General Report of TC 105
Geomechanics through the scales

Rapport général du TC 105
La géomécanique à travers les échelles

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ABSTRACT: This general report presents and discusses the papers submitted to the Discussion Session of TC105 (Geomechanics from Micro to Macro) at the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013. These papers deal with a variety of issues and include experimental, analytical and numerical studies. Overall, they show that the theme of this session is both challenging and promising. The discussion of the papers is preceded by some general remarks about the meaning, trends and perspectives of research in geomechanics through the scales.

RÉSUMÉ : Ce rapport général passe en revue les articles soumis à la 18ème Conférence Internationale de Paris dans le cadre de la session consacrée à la géomécanique de la micro à la macro échelle. Ces articles portent sur plusieurs thématiques, et comprennent des études soit expérimentales, soit analytiques, soit numériques. Dans leur ensemble, ils montrent bien que le thème de cette session est à la fois complexe et riche de perspectives. La discussion des articles est précédée par quelques considérations générales sur le sens et les perspectives actuelles de la recherche dans ce domaine.

KEYWORDS: geomechanics through the scales, experiments, analytical and numerical studies.

1 INTRODUCTION

This general report briefly presents the 15 papers that were submitted to the Discussion Session of TC105 (Geomechanics from Micro to Macro) at the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013. While only 6 papers have been actually selected for oral presentation, all 15 can be found in these proceedings. The focus of this session is on new advances in geomechanics through the scales – from micro to macro – and it encompasses many aspects of geomechanics and geotechnical engineering, from fundamental modeling and laboratory experimental studies to more applied topics and recent challenges related to the safeguard of the environment and the production of energy.

Table 1 lists the papers belonging to the session. In the report, the papers will be presented and discussed in the order adopted in Table 1. Citations of papers belonging to this session will be mentioned in Italics in the text. These papers might be grouped into different tracks, depending on whether they are categorized by material studied (fine-grained *vs.* coarse-grained geomaterials), approach of the study (experimental, numerical and analytical) or application (petroleum, energy, civil …). In this report, we have rather decided to discuss papers depending on whether they are actually dealing with both the micro and the macro scale, or just focusing either on the micro or the macro scale. The discussion of the papers is preceded by a short summary of the activities of TC105, followed by some general comments about the meaning, trends and perspectives of research in geomechanics through the scales.

2 GEOMECHANICS FROM MICRO TO MACRO

2.1 *A short summary of the activities of TC105*

At the 15th ICSMGE in Istanbul (2001) a technical committee was appointed (at that time TC35, now TC105) to promote scientific research on the behavior of geomaterials at the micro scale, so as to clarify the fundamental micromechanisms responsible for behavior observed at higher scales. Since then, the study of the behavior of geomaterials (soils and rocks) through different scales – from micro to macro – has become an emerging field in our community, along with the increasing awareness of the need of integrating these different scales – which is increasingly possible thanks to major advances in both the experimental and computational tools available.

Three specific conferences have been organized by the technical committee TC105 (IS-Yamaguchi in 2006, IS-Shanghai in 2010 and IS-Hong Kong in 2013), and a fourth conference will take place in Cambridge in 2014. Furthermore, a themed issue for Géotechnique (entitled "Soil mechanics at the grain scale") appeared in 2010, followed by a themed issue for Géotechnique Letters (entitled "Geomechanics across the scales") in 2012.

2.2 *General considerations*

Geomaterials are rich in features interacting across the scales – from asperity size to grain size, from the length of force chains to the thickness of shear bands, and from laboratory specimens to the full geotechnical engineering scale. Geomaterials exhibit multi-scale behavior that is intrinsically associated with the interactions of the individual particles (see for example the magnificent review paper by Santamarina 2003). Large-scale geotechnical engineering could gain so much from accurate description of the relevant features exhibited at the finer scales.

The "father" of our discipline, Karl Terzaghi, already reflected on this matter back in 1920: *'[Coulomb] purposely ignored the fact that sand consists of individual grains. Coulomb's idea proved very useful as a working hypothesis, but it developed into an obstacle against further progress as soon as its hypothetical character came to be forgotten by Coulomb's successors. [. . .] The way out of the difficulty lies in dropping the old fundamental principles and starting again from the elementary fact that sand consists of individual grains*'. Ever since, Terzaghi's words were not forgotten. The consideration of the behavior of geomaterials from the most basic units, *i.e.*, the particles, has in fact been the *raison d'être* of micromechanics of geomaterials. This discipline owes much of its success to the Discrete Element Method (DEM), introduced in the 1970s by Cundall & Strack (1970). DEM's dominance in micromechanical analysis remains unsurpassed, with all but a few datasets at the particle scale arising from DEM simulations (*e.g.*, Cundall 1989, Oda & Iwashita 2000, Thornton & Zhang 2006, Anthony 2007, Tordesillas 2007, Zhu *et al.* 2007, just to mention a few). As pertinently enunciated by Sibille & Froiio (2007): '*This has led to the paradox of micromechanics of granular materials as a science based almost entirely on "virtual evidence"*'.

On the experimental side, the past few years have witnessed some major advances, possibly heralding a new era in micromechanics of geomaterials. Measurements of contact forces, contacts and grain kinematics in 2D idealized assemblies of photoelastic discs have been achieved and analyzed (see the work of Behringer and co-workers, *e.g.*, Kondic *et al.* 2012). Experimental 3D measurements on natural geomaterials are becoming possible at ever-increasing spatial resolution, and researchers are facing an unprecedented opportunity to integrate or complement these measurements with data from DEM simulations to probe the rheology of geomaterials, just as Terzaghi envisioned – from observations of behavior of individual particles.

Experimental access to information at the micro scale allows us to answer existing questions as well as to discover new mechanisms operating across the spatial scales, from the particle to the bulk. Of course, this new capability poses new challenges to modeling. Measurements at the small scale have an important role in revealing the physical origins of phenomena observed at the macro scale. However, rational theories are required to underpin this physics in terms of predictive tools, with numerical computations that extend the theoretical work, and allow for analysis of geomaterials with all their complexities, variabilities and uncertainties. While it is beyond any doubt that we can gain much from a more accurate description of these features at the finer scales, a fundamental issue (and the key challenge for the years to come) is to develop models capable of integrating information at multiple scales. This ambitious objective should be kept in mind as the background for the papers discussed in this report.

Table 1. List of papers belonging to this session.

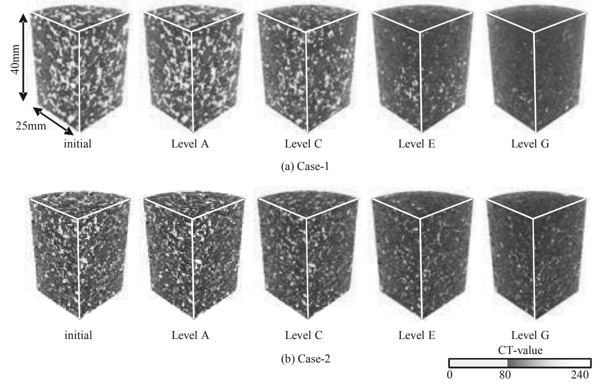
keywords	Authors	Country	Title
lab testing, sand, x-ray CT, compaction	Otani J. *et al.*	Japan France	Microscopic observation on compacted sandy soil using micro-focus X-ray CT
lab testing, sand, x-ray CT, strain localization	Andò E. *et al.*	France Sweden	Grain-scale experimental investigation of shear banding in sand
lab testing, clay, micrographs, creep, consolidation	Yigit I. & Cinicioglu S.F.	Turkey	A look into time dependent behaviour of clays at macro and micro scale
lab testing, clay, chemical modification, soil improvement	Minder P. & Puzrin A.M.	Switzerland	Microstructural changes leading to chemically enhanced drainage
DEM, contact model, methane hydrates	Jiang M.J. *et al.*	China	A Simplified Contact Model for Sandy Grains Cemented with Methane Hydrate
DEM, trapdoor, gravity flow, tunnel	Kikkawa N. *et al.*	Japan New Zealand	Three dimensional discrete element simulation of trapdoor unloading and gravity flow of sandy granular material
DEM, small strain, shear wave velocity	Ning Z. & Evans T.M.	USA	Discrete Element Method Study of Shear Wave Propagation in Granular Soil
DEM, computational fluid mechanics, dense phase flow	Tomac I. & Gutierrez M.	USA	Particulate Modeling of Sand Slurry Flow Retardation
analytical, effective stress equation	Shao L.T. *et al.*	China	Uniform effective stress equation for soil mechanics
analytical, granular materials, crushing, abrasion, poly-disperse mixtures, compaction	Caicedo B. *et al.*	Colombia USA	Modelling crushing of granular materials as a poly-disperse mixture
FEM, multi-scale modeling, wellbore damage	Khoa H.D.V. *et al.*	Norway	Macro- and micro-FE modelling of wellbore damage due to drilling and coring processes
lab testing, sand, plane strain, high pressure, methane hydrates	Hyodo M. *et al.*	Japan	Shear strength and deformation of methane hydrate bearing sand with fines
Lattice Boltzmann Method, relative permeability, petroleum geomechanics	Pak A. & Sheikh B.	Iran	Study of relative permeability variation during unsteady flow in saturated reservoir rock using Lattice Boltzmann method
lab testing, compacted soil, shear strength, constant water content, direct shear test	Heitor A. *et al.*	Australia	Behaviour of a compacted silty sand under constant water content shearing
lab testing, unsaturated soils, resilient modulus, thermo-hydro-mechanics	Zhou C. & Ng C.W.W.	Hong Kong	Experimental study of resilient modulus of unsaturated soil at different temperatures

3 PAPERS PRESENTED TO THIS SESSION

3.1 *Looking inside a soil sample using x-ray tomography*

X-ray computed tomography (CT) is now widely used in material sciences and has amply proved its interest in geomechanics (see Viggiani & Hall 2012 for an overview). The principle of CT measurement consists of recording x-ray radiographs of a specimen at many different angular positions around the object. From these different projections, a three dimensional image of the object can be reconstructed with appropriate algorithms. X-ray CT is therefore a non-destructive imaging technique that allows quantification of internal features of a soil (or rock) sample in 3D.

Otani et al. (2013) used x-ray CT for imaging a sandy soil at different levels of compaction in 1D conditions. The motivation for this experimental study is to check whether the current criteria for quality control of dynamic compaction of soil for riverbanks are appropriate or not. Two cases were investigated, corresponding to a different number of blows to yield the same total compacting energy (cases 1 and 2 in Fig. 1, corresponding to higher and lower individual blow energy, respectively). Quantitative analysis of the 3D images from x-ray tomography allows Otani and coworkers to obtain the distribution of porosity in the sample and to follow its evolution with increasing compaction – see Fig. 1.



(a) Case-1

(b) Case-2

Figure 1. Spatial distribution of porosity in two samples of silty sand at different levels of compaction, as obtained with x-ray CT (*Otani et al. 2013*).

A second experimental study using x-ray tomography is presented by *Andò et al. (2013)*. Further details and results can be found in Andò *et al.* (2012a, 2012b). The motivation for this study comes from the fact that strain localization presents major challenges for continuum models for geomaterials. For such models to be successful, the microstructure of the material (for sand, at the grain scale) should be explicitly taken into account, in one way or another, which in turn requires experimental characterization of shear banding at the grain scale. *Andò et al. (2013)* used x-ray tomography to image samples of two different sands (see Fig. 2) while they deform under triaxial compression.

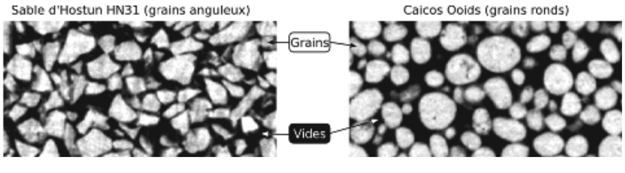


Figure 2. Slices from x-ray images of angular Hostun sand (left) and rounded Caicos ooids (right) tested by *Andò et al. (2013)*.

The results of this study clearly show that thanks to x-ray tomography, combined with either 3D Digital Image Correlation or Particle Tracking, the evolution of the 3D microstructure of a small sample of sand can be followed while it deforms, individual grains can be distinguished in the time-lapse 3D images, and analyzed to give the full 3D kinematics (displacement + rotation) of each individual grain in the sample (see as an example Fig. 3). Analysis of deformation at this scale is, in the Authors' own words, a dream that has come through!

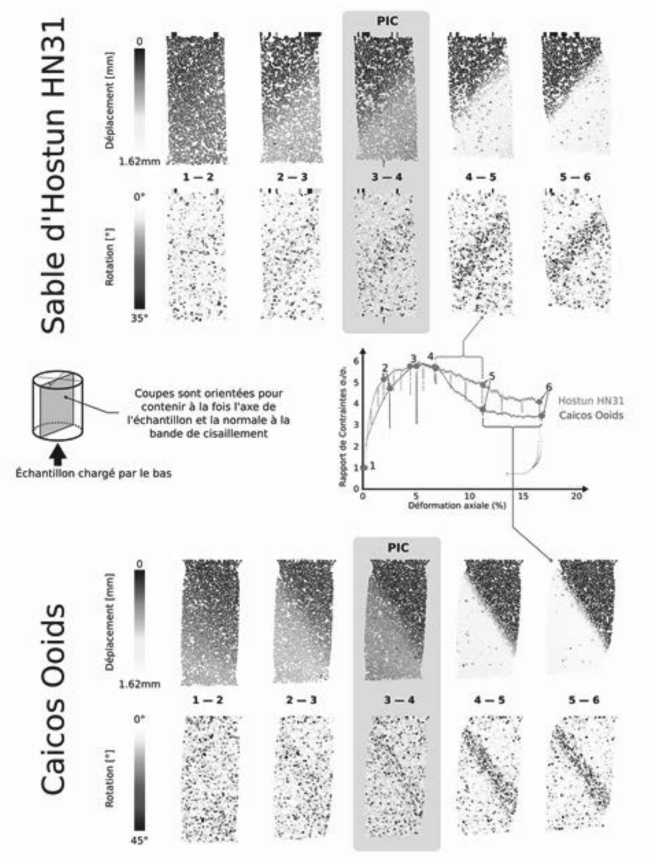


Figure 3. Slices showing grains of a triaxial test on Hostun sand (top) and Caicos ooids (bottom) at 100 kPa confinement, colored by their vertical displacement and intensity of 3D rotation. The increments studied are highlighted on the stress-ratio *vs.* axial shortening in the middle of the figure (*Andò et al. 2013*).

3.2 *Fine-grained soils from micro to macro*

Yigit et al. (2013) present a contribution investigating the time dependent behavior of clays. In this experimental study, ESEM micrographs of kaolinite clay are taken under different levels of load in oedometric compression, and after different amounts of creep time. The pixel size in the micrographs was 8.47×10^{-2} µm, which is small enough to see the macro voids (see Fig. 4).

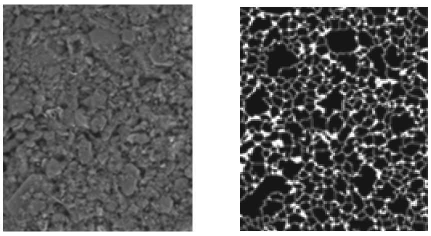


Figure 4. Raw (left) and segmented (right) ESEM micrographs of kaolinite clay (*Yigit & Cinicioglu 2013*).

Quantitative analysis of the processed images reveals that the particle size distribution evolves in rather a surprising manner, and an attempt is made to correlate this to analytical creep parameters coming from Yin (1999). This is a nice example of analysis in which measurements at the micro scale are related to a macroscopic model. Further work might benefit from more robust image analysis techniques.

The study presented by *Minder & Puzrin (2013)* is extremely interesting and very well suited to this session. In order to achieve a *macroscopic* objective (increasing the permeability of a clay soil), the Authors develop an innovative experimental technique to modify the *microstructure* of the soil by using cation exchange. More precisely, the highly selective and strongly exchanging organic cation guanidinium was used to stabilize the interlayer distance between clay platelets. The effectiveness of this chemical treatment is characterized at the micro scale using SEM (see Fig. 5) and laser diffraction (see Fig. 6) as well as at the macro scale, where the improvement appears both in terms of increased permeability (see Fig. 7) and enhanced shear strength.

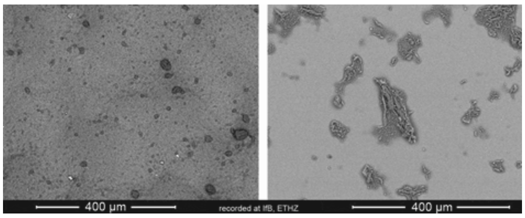


Figure 5. SEM-images of bentonite grains after washing in suspension with demineralised water. The calcium form remains finely dispersed (left), whereas the exposure to guanidinium ions (right) leads to the formation aggregates *(Minder & Puzrin 2013)*.

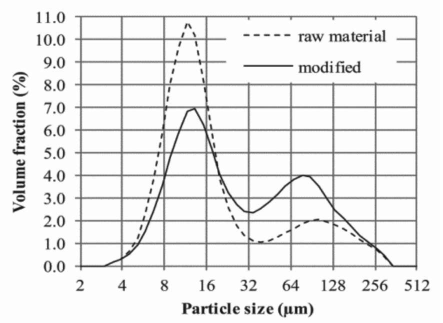


Figure 6. Bimodal particle size distribution measured with laser diffraction. The volume fraction of the larger mode (aggregates) is significantly increased by the treatment *(Minder & Puzrin 2013)*.

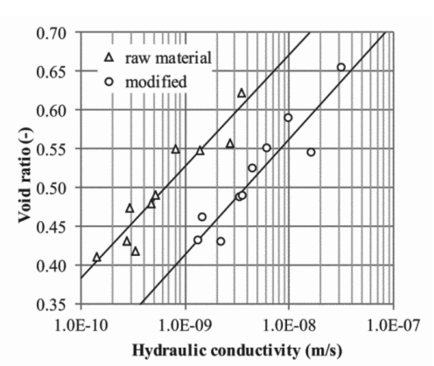


Figure 7. Decrease of hydraulic conductivity during sample compaction (including log-linear regression) of quartz-bentonite mixtures. For identical void ratio the modified soil is constantly about one order of magnitude more permeable *(Minder & Puzrin 2013)*.

3.3 *Learning mechanics from DEM*

In the study by *Jiang et al. (2013)*, DEM is used to describe at the particle level the mechanics of sand containing methane hydrates. In fact, the presence of methane hydrates in deep sea beds significantly alters the mechanical properties of the host sand material, because methane hydrates act as a bond between particles. The study by *Jiang et al. (2013)* introduces a simplified contact model (see Fig. 8), which was experimentally calibrated in the laboratory. The bond failure criterion is directly linked to the strength of methane hydrates, which depends on temperature, mean normal stress, density and methane hydrate saturation of the sand. The results of DEM simulations are compared to experimental results for the case of plane strain compression of a methane hydrate bearing sand; the results seem to show that although highly simplified, this model qualitatively captures the mechanical effects of cementation at the macro scale.

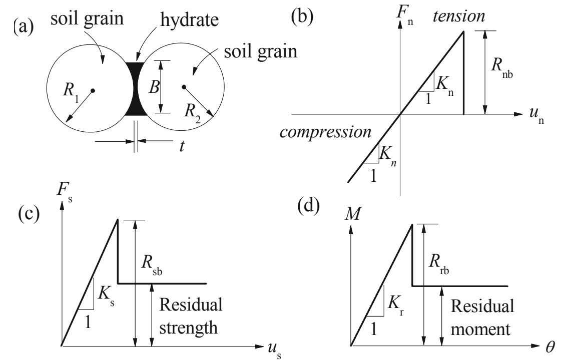
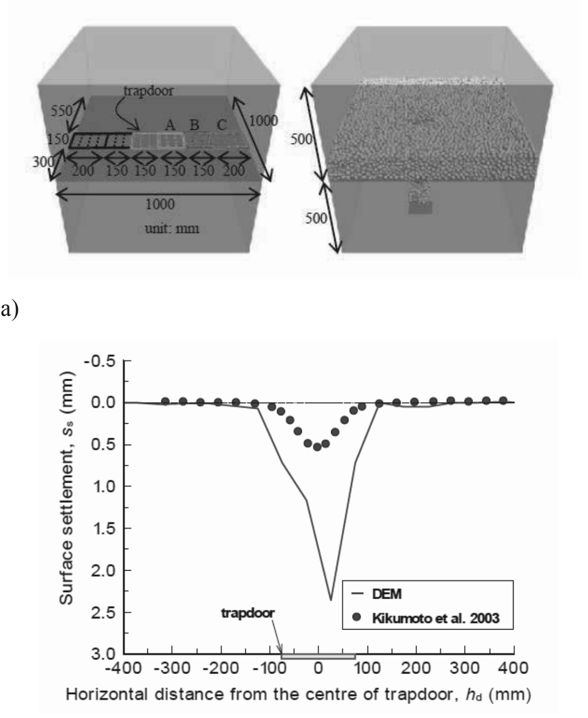


Figure 8. Schematic illustration of (a) MH bonded soil grains and its response: (b) normal contact force F_n against overlap u_n; (c) shear contact force F_s against relative shear displacement u_s; and (d) contact moment M against relative rotation θ (*Jiang et al. 2013*).

Ground loss at the head of tunnels and in mining operations is a classical geotechnical problem with important implications for infrastructure development in urban settings. It has been studied at the laboratory scale for a long time; see for example the now classical trapdoor experiment by Terzaghi (1936). The paper by *Kikkawa et al. (2013)* reports a 3D DEM study of trapdoor unloading and gravity flow of granular material. The geometry of the problem studied is the same of the trapdoor experiments previously performed by Kikumoto & Kishida (2003) – see Fig.9a. Although the results of the DEM simulations agree well with the measurements from the actual experiments in some respects (for example, the vertical stress on the trapdoor when it is moved downward), DEM is substantially off target in other instances, for example in terms of the settlement of the surface of the sand above the trapdoor, see Fig. 9b. These “major discrepancies” are attributed by the Authors to the difference between the actual grains of Toyoura sand (used in the experiments) and the particles used in the DEM modeling (which are much larger and spherical). The general lesson to be learnt here is that the application of DEM to the analysis of boundary value problems is not trivial, especially when one seeks quantitative results and not only for a qualitative insight – calibration of the model remaining a major issue.

It has been often advocated that the use of DEM in micromechanical studies can significantly help advance our understanding of fundamental geomechanics (*e.g.*, O’Sullivan 2011). In the writer’s opinion, DEM simulations are in fact a very useful tool for investigating the complex behavior of particulate materials, especially in conjunction with laboratory tests. In this respect, the study by *Ning & Evans (2013)* is of particular interest. The Authors address the fundamental issue of shear wave propagation in granular soil, using DEM simulations to investigate the effects of excitation frequency, particle size, and mean stress – which is of course possible, yet difficult, with laboratory experiments. Cylindrical assemblies of particles are subjected to shear wave excitation at one end and axial propagation velocities are measured (see Fig. 10). Micromechanical observations of the specimen are presented and analyzed in terms of particle velocity vectors, which highlight the complex motions of individual particles during wave propagation. As an example, velocity vectors in Fig. 11 show dominant S-wave motion (from right to left) in the central area of the specimen, while minor P-wave motion is observed on the sides (with the particle on the right moving downwards and the particle on the left moving upwards).



(a)

(b)

Figure 9. (a) Trap door and gravity flow testing apparatus (left), and DEM simulation (right); (b) Surface settlement of the sand above the center of the trapdoor when dt = 2.0 mm, layer thickness 150 mm *(Kikkawa et al. 2013).*

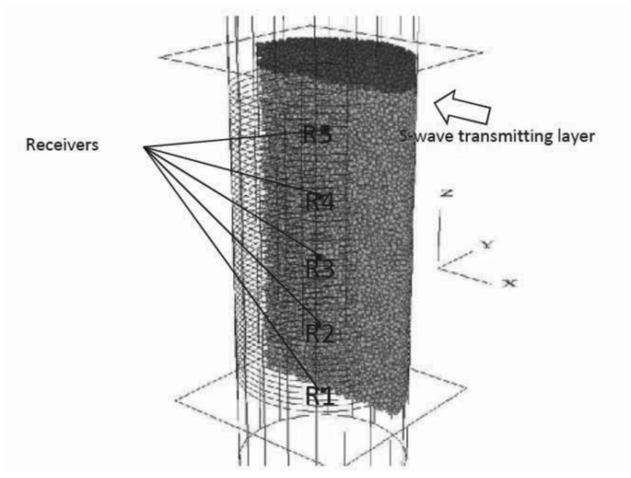


Figure 10. DEM specimen with S-wave transmitting layer and receivers – for clarity, only half of the specimen is shown (*Ning & Evans 2013*).

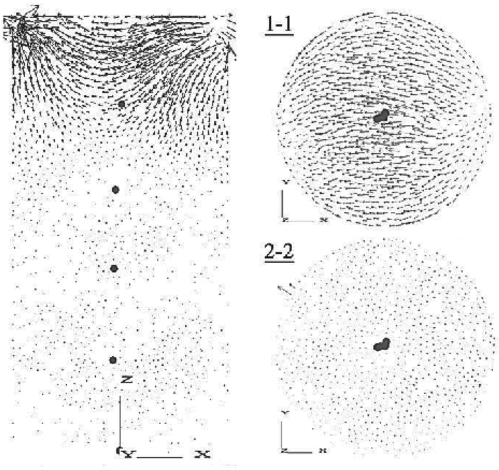


Figure 11. Particle velocity vectors on different cutting planes of a DEM specimen at a 10ms time point after excitation (*Ning & Evans 2013*).

The paper by *Tomac & Gutierrez (2013)* also uses DEM as a tool for understanding processes, the focus of this nice study being the flow of dense sand slurries within a narrow channel – where "dense" means that the volumetric particle concentration is greater than 10%, and "narrow" that the width of the channel is less than 5 times the particle diameter. In these flow processes, clogging and velocity retardation often occur and are governed by sand concentration and slurry flow rate. The numerical model developed by the Authors couples the Discrete Element Method with computational fluid dynamics to study (in 2D) this flow process. A user-defined contact model is developed to capture the non-linear collision of submerged particles and walls. The theory of lubrication is also used to formulate a damping effect which is associated with the model. Some key results of this study are shown in Fig. 12. Maximum sand concentration (*i.e.*, the concentration at which sand transport is not possible and the flow stops) is shown to depend on the ratio of channel width to particle diameter, as well as – to a lesser extent – on fluid pressure. Since solid and fluid phases have different average velocities, it is hard to average and come up with a unique slurry flow characterization at this point; the Authors conclude that a more comprehensive study is needed to address this issue.

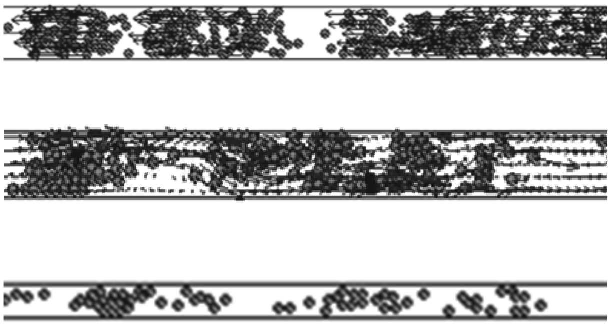


Figure 12. (top) Clogging of sand in 4mm wide channel at initial volumetric sand concentration c_v = 0.49 with particles velocities vectors in direction opposite to the flow; (middle) Unstable flow with formation of particles packs at initial c_v = 0.39 in 4mm wide channel with fluid flow velocity vectors around packs; (bottom) Formation of particles packs at initial c_v = 0.28 in 2mm wide channel (*Tomac & Gutierrez 2013*).

3.4 *Exploring micromechanics analytically*

The contributions by *Shao et al. (2013)* and by *Caicedo et al.* (2013) both present theoretical developments. *Shao et al. (2013)* provide an analytical evaluation of the effect of pore water pressure on the effective stress in the soil skeleton for saturated and unsaturated media. Even though the developments are certainly correct, the objective and conclusions of this study appear somewhat obscure to the reporter.

The paper by *Caicedo et al. (2013)* reports an interesting theoretical development regarding grain crushing – which is of particular relevance when granular materials are used in engineering structures such as paved roads, railroads and highway embankments. The analytical model developed by the Authors aims to predict the evolution of the grain size distribution during loading. As an example, Fig. 13 shows the evolution of the grain size distribution predicted by the model after a very high number (up to one million) of loading cycles. The model uses the theory of poly-disperse mixtures proposed by De Larrard (2000), and predicts grain breakage by combining the geometrical relevance of a size class of grains with a statistical distribution of strength (given by a Weibull distribution). When a particle breaks, the size of its fragments is determined through a Markov process. The combination of these elements appears to capture grain breakage successfully – the application of this model to experimental results is shown to give very good agreement. It is the Authors' contention that their model is a valid alternative to DEM, which can also deal with grain crushing but is computationally very expensive.

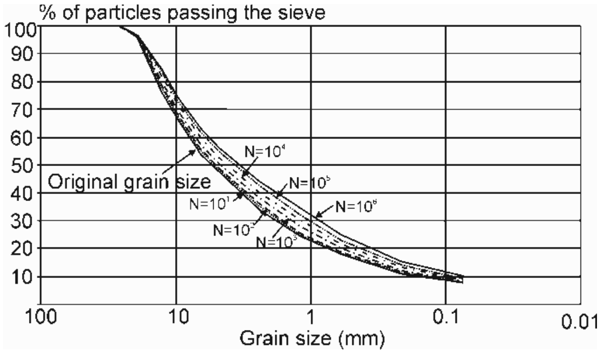


Figure 13. Evolution of the grain size distribution for different number of loading cycles *(Caicedo et al. 2013).*

3.5 *Engineering applications for energy production*

Interestingly, there is only one contribution to this session making use of the Finite Element Method (FEM). This is the numerical study by *Khoa et al. (2013)*, which tackles the analysis of the damage induced by drilling and coring operations in the rock surrounding a wellbore. This is a two-scale analysis, in that a large scale 3D FE model is first used to simulate the stresses induced by drilling and coring (see Fig. 14); these stresses are then injected into a 2D micro scale FE model, the geometry of which is directly built on experimental SEM observations of well cemented sandstone. The results show that the micro FE model is able to pick up mechanisms of failure that simply do not feature in the macro-scale continuum model.

When going to the smaller scale analysis, the Authors implicitly assume that a Mohr-Coulomb elastic perfectly plastic model is capable of reasonably describing the stress state at the micro scale. It should be mentioned that the paper does not give any detail as for the determination of the mechanical parameters used in the analysis at the micro scale. Moreover, strong assumptions are made on the geological history (*e.g.*, the grain skeleton carries the load before getting cemented – which means that as soon as unloading occurs, the inter-granular cement gets loaded in tension and fails).

The approach adopted by Khoa and coworkers is certainly original and interesting. However, although the analysis presented in this study is indeed performed at two different scales, it should be stressed that the only link between the two scales is the stress in one point.

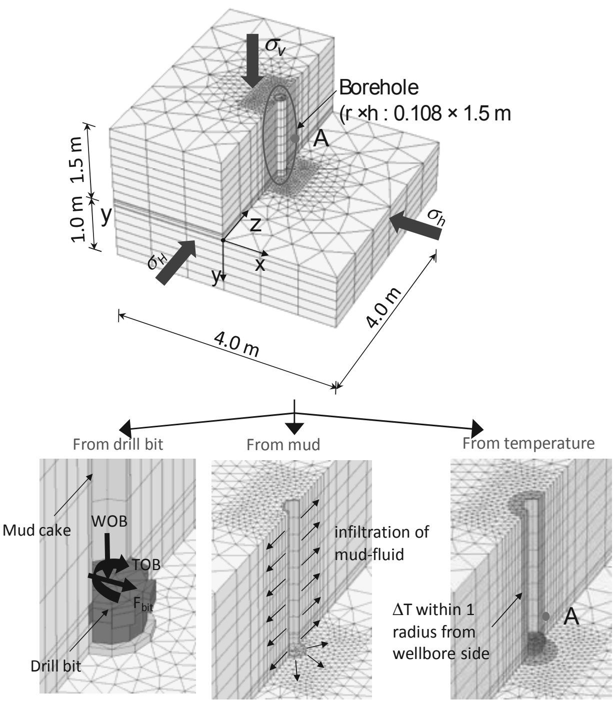


Figure 14. Full 3D FE modeling of different loads due to drill bit torque and axial load, mud-flow into formation and temperature change within one radius from wellbore wall *(Khoa et al. 2013).*

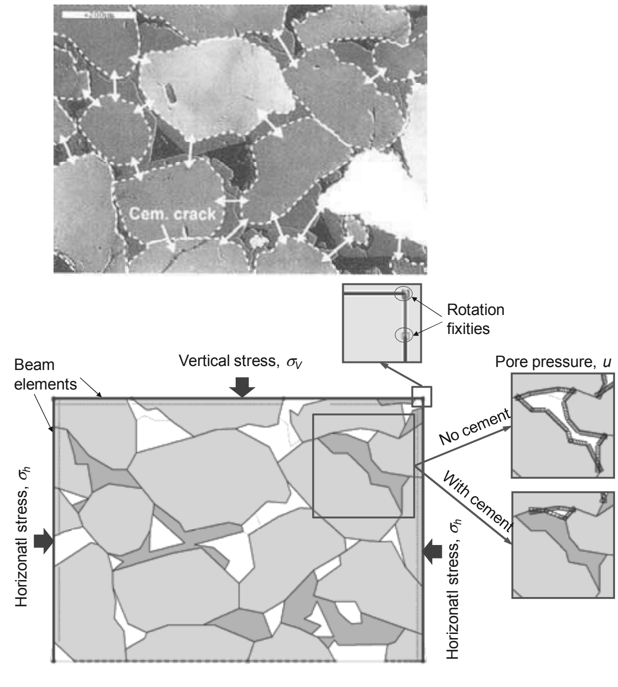


Figure 15. Cathodoluminescence SEM picture (top) from Storvoll & Bjorlykke (2004) and equivalent 2D micro FE model (bottom) used for studying induced damage around a wellbore during drilling and coring operations *(Khoa et al. 2013)*.

The second paper related to energy production is the study by *Hyodo et al. (2013),* who carried out a large laboratory experimental campaign to determine the mechanical properties and dissociation characteristics of sandy soils containing methane hydrate. The testing devices include a high pressure triaxial apparatus, capable of reproducing the in-situ conditions expected during methane extraction. Moreover, a high pressure and low temperature plane strain apparatus allowed the imaging of (localized) deformation of methane hydrate bearing sand due to methane hydrate production. Using this latter apparatus, two tests were performed: plane strain compression and methane hydrate dissociation by depressurization. The dissociation tests were carried out in two different ways, either prescribing a pore water pressure history corresponding to real production of methane hydrate (Case 1), or by simulating the stress conditions in the vicinity of the production well, where the material is close to failure (Case 2).

This is a very interesting application, in which the micro-scale physics (the methane hydrate bonding) is clearly driving the behavior observed at the macro scale. The study certainly lacks direct experimental observations at the micro scale – even though the strain fields obtained by DIC can be considered as measurements at a scale somewhere in between macro and micro. By controlling the pressure (see Fig. 16) Hyodo and co-workers nicely isolate the effect at the macro scale of a micro-scale feature (cementation); in this respect, their contribution fits very well the general theme of the session: from micro to macro.

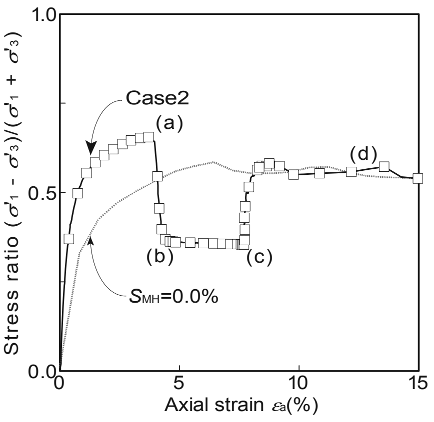


Fig.16. Effective stress ratio *vs*. axial strain during a dissociation test for Case 2. Point (a) corresponds to the point before dissociation, and point (b) to the point when pwp is decreased from 10MPa to 3MPa. Point (c) corresponds to the point when MH is dissociated, and point (d) to the point when the specimen failed due to an increase in pore water pressure (re-pressurization) – note that failure occurred when the stress path reached the strength of the host sand *(Hyodo et al. 2013).*

Pak & Sheikh (2013) present the 2D implementation of a Lattice Boltzmann Method code that allows the simulation of immiscible fluids (water and oil) flowing in porous rock – a classical and central issue in petroleum geomechanics. The code is validated against some basic test cases, and is then applied to partially reproduce experimental results from Valavanides *et al*. (1998) and Tsakiroglou *et al.* (2007) in both steady and unsteady conditions. The comparison between experimental and simulated results is encouraging and shows that the technique is promising (see Figs. 17 and 18).

3.6 *Contributions focusing on the macro scale*

Heitor et al. (2013) present an experimental study on unsaturated silty sands, where materials compacted to different levels are tested at different constant water contents in direct shear. Even though the results of this experimental investigation are justified by means of micromechanical arguments, this remains a study at the macro scale only.

The contribution by *Zhou et al (2013)* deals with an experimental evaluation of the effects of suction and temperature on the cyclic behavior of soils – in particular the resilient modulus. This is also a study at the macro scale only.

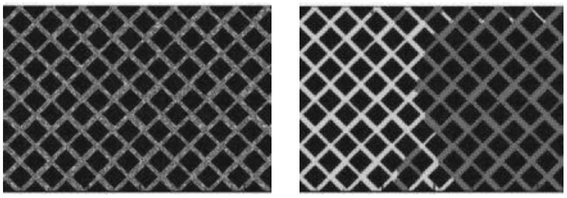


Figure 17. (left) example of initial distribution of the fluids in steady-state simulation; (right) example of invasion of wetting fluid(green) in unsteady state simulation *(Pak & Sheikh 2013).*

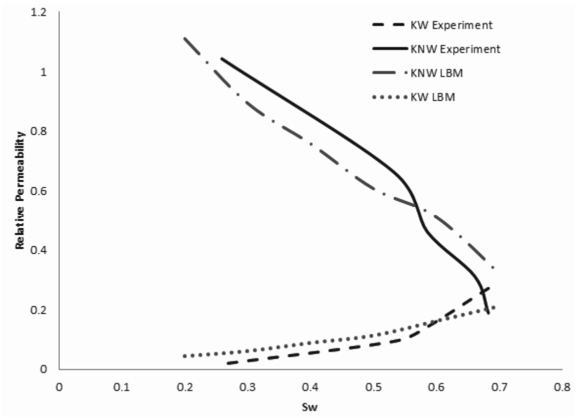


Figure 18. Comparison of Lattice Boltzmann modeling results and experimental relative permeability curves (steady state) *(Pak & Sheikh 2013).*

4 CONCLUSIONS

While our discipline has traditionally focused on the macro scale, the papers submitted to this session show that a broad spectrum of approaches, materials and techniques are now becoming available to explore the behavior of geomaterials at smaller scales. These tools are bringing new insights into the physical processes driving the macroscopic behavior.

As our understanding of the micro behavior of geomaterials progresses, it will be crucial to explicitly build a link between the micro and macro scales – none of the contributions to this session has yet accomplished this ambitious goal. As a matter of fact, bridging the gap between micromechanical studies and continuum approaches at the macro scale is one of the emergent directions in mechanics and material science, not only in geomechanics. This should be the central theme for discussion in this session.

Multiscale methods have emerged recently in geomechanics to bridge different material scales ranging from the micro scale to continuum scale (*e.g*., Andrade *et al*. 2011, Nitka *et al*. 2011, Frey *et al.* 2013). These methods aim at obtaining constitutive responses at the continuum scale, without resorting to phenomenology. However, in most of these studies the multi-scale character is essentially tackled at the modeling level, involving theoretical and computational developments but missing experimental input. In the writer's opinion, experiments should be an essential part of a multiscale approach – how else can one make a realistic connection between micro scale physics and macro scale responses?

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