, Grenoble), has demonstrated the existence of high density elliptical inclusions inside the specimens – most of them located at the mid-height of the samples (i.e. close to the region of the notch). The x-ray images had ~ 30 μm voxel size resolution.

Triaxial compression experiments were performed (at GFZ) using a servo-hydraulic loading frame from Material Testing Systems (MTS). Ultrasonic transmission signals and Acoustic Emissions (AE) were recorded throughout the duration of the tests using sixteen P-wave piezoelectric sensors, glued directly on the surface of the specimens and two P-wave sensors incorporated to the top and bottom caps. Moreover, two strain-gages were used to measure vertical displacements. Two Bentheim specimens were loaded in isotropic compression, in which the confining pressure was increased up to 135 MPa and 160 MPa, respectively. Subsequently samples were loaded in axial direction using displacement control at a rate of 20 μm/min.

AE waveforms and ultrasonic signals were automatically discriminated after each experiment. P-wave onset times were picked and AE locations were calculated, considering time-dependent variations in P-wave velocities and employing an anisotropic heterogeneous ultrasonic velocity model, consisting of five horizontal layers. Furthermore, first motion amplitudes were picked and corrected for the effects of sensor coupling and incidence angle sensitivity according to (Kwiatek et al., 2013). AE events were classified as tensile, shear, and compressive according to (Zang et al., 1998). Moment tensor inversion of AEs was also performed in order to investigate the source mechanisms and the moment tensor components.

Compaction bands in both specimens initially formed at the vicinity of the notch and afterwards propagated towards the centre of the specimens, leaving unaffected the regions of the high density inclusions, as this was demonstrated by AE locations superimposed on x-ray tomography images. A larger number of compressive AE events was observed in the specimen loaded at 160 MPa. A variation of different event types was observed in the specimen loaded at 165 MPa, although compressive events were dominant. Results will be presented from both specimens focusing on the resolved micro-processes that occurred during: a) the onset of compaction bands from the circumferential notch; b) the propagation of compaction bands at the region of the high density inclusions; c) the propagation of compaction bands far from the inclusions.

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# Biological soil improvement: the choice of different microorganisms

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***Keywords:*** *Bio-cementation, Bacillus sphaericus, Chlorella vulgaris, Soil improvement*

***Abstract***

In recent years, application of microbial induced bio-cementation for soil improvement has faced much attention (Dejong et al. 2013). There are various microorganisms which have calcifying capabilities (e.g. various cyanobacteria, eukaryotic microalgae, Bacillus, seudomonas, Vibrio, and sulphate reducing bacteria) (Jansson and Northen, 2010). In addition to calcite formation, the cementation agent can be the extracellular material produced by the microorganism such as polysaccharides, which enhance soil mechanical properties by making bridges between the grains and strengthening the soil micro-fabric. In this study, we investigate both mechanisms. In the present research, the calcite precipitation by bacillus sphaericus and its effect on soil shear strength as well as polysaccharide network generation between and also on the grains by one type of microalgae (chlorella vulgaris) have been experimentally studied. The two cases studied here are merged to demonstrate the effect of different microorganisms on shear behaviour of soils.

**Improving soil shear strength by microalgae: Experimental procedure and results**

The unicellular alga chlorella vulgaris was used in the first part. Its cultivation was performed in medium BG-11 poured in pure water. Two types of soil samples were examined in this experiment: 1. Very fine sand 2.Rock powder. The designation of two types of soil was very close to silty sand, SM, based on ASTM 2487. Wooden boxes, 200x200x50 mm, were filled to the rim with dried soil. Operation conditions have been reported in details elsewhere (Talebbeydokhti et al. 2013). Soil shear strength test was performed by means of a torevane shear test device and the shear strength was determined based on the procedure suggested by ASTM D4648. The soil shear strength improvement at different times, at different temperatures for a certain moisture content is depicted in Figure 1.a. The SEM micrograph of soil samples treated with microalgae is depicted in Figure 1.b.

**Improving soil shear strength by Bacillus Sphaericus: experimental procedure and results**

The soil samples were composed of 70% silty sand, 15% kaolinite and 15% sodium bentonite. The synthetic soil sample, however, was classified as CL (Low plasticity clay) based on ASTM 2487. Direct shear tests were performed on the soil samples based on ASTM 3080. The microorganism considered for biological soil stabilization was Bacillus Sphaericus. The optical density of bacterial solution was 1.7. The soil cohesion in untreated sample, treated with culture media solely and treated with bacteria and culture media, both was found to be 26.3, 30, and 34 kPa and internal friction angle was determined to be 28.5°, 30.5°, 31.2°, respectively (see Figure 2).

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## *Illustrations*

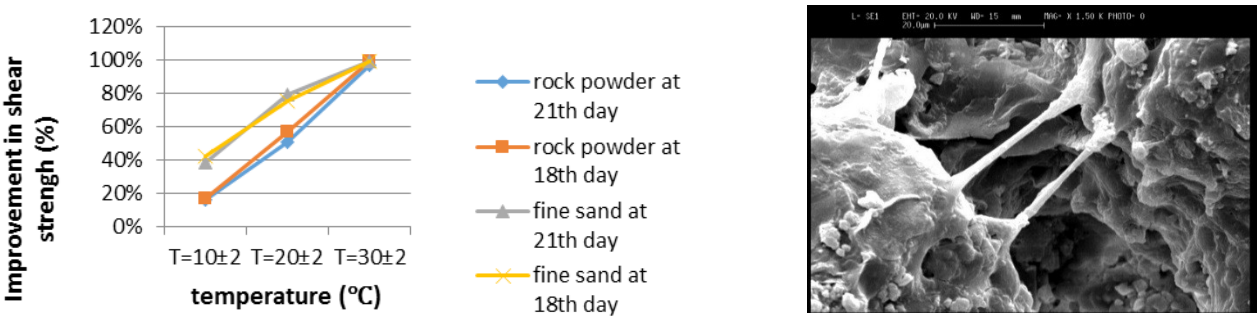
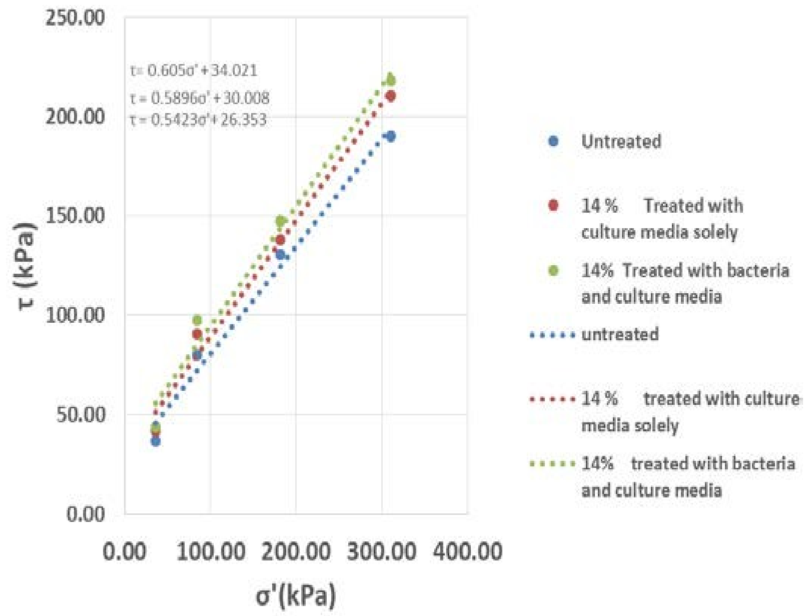



*Figure 1. a) on the left: shear strength improvement versus temperature (moisture content=15%*



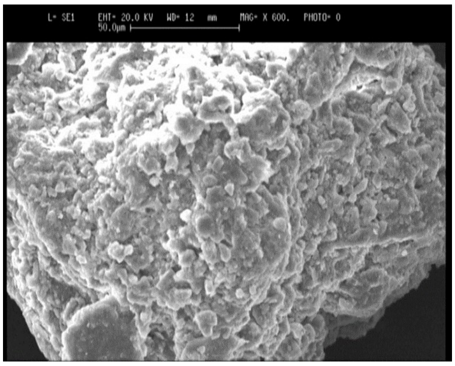



*Figure 2. a) on the left: Increase in shear strength parameters in cured samples with bacillus sphaericus b) on the right: SEM micrographs of sample treated with bacillus sphaericus*

# Boom clay shrinkage analysis under drying conditions

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***Keywords:*** *Convective drying, clay, shrinkage, hydro-mechanical coupling, tomography*

***Abstract***

Boom clay is a potential host rock for deep nuclear waste disposal, selected because of its suitable features: notably a very low permeability and a crack sealing ability by plastic straining (Bernier et al, 2007). The stability over time of the underground cavity has to be investigated under various conditions, among which is the drying solicitation. Such a hydric stress can indeed modify the mechanical equilibrium by cracking and shrinkage of this plastic rock.

In this contribution, the Boom clay shrinkage under a soft convective drying is analyzed, by mean of regular tomographic scans performed during a controlled drying test. The aim is to quantify the volumetric strains and relate them to the evaporation kinetics (as proposed on chalk by Prime et al., in press, and on clay by Prime et al. (2014)). This study makes possible to put in evidence the following points:

- The early high evaporation rate corresponds to an ideal shrinkage of the bulk.
- The shrinkage develops from the evaporation surface with a gradient toward the core of the material.
- The bedding planes, which are typical of the Boom clay, induce an anisotropic shrinkage with a ratio around 2 between the strain values in the two characteristic directions (fig.1).

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Prime N, Fraikin L, Léonard A, Charlier R, Levasseur S. Experimental investigation of hydro-mechanical coupling during clay drying. In *19th International Drying Symposium*, Lyon, France (2014).

### *Illustrations*

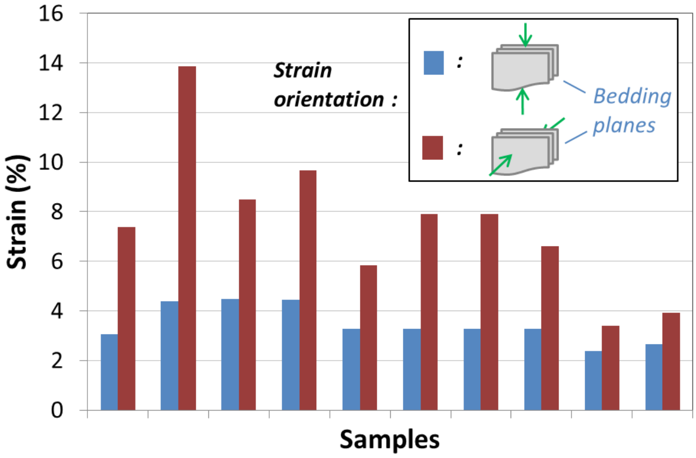


*Figure 1: Comparison of the strains, on the evaporation surface, for perpendicular and parallel directions with respect to the bedding planes*

# A new simplified model using interpolation in stress space for unloading/reloading stress trayectories based on Pastor-Zienkiewicz model for sands

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***Keywords:*** *Sand; Model; Interpolation; Parameters*

***Abstract***

In order to analyse the behaviour of sands under undrained conditions when unloading, most classical plasticity models consider strains as elastic and isotropic. In that case, volumetric plastic strains are zero and mean effective stress does not change, as there in no change of volume. Stress path upon unloading should be a vertical line crossing the hydrostatic axis, but it can be observed from experiments that stress path in unloading turns towards the origin. One possible explanation can be that sands can develop plastic deformations during unloading (Pastor, Zienkiewicz and Chan, 1990).

This work starts studying the constitutive model Pastor-Zienkiewicz for sands. Its formulation has been analysed for monotonic loading and unloading situations. Later, a model extension proposed by Pastor, Zienkiwicz and Chan (1987) and Pastor, Zienkiewicz, Xu and Peraire (1993) has been studied. This last formulation proposes an interpolation of several variables of the model between the point in the stress path at which last reversal took place and its image point within a surface defining the maximum level of stresses reached. This improvement has been implemented in the finite element code GeHoMadrid. Obtained results show a better fitting response compared to experimental data.

The proposed interpolation process involves new parameters in Pastor-Zienkiewicz model for sands. Changes in the formulation affect the flow vector, the loading/unloading vector and plastic modulus through a series of additional parameters. On this poster new proposed formulation for sands when unloading is shown. The new model and its implementation have been validated through the comparison with experimental data from experiments on Fuji River Sand from Tokyo by Ishihara and Okada (1982) using the results of an undrained triaxial compression test. As a result of this comparison, the result test showed that the model is capable of obtaining a better fitting response of sand behaviour.

Due to the fact that the Pastor-Zienkiewicz model for sands needs a calibration of all parameters for

every combination of initial confining pressure and void ratio, this work aims to extend this simplified model by introducing a state parameter.

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## *Illustrations*

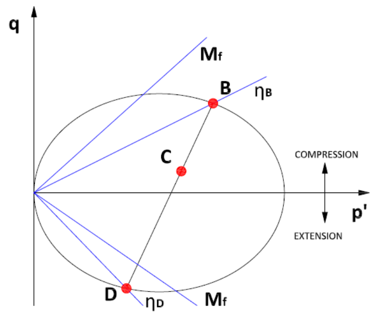


*Fig. 1 - Proposed Interpolation Scheme*

*Fig. 2 - Comparison of Fuji River Sand undrained behaviour under reversal of stress. Experimental results taken from Pastor, Zienkiewicz and Chan (1990) after experiments by Ishihara and Okada (1982)*

# Effect of water on granular matter mechanics, macroscopic scale: Collapse of granular media during wetting.

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***Keywords**: Collapse, wetting, Granular media, Glass bead.*

***Abstract***

*I*n soil mechanics, it is well known that the behaviour of the granular soils, as the sand, in the dry state is similar to the saturated state. Between these two extremes states exist various domains of water content often named: hygroscopic, pendular and funicular.

In the funicular domain, the partially saturated soils can undergo a collapse due to the only variations of water content. This phenomenon was studied under a wetting paths loading by Barden et al. (1973). In the literature, several models describe the collapse behaviour as Alonso et al. (1990) with a phenomenological model based on hydro-mechanical approach, or as Liu et al. (2003) with a numerical model based on the micromechanical approach by Discrete Elements Method.

In the pendular domain, the granular media are more sensitive to the water content, which can be at the origin of an apparent cohesion by capillarity; this behaviour has been shown by simple compression tests (Soulié et al., 2006) and by direct shear tests (Richefeu et al., 2006).

The aims of this experimental study is to identify and analyse the collapse phenomenon on a granular material constituted by a polydisperse assembly of glass bead during a wetting path from pendular domain to saturation with two different grain sizes. All samples are prepared with initial gravimetric water content w 0 = 5%. This initial water content corresponds to pendular domain and thus creates capillary bridges between grains witch cause apparent cohesion.

After the positioning of the sample in the triaxial cell, we arrange the axial and radial local sensors

on the sample. Local sensors are used for monitoring the evolution of axial and radial displacements at different points of the sample during the wetting path, without external stress. The wetting path is done by applying a gradient of water pressure ( u w = 5 kPa at the bottom of the sample by a pressure-volume controller).

The experimental results during the wetting path show that the collapse of the granular assembly is purely due to hydraulic effects, caused by the progressive fusion of the capillary bridges. The scope of the collapse is even more significant for smaller grain size (Figure 1). This phenomenon can be explained by a large number of contacts (initial number of capillary bridges per volume). Our results show that the collapse depends on the density of the granular assembly and on the grain size.

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### *Illustrations*

***Glass bead Φ < 50 µm*** ***Glass bead Φ 100 − 200 µm***

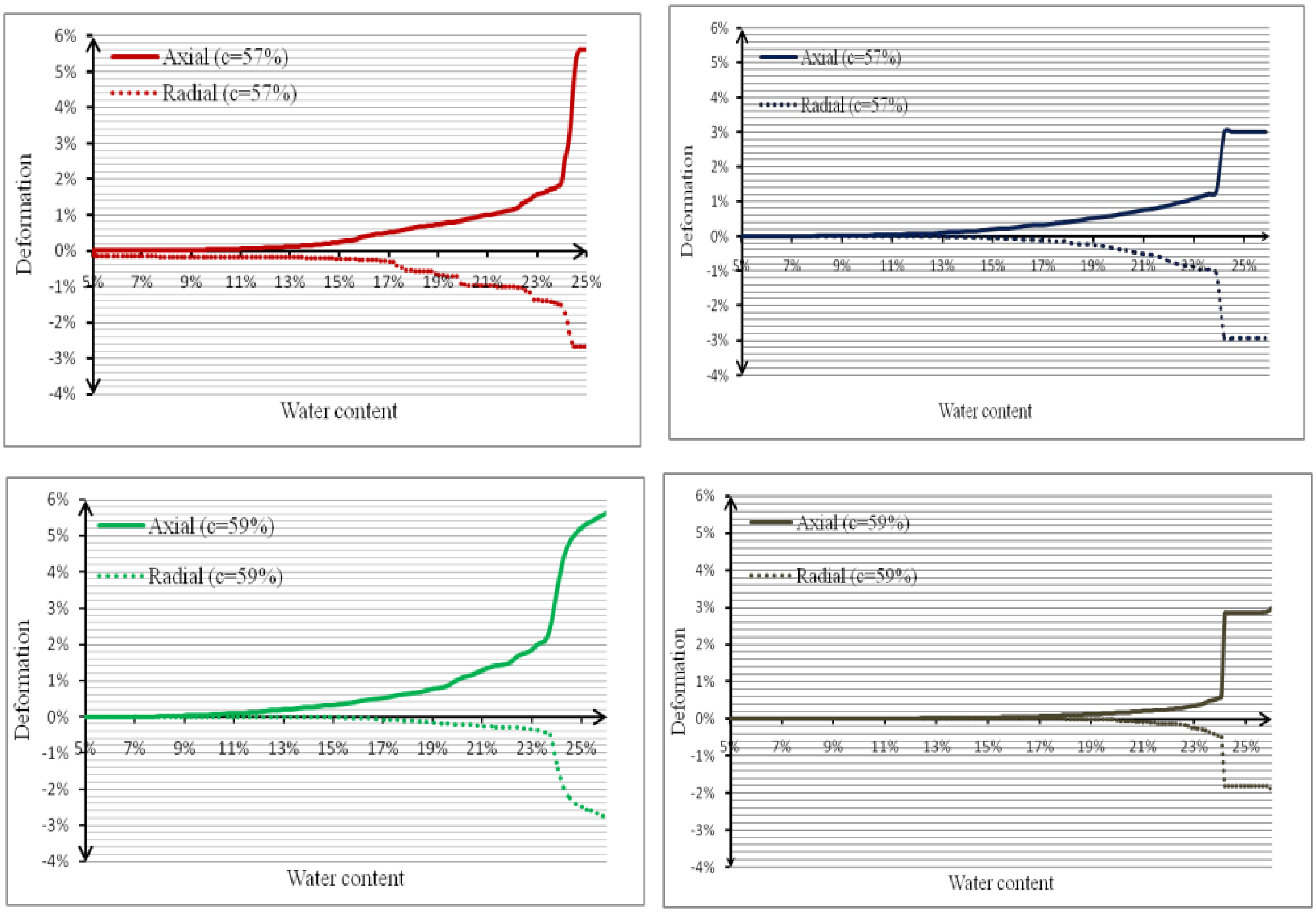


*Figure 1: Axial and radial deformations during wetting of Glass beads:*

*grain size ∅ < 50µm a) c = 57%; b) c = 59%*

*grain size ∅ =100-200µm c) c = 57%; d): c = 59%*

***Thank you for your contributions....***