ALERT Geomaterials

Alliance of laboratories in Europe for Research and Technology
Aussois, 30/09 – 02/10, 2019

30th ALERT Workshop / POSTER SESSION

Booklet of abstracts

Editors: Nadia Benahmed
Antoine Wautier
(IRSTEA, France)

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

30th ALERT Workshop

Poster Session

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ISBN: 978-2-9561359-5-1

Dear colleagues,

We are pleased to welcome you to Aussois and to our 30th ALERT Workshop and School.

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

We would like to express our thanks to all of you who came to Aussois to present and share your own work!

We wish you a good workshop and school experience and a pleasant stay in Aussois!

Kind regards,

Nadia Benahmed and Antoine Wautier.

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Calibration software ExCalibre

Kadlicek, T.+; Masin, D.*; Sula, I.*; Najser, J.*; Sejnoha, M. **; Janda, T.**; Benes, S.**

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Keywords: calibration, constitutive, models, hypoplasticity, elastoplasticity

Abstract

This poster presents the online calibration application called ExCalibre developed in cooperation with Charles University in Prague, Czech Technical University and Arcadis LtD. The calibration is currently available for the elastoplastic Modified Cam-Clay model [1], hypoplastic sand [2] and hypoplastic clay [3] models. A successful calibration requires data from basic laboratory experiments such as oedometric or isotropic compression test and drained or undrained triaxial shear tests. The experiment's data has to be prepared in the predefined excel format which is uploaded before the calibration. The application benefits from a clear physical meaning of the aforementioned advanced constitutive models and employs Newton's optimization method for the further optimization. Thorough testing of developed calibration procedures proved ExCalibre to be a reliable and powerful calibration tool for both academic and practical purposes. The software is currently available at the webpage soilmodels.com/excalibre/.

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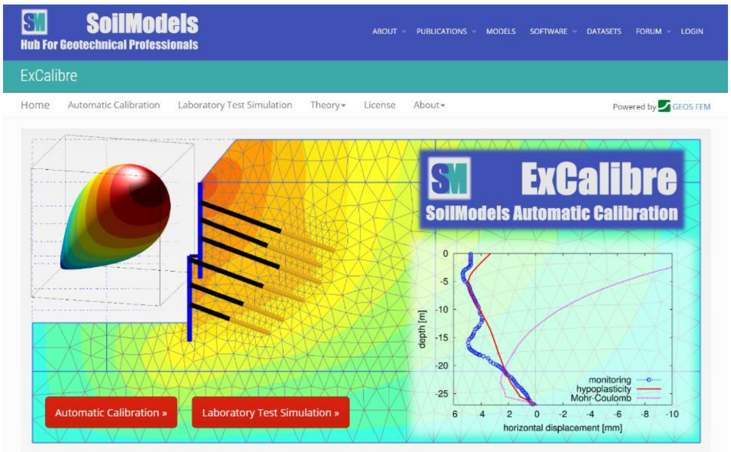

Figure 1 : *ExCalibre opening page*

Evaluation of geomaterial properties in Debre Sina landslide area using numerical simulation and GIS

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Keywords: critical slope failure angle, Manning's coefficient, DEM.

Abstract

Steep relief, heavy precipitation and abundant debris geomaterials comprise major causes of landslides. Due to favorable topographic and geomaterial property conditions corresponding to landslide incidences, the study area (Figure 1) is frequently affected by landslide problems Abebe B. et al (2010). A landslide event occurred in the year 2005 caused losses of over 900 hectares of arable lands, displacement of more than 4,049 peoples, and destruction of more than 1,200 local houses in the vicinities named Debre Sina town, central Ethiopia, Woldearegay K. (2013).

In order to assess the risk caused by flows and to demarcate vulnerable area where the mitigation measures are required, it needs to know the resistances of a given area to the impacts of the flows. Such characterstics of a given area rests on the geomaterial property of the soil and physiographic characters of the channels and flood plains. The Manning's roughness coefficient value is among the most common parameters used to characterize the channels.The simulation outcome is important for determining a possible affected area, which is an essential element for producing hazard maps Petrascheck, A. and Kienholz, H (2003).

We made a numerical simulation analysis after preparation of the Digital Elevation Model (DEM) of the study area (Figure 2) from a raster file freely obtained from Japan Aerospace eXploration Agency (JAXA), using Geographic Information System (GIS) application. We used a Google earth image (Figure 3) taken near to the event, in the year 2007 to verify the water coures identified on the topographic map. The Google earth image had also revealed some scarps of the slope failure event.

A comparison of predicted and observed flow area (Figure 4) was made with a simulation result obtained using parameters of, critical slope failure of 23 degree, deposition angle of 0 degree and Manning's coefficient value of 0.12. The predicted flow had shown more or less similar path and pattern of flow with obeseved water coursesand inundated area. Using the predicted flow velocity (Figure 5) and cross sectional area of initial slope failure, we estimated a total of 8,471,880m^3 volume of discharge.

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Figures

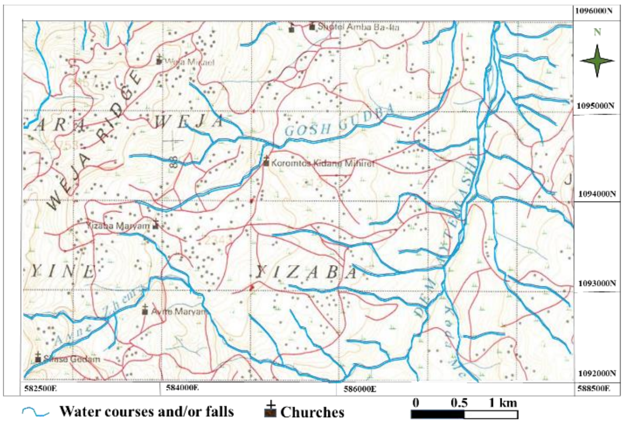


Figure 1: *Topographic map of the study area*

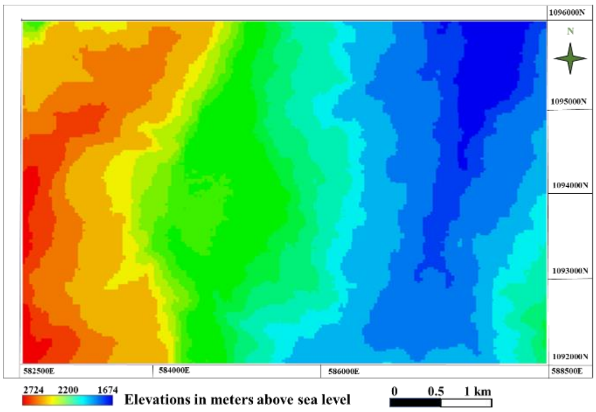


Figure 2: *DEM of the study area.*

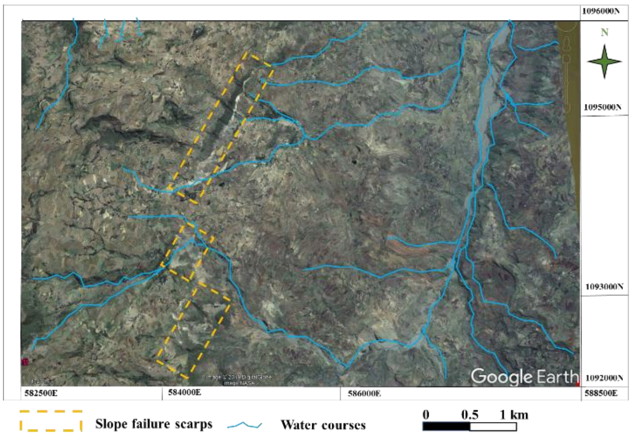


Figure 3 : *Google earth image of the study area, taken on June 2007.*

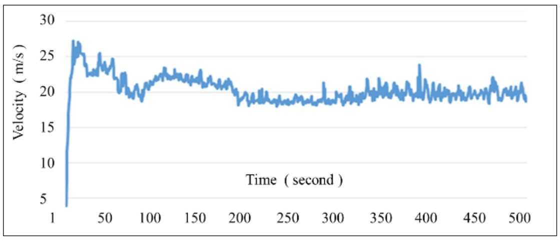
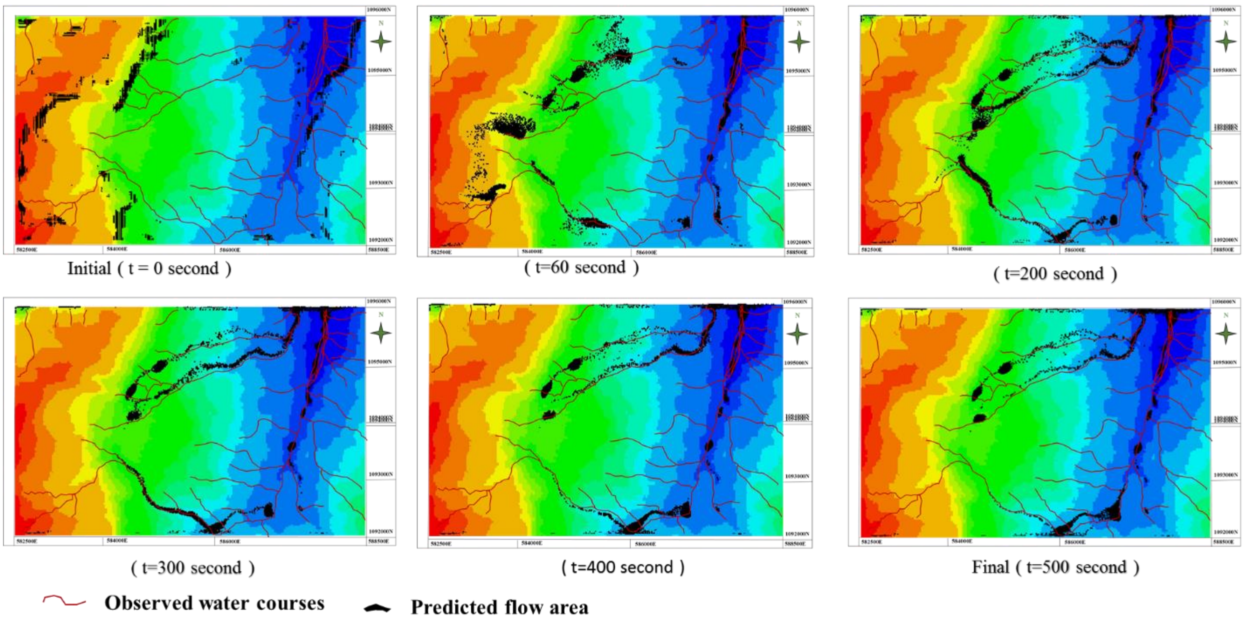


Figure 5 : *Velocity of the predicted flow.*



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Clay hypoplasticity with intergranular strain anisotropy

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Keywords: anisotropy, constitutive modelling, hypoplasticity, intergranular strain

Abstract

The present work is devoted to extending and evaluate a constitutive model for anisotropic clays for cyclic loading. The reference model corresponds to the anisotropic Hypoplasticity for clays by [1], which accounts for an elastic tensor depending on the bedding plane's orientation. The proposed model results from extending this hypoplastic model with the Intergranular Strain Anisotropy (ISA) by [2].

Simulations of different monotonic and cyclic tests are then performed to evaluate the model capabilities. Effects emerging from the sample anisotropy, such as "inclined" $q - p$ cycles under undrained conditions, and different pore pressure accumulation curves depending on the bedding plane were also successfully captured by the proposed model. The results show that the ISA extension enhances the model in many aspects, as the increase of the stiffness and reduction of the plastic strain rate on cyclic loading.

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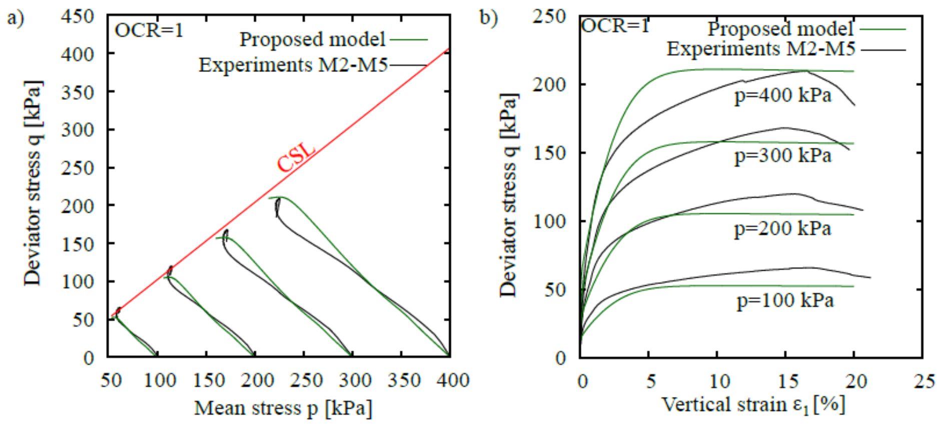

Figure 1: *Monotonic undrained tests with Kaolin clay. Experiments by [3].*

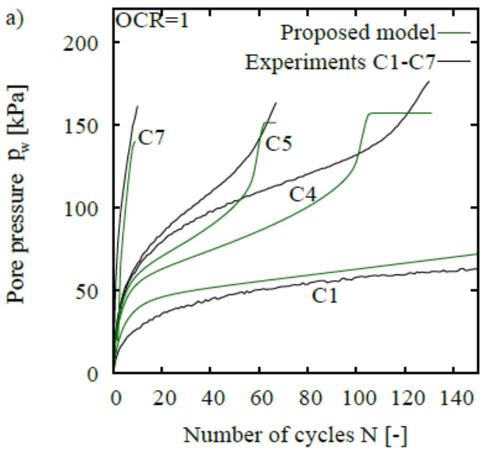

Figure 2: *Accumulation of pore water pressure on cyclic undrained triaxial tests. Experiments by [3].*

Complex yield criteria for three-dimensional granular flows

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Keywords: Navier-Stokes equations, OpenFOAM, Drucker-Prager, Mohr-Coulomb, Matsuoka-Nakai

Abstract

The incompressible non-Newtonian Navier-Stokes equations have become a popular method for the simulation of granular flows [1, 2, 3]. The success of the μ(I)-rheology [4] is certainly not insignificant for this. Within the framework of plasticity [5], this rheology can be described in terms of a yield surface and a flow rule. The yield surface is of Drucker-Prager type, parametrized with the inertial number I and the flow rule follows from incompressibility as von-Mises type.

However, the yield-strength of granular material depends on the loading type, e.g. plane strain shearing, triaxial extension or triaxial compression, which cannot be modelled with a Drucker-Prager yield criterion. Thus the Drucker-Prager yield criterion is no longer used in soil mechanics. The Mohr-Coloumb critrion or the Matsuoka-Nakai [6] criterion yield much more realistic results for the shearing failure of granular material. The difference to the Drucker-Prager criterion can be remarkable, especially if the loading type changes in time or space.

We demonstrate that the Drucker-Prager criterion within the μ(I)-rheology can be easily replaced with an arbitrary yield surface, using the usual assumption of alignment between streching and deviatoric stress. We introduce the Matsuoka-Nakai yield criterion and thus obtain a rheology for granular flows that appropriately predicts different yield-strengths for different loading types. This rheology is, similar to the classic μ(I)-rheology, fully compatible with the incompressible Navier-Stokes Equations and can be implemented into CFD frameworks such as OpenFOAM [7].

We simulated axial symmetric granular collapses (Fig. 1) and achieved a good agreement of the simulated final pile forms with experiments [8] (Fig. 2). The stress in the soil differs substantially (approximately 44%) The runout varies slightly for a high pile (approximately 5%).

M.~Rauter acknowledges the support from SLATE (H2020-MSCA-ITN-2016-721403) - "Submarine landslides and their impact on continental margins" European Training Network.

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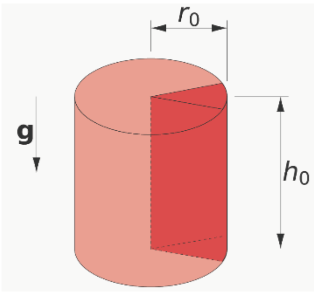

Figure 1 : *Granular collapse of a column*

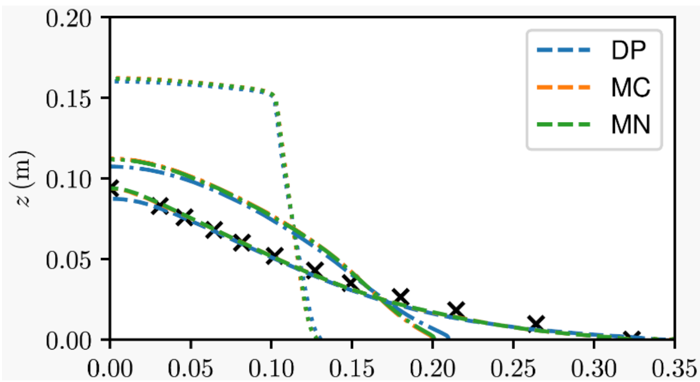

Figure 2 : *Surface shape of granular collapse: all models (DP Drucker-Prager, MC Mohr-Coulomb, MN Matsuoka-Nakai) at t = 0:1s, 0:2s, 0:5s and deposit of experiment (black crosses)*

Peak strength influenced by scattering density - Simulations with hypoplasticity

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Keywords: peak strength, constitutive modeling, hypoplasticity, FEM

Abstract

In experimental testing, it is impossible to obtain a soil sample with a homogeneous void ratio. Therefore a homogeneous deformation, i.e. an element test, is questionable well before the peak. The density or void ratio in a soil sample is naturally scattered and is thus not constant. Even for an ideal material consisting of spheres of the same size, inhomogeneities are to be expected due to inhomogeneous sample mounting. Recent tomographic studies on sand showed that inhomogeneities exist from the beginning of triaxial tests [1,2].

It is common practice to calibrate a material model on the basis of element tests, see Figure 1. If the void ratio is included in the material model, only the mean density can be taken into account in a single element test. The question arises, if the samples density is sufficiently described by its mean value.

In this contribution we carry out simulations of fine-meshed biaxial tests of Hostun sand [3] with hypoplasticity [4]. In hypoplasticity, the stress rate is expressed as a function of stress, stretching and void ratio. In the simulations, the void ratio is uniformly distributed and randomly scattered over 5000 elements. In all simulations the mean value of the void ratio coincides, but the range of the void ratio is varied. The average response of stress and strain of the fine-meshed tests is evaluated, see Figure 2 and [5].

The purpose of the poster is to show that an initial scattered density strongly influences peak strength. The higher the scatter is, the lower is peak strength, see Figure 2.

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Figures

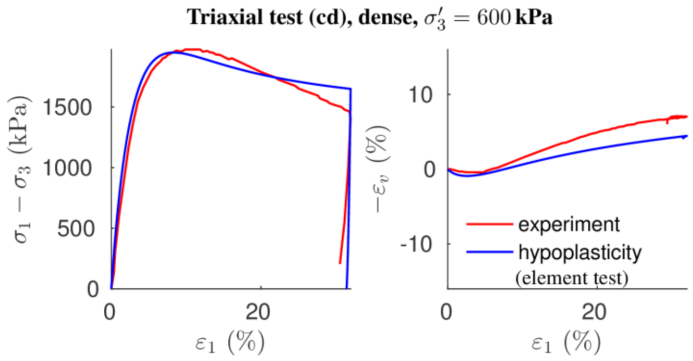

Figure 1 *: Calibration of hypoplasticity on the basis of a drained triaxial test. Only the mean value of density is taken into account in the simulation of the single element test. The question arises, if the samples density is sufficiently described by its mean value. Hostun Sand (data from [3]) is simulated with hypoplasticity [4].*

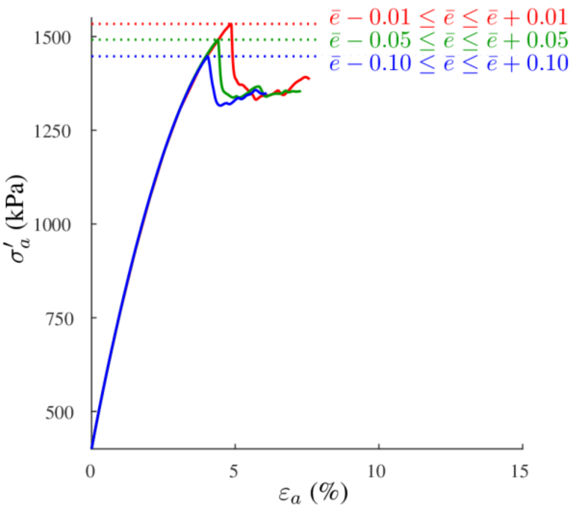

Figure 2 : *Simulations of fine-meshed biaxial tests with the same average void ratio e = 0.85. Average response of axial stress and axial strain of the fine-meshed tests for different ranges of void ratio. The average density is not sufficiently indicative for strength predictions. The larger the scatter of void ratio (by keeping the average void ratio), the lower peak strength. Hostun Sand is simulated with hypoplasticity [4].*

Acknowledgement

G. Medicus is financed by the Austrian Science Fund (FWF) P 28934-N32. G. Medicus and B. Schneider-Muntau are supported by Le Pôle interdisciplinaire d'études françaises de l'Université d'Innsbruck (*Frankreich-Schwerpunkt der Universität Innsbruck*).

Application of the intergranular strain concept to barodesy

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Keywords: small-strain, reloading, barodesy, hypoplasticity, soil cyclic behavior

Abstract

The reloading behavior of soil differs significantly from the behavior at first loading. A change of the deformation direction leads to an increase of the stiffness. The increased stiffness is then decreased with ongoing stretching. Constitutive models should be able to capture those reloading effects in order to predict realistic deformations. To capture so-called *small-strain* effects the models need to consider the deformation history of the soil. If a model does not include any additional information about the deformation history, it has to be enhanced with special extensions. For hypoplastic models (e.g. [1, 2]) the intergranular strain concept [3] has proven to be a suitable approach to model small-strain and cyclic effects. This concept assumes an increased stiffness and an elastic behavior for small-strain cycles.

This contribution presents the adaption of the intergranular strain concept for barodesy [4]. The calculations are compared with experimental results as well as with simulations using hypoplasticity. Barodesy [5, 6] is a nonlinear material model, based on the asymptotic behavior of the soil and has similarities to hypoplasticity. As the basic structure of barodesy substantially differs from hypoplasticity, essential changes concerning the mathematical structure of the intergranular strain concept are necessary. We present two different approaches for an application of this concept. These approaches differ in the determination of the incremental elastic stress response, which is used for reversible deformations. The so-called *IEM-approach* (internal elastic model) determines an incremental elastic response from barodesy by a mathematical decomposition of the model. The so-called *EEM-approach* (external elastic model) uses an additional elastic model. For both approaches, the interpolation scheme of the original intergranular strain concept is used. The results are in accordance with simulations by hypoplasticity and with experimental data. Figure 1 shows the improvement of the reloading behaviour of barodesy for simulations of an isotropic compression test.

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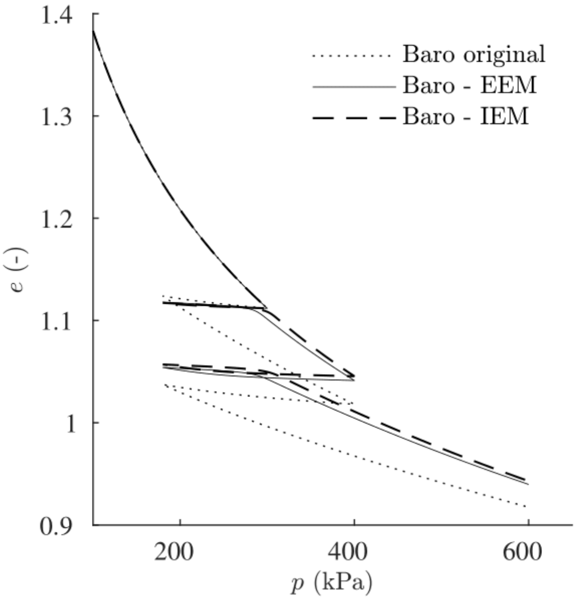

***Figure 1**: Isotropic compression tests using both intergranular strain approaches simulated with barodesy. The intergranular strain extensions lead to an increase of the stiffness after a change of the deformation direction. Figure from [4].*

Acknowledgement

M. Bode and G. Medicus are financed by the Austrian Science Fund (FWF): P 28934-N32. D. Mašín is financed by the research grant LTACH19028 of the Czech Ministry of Education, Youth and Sports and by the institutional support by the Center for Geosphere Dynamics (UNCE/SCI/006). M. Bode, W. Fellin, G. Medicus are supported by Le Pôle interdisciplinaire d'études françaises de l'Université d'Innsbruck (*Frankreich-Schwerpunkt der Universität Innsbruck*).

Are empirical correlations still an option?
A conscious approach to avoiding soil shear testing

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Keywords: empirical correlation, residual shear strength, critical state, index property, landslide.

Abstract[1]

Well-constrained estimates of strength parameters, such as the critical state and the residual friction angles, are decisive for reliable slope stability analyses. These parameters can be evaluated in the laboratory according to standardised procedures, yet it frequently happens that resources for sampling and testing are insufficient, or the availability of soil samples for testing is limited. The representativeness of a small number of results obtained on a handful of small-sized samples, even if of good quality, also can be questioned when compared to the size of the investigated problem, which can easily exceed 10^6-10^9 times that of the samples. Significant *in situ* heterogeneities in composition and hydro-mechanical conditions add to this question and, provocatively, one might ask if time-consuming laboratory testing is worth the hassle. Statistically significant correlations exist between strength parameters and simple index properties. The seek for such empirical correlations to ease the burden of shear testing (while in principle increasing the number of soil samples) has made the use of correlations common in estimating the soil behaviour in some applications. What lies behind the scenes is a balance between the resources saved by avoiding shear testing, and the uncertainties added to the estimates – and to the problem answer – by the use of the correlations. This is well-known by practitioners, who are often faced with this option in cogent regulations.

In Roháč *et al.* (2019), we analysed the performance of established correlations in relation to a case study in the Czech Republic: the 2013 *Dobkovičky* landslide (Stemberk *et al.*, 2016; Roháč *et al.*, 2017). Evaluations both of index properties and strength parameters were available, so we could compare correlation-based estimates with experimental results, and also obtain site-specific correlations based on the latter. We discussed the results also in relation to values of mobilised friction angle resulting from back analyses of the landslide (Figure 1). We found systematic deviations, which might come both from a biased calibration set associated with the correlations, and from uncertainties in our shear strength estimates. These might originate, in part, from the choices of shear device, sample size, and rate of shearing. Nonetheless, we observed that estimates of the critical state friction angle were much better constrained than those of the residual friction angle. This was actually expected, as the critical state – an asymptotic state of the soil mechanical behaviour – is unique for a

The research was supported by the GAUK 1488217, by the GAČR 17-21903S and the fund for International Mobility of Researchers at Charles University (project No.CZ.02.2.69/0.0/0.0/16_027/0008495, key activity 1-PřF-GEOMOBIL).

given mineralogy and soil shape, whereas the residual depends also on viscous properties and changes in pore water state.

In our site-specific correlations, we observed that the index properties can only explain a minor part of the variance in experimentally-evaluated friction angles, with the plasticity index being the most significant control, and clay mineralogy possibly representing the strongest unconstrained factor. The rest of the variance was "simply" attributed to reasonable uncertainties associated with the experimental estimates of index properties and strength parameters. This is actually worrying, because implies that even small uncertainties, especially in relatively homogeneous calibration sets, can override a correlation's predictive capability.

We conclude recommending caution in (ab)using correlations, and warmly insist that both experimental and empirical estimates should come with reasonable estimates of their uncertainties. Despite a still-questionable representativeness, accurate element-volume testing in the laboratory remains preferable when it comes to evaluating strength parameters for a slope stability analysis, whereas empirical correlations can still come handy in quick-and-dirt assessments. On the other hand, analyses with advanced constitutive models require the accurate determination of sets of parameters – including hydro-mechanical characteristics, as well as time- and rate-dependent features – which can only be captured through specific testing.

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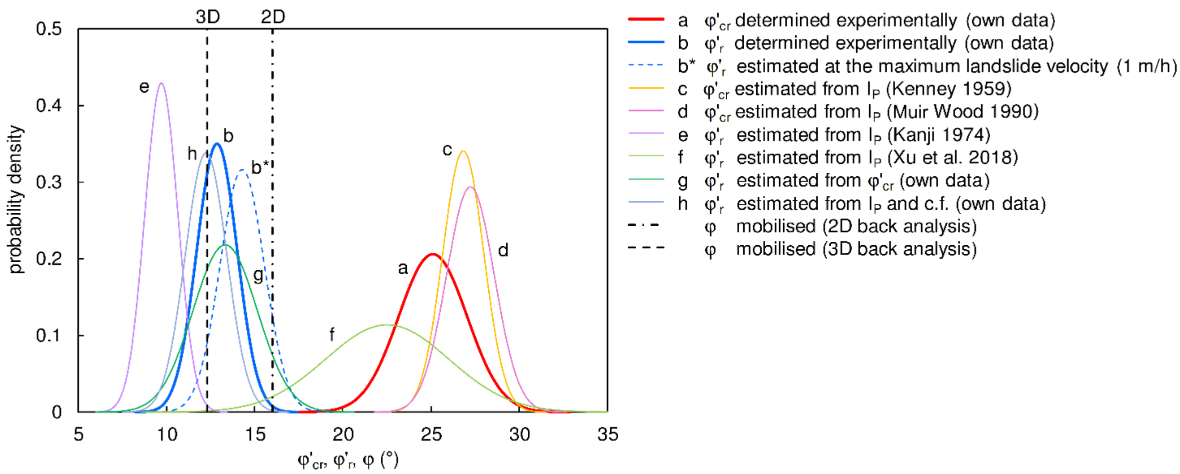

Figure 1: *Critical state and residual friction angles evaluated from laboratory shear tests, or through various empirical correlations, compared to mobilised friction angles evaluated by back analyses.*

Two-phase SPH modelling of debris flows with considering the role of excess pore-water on propagation stage

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Keywords: debris flow, pore water pressure, two-phase.

Abstract

The principal objective of this study is to develop mathematical and numerical modelling for simulating two-phase debris flows in which considering the effect of pore water dissipation is essential for risk analysis. A typical debris flow consists of low permeable soil in which lateral spreading is highly affected by pore water pressure. Therefore, a key aspect in order to develop accurate model is to combine propagation and consolidation model in order to consider the effects of pore water pressures in each time-step.

In this study, the two-phase model proposed by Pastor et al. (2017) is extended and also an improvement in description of pore pressure evolution is presented. The mathematical approach is based on the mathematical model of Zienkiewicz and Shiomi (1984). Concerning the numerical technique, the Smoothed Particle Hydrodynamics (SPH) is used for problems that are basically in the form of partial differential equations. This study provides a contribution to enhance the two-phase numerical model with adding a 1D finite difference grid to each SPH node in order to improve the description of pore water pressure (SPH-FD Model).

The performance of the model is assessed using two benchmark exercises, including 1) flume tests equipped with a (permeable) rack and 2) a real case (Johnsons Landing landslide) for which we have had access to their reliable information. The reasonable results obtained from analysis of the mentioned benchmarks indicated that the propagation-consolidation model is capable to properly reproduce the behaviour of the debris flows, and more importantly to correctly performs the time-space evolution of pore water pressures during the whole propagation stage over an impermeable and permeable bottom boundary.

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Figures

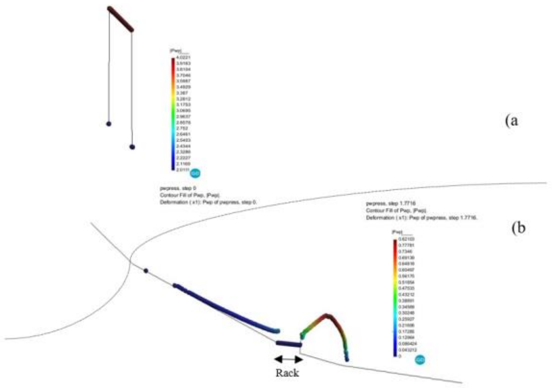

Figure 1: *Total pore pressure at a) starting condition and b) time 1.8s of the flume test.*

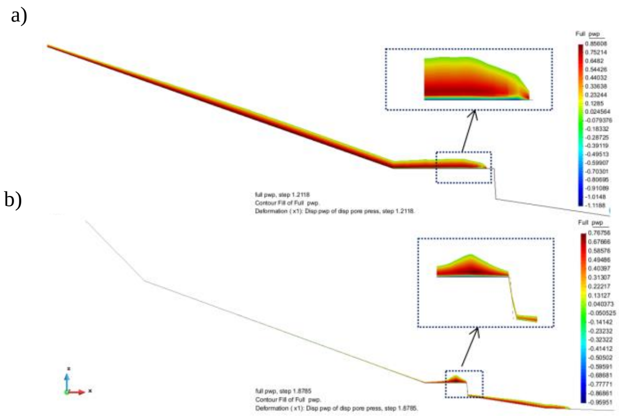

Figure 2: *The distribution of relative pore-water pressure a) over the rack (a zoomed portion of the plot) and b) after the flow passes the rack. (flume test)*

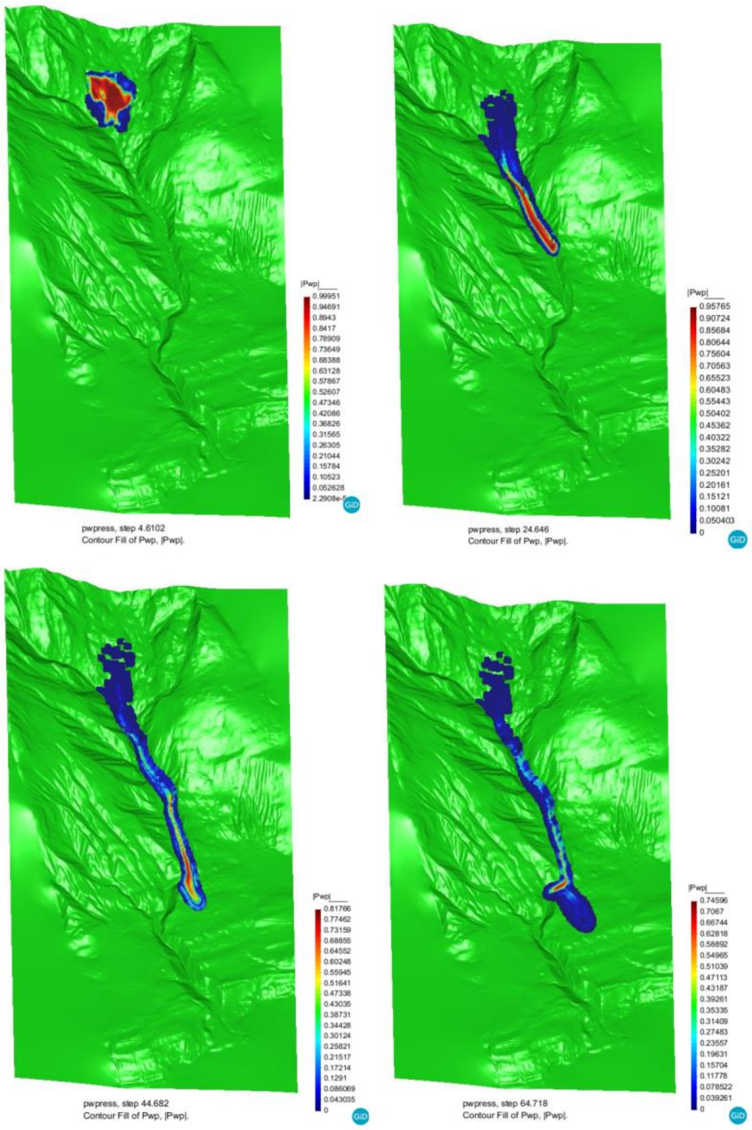

Figure 3: *Results sequence of pore pressure evolution at 5, 25, 45 and 65 seconds of the real case (Johnsons Landing landslide).*

Debris flows runout estimation by random walks

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Keywords: random walks, runout, debris flows

Abstract

Avalanches, debris flows, mudflows and landslides are natural phenomena that take place regularly in mountainous regions, frequently involving damage of life and property.

Among the different methods applied to estimate hazard maps for downslope gravitational processes, like debris flows and mudflows, random walks on a digital terrain model give an interesting alternative combining good accuracy with an affordable computational cost. This type of multiple-flow-direction approach can simulate the movement of a mass point from an initiation site to the deposition area taking into account possible divergent or persistent characteristic of the gravitational processes. Therefore, random walks on a digital terrain model can be considered to assess process paths and runout areas of downslope gravitational processes.

The random walk routing proposed by Mergili and co-workers in 2015 is applied to back-calculate the runout of the debris flow which occurred in 1982 at La Guingueta catchment, in the Eastern Pyrenees. Comparison with historical documentation of the debris flow is highly satisfactory.

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Application of two SPH models to the Tate's Cairn debris flow

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Keywords: debris flow, one-phase SPH, two-phase SPH.

Abstract

Mathematical and numerical modelling for the debris flow propagation from initiation to deposit in the run-out zones is not an easy task due to the complexity of the phenomenon yielding a system of time-dependent non-linear hyperbolic equations.

In this study, two different depth-integrated mathematical models for debris flows are considered. The first one is a basic one-phase Voellmy viscous model. The second one is the two-phase approach proposed by Pastor and co-workers in 2017, based on the work of Pitman and Le in 2005. These mathematical models are numerically solved by the Smoothed Particle Hydrodynamics (SPH) technique.

In order to assess the performance of each SPH model, both are applied to the Tate's Cairn debris flow that took place in Hong Kong in 2000 after an intense rainfall. The influence of different physical parameters (Voellmy coefficient, erosion coefficient, angle of internal friction) is analyzed in both models.

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Figures

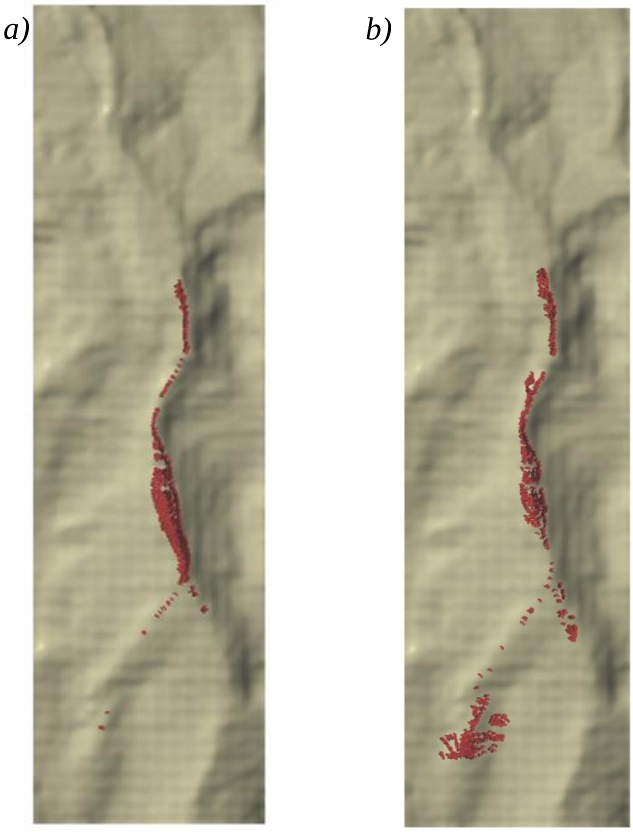

Figure 1: *Comparison of the results with: a) one phase and b) two phases.*

Modelling of Deformation of Internal landfill of Open Cast Coal Mine-Bilina

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Keywords: Mohr Coulomb, hypoplastic, constitutive modelling, internal dump.

Abstract

A numerical study for stability of internal spoil heap generated during extraction of coal of an open-cast coal mine Bilina in the North of Czech Republic has been carried out using Finite Element Method (FEM) Plaxis 3D over years. In this model, whose dimensions are approximately 6 km x 4.5 km, Mohr-Coulomb constitutive model were adopted enabling to calculate the deformation and stability of the soil.

In the next phase of the project, new methods will be adopted enabling to calculate stability factors of safety by Surface layer method and Shear strength reduction method with hypoplastic constitutive model.

Figures

Figure 1: *Open-cast coal mine Bilina, 2018*

Cyclic lateral design of offshore wind turbines monopiles in weak rocks

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Keywords: piles, multi-directional loading, cyclic loading, *P*-*y* curves

Abstract

Monopiles contribute around 25-30 % of an offshore wind turbine capital expenditure. It is thus important for the development of future wind farms to secure and optimise their design. This is why, EDF Renouvelables has performed an extensive program of in situ onshore pile testing (OPT) in a former quarry with rock properties similar to the ones encountered in some offshore projects. In that context, and on the basis of these tests results, the present work aims at improving the design methods. The most commonly used procedure for predicting the behaviour of laterally loaded piles is the so-called *P*-*y* curve formulation, in which the action of the ground is modelled by a system of non-linear springs. In its present form, cyclic and multi-directional loading are not accounted for. This is why, an extension of the *P*-*y* curves framework to account for these two effects is developed and validated using OPT results. Finite element modelling is also performed in order to (i) validate the key assumptions of the extended *P*-*y* approach, (ii) assess the 3D effects and (iii) discuss the upscaling of pile testing results to real monopile dimensions.

Figures

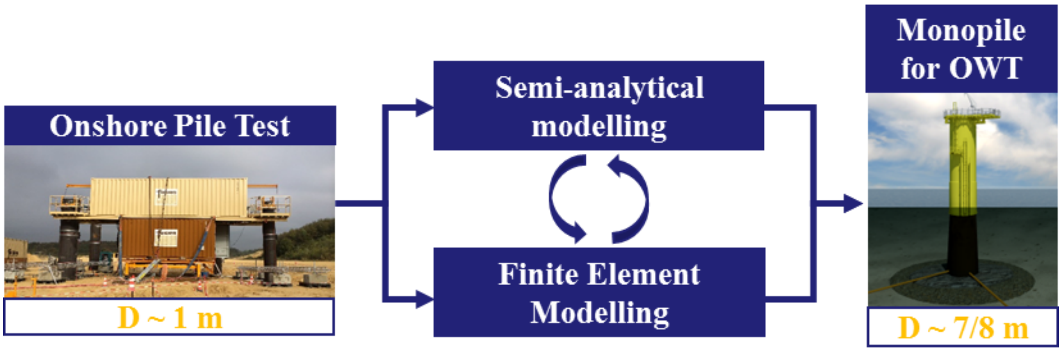

Figure 1 : *Methodology to fulfil industrial and design goals*

Inclusion of capillary effects in a multiscale model for granular materials

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Keywords: capillary forces, multiscale model, capillary bridge, water cluster, surface energy minimization

Abstract

Accounting for microstructure is the main difficulty in mechanical modelling of granular materials. The use of models based on statistical homogenization can be an interesting alternative compared with classical constitutive laws, which do not account properly for the microstructure, and with DEM, which is computationally expensive.

The H-microdirectional model [5] consists in studying at mesoscale an assembly of ten grains, which form two hexagons in orthogonal planes. All the symmetries in this bi-hexagonal cell permits to relate analytically external forces to grain displacements, and stress to strain by use of Love-Weber formula and a kinematic localization approximation. The concept of Representative Elementary Volume is then recovered by assuming that granular material is composed of a collection of cells oriented is different directions, according to a statistical distribution. Macroscopic stress and strain are then deduced from their mesoscopic counterparts by statistical averaging. Currently, this model has been developed for 3D dry materials [8]. The aim of this works is to extend the H-model to unsaturated soils.

A methodology for capillary forces calculation is developed here. We use surface energy minimization [1] to determine the geometry of the water interfaces for a constant water volume. The capillary forces are deduced from the surface energy with the Virtual Work Principle. The methodology is validated on capillary bridges between two grains by comparison with results in the literature ([2], [4], [6], [7]). Then, the merge of two capillary bridges in a triplet of grains is studied. A comparison with experiments from [3] permits to validate the methodology on a more complex case, before studying the capillary forces in the bi-hexagonal cell of the H-model.

In the H-model, capillary actions at macroscale are taken into account by distributing volumes of water in the mesoscopic cells. For given volume of water and opening angle of the bi-hexagon, the water regime that minimizes the surface energy is selected. An abacus of forces is created in order to add external capillary forces in the cells, depending on water volume and opening angle of the cell.

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Figure

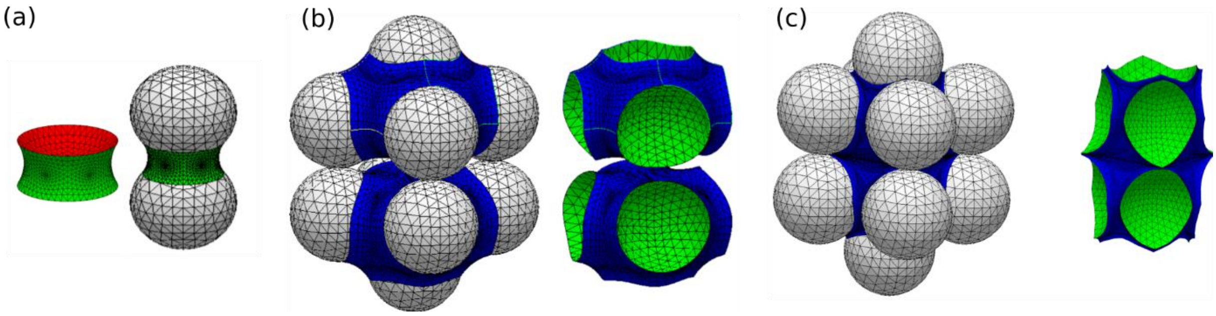

Figure 1: *Simulations of water volume between grains with Surface Evolver: (a) capillary bridge, (b) two clusters in a bi-hexagon, (c) one cluster in a bi-hexagon*

Two-phase SPH model of Selanac debris flow-Serbia

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Keywords: debris flow, swo-phase, SPH, ERT

Abstract

Selanac debris flow occurred in May 2014, after cyclone Tamara (Ivette) attacked Balkan region. A huge amount of material (almost 30m deep in source area) started to flow between two existing gullies. After some time, transported material made a dam on Selanačka river in the bottom. From a geological point of view, it represents very heterogeneous material of ophiolites, and transported material contains from small size cm rock particles to huge blocks over 2 m in diameter.

The main aim here is to show the first results of numerical two-phase modeling considering results and investigation that are made by now. Two-phase SPH model is proposed by Pastor et al. (2017). The mathematical approach is based on the mathematical model of Zienkiewicz and Shiomi (1984). Previously results were made using RAMMS debris flow software, using Voellmy criterion (Voellmy, 1955), which uses a one-phase model. Final results were compared with data obtained from ERT geophysical scanning in order to define deposition volume and also a comparison of the two epoch DEM topological models.

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Figures

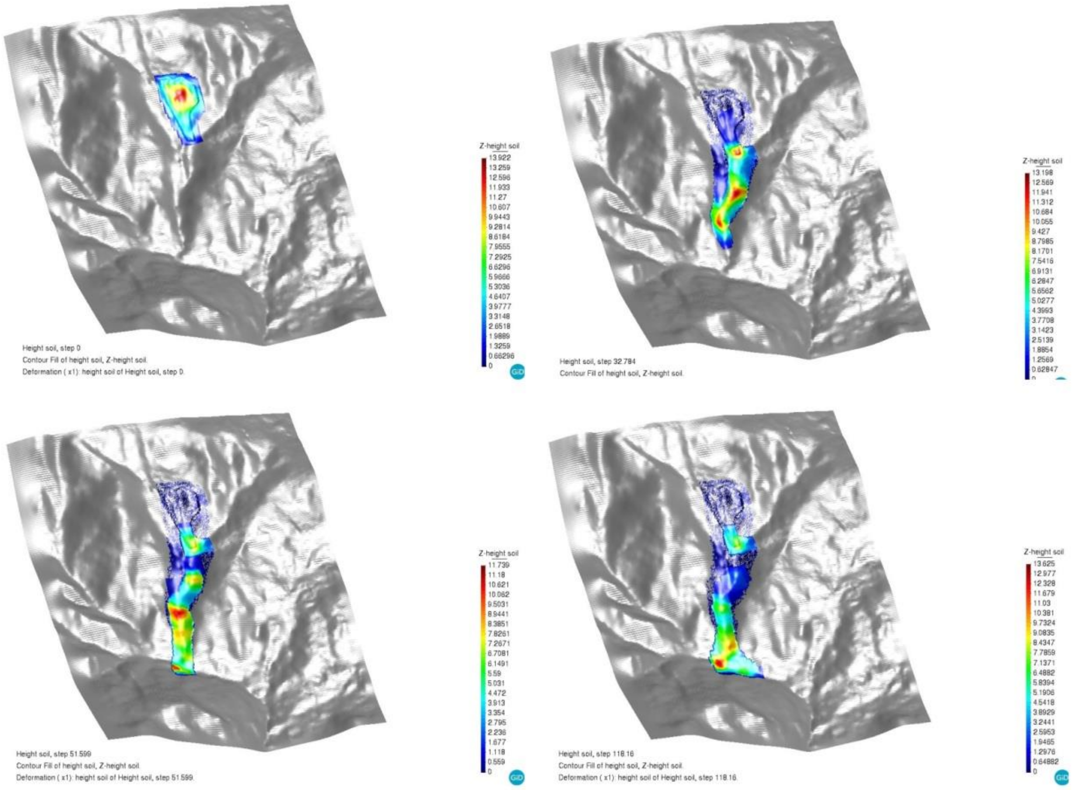

Figure 1: *Final two-phase model from initiation to final deposition*

Contact phase-field modeling for chemo-mechanical degradation processes in geomaterials

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Keywords: contact phase-field modeling, contact thermodynamics, pressure solution, microstructural geometry

Abstract

The microstructural geometry of materials has a significant influence on their macroscopic response, all the more when the process is essentially microscopic as for microstructural degradation processes. However, the microstructural geometry tends to be constitutively approximated, for instance by ideal spherical packings. Contact phase-field modeling enables to both track the microstructural geometry's dynamics and include catalyzing/inhibiting effects, accelerating/delaying equilibrium, such as temperature or the presence of certain constituents. To emphasize the influence of those two effects, we study numerically the chemomechanical response of digitalized geomaterials at the grain scale subject to pressure solution. We argue for accurately modeling the microstructural geometry in order to better capture the microscopic transient nature of pressure solution creep.

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Figures

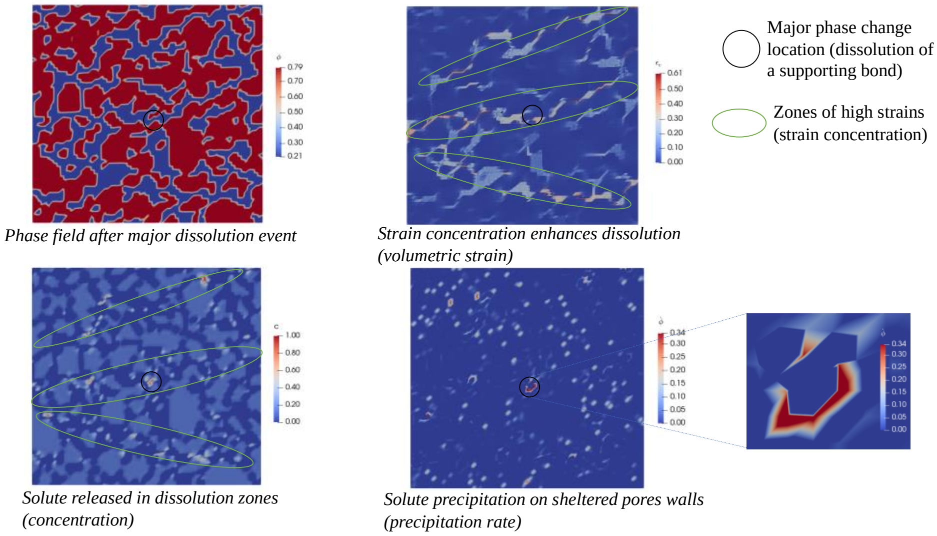

Figure 1: *Numerical results performed on digitalized ct scans of a sandpack using phase-field modeling; the particular microstructural geometry drives the strain concentration, which drives the dissolution/precipitation.*

Compaction bands formation in high-porosity limestones: Experimental observations and modelling

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Keywords: compaction bands, limestones, digital volume correlation, gradient-dependent plasticity.

Abstract

The mechanical compaction of sedimentary rocks can give rise to the formation of compaction bands which may significantly affect the performance of geosystems. Despite being identified in sandstones, experimental characterization of compaction bands in limestones remains a challenge (Baud *et al.*, 2017). In this study, the Digital Volume Correlation technique is applied on a high-porosity limestone tested in axisymmetric compression under different confining pressures. Strain localization bands are thus identified on 3D deformation maps and their types are studied based on kinematic considerations. In addition, to model the formation and evolution of compaction bands, high-order continua are required (Sulem and Vardoulakis, 1995). These continua take into account the microstructure by introducing additional parameters in their formulations. A new method based on X-Ray Computed Tomography images is proposed to calibrate the higher-order parameters of a gradient-dependent plasticity model. Finally, triaxial experiments are simulated using the Finite Element code, *Numerical_Geolab*, to follow the compaction bands formation and propagation.

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Figures

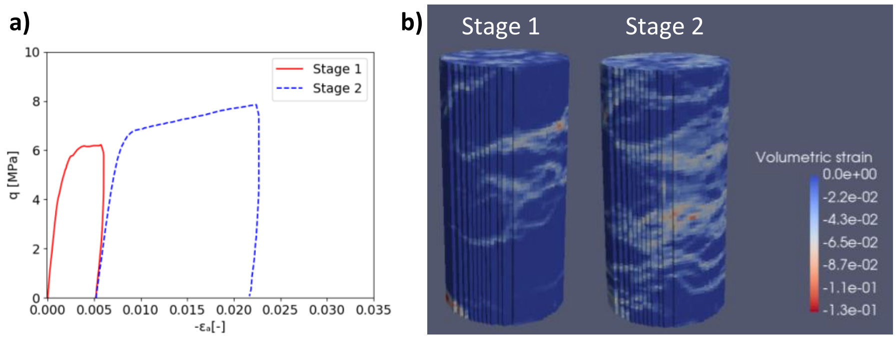

Figure 1: *a) Deviatoric loading vs axial strain under relatively high-confining pressure applied into 2 stages; b) The incremental volumetric srain maps during each loading stage.*

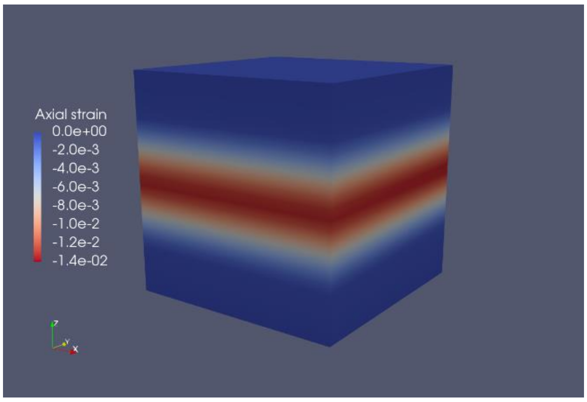

Figure 2: *Numerical modelling of compaction banding under triaxial loading.*

Evaluation of shear band thickness evolution during triaxial tests of graded sands using digital image correlation

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Keywords: strain localization, digital image correlation, granular mechanics, triaxial experiments.

Abstract

Strain localization is an ubiquitous phenomenon observed in many materials characterized by a loss of homogeneity of the field of deformation. In the particular case of geomaterials, this feature often occurs in the form of shear bands observed on outcrops or accompanying the failure of cavities, landslides or fault zones. The characterization of the size of the zone where most of the deformation concentrates is therefore a key parameter to the design of geostructures and the understanding of many natural hazards[1]. It influences also the strength weakening of the material and many multi-physical processes as it affects the temperature increase or the pore pressure evolution[2]. In this study, we focus on the observation of the influence of the microstructure size on the shear band thickness and in particular the impact of different particle size distributions. Indeed, most of the thickness studies have been done with sands presenting a narrow distribution compared to the distributions observed in fault zones for instance[3,4].

Triaxial experiments have been conducted on silica sand samples presenting uniform, well-graded or fractal particle size distributions. The shear band thickness evolution is assessed by Digital Image Correlation[5] (DIC) using cameras placed at different angles around the triaxial cell. From the field of deformation obtained from the displacements of elementary cells identified on the membrane, the fitting of a gaussian distribution or the definition of a threshold value has enabled to define the shear band size. The width of the shear band exhibits a rapid decrease until reaching a residual value, which depends only on the mean grain size even for broad distributions of grain sizes. The ratio of the band width to the mean grain size exhibits a value between 10 and 15 comparable with previous studies[4,6]. This residual value obtained from the DIC is compared with an estimation of the thickness based on the porosity variation obtained by X-ray computerized tomography scans after the experiments[7,8].

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Granular Convection

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Keywords: convection, vibration, granular temperature, X-Ray, radiography, fluidised

Abstract

When vibrated, previously solid granular materials can lose internal stability, fluidize, and eventually start to flow [1]. Both the loss of stability and the dynamics of vibrated granular flows are not yet fully understood. There is, however, increasing evidence for the relationship between this loss of stability and the fluctuation velocity of the grains. This is variously termed the kinetic stress or granular temperature, and has been proposed to be responsible for the decrease in stability, and the onset and rheology of flow [2]. Still, there have not yet been experimental measurements of velocity fluctuations far from boundaries in dense granular flows. Here, we present full 3D measurement of velocity fluctuations during steady state granular convection made using a novel X-Ray radiography technique. The measured fluctuations are high at the bottom near the source of vibration, lower in the middle and highest at the free surface at the top of the sample. The same trend is observed in measurements of the second invariant of the gradient of the steady state velocity fields. In the future, we will be able to use this new measurement technique to validate new constitutive models based on the Granular Solid Hydrodynamics framework [3], which can describe the dynamics of vibrated granular materials and give us deeper insights into the behavior of soils under seismic, cyclic and dynamic loading.

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Figures

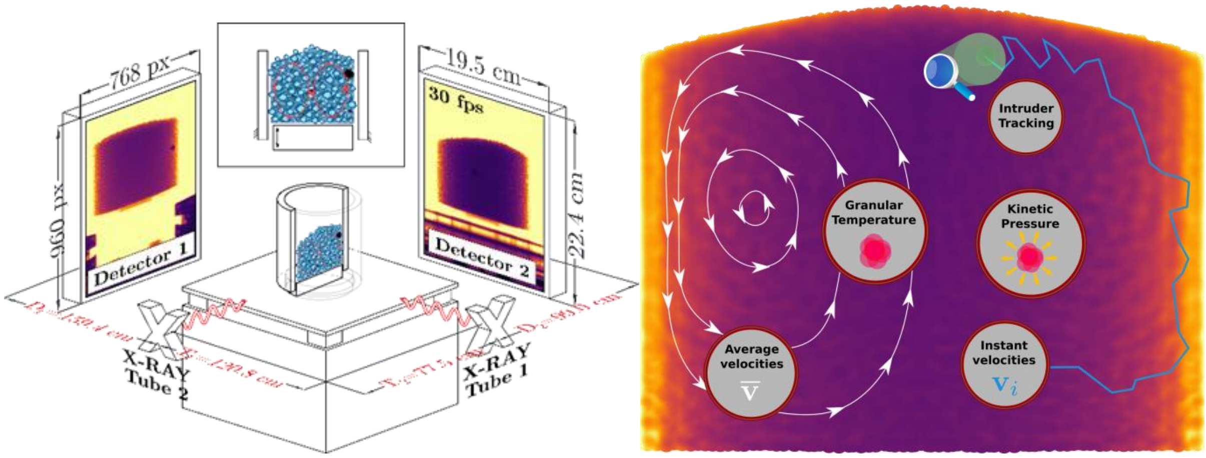

Figure 1 : *Experimental setup for granular convection experiment (left) and Granular temperature measurement procedure (right)*

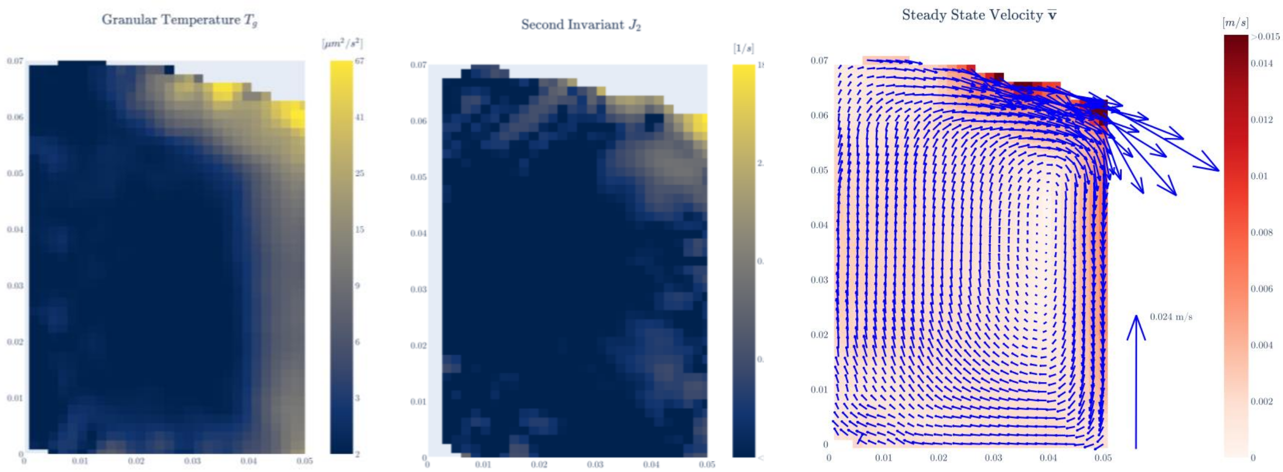

Figure 2. *Measured steady-state fields in r-z half plane (a) Granular Temperature (b) Second invariant of velocity gradient (c) Steady state average velocity*

Parallel GPU-based LBM-DEM approach for erosion onset by impinging jets

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Keywords: LBM, DEM, erosion, cohesive, granular, jet, GPU.

Abstract

This work presents a GPU-based parallelization approach to model particulate flow (i.e. Fluid/Particle interaction) with the focus on soil erosion at the micro-scale. The method adopted here is a fully resolved two-dimensional fluid-particle model based on the coupling of the Lattice Boltzmann Method (LBM) for the fluid phase and the Discrete Element Method (DEM) for the solid phase [1], including inter-particle cohesion model [2]. In this respect, the computational speed and the efficiency of the code were significantly improved using GPUs.

As regards possible applications of our GPU code, impinging jet over a cohesive granular sample was studied, aiming to quantify the erosion onset (i.e. initiation of bond breakage and particles detachment at the impinged surface). We found that the threshold condition is well described by a generalized Shields criterion for weakly cohesive soils.

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A 2nd gradient Thermo-Hydro-Mechanical model to investigate gas transfer processes in low-permeable media

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Keywords: Numerical Modelling, Excavation Damaged Zone, Strain localisation, Gas Migrations

Abstract

Nowadays, the deep geological disposal based on the multi-barriers confinement concept, is considered as one of the most promising solutions for the safe storage of radioactive wastes. Many Thermo-Hydro-Mechanical (THM) phenomena are likely to occur during the construction and the lifetime of the repository, which could alter the confining function of the different constituent layers.

Among these, the underground excavation process tends to create a so-called Excavation Damaged Zone (EDZ) in the surrounding of the storage galleries, where the mechanical and hydraulic properties are affected [1]. For instance, the hydraulic permeability is increased compared to the sound rock formation. Moreover, during the exploitation of the system, a certain amount of gases, such as hydrogen could actually be generated in the nearfield of the repository due to the anoxic corrosion of the metal components, and could potentially lead to the alteration of the host rock behaviour.

In light of this, the present work aims at developing a numerical tool within the finite element code LAGAMINE[2], able to reproduce simultaneously the development of strain localisation bands due to excavation and the multiphysical couplings associated with gas generation and migrations. This model includes on the one hand a THM part [2] to describe triphasic porous media under unsaturated and non-isothermal conditions. On the other hand, since the problem involving strain localisation is not well posed when modelled using classical medium, the local second gradient approach [3] is also integrated to the model. It helps avoiding the pathological mesh dependency by considering an enrichment of the continuum with microstructure effects through a regularizing internal length [4].

This model is subsequently used for reproducing two *in situ* gas injection tests[3] conducted in two distinct directions in the Boom Clay Formation, which is investigated by the Belgian National Radioactive Waste Management Agency (ONDRAF) as potential host rock for a deep geological disposal. The 2D plain strain simulations provide information about the fracture structure and permeability evolution due to the excavation (Figure 1), and about the

[2] Developed at the University of Liège

[3] Experiments E4 and E5 performed in the framework of the MEGAS European project in the Underground Research Laboratory (URL) in Mol [5]

stress state during a phase of pore pressures stabilization, and during a last phase of gas migrations (Figures 2 & 3).

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Acknowledgement

The Belgian Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS), is gratefully acknowledged for its financial support of the work presented in this paper.

Figures

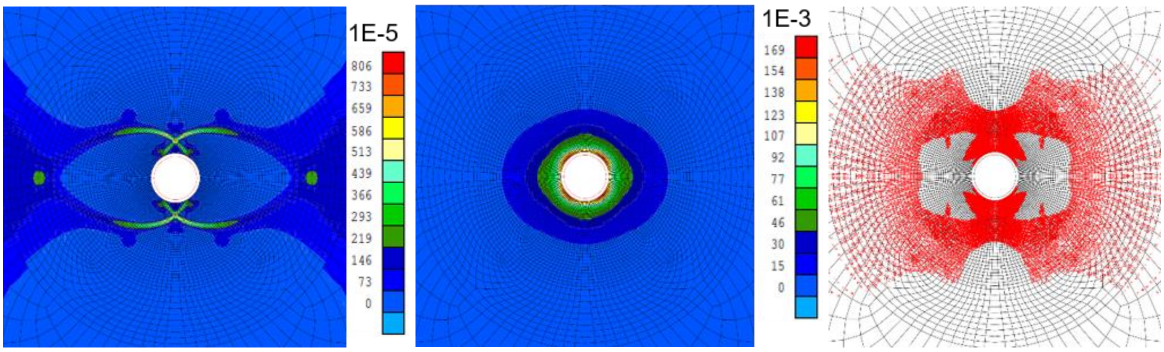

Figure 1 : *Evolution of total deviatoric strain (left), deviatoric strain increment (middle), and plasticity (right).*

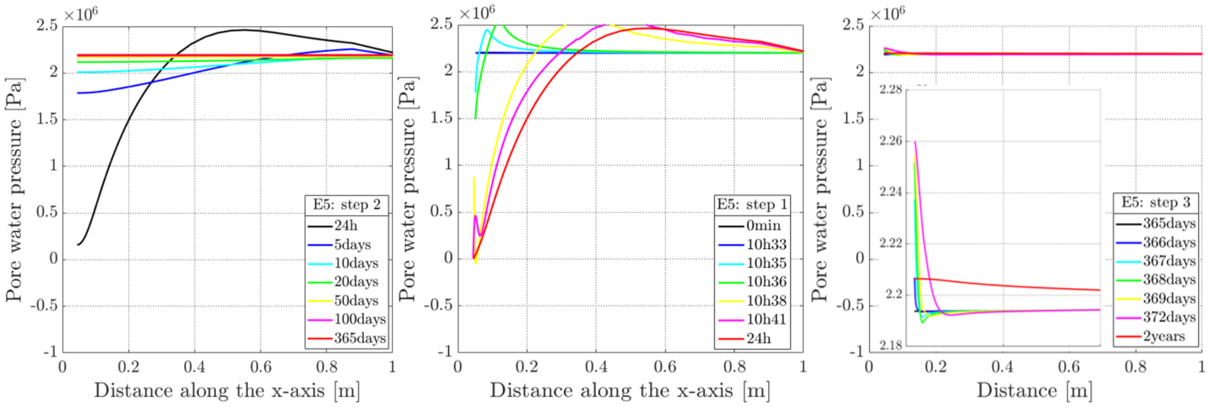

Figure 2: *Evolution of pore water pressures for excavation (left), stabilization (middle), and gas migrations (right).*

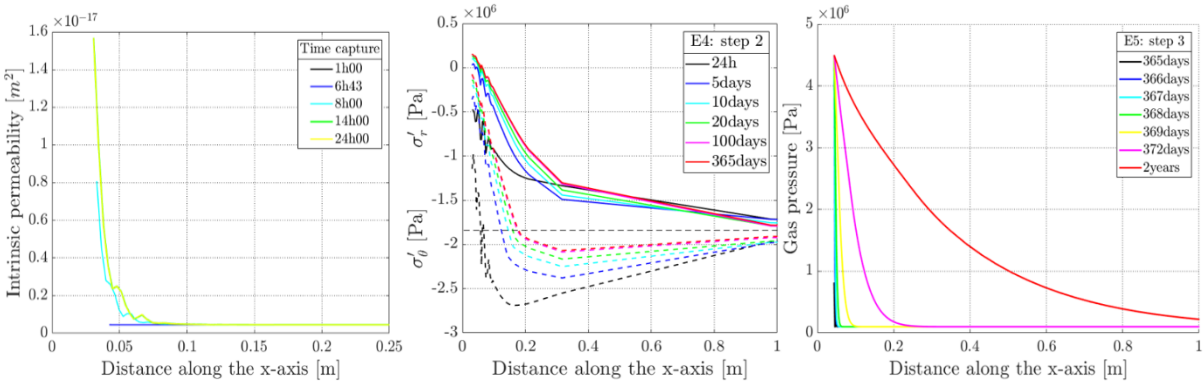

Figure 3: *Evolution of permeability (excavation - left), stresses (pressure stabilization - middle), ans gas pressures (gas migrations - right).*

Combining physical modelling and machine learning to improve avalanche risk forecasting

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Keywords: cutoff walls, cement-bentonite, contaminant transport, pollutant mitigation, monitoring

Abstract

Snow avalanches are a major natural hazard in mountainous areas. Accurate avalanche forecasting is essential to efficiently warn the public and the authorities.

Currently, no avalanche risk forecasting model use both observations (present and past) [1] and the knowledge of physical process occurring into the snowpack [2]. Moreover, state-of-the-art detailed mechanical models [3] are numerically expensive and very sensitive to errors in meteorological and snowpack models. Models based on machine learning start to appear [4] but are generally limited to meteorological data or simple snowpack variables and do not exploit our current knowledge on avalanche release.

The objective of this thesis is to combine pros of these two approaches in order to propose new avalanche risk indicators. The idea is to combine our knowledge of mechanical processes in the snowpack and machine learning with past observations. The proposed model aims to be numerically efficient, while keeping a comprehension of physical phenomenons occurring in the snowpack. This project is subdivided in three steps :

- **New mechanically-based indices of snow stability**: Comprehension of avalanche release is improving, especially with the explicit modelling of physical processes. Nevertheless, current models are either numerically expensive or use very simple stratigraphy of the snowpack (2 layers). An innovating approach is proposed : using a detailed model on a representative set of detailed snowpacks and extrapolating on all possible snowpacks with statistical methods. This extrapolation should permit a numerical efficiency of proposed stability indicators.
- **Machine learning of the relation between mechanical indices and observed avalanches activity** to obtain a forecasting method of natural avalanche risk : The aim of this part is to combine indices obtained in the first step with past avalanche activity, both avalanche activity observed by Météo-France network and the long observation dataset of ONF/IRSTEA on specific avalanche paths. Classification techniques will be used to maintain the comprehension of phenomenons during machine learning, as much as possible.

- **A similar approach for triggered avalanches**: the issue is to represent correctly the additional charge on the snowpack and to ensure the reliability of the results in spite of the low amount of data available on triggered avalanches.

At each step, an evaluation of the results will be performed. The overall aim is to propose a new model to estimate the avalanche risk reliable, efficient and comprehensible.

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Studying granular media with neutron diffraction

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Keywords: granular media, granular mechanics, full-field measurements, stress distribution, stress-strain relationships, digital image correlation, plane-strain apparatus, oedometer.

Abstract

Despite their seeming simplicity, granular media are highly complex materials, possessing inherently heterogeneous structure and properties that are manifested by the mobility and interaction of their constituent particles. Under the effect of applied stress, these materials exhibit significantly varying behaviours and mechanics throughout their granular skeleton, indicating that they are being governed by powerful local stress-strain relationships. Understanding and characterising such relationships has always been central in the study of geomechanics and, over the past few decades, strain localisation phenomena have been extensively investigated (e.g., Desrues et al., 2018). However, even if, through the employment of various modern experimental techniques, such as X-ray and neutron tomography, it has become possible to reveal intricate details on strain localisation phenomena in granular media (e.g., Hall et al., 2010), details on the evolution of force/stress distribution are, in most cases, a key, missing piece of information in the investigation of the (micro-)mechanics and failure mechanisms in such materials and to be understood, requires appropriate, spatio-temporally-resolved local measurements.

Neutron diffraction (ND), a well-established experimental tool to probe crystalline matter, has recently been successfully employed to study granular media under load and provide missing information on stress distribution and evolution, by inference from measured crystallographic strains of the grains. More specifically, Hall et al. (2011) showed that the ND method can be used to provide microscale insight into the evolution of elastic crystallographic – or grain – strains, from which stresses may be inferred, in a quartz sand specimen under load. However, no information on spatial variations was achieved. Soon after, Wensrich et al. (2012) reported the spatial distribution of granular stresses throughout a preloaded copper powder specimen inside a solid die, but no in-situ loading was involved.

Herein, new results showing the spatio-temporal distribution of granular stresses during the in-situ loading of quartz sand are presented, also associated with traditional macroscale boundary measurements, plus digital image correlation (DIC) mapping of strain fields, a combination of measurements that constitutes a completely novel multiscale experimental approach for granular (geo-)materials (Athanasopoulos et al., 2019). A key component that enabled this new approach is the development of a new, specially designed plane-strain loading apparatus. It is noted, however, that, as in the cases of Hall et al. and Wensrich at al., these results involve only a single subset of grains throughout the specimen, with a specific orientation. To this end, most recent results (e.g., Figure 1) from the constrained uniaxial (i.e., oedometric) loading of a quartz specimen are also presented. In this case, no spatial variations are involved, but for the evolution of the granular stresses multiple subsets of grains have

been taken into consideration, in different orientations. This has been accomplished by utilizing a newly defined set of equations to deduce, in a physically realistic manner, the contribution of each one of them in the total granular stress (i.e., the micro-stress), as well as a newly assembled dataset of reference measurements, also presented herein.

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Figures

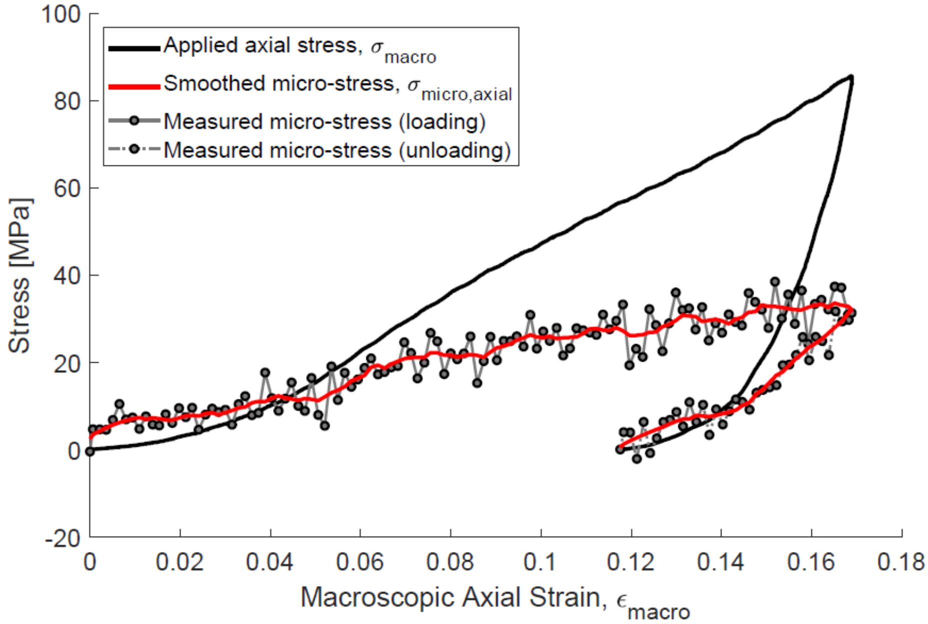

Figure 1 : *The applied axial stress (in black), together with the axial component of the raw micro-stress (in grey) and its smoothed version (in red), as functions of the macroscopic axial strain, from an oedometric loading experiment on Fontainebleau quartz sand.*

Poromechanical behavior of cement modified with a biopolymer under carbonation in supercritical conditions

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Keywords: supercritical carbonation, cement, nanocellulose, poromechanical behavior.

Abstract

Geological storage of CO_2 has been taking importance worldwide as one of many alternatives for reducing CO_2 emissions to the atmosphere and the consequences that it brings to our planet. Different types of geological storage require cemented injection wells. The hardened cement paste will be subject to the accumulation of the injected gas (CO2) during the entire injection process and during its useful life. Several different admixtures are commonly used in order to improve cement properties. Bacterial nanocellulose is a biopolymer which can be applied as additive due to its high mechanical properties, adequate thermal behavior and environmental convenience. Previous works have shown that nanocellulose can modify important properties such as compressive strength, microstructure, thermal performance, degree of hydration and viscosity. In this work, a supercritical carbonation test was performed to modified and non-modified cement samples with bacterial nanocellulose content. Thermogravimetric analysis, mercury intrusion porosimetry and uniaxial compression tests were performed on samples in order to study the change in porosity and mechanical behavior. Results were analysed and used as input parameters in a couple chemo-poromechanical model of finite elements. Carbonation depth and properties of the degraded zone can be obtained through this method. A degradation in all cement samples can be observed and mechanical properties are diminished and changes in their microstructure are noticed. Preliminary results show that bacterial nanocellulose additions affect initial poromechanical behaviour and improves cement carbonation resistance in supercritical conditions models.

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Figures

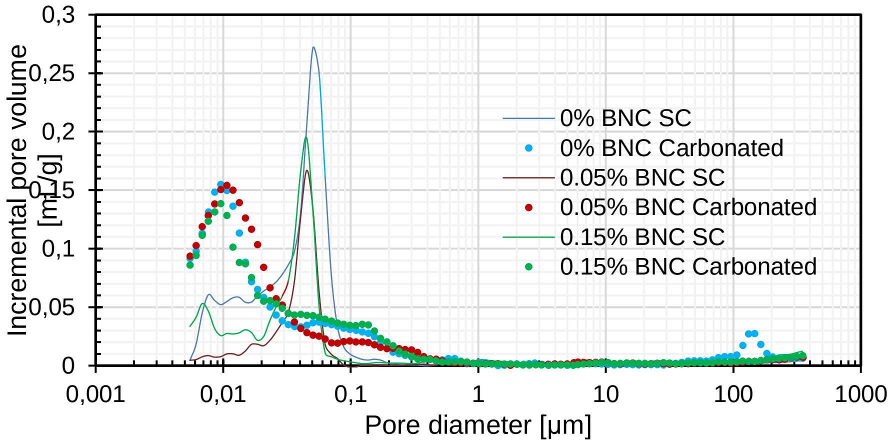

Figure 1 : *Pore sizes distribution (MIP)*

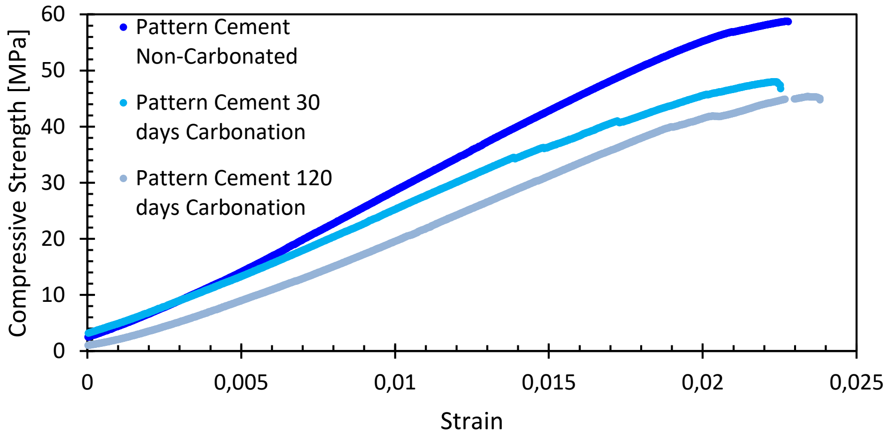

Figure 2 : *Uniaxial test*

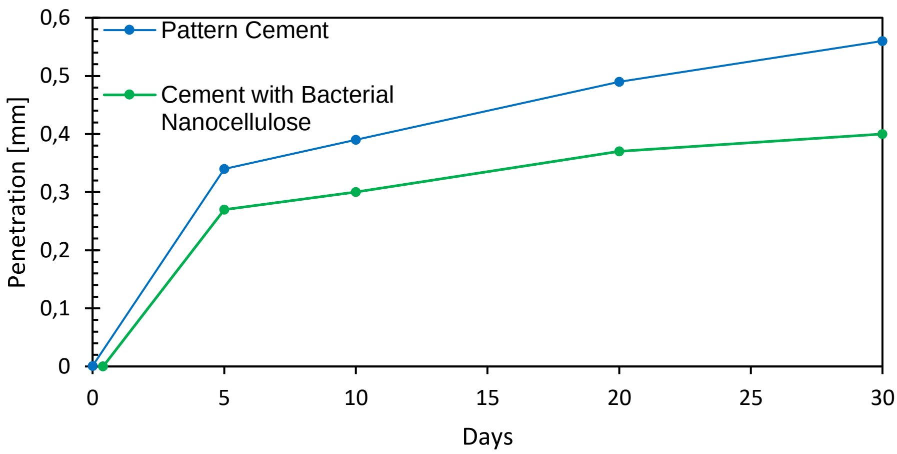

Figure 3 : *Carbonation Front*

Using lignin as stabilizer in an expansive Patagonian soil

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Keywords: expansive clays, biopolymer, lignin, stabilizer

Abstract

A clayey soil subjected to changes in water content by wetting and drying cycles presents volumetric deformations that can generate pathologies in structures or civil constructions such as roads, retaining walls and houses [1-5]. This behavior depends mainly on the physical-chemical characteristics of the clay, the history of tensions and suctions to which it was subjected [1]. In soils composed by minerals that are susceptible to changes in moisture content, expansions can produce swell pressure higher than that transmitted by the foundation, resulting in a differential lift that can damage the structures [4-5]. Traditional inorganic additives such as lime and cement have been mainly used as stabilizers to reduce the swelling-shrinkage effect of expansive soils [6]. The use of polymeric organic additives has been developed extensively in agriculture to control the migration of fines and improve water retention properties in arid or semi-arid areas [7]. In this paper, Calcium lignosulfonate (CLS), an organic polymer, is used as stabilizer. CLS is a sub-product of the paper pulp industry. The soil used (CRclay) is classified as a silty clay of high plasticity (MH) that contains 90% of clay fraction (smaller particles 2mm) with a plasticity index equal to 35% and a LL of 75%. The minerals were identified through X-ray diffraction; the clay mineral corresponds to 100% montmorillonite. Results show a free swelling over 150% and 1.5 MPa of swelling pressure using the oedometer test. To study the stabilizing effect of CLS, five soil-polymer mixtures (10%, 7%, 5%, 3%, and 0% of CLS by mass) were studied, evaluating physic-chemical properties, free swelling, swelling pressure, hydraulic conductivity and water retention. As it is shown in Figure 1 and Figure 2, using CLS as stabilizer the free swelling of CRclay were significantly reduced and this reduction was higher as higher was the percentage of additive, but 7% and 10% of CLS produced almost the same effect in both swelling pressure and free swelling.

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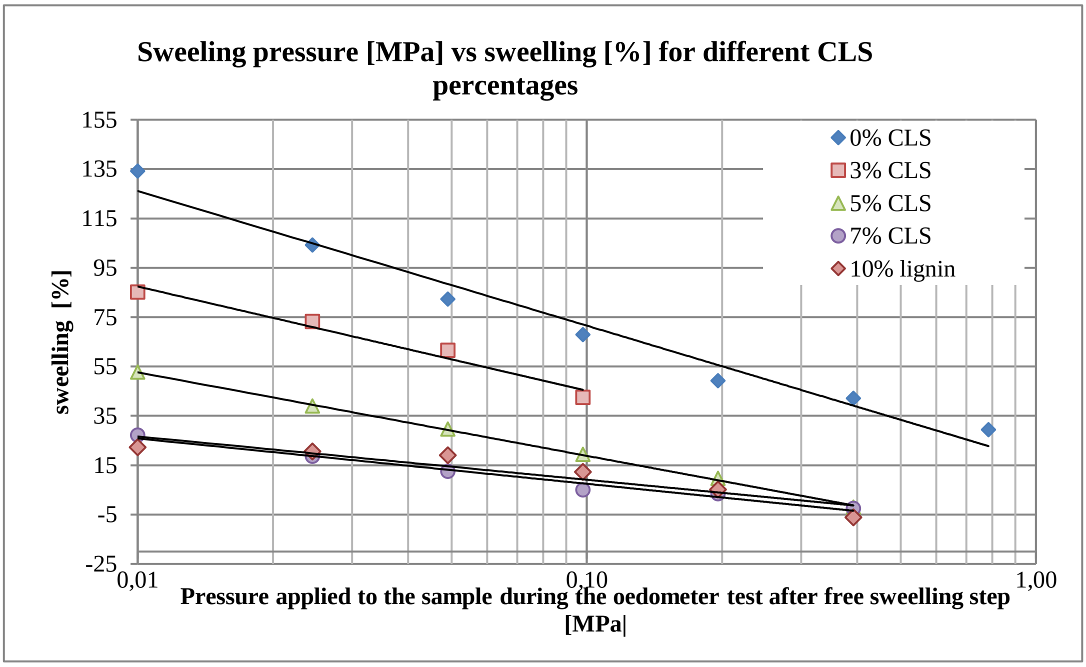

Figure 1: *Swelling pressure vs CLS percentage, for different percentages of mixture CRclay-CLS, tested one day after molded*

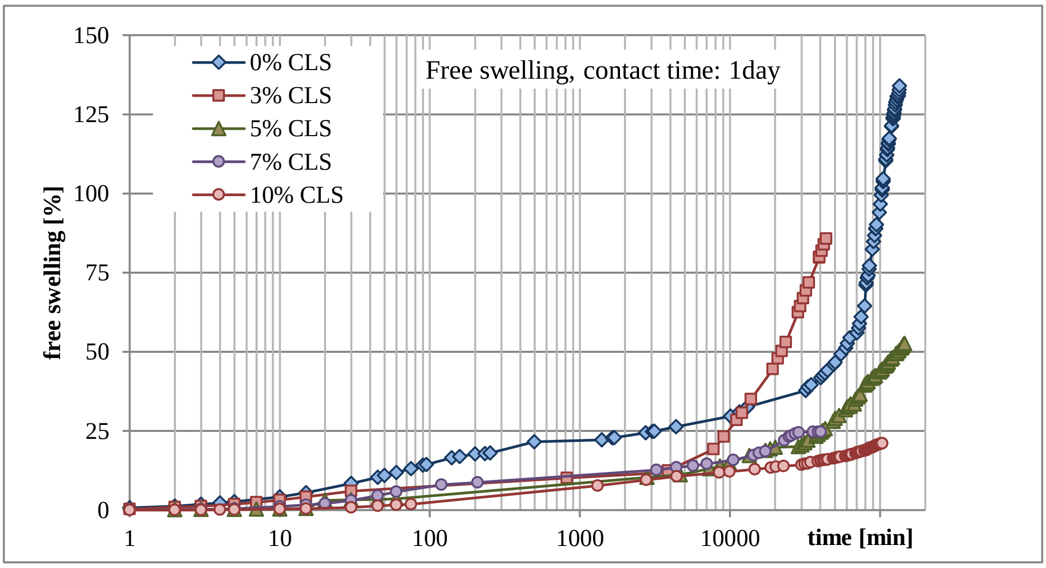

Figure 2: *Free swelling vs time, for a mixture (CRclay-CLS) at different percentages, tested one day after molded*

Mechanical evolution along proportional strain paths and relations to critical state concept

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Keywords: critical state, proportional loading path, homogeneous domain, granular materials, DEM simulation

Abstract

Critical state (CS) is a key concept in Critical State Soil Mechanics (CSSM) [1, 2]. It relates to a stationary state where stress and volume tend to be constant under continuous shear strain. The drained triaxial test is one of the most common loading paths used to observe the critical state phenomenon. In drained tests, samples are controlled by increasing axial incremental strain and constant lateral confining pressure. Volumetric strain and deviatoric stress responses are recorded according to this loading control. This particular type of control allows the existence of stationary states in volume and stress (the so-called critical state). Conversely, under proportional strain loading conditions, the volumetric strain is completely controlled and no longer a response variable. Except for the particular case of undrained triaxial test, the continuous change of volume prevents to observe stationary states in volume and stress along proportional strain paths.

In this study, we revisit the definition of critical state of granular materials with respect to different loading paths. A series of quasi-2D[4] drained biaxial tests are simulated under different initial pressures and densities, and three dilatant proportional biaxial tests in dense samples are computed by imposing $\mathrm{d}\varepsilon_1 = \lambda \mathrm{d}\varepsilon_2$ ($\lambda = -1.2, -1.3, -1.4$) for the two principal strain directions. The evolution of deviatoric stress q, pressure p and void ratio e^* in homogeneous domain (i.e. the shear band area in dense samples and the whole area in loose samples) [3] are shown in Fig.1 and Fig.2. Along the dilatant proportional loading paths, we show that the deviatoric stress experiences a non-monotonic evolution before eventually approaching zero. Irrespective of the dilatant rate characterized by λ, the variables (p, q, e^*) evolve along similar values after the strain level becomes sufficiently large to erase the material memory. When comparing the results from drained and proportional strain paths, it is interesting to find that the convergent curves of three proportional tests in both p-q and p-e^* spaces all coincide with a conceptual line gathering all the critical states obtained from drained tests. In other words, the Critical State Line (CSL) commonly defined from drained

[4] i.e. 3D simulations with a single layer of spherical particles.

loading paths acts as an attractor for the evolution of (p, q, e^*) for dilatant proportional loading paths.

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Figures

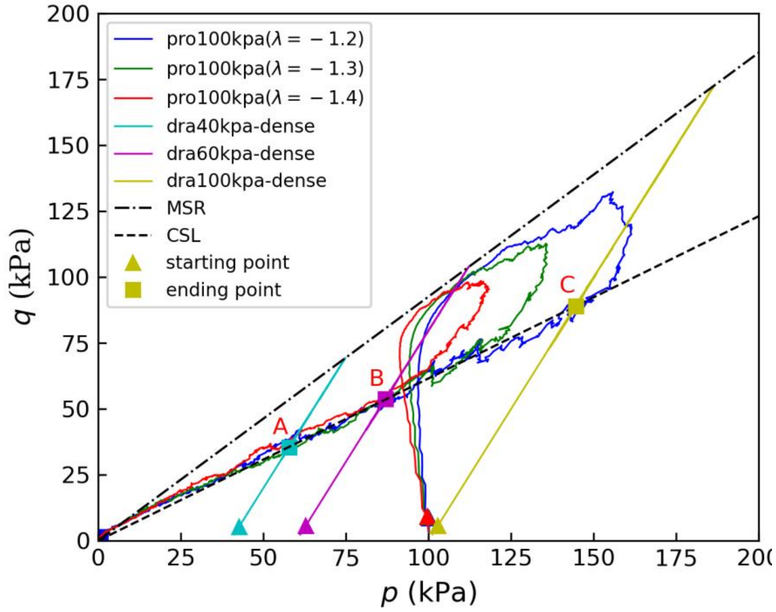
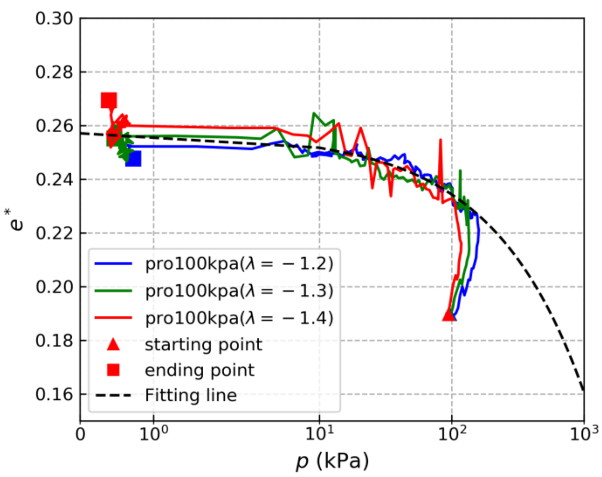
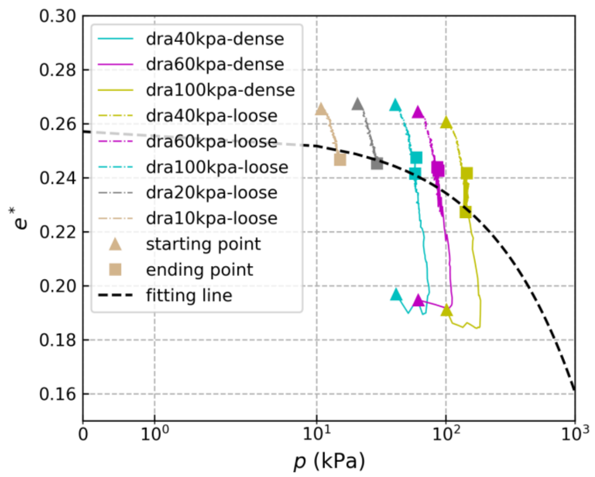


Figure 1: *Stress paths of drained tests and proportional tests. The starting and final points are marked by triangles and squares respectively. CSL refers to critical state line and MSR refers to maximum stress ratio line.*



(a) Proportional strain biaxial tests



(b) Drained biaxial tests

Figure 2: *The evolution of void ratio respect to pressure p in (a) proportional strain biaxial tests and (b) drained biaxial tests. The three proportional tests merge on a master curve that is shown in the form of a dashed logarithmic fit. The label e* refers to void ratio in homogeneous area (shear band area in dense samples and the whole area in loose samples).*

Hydro-mechanical modelling of infiltration test to study the behaviour of binary bentonite mixtures

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Keywords: infiltration column, bentonite mixture, hydro-mechanical modelling

Abstract

Binary mixtures of high-density MX80 bentonite pellets (80% mass ratio at a dry density ρ_d=2.0 Mg/m^3) and powder (ρ_d=1.1 Mg/m^3) are currently proposed as engineered barrier system for the long-term disposal of radioactive wastes [1]. These mixtures once installed in vertical sealing systems VSS at ρ_d=1.49 Mg/m^3 will undergo coupled hydro-mechanical and gas loadings. A fully instrumented vertical infiltration column – 100 mm diameter and 350 mm high with pressure transducers, total stress and relative humidity sensors – has been recently developed using independent fast infiltration systems on top and slow infiltration rates at the lateral boundaries to mimic the peculiar saturation of the VSS. Figure 1 shows the experimental setup with water pressure volume controllers PVC and an independent air pressure system at the bottom boundary to study the air transport properties at different hydration stages. A 2D plane-strain numerical model based on the discretisation of pellets and powder using Code_Bright FEM [2] has been used to gain insight into the coupled hydro-mechanical response of this multi-porosity material upon hydration. The hydro-mechanical properties have been studied for both pellets and powder materials, focusing on the water retention properties, water permeability, compressibility on loading and on suction changes, as well as on the swelling pressure properties [3]. Figure 2 presents the spatial and time evolution of the degree of saturation of the numerical model. Local responses have been particularly analysed: water mass transfer between powder and pellets, evolution of local degrees of saturation and porosities (inside pellets and powder), deformed shape of the pellets, and mean stress evolution in pellet and powder domains. The swelling pressure response is complex as the material is heterogeneous at least during the initial stages of hydration. The model allows observing that the mixture tends towards a homogeneous structure of porosity (around 0.43) as the pellets expand and compress the highly deformable clay powder. Figure 3 shows an example of these evolutions of porosity (mid-height of column) for both pellet and powder materials.

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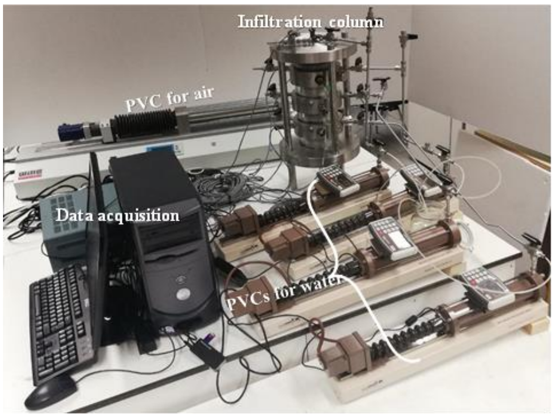

Figure 1*: Infiltration column during the hydration process. Auxiliary devices for water/air injection and data acquisition system.*

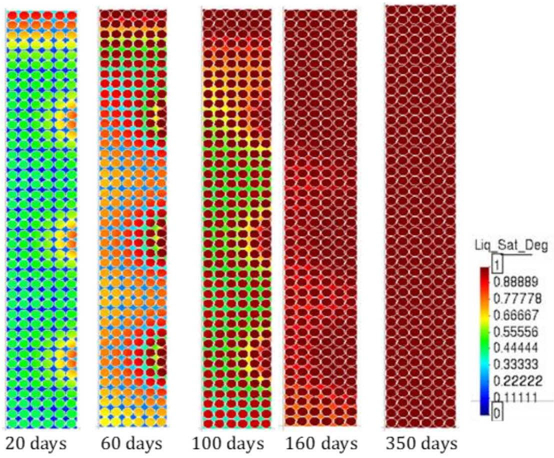

Figure 2: *Spatial distribution of degree of saturation at different elapsed times (pellets and powder materials). 2D plane-strain model with symmetry at the left. Top and lateral water injection boundary conditions*

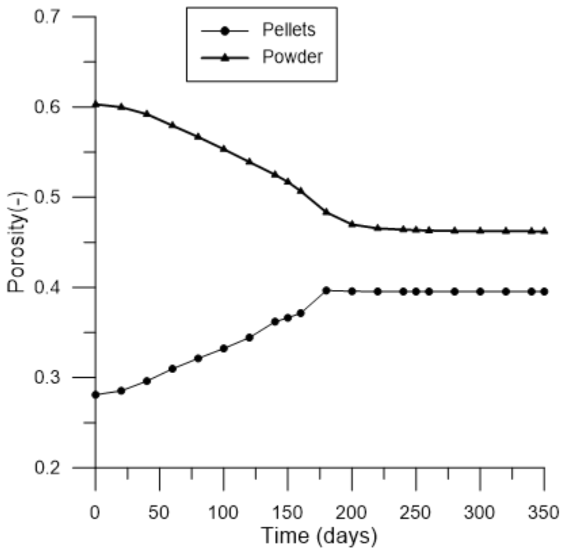

Figure 3: *Time evolution of porosity (mid-height of column) during saturation for both pellet and powder materials.*

Numerical study on mitigation and monitoring of contaminant transport across cement-bentonite cutoff walls

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Keywords: cutoff walls, cement-bentonite, contaminant transport, pollutant mitigation, monitoring

Abstract

Cutoff walls are widespread solutions for the confinement of contaminated areas, due to their capability in limiting the transport of pollutants in the subsoil. These barriers are generally constituted by cement-bentonite mixtures, with the aim of providing low hydraulic conductivity, low hydrodynamic dispersion and long term durability. However, the aggressive chemical environment to which walls are subjected may cause the degradation of the transport properties of the mixture. Assessment of confinement performance is thus crucial issue in cut off wall design. The use of dedicated devices cast in place inside the wall when the mixture is still fluid proved particularly suitable to intercept and analyse the fluids flowing through the barrier. In this research, the results of a numerical study are presented, with the goal of suggesting design criteria for devices. Besides the mitigation and retardation role played by the devices, their potential use for monitoring purposes is also highlighted, with the goal of providing an estimate of the transport property of the cement-bentonite mixture at the site scale.

The activity discussed is part of the public administration agreement between Politecnico di Milano - Department of Civil and Environmental Engineering and the Italian Ministry of Economic Development, Direzione Generale per la Sicurezza anche Ambientale delle Attività Minerarie ed Energetiche – Ufficio Nazionale Minerario per gli Idrocarburi e le Georisorse – Programme Clypea

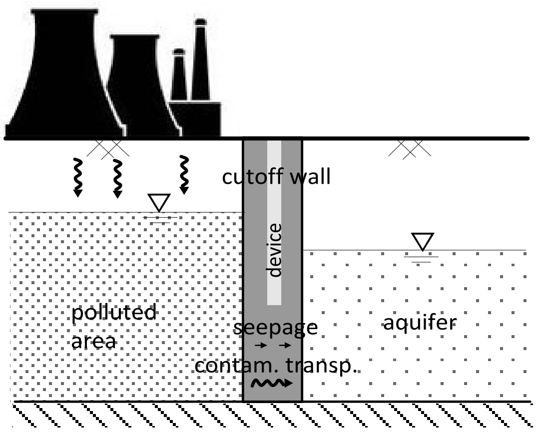

Figure 1 : *Representation of a cutoff wall confining contaminated areas.*

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