ALERT Geomaterials

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Editor: Nadia Benahmed

(IRSTEA, Aix-en-Provence – France)

ALERT Geomaterials

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Dear colleagues,

We are pleased to welcome you to Aussois and our 28th 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. Presentation of recent advances offers 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.

Table of contents

On the compaction of crushable 3D grains

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Keywords: Discrete element method, contact dynamics, fragmentation, crushing, compaction

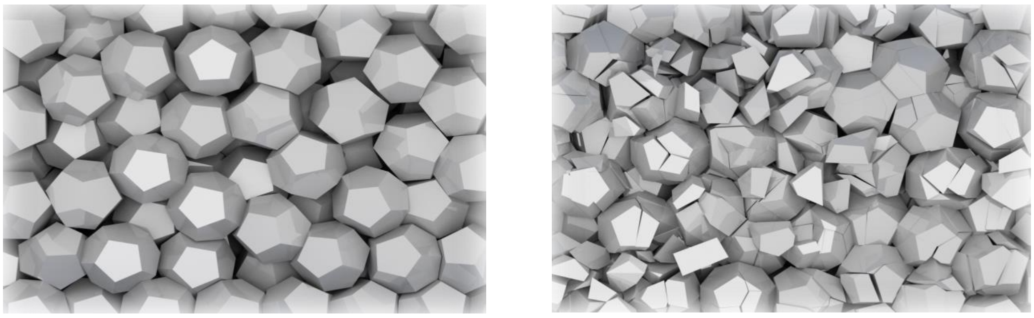
Abstract

The effect of grain fragmentation on the behavior of granular materials is of both fundamental and practical interest in applications involving powders, soils and rocks. An assessment of the impact of fragmentation on the mechanical response is difficult to access from experiments. For this reason, numerical approaches have been extensively used to address this problem. In the framework of discrete element modeling, the simulations have typically used cohesive aggregates of spherical particles to model crushable grains. However, these methods are not capable to reproduce the complexity of shapes and sizes of fragments.

We present a 3D approach to grain fragmentation named bonded-cell model (BCM). By creating aggregates via a 3D Voronoï tessellation, we can create grains in which successive breaking reproduce polyhedral fragments. The interactions between cells of aggregates are governed by a set of bonding parameters at face-face contacts between cells and frictional contacts between aggregates.

We analyze the effects of cell geometry (size and irregularity) and bonding parameters on the strength of the grains compressed between platens. We show that the compressive strength of the grains is a nonlinear function of the bonding parameters. We investigate the compaction of assemblies of crushable grains under uniaxial compression (see Fig. 1) and we analyze the evolution of the fragment size and shapes distribution, load-density relation, and the microstructure during compaction.

Figures



(a) **(b)**

Figure 1 : *Snapshots of (a) an intact, and (b) a fragmented sample after performing a uniaxial compression test.*

Fragmentation of grains under impact

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Keywords: Granular Materials, Breakage, Contact Dynamics method, Fragmentation, Voronoï cell.

Abstract

Many industrial granular processes involve desired or undesired fragmentation of grains. However, despite experimental measurements and numerical modelling approaches, the mechanisms of single grain fragmentation and its effects on the behaviour of granular materials are still poorly understood. In this work, we investigate the fracture and fragmentation of a single grain due to impact at low energies, using three dimensional DEM simulations by means of the contact dynamics method. The grains are assumed to be perfectly rigid but modelled as an assembly of glued polyhedral Voronoï cells. The strength of the glue represents the internal cohesion of the grain along normal and tangential directions. The numerical method allows us to calculate the forces and torques at the interface zones between cells. The inter-cell joints can open either in tension (mode 1) or by slippage (mode 2) when the fracture strength is reached. A series of simulations for a range of different values of parameters (number of cells, fracture strength, impact velocity) were performed. The efficiency of the process has been defined as the ratio between the energy liberated by the fracture and the kinetic energy at the impact. It was found that the efficiency increases with the number of cells. Also, the process efficiency is inversely proportional to the internal cohesion. Finally, an impact velocity that maximizes the efficiency have been found at 0.08 m/s.

Figures

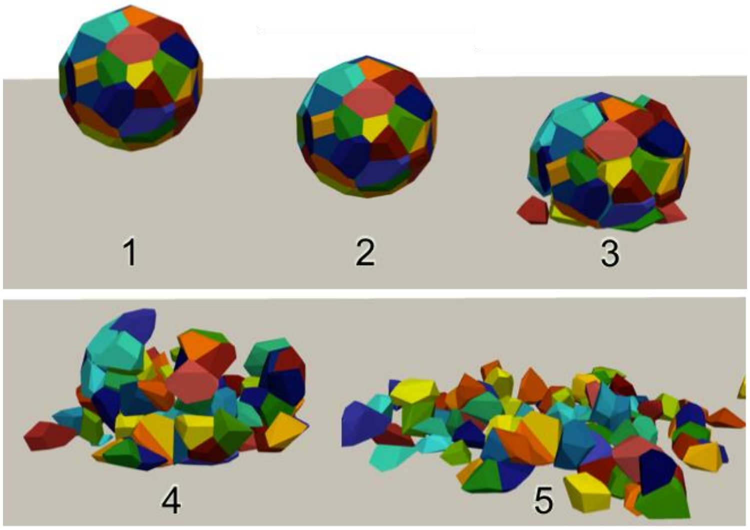

Figure 1 : *Snapshots of a single particle falling on a rigid plane and breaking into pieces. The simulations were performed by means of the contact dynamics method with particles modeled as bonded aggregates of rigid cells.*

Mechanical Earth Modelling to Predict Reservoir Sand Failure

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Keywords: Petroleum, Sand Production, Mechanical Earth Model

Abstract

Mechanical Earth Modelling (MEM) is a valuable tool to understanding the subsurface environment by allowing the envisionment of stress and strain distributions across reservoir structures. In this work we present the results of a coupled numerical simulator, REDBACK, when it is applied to dynamic, four-dimensional (4D), reservoir scale simulations in the Oil Search operated field of Usano (Figure 1). With the MEM's integration of solid and fluid mechanics within porous media, simulating the evolution of stress and strain in the reservoir allows optimal field development strategies that reduce sand production to be formulated. In the following study, the resultant model allows predictions ranging from spatial to time-dependent risks under pre-determined operational scenarios. By emulating the compressive tectonic environment that the field experiences, and simulating pressure depletion and replenishment since beginning of operations, identification of critical wells, compartments and layers can be made and greater focus can be applied to develop a more targeted production optimisation strategy as the field approaches end of life.

Usano is a mature oil field in Papua New Guinea that has experienced a number of issues with sand production, resulting in production constraints that impact the amount of oil recoverable from the field. With the aid of a Mechanical Earth Model (MEM), longer-term strategies can be implemented to ensure longevity of the field by devising and adhering to appropriate operating parameters that can be inferred from the model. Ultimately, the MEM will be able to optimize production from the field as it experiences pressure depletion along with increasing gas velocities and water cut, all of which are symptoms of field maturation.

The project aims to model the field-wide stress distribution of Usano's three main reservoir layers by simulating the impacts of production, injection, geological features and tectonic loading on the layered structure (Figure 2). From the model, critical wells where the risk of sand production is significant can be identified. Subsequently, the study will consider the sand production risk as a function of the forecasted depletion of the reservoir under tectonic compression. Through this approach, the layers and locations within the field that will attribute to higher risk of sand production can also be determined (Figure 3). These results will enable targeted long-term production optimization strategies in conjunction with a qualitative assessment of the time at which the risk of sand production becomes a critical issue under varying operating scenarios.

In order to reach these conclusions, field data was collected, screened and inputted into REDBACK, which allows modelling of elasto-plastic materials under stress. Through upscaling and calibration procedures, the model was adjusted so that it is closely representative of the real field responses. To provide the required recommendations, we run simulations and sensitivity analyses that allow us to draw conclusions that address the

aforementioned objectives. In addition to the current field scale operational conclusions drawn from the MEM, the approach can also assist in more engineering-scale problems, such as the understanding of wellbore collapse through borehole stability, and fault activation.

Figures

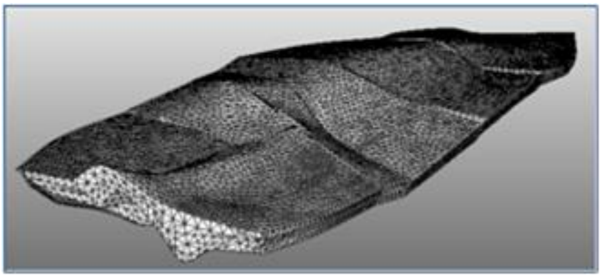

Figure 1: *Resultant finite element mesh generated from Petrel reservoir model prior to REDBACK simulation*

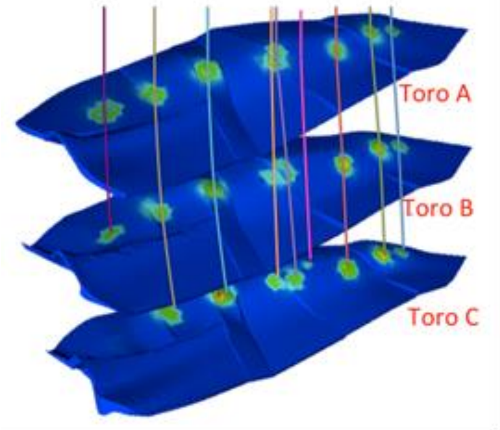

Figure 2: *Visualisation of three constituent reservoir layers and nine wellbore locations where pressure depletion and injection are imposed in the simulation*

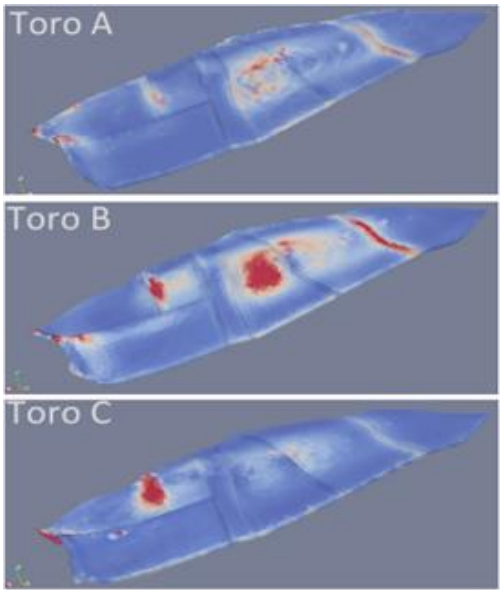

Figure 3: *Risk map (blue – low; red – high) output from REDBACK simulation of tectonic field compression for each constituent layer of the reservoir*

Agglomeration process of wet granular material: effects of size distribution and Froude number

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Keywords: size ratio, capillary bridge, molecular dynamics, rotating drum, iron ore

Abstract

Granulation or agglomeration process of solid particles was applied in a wide range of the industrial fields including steel making [1], pharmaceutical industry [2] and and powder metallurgy [3]. In the iron-making industry, agglomeration process is one of the most critical stages in the sintering process. An agglomeration drum is a rotating, cylindrical dum which utilizes a tumble and grow action to form spherical granules in the presence of a liquid binder. More specifically, material and liquid binder are fed into the drum. As the drum rotates, material fines get tacky in the presence of the binder, and pick up more fines as they contact with other wet particles. There are various parameters which effect on the granule formation and development including initial particle size distribution, raw material properties, filling level of particles in the drum, the amount and viscosity of the binding liquid, ratio between drum diameter and particle size, the particle size, and rotational speed of drum.

In this work, we simulate the agglomeration process of solid grains composed of spherical particles in the presence of a viscous liquid by means of molecular dynamics (MD) simulations [4]. We are mostly interested in application to iron ore granulation in a rotary drum agglomerator. We are also interested in understanding the agglomeration process at the particle scale like accretion, erosion, redistribution of binding liquid. And investigation the effects of control parameters such as flow regime (rotational speed) which defined by Froude number, and initial size distribution. The presence of liquid binder is modeled as a capillary attraction force as well as liquid viscous force. The capillary cohesion force is simulated as an attraction force at the contact between particles and expressed as an explicit function of the gap, liquid volume, surface tension and the particle-liquid-gas contact angle [5]. During the rotation, the dry particles flow around the spherical granule. This state continuously occurs the accretion and erosion phenomenon between dry and wet particle. We find that the granule growth increases exponentially with the number of rotations of drum. This growth rate is proportional to the increase of size ratio. However, the changing of different values of Froude number between rolling and cascading regime cannot dominate the granule growth.

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Figure

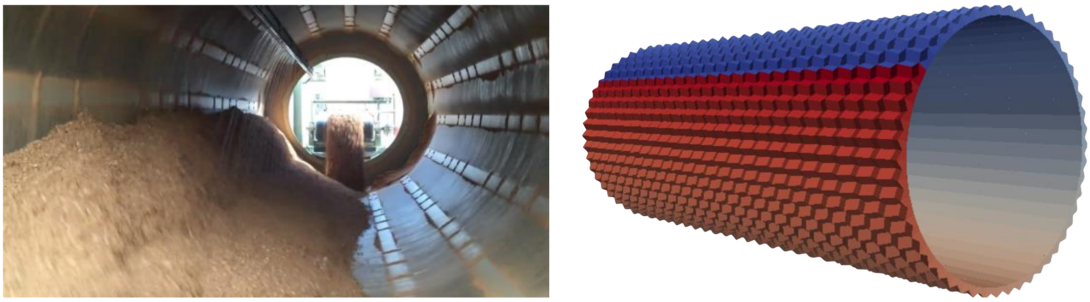

Figure 1: *Industrial and numerical granulation drum.*

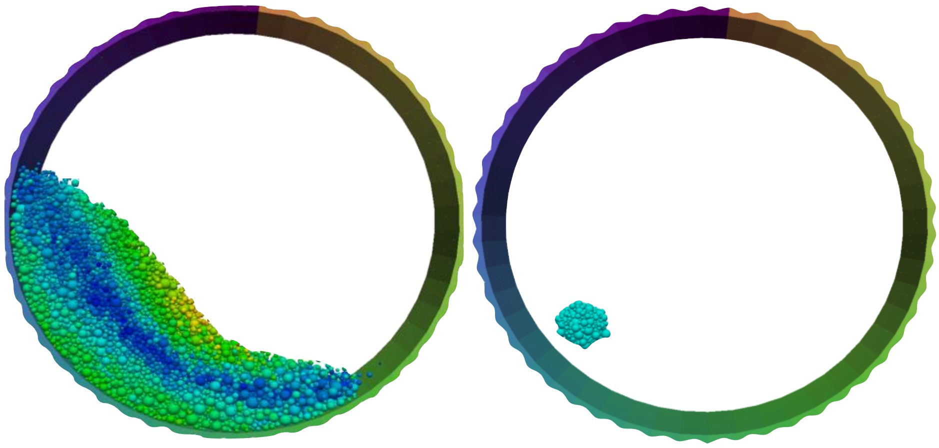

Figure 2: *Snapshots represent the agglomeration process of solid particles in a horizontal rotating drum, granular flow on the left and granule is formed and it grows with the number of rotations of drum on the right.*

Evaluation of coarse-grained soils liquefaction potential by means of an index test

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Keywords: liquefaction potential, index test, pore water pressure

Abstract

Laboratory investigations of liquefaction have been done mostly by means of an undrained cyclic triaxial test, which is time-consuming. The objective of this research is to evaluate the liquefaction potential of coarse-grained soils using a new method (index test) developed at the Institute of Geotechnical Engineering at the TU Dresden. The newly developed method enables the investigation of the pore water pressure build-up within a much shorter time period (ca. 30 minutes). During the test, a loose cylindrical soil sample is installed in a membrane envelope and slowly saturated from the bottom to the top of the specimen. Initial effective stresses are increased by applying suction to the sample. Finally, the sample is cyclically loaded in undrained conditions, with defined frequency and loading displacement. Loading is applied onto the top cap of the specimen in horizontal direction. During the test, the build-up of pore water pressure is registered and evaluated.

First tests have been performed on a soil with granulometric properties corresponding to Sand 2 (narrow grain size distribution curve, coarse sand), depicted in Figure 1. Soil samples with different initial relative densities were investigated in order to show the influence of soil density on the liquefaction potential. Initial state in tests was defined as:

- total stress: σ = 0 kPa (relative atmospheric pressure)
- pore water pressure: u_0 = -22 kPa (suction)
- effective stress: $\sigma'_0 = \sigma - u_0$ = 22 kPa
- sample geometry: D = 50 mm, H = 100 mm

Loading conditions were:

- frequency: f = 5 Hz
- displacement: A = 2 mm

In performed tests, the loading stop criterion was set to be $u \approx -6$ kPa and number of cycles needed to reach this value was measured. The obtained results are presented in Figure 2, where is clearly shown that samples with higher initial relative densities need to undergo more loading cycles in order to loose stiffness and liquefy ($u \rightarrow 0$, $\sigma' \rightarrow 0$).

Additional tests have been performed on a soil with broad grain size distribution curve (Sand 1, medium sand) to investigate the influence of different granulometric properties on the liquefaction potential. Samples of both soils were installed with approximately same initial relative densities ($I_{D0,S1}$=0.16, $I_{D0,S2}$=0.19) and were tested under above mentioned conditions. Results presented in Figure 3 show that coarse sand liquefies much faster than medium sand, under same initial and loading conditions.

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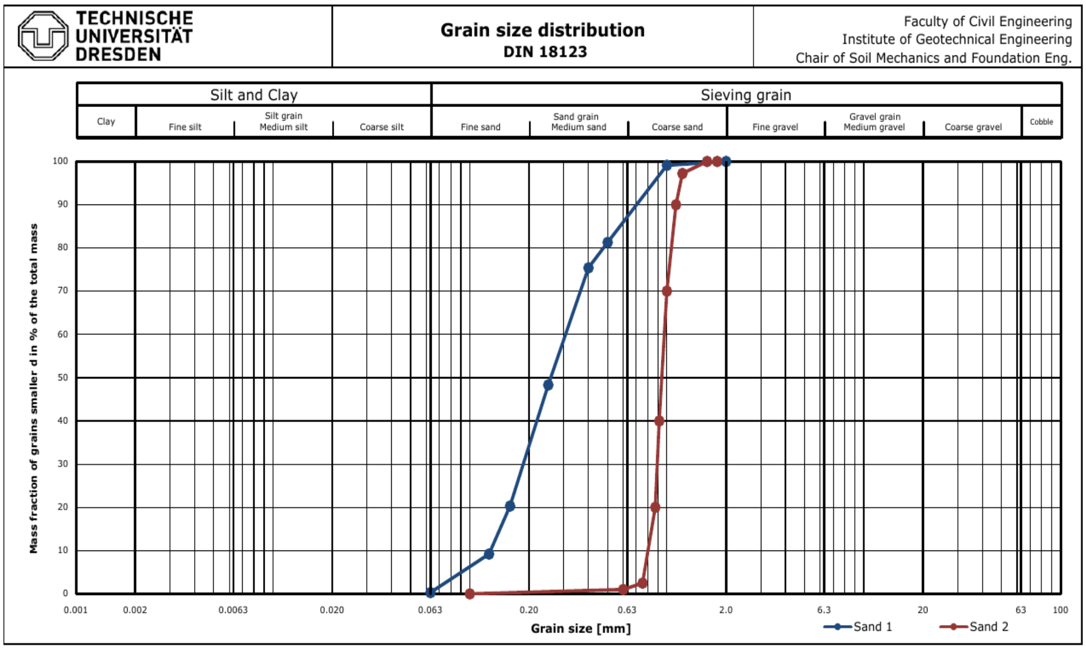

Figure 1 : *Grain size distribution curves of tested sands*

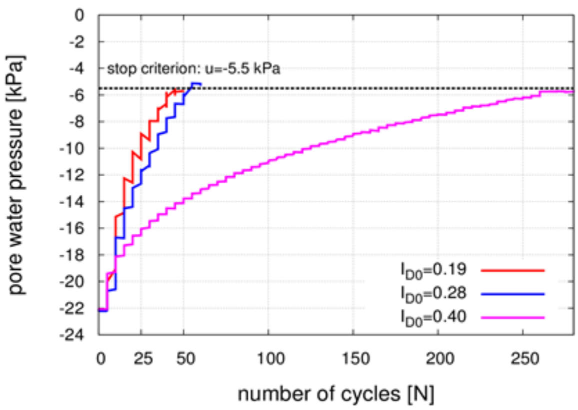

Figure 2 : *Pore water pressure build-up during the tests on Sand 2 with different initial relative densities*

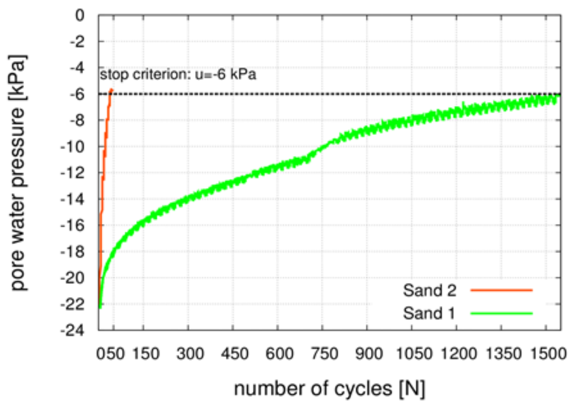

Figure 3 : *Pore water pressure build-up during the tests on sands with different granulometric properties*

Applications of Barodesy

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Keywords: Barodesy, constitutive modeling, FEM, SPARC, rotation of principal stress

Abstract

Barodesy, introduced by Kolymbas (2009), is a constitutive model which exhibits similarities to hypoplasticity (Kolymbas & Medicus, 2016). It is written as a single tensorial equation, i.e. the stress rate is expressed as a function of stress, stretching and void ratio. Barodesy is based on proportional paths and the asymptotic behaviour of soil (Goldscheider, 1967). It comprises fundamental characteristics of soil behaviour, such as critical states, asymptotic states, barotropy, pyknotropy and a stress-dilatancy relation. Standard element tests are compared with experimental data of different clay types in Medicus (2015), Medicus et al. (2016) and Medicus & Fellin (2017).

The purpose of the poster is to show applications of barodesy:

- Barodesy is able to predict the rotation of principal stress and strain axes in simple shear tests, as compared with DEM simulations by Thornton and Zhang (2006), see Figure 1.
- FEM slope stability calculations based on a strength reduction method (Schneider-Muntau et al., 2017a), see Figure 2.
- Simulations of shear bands with the mesh-free code Soft PARticle Code (SPARC) and FEM simulations (Schneider-Muntau et al., 2017b), see Figure 3.

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Figures

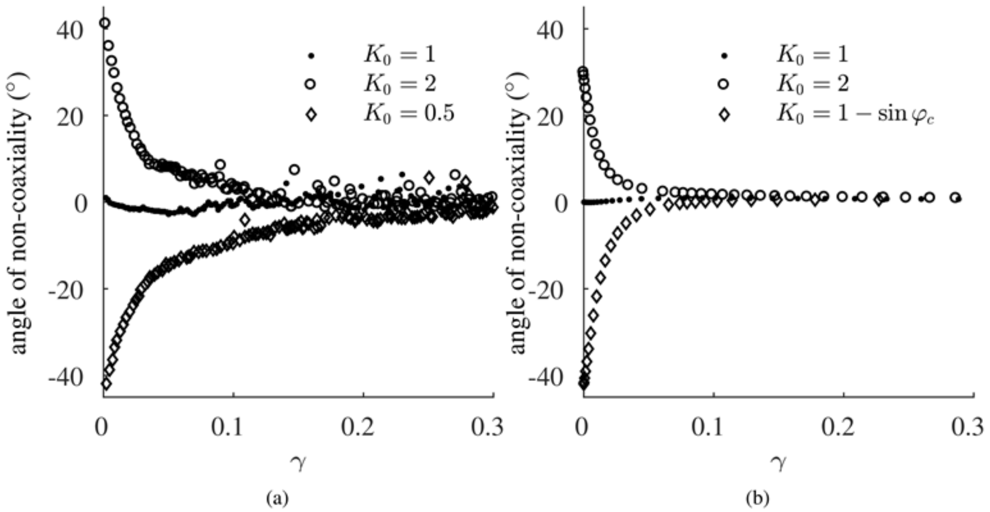

Figure 1: *Evolution of the angle of non-coaxiality in a simple shear test with different initial K0 values: (a) DEM simulations by Thornton and Zhang (2006) (b) Weald Clay with eini=0.68 simulated with barodesy (Medicus & Fellin, 2017).*

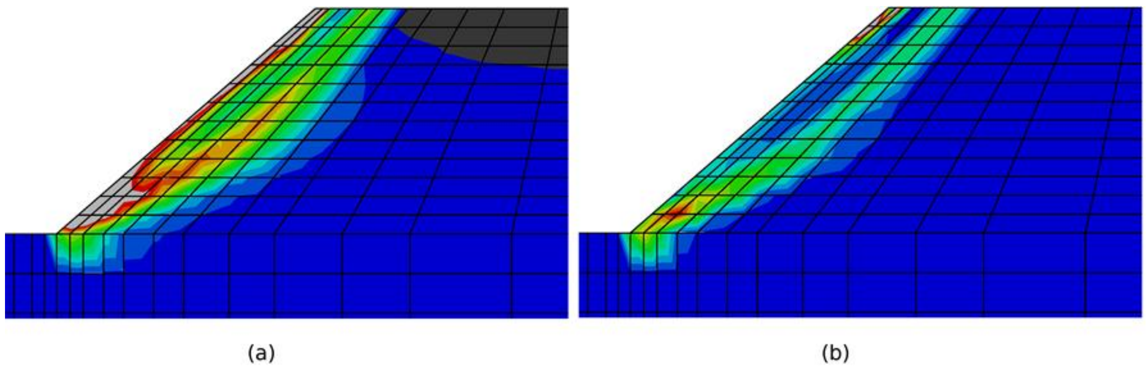

Figure 2: *FEM analyses of Weald clay (Schneider-Muntau et al., 2017a): (a) second strain invariant γs, with values from 0.00 (blue) to 1.00 (red) (b) void ratio with values from 0.49 (blue) to 0.68 (red).*

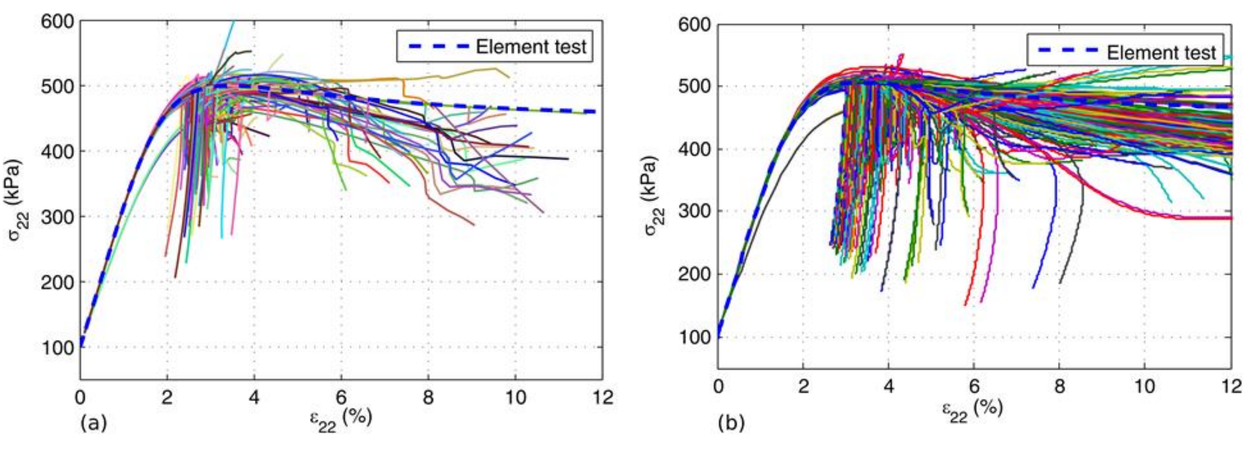

Figure 3: *Biaxial test simulations of Dresden clay (Schneider-Muntau et al., 2017b): Stress-strain curves of all particles in simulations with an imperfection implemented in SPARC (a) and all elements in FE (b). The dashed blue line shows the simulation of a single element test.*

Volumetric changes induced by principal stress rotation modelled with different constitutive relations

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Keywords: principal stress rotation, constitutive models, Hypoplasticity, SANISAND, Barodesy

Abstract

The rotation of the principal stress direction is an advanced stress path, which can be realised with different test apparatus. In this poster the results from a 1γ2ε apparatus (Fig. 1, Joer et al., 1998) and a hollow cylinder apparatus (Tong et al., 2010) are compared with numerical simulations with several constitutive models for granular media. The used constitutive models are Hardening Soil with small-strain stiffness (Benz, 2007), SANISAND (Taiebat and Dafalias, 2008) as representative elastoplastic models and Hypoplasticity (Kolymbas, 1985, 1991) in the formulation of von Wolffersdoff (1996) with and without the intergranular strain concept (Niemunis and Herle, 1997) and Barodesy (Kolymbas, 2015).

From the numerical results (Fig. 3) it can be seen, that models formulated in principal stresses (such as Hardening Soil) are not able to reproduce the contractive volumetric behaviour observed in the experiments (Fig. 2). The other investigated models can reproduce the volumetric response qualitatively. However, tests can be found, where the results of the numerical calculations and the experiments differ fundamentally (e.g. the experiment shows contractant behaviour and the numerical calculation shows dilatant behaviour).

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Figures

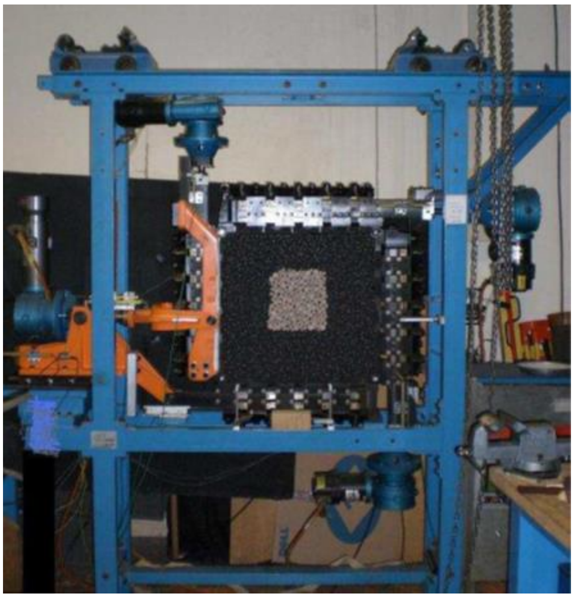

Figure 1 : *1γ2ε apparatus (Mader, 2008)*

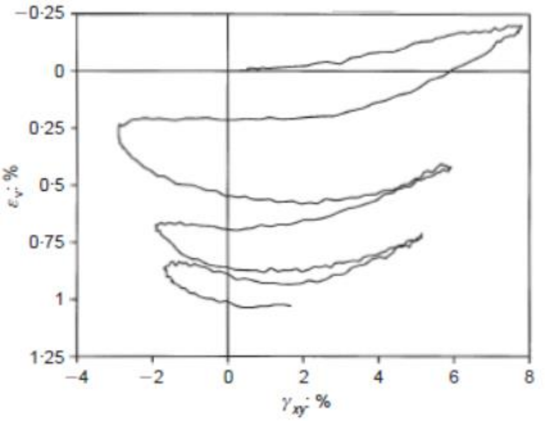

Figure 2 : *Volumetric changes due to the rotation of the principal stress axes in a 1γ2ε apparatus (Joer et al., 1998)*

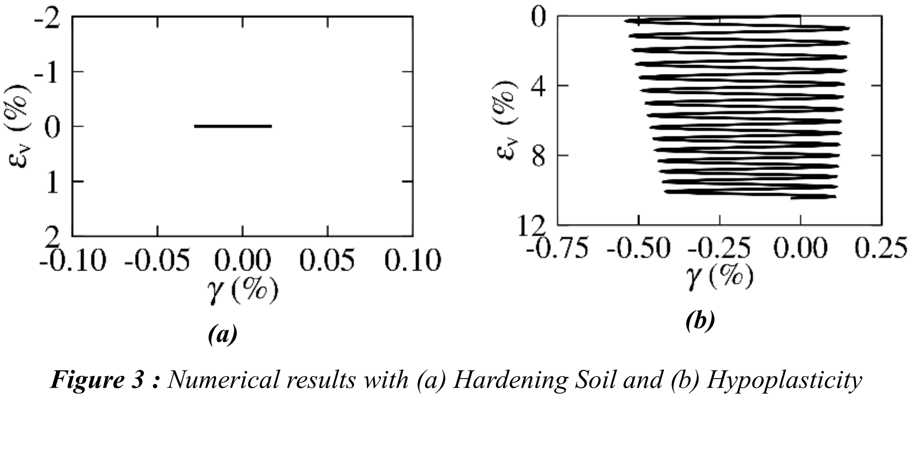

Figure 3 : *Numerical results with (a) Hardening Soil and (b) Hypoplasticity*

Modelling of the progressive failure of the sensitive landslide in Saint Monique, Quebec

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Keywords: Generalized Interpolation Material Point Method, large deformation, strain rate effect, fall cone test, sensitive clays, progressive failure of slope

Abstract

Numerical modellings of geo-mechanical problems in which large deformations are present is a challenging task. Generalized Interpolation Material Point Method (GIMP) is an advanced numerical method well suitable for such problems. This work concentrates on the modelling of the progressive slope failure, one of the typical geo-mechanical problems involving large deformation problems. Such failures are most relevant to the sensitive clays landslide in Scandinavia and Canada.

The paper describes the applications of the GIMP to model the progressive failure of a sensitive landslide in Saint Monique, Quebec. In this analysis, the Tresca constitutive model is enhanced by a strain rate effect and an undrained shear strength degradation effect. In order to validate the constitutive model and the numerical technique, we first replicated fall cone penetration tests with the strain rate effects for remoulded kaolin clays [1] and quickness tests of remoudled sensitive clays [2]. Both simulations have shown good agreements with the experiment in the large deformation regime.

To simulate the sensitive clays landslide in Saint Monique, the soil properties have been calibrated based on the recent soil investigations on-site [3]. The undrained shear strengths were determined from laboratory test (direct shear test) and the in-situ tests (vane shear test and CPTUs). The soil investigation reveals that the undrained shear strength of the normally consolidated sensitive clays on that site increase linearly with depth. The clays have the average sensitivity of 55. With this given soil properties and geometry, the landslide was classified as a spread failure (upward progressive failure). The upward progressive failure consists of two processes: (i) the propagation of a horizontal quasi-static failure surface (a shear band) and (ii) the extension and dislocation of the soil mass above the remoulded shear surface, forming horsts and grabens (see Figure 1). The numerical model shown can replicate the sensitive clays landslide. Furthermore, the research investigates the influence of the strain rate effects on the dynamic motion of the landmass and the landslide characteristics such as run-out distances.

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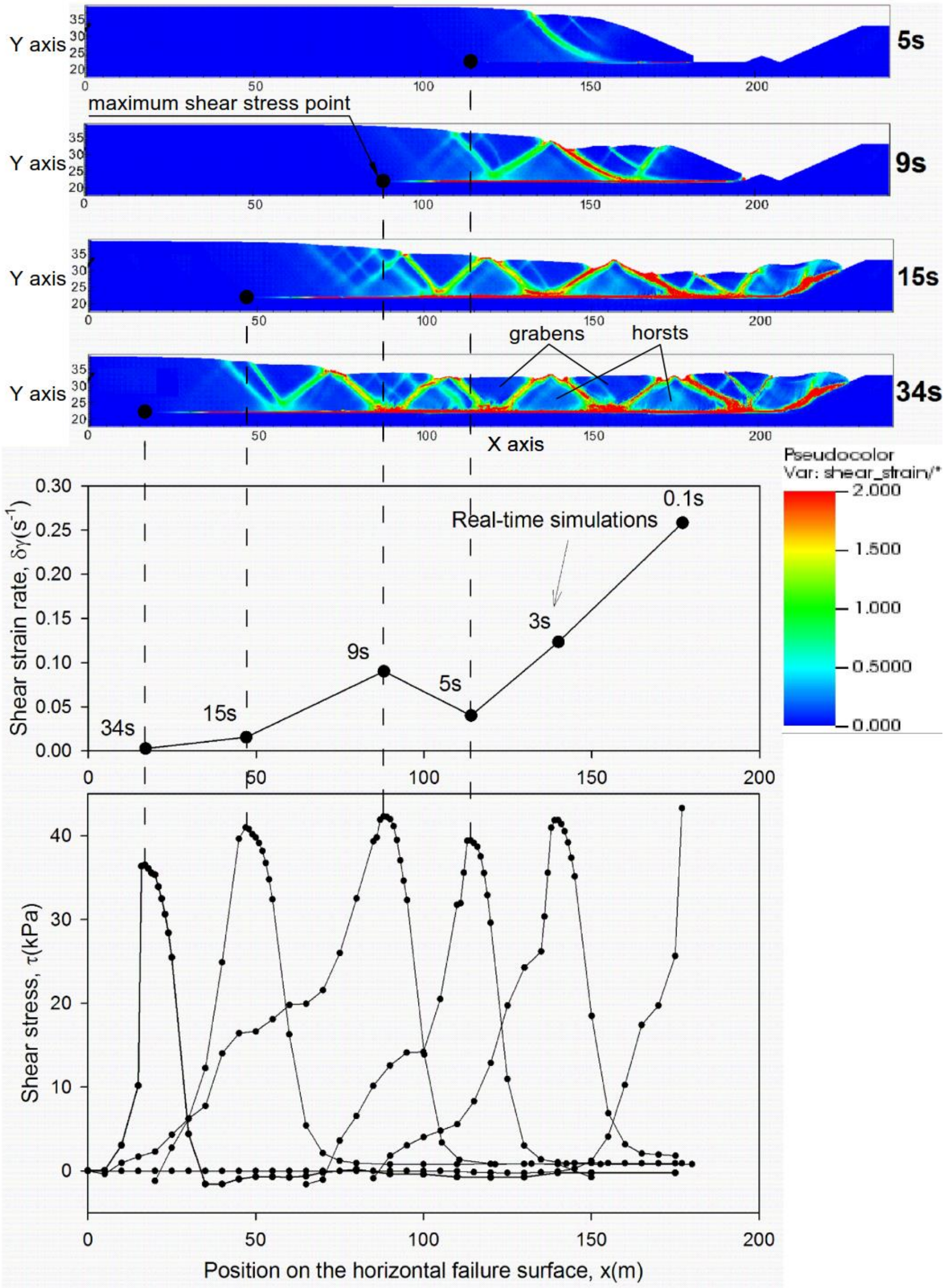

Figure 1: *Progressive failure of the sensitive landslides in Saint Monique, Quebec*

Compression Waves As Phase-Field Instabilities

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Keywords: phase-field model, Allen-Cahn equation, elastic energy, interface, compression bands, pore collapse, wave propagation, Grinfeld instability, bifurcation

Abstract

How can a constant loading of a porous medium lead to an oscillatory response? As an example, Guillard et al. demonstrated that behaviour by considering an oedometric compression of a granular medium, modelled by puffed rice [2]. A constant vertical loading creates after a certain transient time a regime of upwards propagation of compression bands nucleating at the bottom. A novel approach for geomechanics is applied to investigate this non-intuitive phenomenon. The porous medium is modelled by a phase-field model, considering the matrix and the pores as two interacting phases separated by a diffuse interface. The phases are governed by an order parameter, the concentration of the matrix phase, i.e. the solid porosity. This parameter can be seen as a smooth indicator function, equal to 1 in the matrix phase and 0 in the pore phase. Based on the prescription of the free energy of each phase, the system can be described by an Allen-Cahn-like equation, result of the momentum balance and energy balance, derived from a thorough Internal State Variable thermodynamics framework [1,3].

The oscillatory bands are modelled as pore collapse waves. It can be shown that the phase-field model asymptotically converges, as the interface layer shrinks, towards a Grinfeld instability [4]. As such, an elastic overloading of the interface leads to a structural rearrangement of the system to minimise its free energy. A stability analysis identifies the instability as a first-order bifurcation quantified by a critical loading and a critical wave number. The purpose of this study is to provide an explanation of the upward wave propagation nucleating at the bottom. Compaction bands, modelled microscopically as pore collapse solely for now, could be seen as phase-field instabilities, i.e. phase changes, namely the matrix phase taking over the pore phase.

It should be pointed out that phase-field modelling is dedicated to interfacial problems and regularises the discontinuities and instabilities usually associated, which is highly valuable for numerical simulations [5]. It is thus able to regularise pioneering models such as [6] for compaction bands - or so-called “cnoidal waves”, avoiding localised discontinuities, thanks to the diffuse interface.

This innovative phase-field modelling paves the way for predicting natural patterns formation in porous media, e.g. mineral growth, as it has been successfully applied to chemical and material sciences phenomena such as dendrite growth and precipitation. Among others, the main advantages of phase-field modelling are the diffuse interface avoiding discontinuities, no explicit tracking of the interface and multi-physics easily prescribable in the free energy. It

thus allows to model topologically complex structures such as bicontinuous structures and especially porous media.

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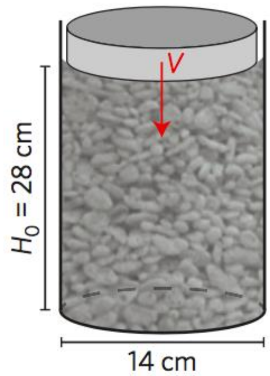

Figure 1: *Oedometric compression of puffed rice*

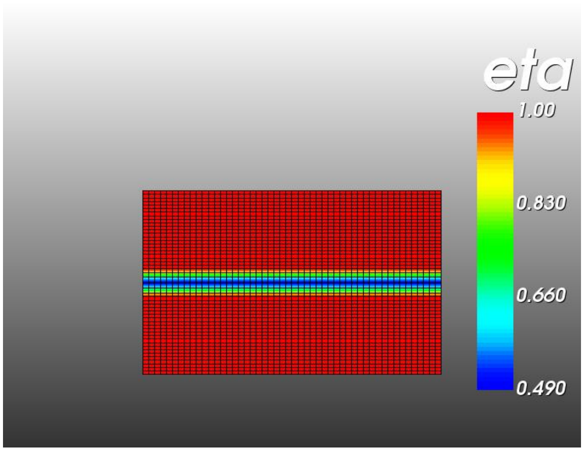

Figure 2: *Compression band*

(matrix in red, pores in blue, interface in green)

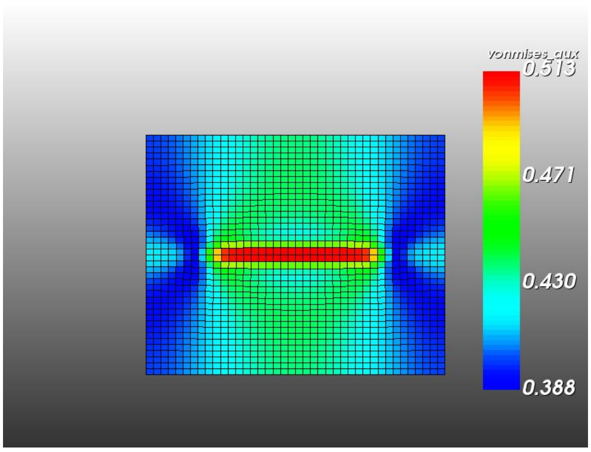

Figure 3: *Characteristic lines during pore collapse (pores in red, matrix in blue/green)*

Real scale test design of a sand flowslide by MPM slope (in)stability analysis

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Keywords: Slope stability; Material Point Method; Real scale test

Abstract

During a flowslide a large amount of granular material moves within seconds or gradually over hours. The ability to predict flowslides is an important asset for the design, construction, maintenance and safety assessment of submerged slopes; even more so in view of intensifying land use and the impact of climate change on low-lying coastal areas worldwide. However, these phenomena are not yet well understood. Submerged flowslides take place in a variety of different settings, including planes as low as 1 degree and can cause significant damage to both life and property. *Despite the variety of different movements present in submerged environment, only slides, debris flow and turbidity currents provide a substantial contribution to gravity driven sediment transport* Locat et al (2002). Flowslides are considered highly complex (multi-phase, multi-physics and multi-scale) and the use of numerical methods for the solution of these problems plays a key role for the optimization and the design of many projects.

An integrated numerical solution for the simulation of flowslides from initiation to deposition of sediments, is proposed using the Anura3D MPM software. As validation case study, the Pinken sand quarry in Belgium was chosen. Here is an overview of the analysis for instabilities in submerged sand slopes which can result in failure triggered by the rapid extraction of sand from the toe of the slope providing insight and knowledge about the causes of flowslides in Pinken.

This research project is funded by: NWO, Understanding Flow Slides in Flood Defenses (MPM-Flow), 2014 , support grant 13889, The Netherlands.

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Figures

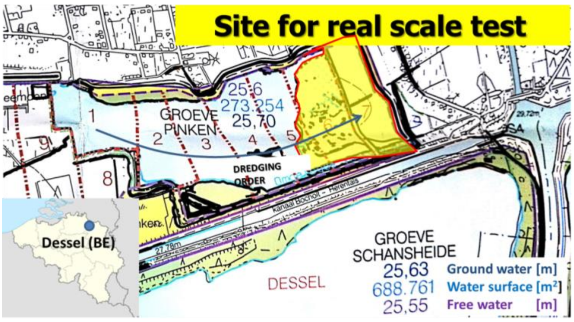

Figure 1: *Map of Pinken quarry in Dessel (BE) for dredging operations and for real scale test planning*

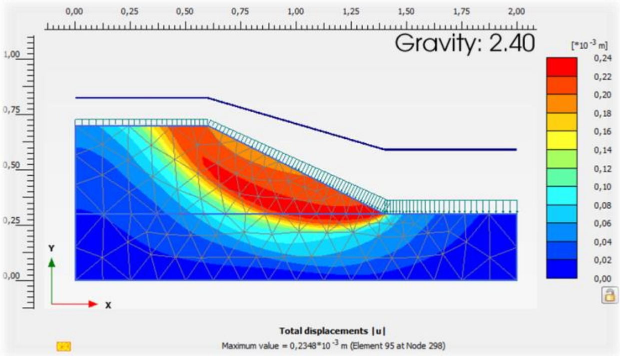

Figure 4 : *Plaxis2D (FEM) simulation with quasistatic loading*

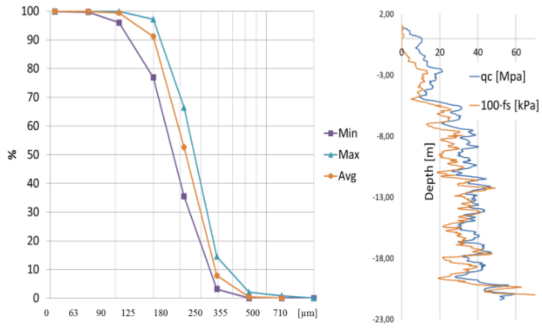

Figure 2: *Grain size distribution and CPT data set*

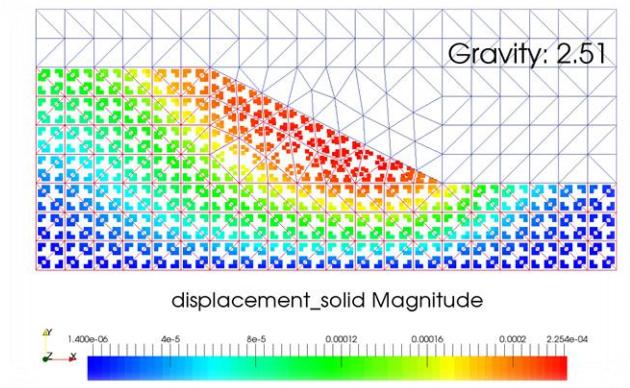

Figure 5: *Anuda3D (MPM) simulation with quasistatic loading*

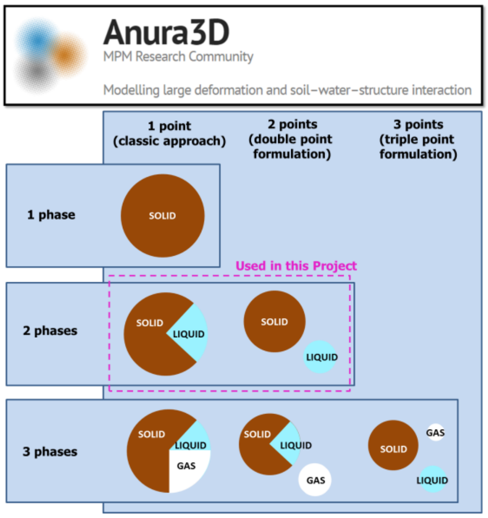

Figure 3: *Available formulations for dry, coupled and fully coupled analysis.*

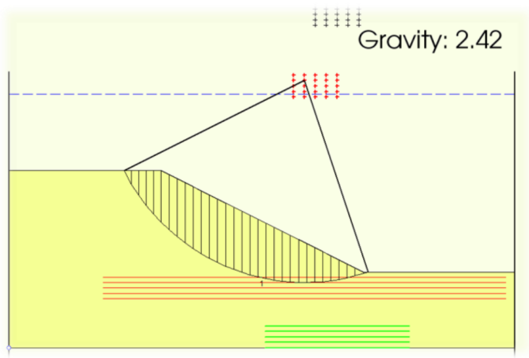

Figure 6: *Bishop's slice method for slope stability analysis by DGeoStability software*

Fluid Flow in sandstones with lab induced shear-enhanced compaction bands via High Speed Neutron Tomography

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Keywords: High Speed Neutron Tomography, lab induced Compaction Bands, fluid flow, porous sandstones

Abstract

Pure and shear-enhanced compaction bands (CBs) have been previously identified in natural high porosity outcrops [1 and 2, respectively]. The former were formed normal to the direction of the maximum compressive principal stress, while the latter were formed at 38-53^{o} relative to the maximum compression. Both deformation features are characterised by textural changes due to grain rotation, fragmentation and crushing leading to local variations in porosity and presumed permeability. Therefore, both deformation bands impact fluid flow with significant implications for a number of geo-energy applications, such as hydrocarbon production in subsurface geological reservoirs and CO_2 storage into acquirers or depleted reservoirs.

At the lab scale a range of non-destructive experimental techniques have been applied to describe primarily the mechanical response during the creation and evolution of CBs, providing understanding of the spatio-temporal evolution of their properties [3, 4]. The aim of this work is to better understand the interaction between fluid-flow and CBs. To do so, we track the fluid flow in porous sandstones, performing water imbibition tests on specimens with lab induced CBs, using High Speed Neutron Tomography (HSNT).

The advantage of using neutrons is the high contrast between the rock material and the water, due to the high absorption of neutrons by hydrogen. Neutron radiography has been previously applied to characterise fluid flow in a shear band [5, 6], whereas x-ray CT has been used during capillary imbibition tests to characterise flow in a CB [7]. Here we report the first time that in-situ HSNT is used to characterise the fluid flow front during water imbibition tests in porous media such as sandstones containing lab induced CBs.

Imbibition tests and in-situ HSNT have been performed in the CONRAD Neutron Tomography instrument at the HZB [8]. HSNT was performed acquiring the projections while the rotation stage was moving, with a constant speed, from 0° to 180° and back. The acquisition time for each of the 300 radiographies was 0.2 sec, which results in a total time of 1 min per tomography. Specimens, wrapped with Teflon tape and placed in a fluorinated membrane, were settled in a cup sealed with silicon and fixed at the rotation stage. A small

reservoir was connected to the cup through an electro-operated valve so that the supply of water to the cup could be controlled during the experiments. Both image reconstructions and flow front detection and tracking have been achieved by using in-house software (based on ASTRA libraries in the case of reconstructions).

Our results show that HSNT can successfully capture the 4D evolution of the water front during imbibition tests in porous sandstone specimens with lab induced shear-enhanced CBs. It appears that the flow front is affected by the network of these deformation features. In particular, local increase in flow speed is observed inside these bands (Fig.1). When the water front is approximately at the level of these bands, shear-enhanced CBs are visualised by HSNT, whereas when the saturation of the sample increases, this is not feasible anymore. Shear-enhanced CBs are characterised by grain fragmentation, compaction and porosity loss, as it was verified by AE monitoring during the lab experiments [4]. These textural changes presumably lead to local increase in capillary pressure, thus saturation accelerates locally. There is a good correspondence between the AE locations and the HSNT visualisation of the bands (Fig. 1).

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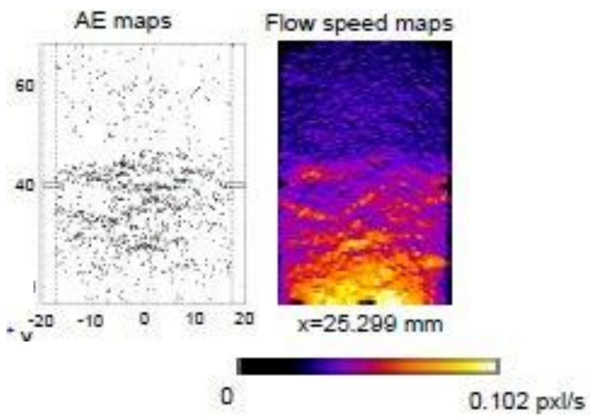

Figure 1 : *Acoustic Emission and Flow speed maps (cross-section of a sample). Yellow (flow map) indicates high speed.*

In-situ Grain-strain Mapping of Quartz Sand Using Neutron Diffraction Scanning

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Keywords: plane-strain, neutron diffraction, grain-strain

Abstract

In recent years neutron diffraction scanning has been successfully used as an experimental tool for studies on granular media under load, to infer force/stress distribution from the crystallographic (grain) strains of the material (Hall et al., 2011, Wensrich et al., 2014). The main goal of this PhD research project is the development of the neutron diffraction technique for granular geomaterials, through a specially designed plane-strain loading apparatus (Figure 1), to map spatial variations and evolutions of granular strains under loading and to investigate how forces are transmitted through the material and how this evolves with (localised) deformation.

The presented work considers a novel plane-strain biaxial experiment (Figure 1) performed on a Fontainebleau NE 34 quartz sand specimen (height: 60 mm, width: 30 mm, thickness: 20 mm, D_{50} = 210 μm) at the neutron diffractometer SALSA, at the Institut Laue-Langevin in France. Neutron diffraction scanning provided the opportunity to measure over a grid of gauge volumes the averaged “d-spacing changes” in the crystal lattices of the constituent grains (i.e., the “grain strains”) of each gauge volume of the sample, during mechanical loading and as a function of an applied boundary load. From these data, full-field 2D mappings of the grain-strain distribution evolution were acquired, as well as single d-spacing average values for each of the produced diffraction mappings (Figure 2).

The loading was realised in steps over a load-unload cycle (Figure 2) with a confining pressure of 3 MPa. At each load step the loading was paused with a fixed piston displacement while scanning diffraction measurements were made over a 2D grid of 50 points, using rows of five 2x2x2 mm^3 gauge-volumes through the thickness of the sample. The 2D diffraction mappings of the crystal strains at each load step show a spatially structured grain-strain distribution, based on the averaging of the sum of the 5 small volumes at each point of the 2D grid.

Further experiments are underway with a new optimised version of the loading device, in terms of both the experimental approach and neutron scattering. More specifically, the new apparatus incorporates simultaneous Digital Image Correlation (DIC) measurements. As a result, a multiscale characterisation of the total, “macroscopic” strain field (through DIC) and the force transmission (through neutron diffraction) in the sample will be possible. The new configuration will also involve smaller sample size and improved boundary conditions, which will lead to both higher scanning coverage of the sample and shorter scanning time for each grid point.

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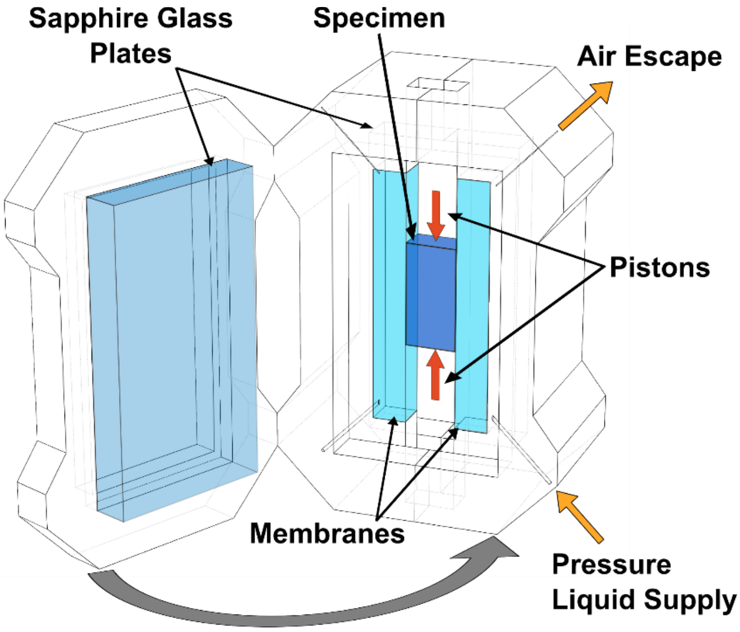

Figure 1 : *Schematic of the plane-strain loading apparatus.*

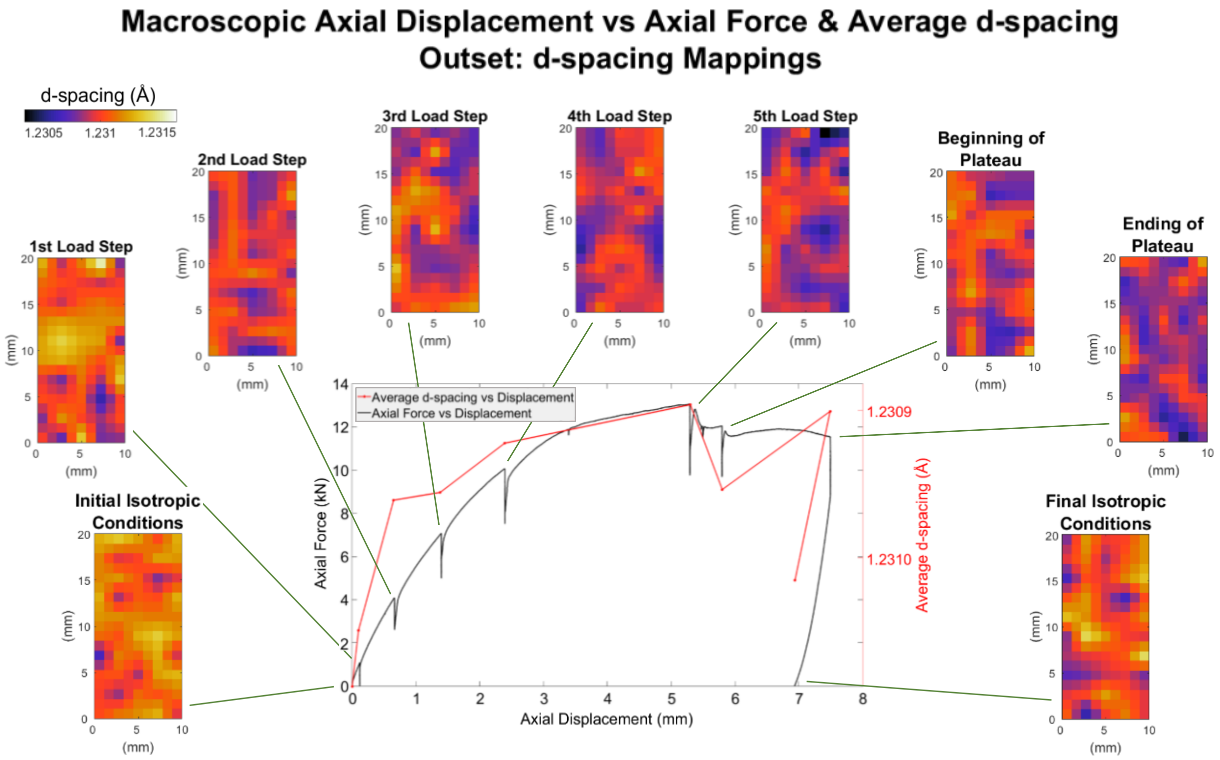

Figure 2 : *Inset: Macroscopic axial displacement as a function of the axial force and the average d-spacing. Outset: 2D grain-strain mappings per load step (darker colours being more compressed and lighter being less).*

Development and implementation of moving boundary conditions in the Material Point Method

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Keywords: MPM Material Point Method, edge detection, moving boundary conditions, PFM Proximity Field Method

Abstract

A new technique has been developed, which applies boundary conditions to moving boundaries in the Material Point Method (MPM), a finite element variant which uncouples the material from the background mesh (Sulsky et al., 1994, Wang et al., 2016a). This method is able to capture complex geotechnical behavior, such as that seen in slope failures (Wang et al., 2016b, 2016c). The application of boundary conditions in MPM is still a challenge, because the location of the boundary can be unknown in MPM, due to the fact that the material points, by definition, are not located at the boundary of the background grid. Boundary conditions applied on fixed boundaries coinciding with the background grid of MPM can be applied directly onto the background grid. The new technique expands the concept of applying boundary conditions to the background grid to boundaries which do not coincide with the grid (Cortis et al., 2016), to boundaries which move through the grid in time.

To apply boundary conditions to the background grid, the location of the boundary must be known. Thus an edge detection method has been constructed to locate the boundary based on the information provided at the material points. The Volume of Fluid (VOF) method and Surface Marker Method (SMM) (Sethian, 1996), used in fluid dynamics, have been tested and proven insufficient. A new method, called the Proximity Field Method (PFM) has been designed based on the Level Set Method (Sethian, 1996). PFM uses a composite Bézier curve to define the boundary. PFM constructs a proximity field based on the distance towards the material points and defines the boundary as the zero level of this field (Figure 1). Where SMM and VOF were unable to detect the boundary at larger strains, PFM was capable of modelling the large strain conditions for which MPM has been developed.

PFM has been used to apply a surface traction to MPM. The surface traction is distributed from the detected boundary to the nodes of the background grid according to the shape functions. This technique has been tested with a bearing capacity problem. The vertical load of 50 kPa is distributed to the background grid according to its location. In case the boundary is close to the grid nodes the load is concentrated at these nodes (Figure 2), otherwise when the boundary is far from the nodes the load is distributed to the closest nodes (Figure 3). The deformation due to the surface traction was comparable to the results found with FEM. Therefore, this implementation of a moving boundary in MPM can be considered validated.

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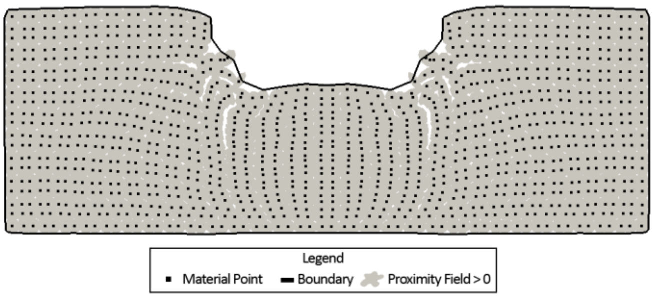

Figure 1 : *Proximity field with the detected boundary*

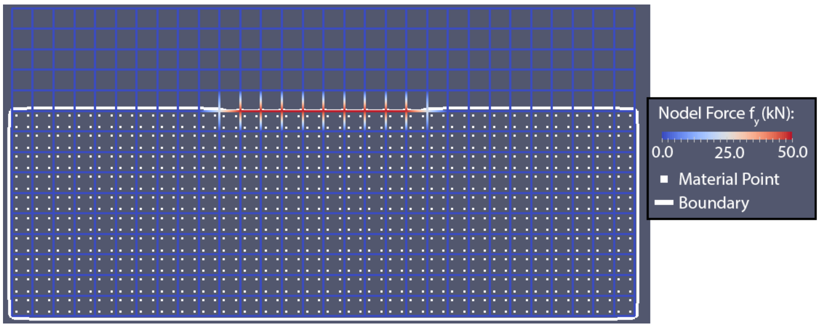

Figure 2: *Distributed load with the boundary close to the grid nodes*

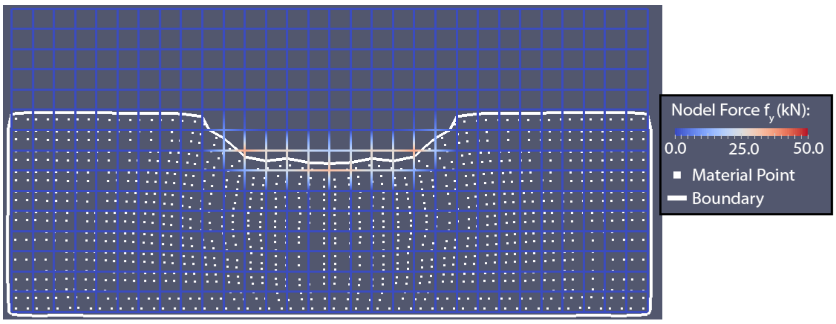

Figure 3 : *Distributed load with the boundary far from the grid nodes*

Elastic Properties of Gas Hydrates Bearing Sediments Based on Micro-Mechanical Approaches

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Keywords: gas hydrates, sediments, inclusions, homogenization, micro-mechanics

Abstract

Many experimental tests conducted on natural or synthetic samples have shown that the mechanical response of the soil is strongly affected by the presence of gas hydrates. It appears that gas hydrate bearing sediments have an elasto-plastic behaviour with a strain-softening tendency and that the elastic part is far from being linear. As a first step towards a complete numerical modelling, this work focuses on two homogenization approaches to simulate the elastic behaviour of gas hydrate bearing sediments. An analysis based on averaging calculations and then a numerical periodic homogenization using the finite-element method.

The analytical part is based on two different approaches using the Eshelby's result in the inhomogeneity problem of an inclusion embedded in a solid matrix [1]: first the self-consistent approach and then the Mori-Tanaka scheme. The sediments are viewed as a medium with two different scales of porosity, a micro-porosity with empty pores and a macro-porosity filled with gas hydrate. The presence of a fluid in micro-pores is not considered here since the pore pressure can be seen as an independent loading parameter in addition to the macroscopic strain, which means that the stiffness of the empty micro-pores is equivalent to the stiffness of the drained saturated pores [2]. The Figure 1 is an illustration of the two homogenization calculations that are conducted to deal with the double scale of porosity. Comparative results can be established for different inclusion geometries (spherical, or elliptical cylinders). The Figure 2 represents the homogenized stiffness tensor components against the gas hydrate volume fraction of elliptical inclusions, based on the elastic properties of the Toyoura sand [3], and of the structure I hydrate [4].

The computation of the homogenized elastic properties of a Representative Elementary Volume (REV) using the finite-element method is less restrictive on the choice of the microstructure geometry and can be very useful for the modelling of a constitutive behaviour. Indeed, multi-level finite-element methods can be used in the development of a numerical mechanical model for gas hydrate bearing sediments including inelastic behaviour. The principle of the method adopted here is that the local mechanical problem is solved through the finite-element method for a discretised periodic elementary cell subjected to a uniform macroscopic strain loading [5]. The REV is the result of a periodic replication of this discretized elementary geometry. A plane strain problem is implemented in a finite-element code developed in the laboratory, with a periodic cell composed of two different materials: a homogeneous matrix representing the solid and micro-porosity introduced in the analytical scheme of calculation, and elliptic inclusions of a homogeneous stiffer material corresponding to the gas hydrate formations. Several mesh geometries are randomly created with different hydrate volume fractions, which means different hydrate saturations (Fig.3).

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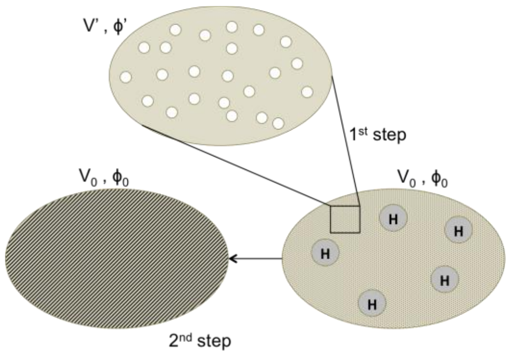

Figure 1: *Schematic representation of the analytical calculation steps*

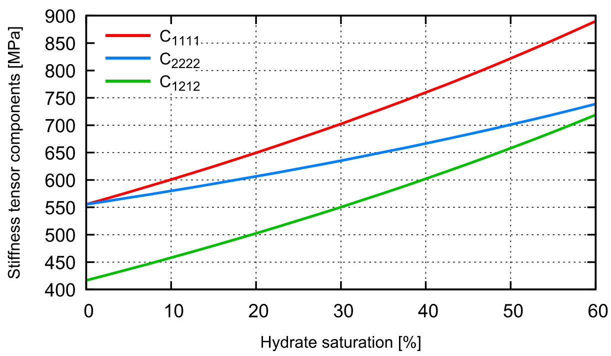

Figure 2: *Components C1111, C2222, and C1212 of the homogenized stiffness tensor against the gas hydrate volume fraction*

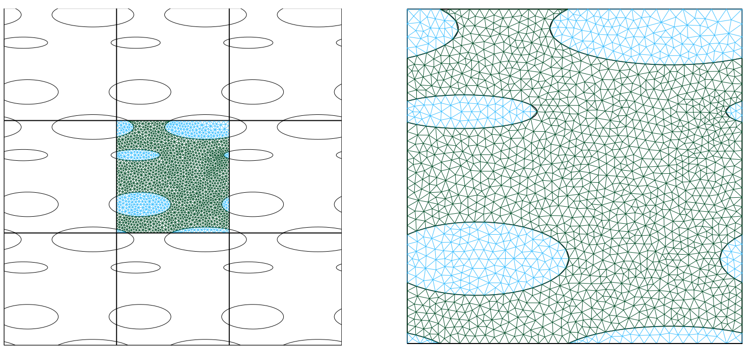

Figure 3: *Finite-element mesh of a periodic cell with randomly distributed elliptical inclusions*

Assessment of natural deformation bands in sandstones

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Keywords: Deformation bands, sandstones, x-ray CT, permeability.

Abstract

Deformation bands in sandstones have been identified at the field-scale and have been experimentally replicated at the laboratory-scale by many researchers [see 1]. The presence of deformation bands in geological reservoirs significantly affects their productivity; thus, a more concrete understanding of the properties of such bands is required to better assess the reservoir behavior before and during its production. How does the porosity and permeability of deformation bands evolve/change due to geological history? How does this affect the porosity and permeability of the host rock? Do these deformation bands act as baffles or conduits to fluid flow?

In order to answer the above questions, it is crucial to better define the actual structure and the textural characteristics of natural deformation bands as well as their geometric attributes. In the present study, we focus on rocks coming from Rio do Peixe Basin (RPB), northeast Brazil. RPB has been described as a basin consisting of half-grabens, tilted towards the south and southeast and controlled by three major faults [2]. Plugs with a diameter of 38 mm were collected from different formations marked by the orientation of deformation bands (north-south, east-west, and northeast-northwest). Samples are composed of coarse sandstone and conglomerates affected by deformation bands [Fig. 1]. Porosity and permeability were measured for each of the samples (using UltraPoroPerm 500 equipment). These rocks have porosities ranging from 10% to 13% and a very low permeability (0.010 to 8.22 mD).

To get further insights into the 3D structure of these deformation bands as well as a deeper understanding of their textural characteristics and geometry, we are currently x-ray scanning (*Nikon XT-H 225/320 LC CT system*) these samples. We seek to understand how these natural deformation bands may affect the permeability of these rocks and thus, enable the prediction of the petrophysical behaviour of the RPB reservoir.

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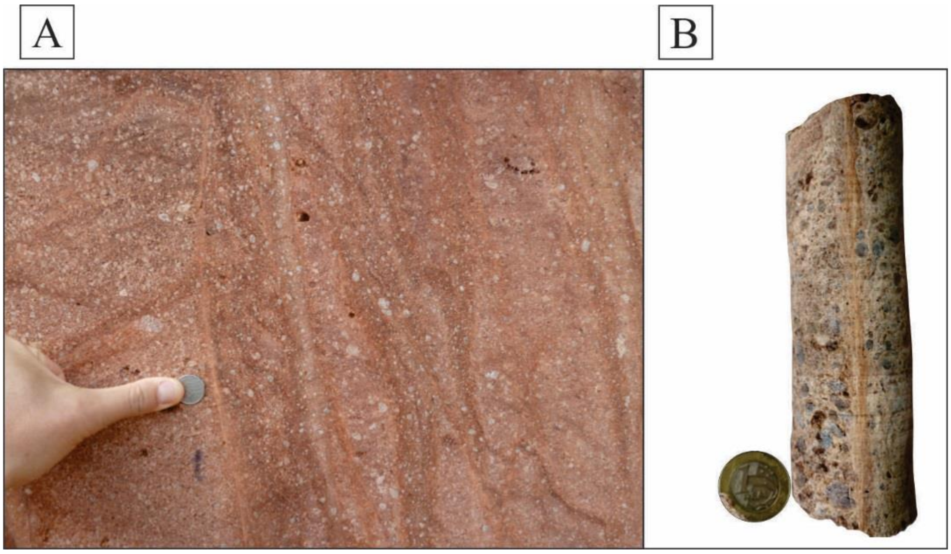

Figure 1: *a. Material exposed to the outcrop; the thumb is places next to a deformation band; b. plug coming form (a).*

Highly deformed grain: from the Hertz contact limitation to a new strain field description in 2D and 3D

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Keywords: Digital Image Correlation, Soft Grain, Finite Element Method, Hertzian contact, Material Point Method

Abstract

When dealing with the contact between two particles in the small deformation regime, Hertz contact is the most common mechanical description. Nevertheless in the case of jammed granular systems some grains can be far above the small deformation hypothesis which ruins the macroscopic description of the system. By mean of novel 2D and 3D experimental and numerical approaches, we investigate when the Hertz strain field is not valid anymore and how it can be improved in the highly deformed regime.

We set-up a step by step single disk compression experiment attached to a very high resolution imaging apparatus (5 microns accuracy over 5cm2 particles). Strain is then precisely measured via Digital Image Correlation while the effect of boundary conditions is investigated: (i) slippery contact, (ii) frictional contact, (iii) finite/infinite cylinder length.

In parallel of these experiments, numerical simulations are carried out in the same mechanical conditions by means of Finite Element approach and Material Point Method (MPM) [1]. This last method is based on the discretization of each particle 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.

Both computed and measured, numerical and experimental strain fields, are compared with theoretical result to determine when and where limitations appear in theory and numerical simulations for the different mechanical situations.

Finally, in a last part, 3D measurements of the strain field in a highly compressed soft bead is developed. It is measured for slippery and frictional contacts by mean of a CT-scan and 3D Digital Image Correlation Method. Preliminary results will be presented.

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Fundamentals of geomechanics and its applications to petroleum industry

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Keywords: Geomechanics, wellbore, sand production, mud weight

Abstract

Geomechanics plays an essential role in drilling and production petroleum industry from beginning with pre-drill well planning and continuing with wellbore stability support while drilling and sand production management. This paper will cover an overview about geomechanics from its fundamental knowledge and geomechanical models to its applications in practical problems of oilfield operations such as wellbore instability, sand production. Additionally, a full review about input data and how to get them by measuring in laboratory and calibration with field measurement will be presented. This would be a practical document for any projects related to geomechanics application in reservoir development and management.

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Elastic waves in particulate glass-rubber mixture: experimental and numerical investigations/studies

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Keywords: Granular mixtures, Triaxial cell experiment, DEM simulation

Abstract

The elastic response of disordered mixtures of granular and soft matter is investigated by wave-propagation, both experimentally and numerically. This allows inferring fundamental properties of granular and soft disorded materials such as elastic moduli and dissipation mechanisms. Mixtures are prepared with different volumes of soft matter mixed with hard matter to identify the transition from a rigid to a soft granular skeleton. We compare physical experiments in a triaxial cell equipped with piezoelectric transducers and Discrete Element simulations. Interestingly, the behavior is highly nonlinear and also non-monotonic with increasing the percentage of soft content. The presence of soft particles alters the formation of force chains. The qualitative agreement between experiment and simulation is well captured despite of complex interaction between soft and stiff particles that render several ongoing challenges, e.g. the presence multi-body-interactions instead of pairwise contacts.

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Figures

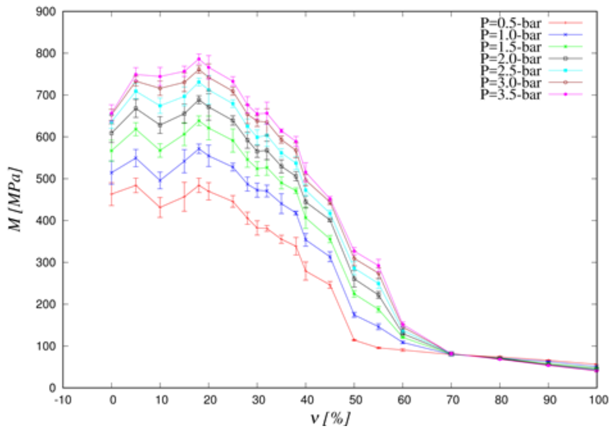

***Figure 1** : P-wave modulus versus fraction of rubber*

Suffusion induced heterogeneity of an eroded soil in terms of fines content and void ratio

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Keywords: internal erosion, suffusion, x-ray tomography

Abstract

Internal erosion of soil induced by seepage flow is considered the main causes for the dysfunctions of earthen structures (dikes, earth dams, etc.). One of the phenomena of internal erosion called suffusion denotes the migration of the finest soil particles under the action of water through the surrounding soil matrix formed predominantly by the large grains. This process can progressively degrade the soil's structure and lead to substantial changes in physical, hydraulic and mechanical characteristics of the soil.

In previous studies on mechanical behavior of eroded soil by suffusion, a direct comparison between original soil before erosion and soil after erosion is often used to investigate the effect of suffusion on soil strength by means of the triaxial test. Typically results on non-cohesive soils can be found in Chang et al. (2012), Xiao and Shwiyhat (2012), Ke and Takahashi (2014). However these results are somehow contradictory, as for instance in Chang's study, where it is concluded that the shear strength of eroded soil decreases compared to non-eroded soil while Xiao and Shwiyhat have come to the opposite conclusion. The potential reasons for this discrepancy might be attributed to the occurrence of heterogeneity induced by the erosion process and by the further rearrangements of coarse grains. Such heterogeneity has never been taken into account, nor mentioned, in the actual analysis.

By using x-ray computed tomography (x-ray CT) a soil's specimen structure was captured before and after suffusion process. After some image processing, it can be convincingly showed that the soil's structure after erosion process is indeed highly heterogeneous in terms of fine particles distribution and void ratio (Figure 3). Owing that the principle of the triaxial test interpretation assumes that the tested sample must be homogeneous, an eroded soil that is no longer homogeneous cannot be directly compared to a non-eroded soil via the triaxial test. Alternative approaches are needed to accurately investigate eroded soil's resistance.

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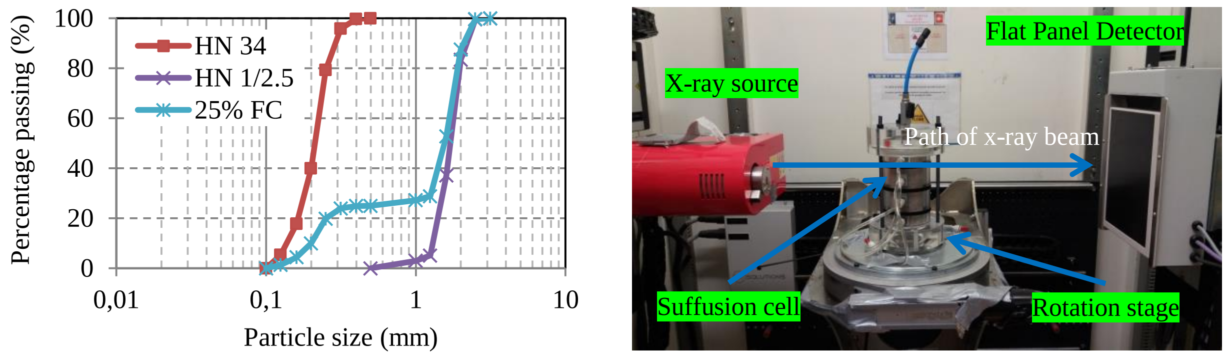

Figure 2: *Materials and setup of the suffusion equipment in the x-ray scanner*

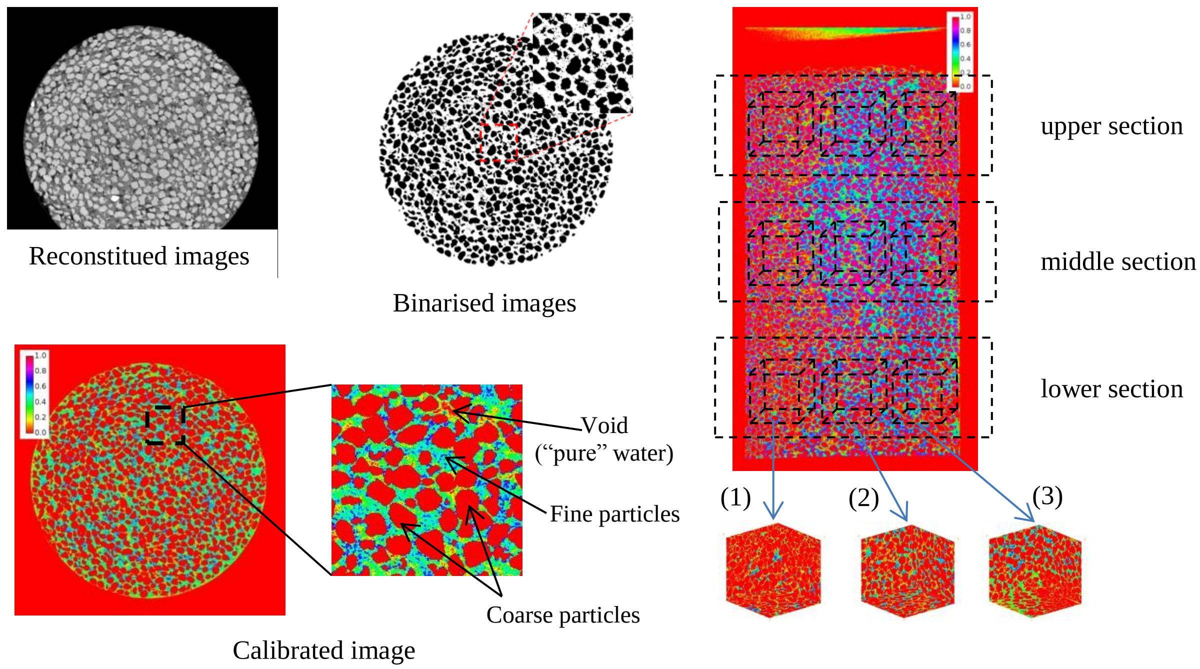

Figure 2 : *Image processing*

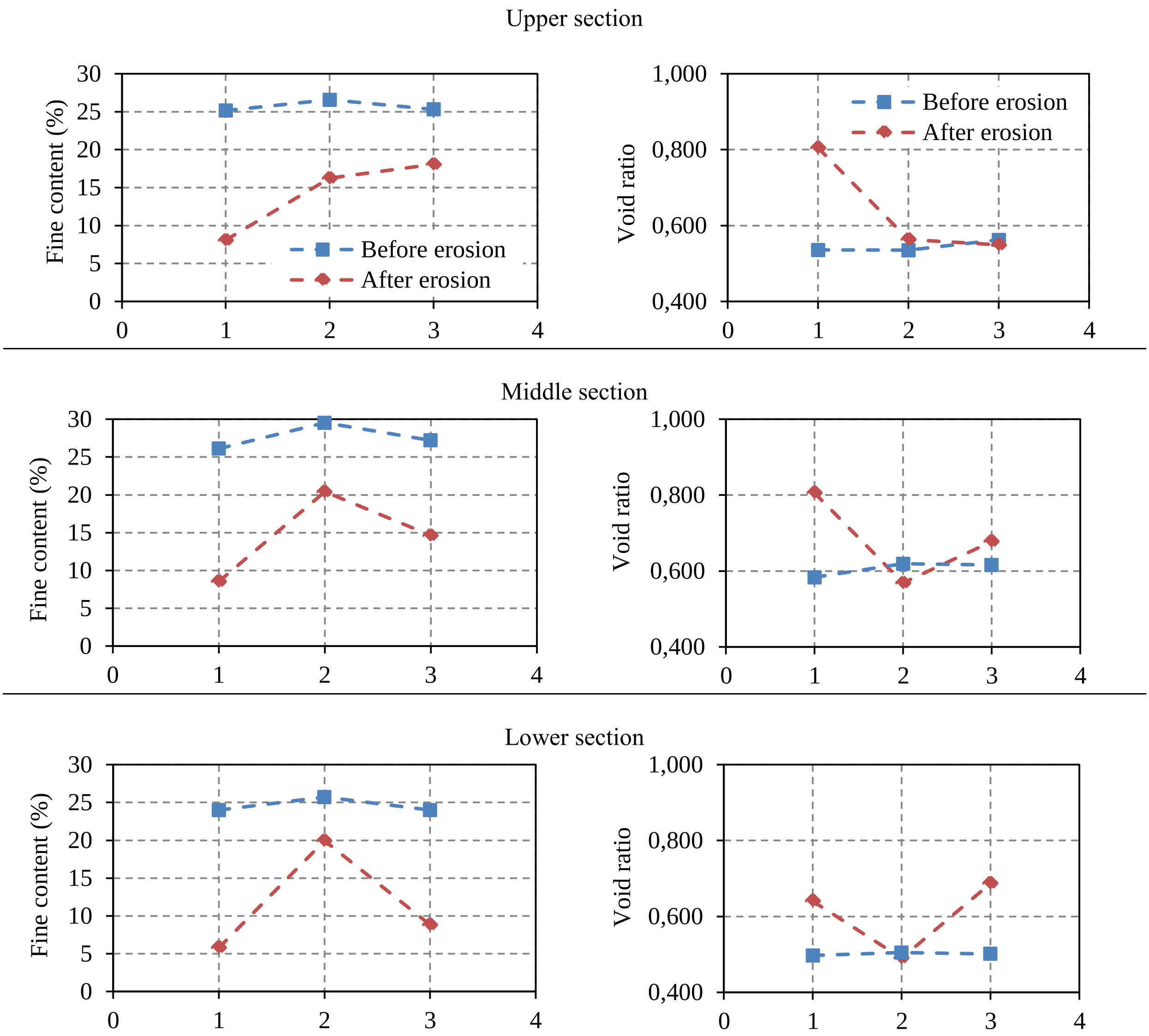

Figure 3: *Evolution of fine content and void ratio before and after erosion process*

Numerical modelling of suffusion: micromechanical analysis of flow driven microstructure evolutions

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Keywords: suffusion, DEM, micromechanics, force chains, pore network

Abstract

Suffusion is the selective erosion of the finest particles of a granular material subjected to an internal flow. Among the four types of internal erosion and piping identified today, suffusion still needs further research efforts. Indeed, the driving mechanisms at the microscale are still poorly understood as well as the consequences of microstructure changes on the overall mechanical behaviour.

Thanks to the use of DEM-PFV numerical simulations (Chareyre et al. 2012), microstructure evolutions of a non-cohesive granular material, when submitted simultaneously to a mechanical and hydraulic loading at the representative elementary volume scale, can be tracked (Fig. 1). Recently developed micromechanical tools (Wautier et al. 2017) make it possible to investigate the flow impact down to the microscale. In particular, it is shown that i) the study of the pore network properties is able to accurately predict the observed transport distances (Fig. 2) and ii) internal flow is able to direct important force chain reorganizations (Fig. 3). As a result, in the case of an unstable material in the sense of the second order work criterion (Nicot et al. 2009), an internal flow even appears able to trigger off underlying instabilities.

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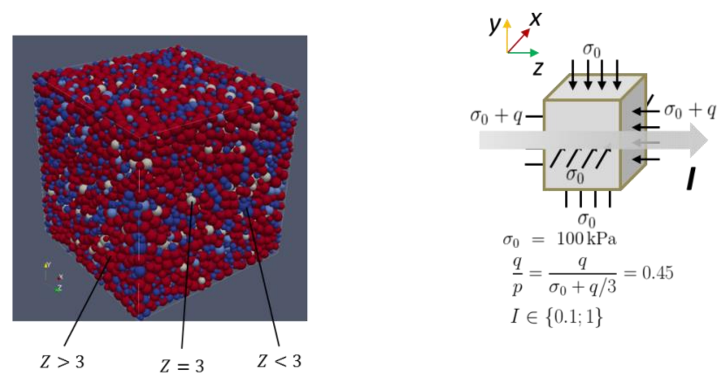

Figure 4 : *Numerical sample before hydraulic loading with particles colored according to their coordination number (left) and boundary value problem simulated (right)*

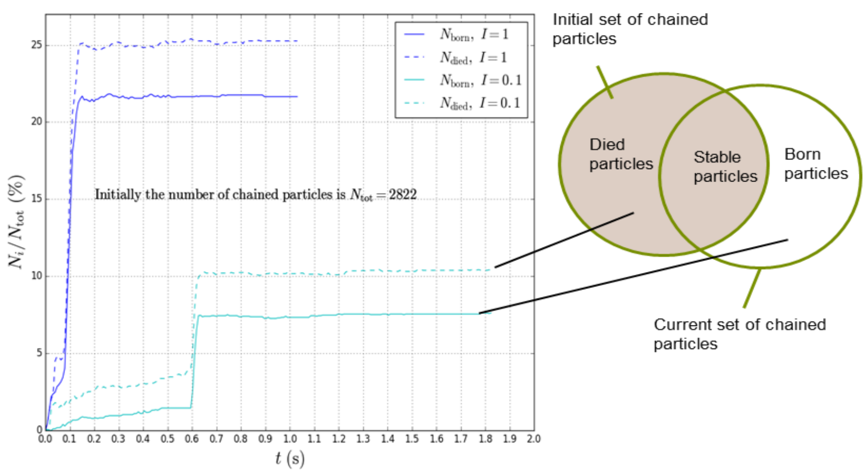

Figure 5: *Flow impact on force chain reorganizations for tow hydraulic gradients* $\boldsymbol{I} \in \{\mathbf{0.1}, \mathbf{1}\}$.

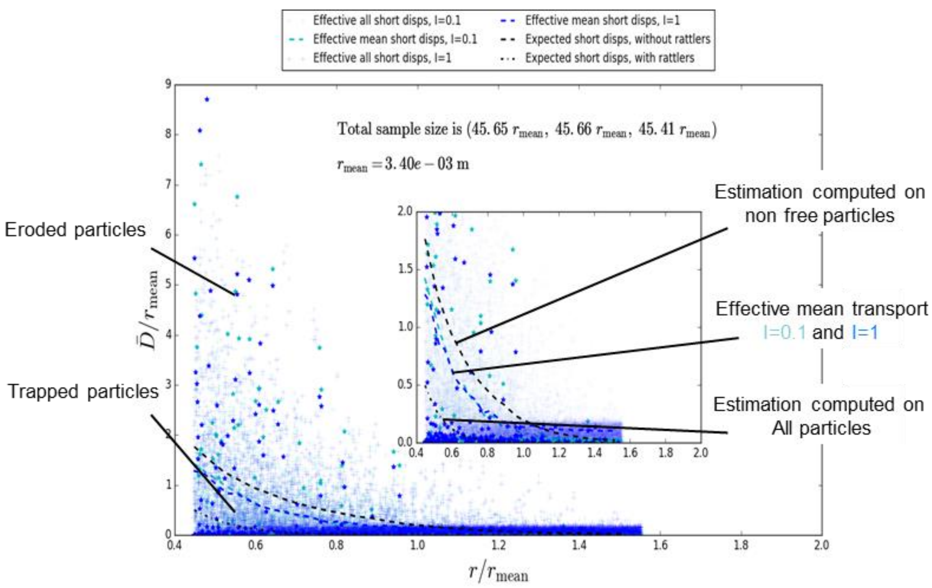

Figure 6: *Comparison between predicted and observed travelled distances under the action of two hydraulic loadings* $\boldsymbol{I} \in \{\mathbf{0.1}, \mathbf{1}\}$.

Benchmark cases for a multicomponent lattice Boltzmann model

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Keywords: Liquid bridges, lattice Boltzmann, multiphase flow, unsaturated media

Abstract

Multiphase flows are ubiquitous in industry and nature. Practical situations involving multiphase flow include infiltrated rainwater into soil by displacing air, petroleum engineering applications and industrial processes such as riser reactors, gas-liquid flows in evaporators and condensers, fluidized beds, dryers, etc [1,2].

Capillary forces play a key role at the pore scale of partially saturated granular materials. We perform numerical simulations using the multicomponent Shan-Chen LB (Lattice Boltzmann) model [3,4] to simulate multiphase flow and have a better understanding of the hydrostatic effects at the microscale.

In order to ensure the validity of the numerical model, fluid displacement in capillary tubes is simulated and compared with analytical results. Hysteresis in the relationship between capillary pressure (P_c) and degree of saturation (S_w) is studied using multiphase lattice Boltzmann simulations of drainage in capillary tubes ranging different cross-sections (figure 1.). Furthermore, the profile of the remaining liquid retained in the corners of polygonal pores is studied and proven to match the analytical solution given by the Mayer and Stowe-Princen (MS-P) method [5].

The benchmark is completed with an analysis of the rupture behavior of funicular and pendular water bridges in elementary microstructures (assemblies of 2 or 3 static spherical bodies). The equilibrium shapes of pendular bridges are numerically simulated (figure 2.) and compared with the bridge profiles given by the analytical calculation based on solution of Young-Laplace equation. We also analyze the effect of pendular bridges that coalesce around a throat formed by three adjacent beads due to the effect of a drying process. Pendular and funicular regime is studied (figure 3.) complementing the work of previous articles [6,7]. The validated LBM procedure is then applied to more realistic and complex pore geometries as found in granular soils.

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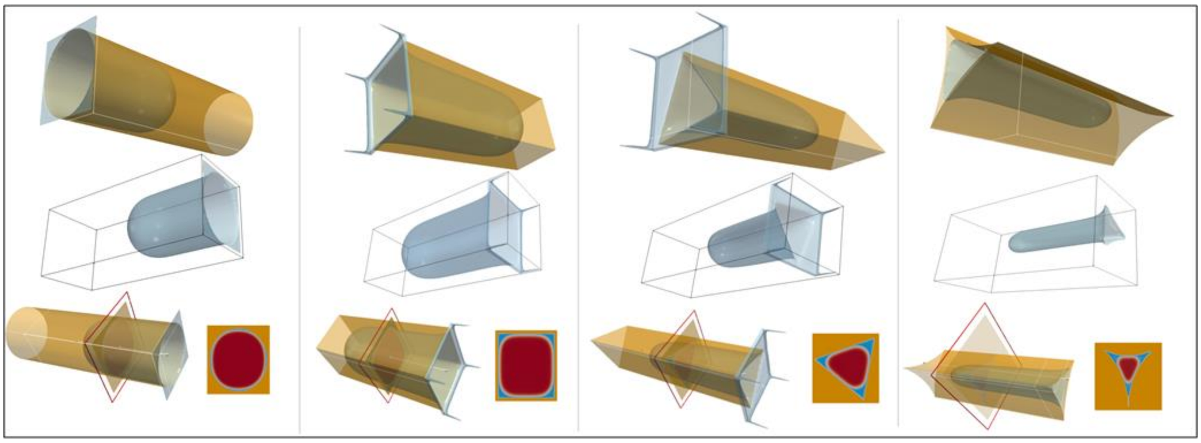

Figure 1: *Schematic geometries of circular and polygonal tubes. Fluid interface is displayed without the tube in the middle. Water adopts different configurations in the corners depending on the cross-section shape.*

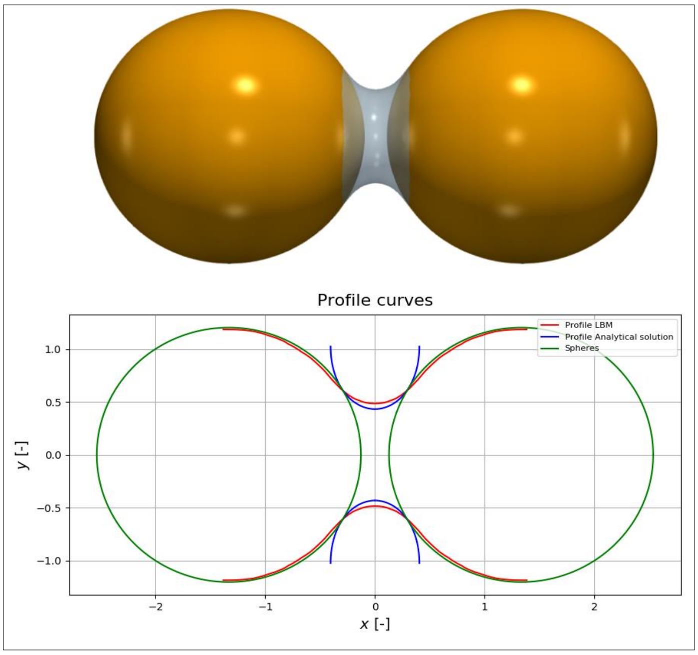

Figure 2: *. Capillary bridge between 2 identical spherical bodies. Profiles obtained numerically are in agreement with the analytical solution.*

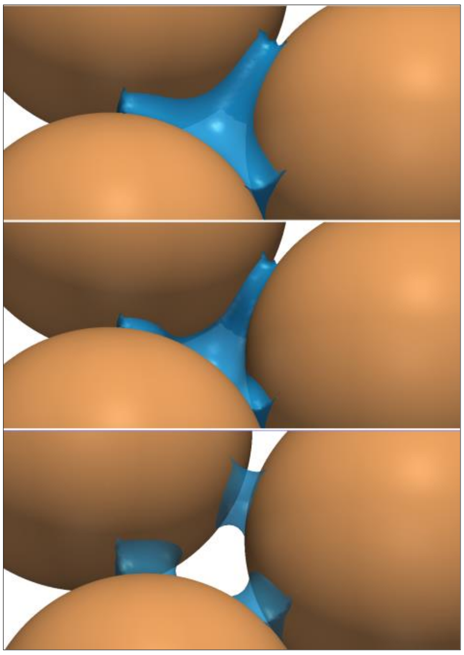

Figure 3: *Capillary bridges formed after the splitting of a meniscus within a pore throat when the capillary pressure is increased.*

Bédoin weakly cemented sands: how do they deform?

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Keywords: weakly cemented sand, deformation band, cement, triaxial compression, X-ray computed tomography, Digital Image Correlation

Abstract

Laboratory work is important to understand localised deformation occurring in nature. Here, we discuss a field case located in Bédoin, southern France (Saillet and Wibberley, 2010). The outcrops are made of weakly cemented sands deposited in the Cretaceous. The site exposes deformation features (Fig. 1) named conjugate deformation bands (Fossen et al., 2017). Our work aims at shedding light into the characteristics of these deformation features. To do so, we explore the mechanical behaviour of the natural material coming from these outcrops, focusing on the role of cement and grain texture.

A thorough field trip has been carried out to collect weakly cemented sands from these outcrops so as to study this material at the laboratory scale. To sample the material we used two ways: a. a sampler was machined, which helped to maintain undisturbed volumes of weakly cemented sands (containing or not deformation features); b. grains coming from the region of the deformation band and far from it were collected by hands. Both materials were tested in the laboratory.

The experimental programme consists of triaxial compression tests coupled with x-ray tomography and involving image processing. Imaging consists of quantitative data analysis and Digital Image Correlation (DIC). Quantitative measurements need to be developed on images treated with segmentation procedures. Cement content, cement distribution, pore space distribution and preferential orientation of grains are analysed, among other properties. DIC is related to the mechanical testing of the material: it offers comparisons of displacement maps throughout the specimen meanwhile it undergoes deformation, leading to shear and volumetric strain maps (during the experiment).

Triaxial compression tests with *in situ* x-ray tomography have been performed on three natural specimens under the same conditions of confinement and humidity. One of the natural specimens included a pre-existing deformation band, one had a big pore inclusion (revealed by the x-ray tomography) and the last one was relatively homogeneous. All specimens were coming from the same region. The idea has been to deform all samples and see how deformation initiates and evolves through the samples. Triaxial compression tests have been run in a previous study on samples collected from the same field (Skurtveit et al, 2013); however, the material tested in Skurtveit (2013) is not intact (freezing and thawing, tamping) and x-ray tomography has been performed only before and after the test.

Our results so far have shown that all specimens developed similar stress-strain behaviour (Fig. 2), with differences in the values of deviatoric stress at peak and in the residual state. This might reflect the differences in the cementation degree. DIC results will be shown for some of the specimens aiming at exploring the evolution of deformation during the triaxial

compression of the specimens and comparing primarily the pre-peak strain maps of the different specimens. This is an on-going work trying to explore whether the deformation features which developed in all three specimens (one homogeneous, one with a big pore inclusion and one with a pre-existing deformation band) share common characteristics.

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Figures

Figure 7 : *Conjugate deformation bands in the outcrop (red tool as scale, l = 15 cm)*

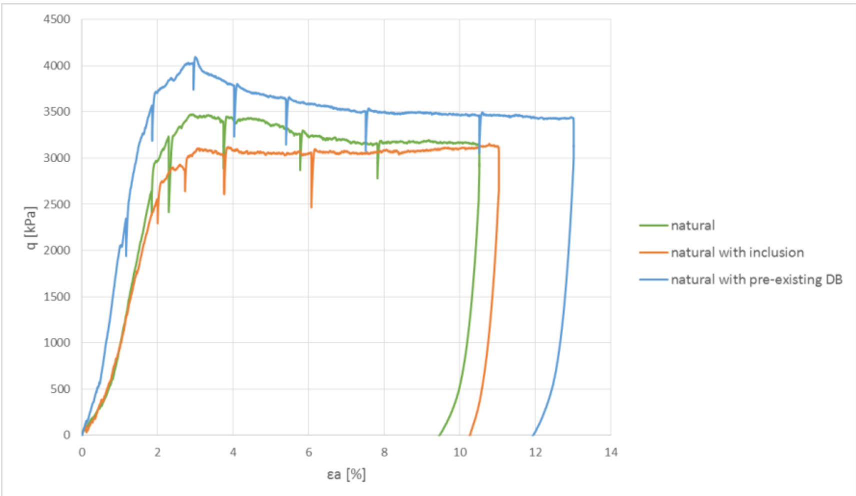

Figure 8: *Stress-strain response of the natural material under triaxial compression*

SANISAND-F: A fabric-based sand constitutive model with kinematic hardening within Anisotropic Critical State Theory

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[†] *University of California, Davis*

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Keywords: Constitutive Model, Fabric, Soil Anisotropy, Soil Plasticity

Abstract

SANISAND is the name for a family of plasticity models for sands within the framework of Bounding Surface (BS) plasticity which have proven their ability of realistic simulation of the sand behaviour under conventional monotonic and cyclic loading paths with a single set of model constant values within Critical State Theory (CST). The proposed SANISAND-F model is a newly developed kinematic hardening model of this family, which is formulated within the Anisotropic Critical State Theory (ACST) to account for the effect of fabric on the anisotropic response of sands. The ACST proposed by Li & Dafalias (2012) introduces the fabric anisotropy variable A that equals the first joint invariant of properly defined and evolving deviatoric fabric and loading direction tensors. The A evolves towards its critical state value and thus completes the two mathematical conditions of the clasical CST proposed by Roscoe et al. (1953) and Scofield & Wroth (1968) to account for the role of the fabric. Moreover, it is being used to extend the notion of the classical soil's state parameter ψ by defining the new dilatancy state parameter ζ that delineates between contractive and dilative response. The specific constitutive propositions of the SANISAND-F are presented in this work in a multiaxial formulation. The model is validated against undrained shearing tests on Toyoura sand (Figure 1a), which are characterized by a fixed but rotated set of principal stress axes. The simulation results (Figure 1b) show that the model is capable of simulating the highly anisotropic behaviour of sands.

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Figures

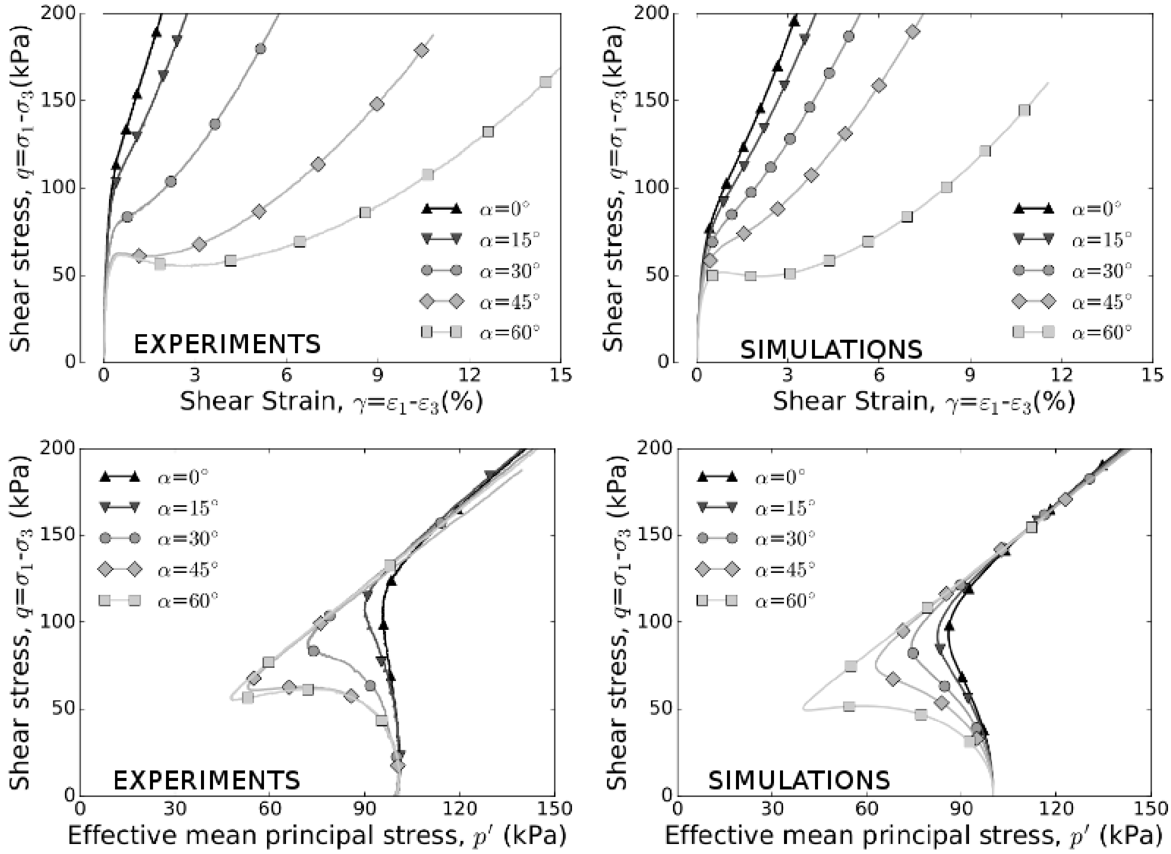

Figure 9: Experimental data and SANISAND-F simulations for b=0.25 and a=0°−60°. Toyoura sand, e=0.813−0.818. Data after Yoshimine et al. (1998).

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