8th International Workshop on Bifurcations and Degradations in Geomaterials

May 28-31, 2008
Lake Louise, Alberta, Canada

http://www.schulich.ucalgary.ca/civil/IWBDG2008/

Welcome to IWBDG2008

The Organizing Committee is pleased to welcome you to IWBDG2008 in beautiful Lake Louise where we have planned a technical program representing the diverse facets of research and applications within the general field of geomechanics.

Outstanding speakers use specific aspects in their own areas of research to extend our general understanding of principles and mechanisms of failure in geomaterials. The presentations cover a wide range of topics and form the basis for scientific/technical exchange and stimulating discussions.

The IWBDG2008 program allows time for the informal discussions that are important aspects of a technical meeting, and provides opportunities for you to enjoy the natural beauty of Lake Louise and the splendour of the Rocky Mountains.

We wish you an informative, enjoyable and fruitful workshop.

Richard G. Wan
Chair, IWBDG2008

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PROGRAM AT A GLANCE

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9:20	9:45	H-B. Muhlhaus	S. Sivathayalan	P-Y. Hicher	J.G. Gaidos
9:45	10:10	A.M. Puzrin	X.S. Li	R. Wan	J.P. Hambleton
10:10	10:35	T. Nakai	F. Laouafa	A. Tordesillas	J. Maciejeweski
10:35	10:55	Coffee Break	Coffee Break	Coffee Break	Coffee Break
10:55	11:20	G. Viggiani	I. Vardoulakis	D.I. Garagash	R.Y. Moghaddam
11:20	11:45	N. Lenoir	D. Chan	S. Kimoto	J.S. Chen
11:45	12:10	Y. Yamakawa	G. Marketos	J.L.H. Grozic	R.A. Regueiro
12:10	12:35	A. Rechenmacher	T-F. Wong	M. Iwata	M. Zeghal
12:35	14:10	Lunch	Lunch	Lunch	Lunch
14:10	14:35	R. Nova	F. Oka		A. Dyskin
14:35	15:00	W. Wu	K. Oda		E. Pasternak
15:00	15:25	D. Peric	H. Nonoyama		C. Dascalu
15:25	15:50	K-T. Chau	F. Zhang		A. Daouadji
15:50	16:15	K.A. Issen	R.I. Borja	**Free**	I. Einav
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16:35	17:00	R. Chambon	S. Bonelli		K. Hill
17:00	17:25	J. Tejchman	J. Graham		J. Labuz
17:25	17:50	C.D. Foster	M. Gutierrez		DISCUSSION
17:50	18:15	Y. Higo	H. Huang		CLOSURE
19:30	-	**Welcome Reception**	**Dinner**		**Banquet**
		Brewster Dance Barn	**Chateau Lake Louise**		**Chateau Lake Louise**

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TECHNICAL PROGRAM

Wednesday, May 28th, 2008
Day 1

8:00 – 8:30	***Registration***	***Heritage Hall***
8:30 – 8:55	***Opening Ceremony***	***Mount Temple A***

Anisotropy and Structured Media — ***Mount Temple A***
Chair: M. Gutierrez

8:55 – 9:20 ***Critical plane approach to analysis of failure criteria and damage evolution rules in anisotropic geomaterials***
[Z. Mroz] and J. Maciejewski

9:20 – 9:45 ***Modelling of noncoaxial viscoplastic deformations in geodynamics***
[H-B. Muhlhaus] and L. Moresi

9:45 – 10:10 ***Experimental and numerical validation of the energy balance approach to the shear band propagation in soils***
[A.M. Puzrin] and E. Saurer

10:10 – 10:35 ***A simple method to consider density and bonding effects in modeling of geomaterials***
[T. Nakai], M. Kikumoto, H. Kyokawa and F. Zhang

10:35 – 10:55	***Break***	***Coffee & Tea in Heritage Hall***

Physical Models and Lab Experiments — ***Mount Temple A***
Chair: I. Vardoulakis

10:55 – 11:20 ***Combining X-ray CT and 3D digital image correlation for studying localized deformation in stiff clay under triaxial compression***
[G. Viggiani], S.A. Hall, N. Lenoir, P. Bésuelle and J. Desrues

11:20 – 11:45 ***Combining X-ray CT and 3D digital image correlation for studying strain localization in granular materials***
[N. Lenoir], Y. Pannier, S.A. Hall, M. Bornert, P. Bésuelle, J. Desrues and G. Viggiani

11:45 – 12:10 ***Image analysis of diversified geometrical patterns of shear bands on granular material engendered by bifurcations***
[Y. Yamakawa] and K. Ikeda

12:10 – 12:35 ***Grain column evolution in shear bands in sand***
[A. Rechenmacher]

12:35 – 14:10 **Lunch** ***Tom Wilson Restaurant***

Instability and Localization Analyses of Geomaterials Using Constitutive Models ***Mount Temple A***
Chair: F. Darve

14:10 – 14:35 ***Loss of controllability in partially saturated soils***
G. Buscarnera and [R. Nova]

14:35 – 15:00 ***Localization analysis with strain-gradient extended hypoplasticity***
V.A. Osinov and [W. Wu]

15:00 – 15:25 ***Strain localization in elastic-plastic composites subjected to plane stress loading***
[D. Peric] and H. Rasheed

15:25 – 15:50 ***Fluttering instability in geomaterials***
[K-T. Chau] and J.D. Zhao

15:50 – 16:15 ***Theoretical and experimental implications of true triaxial testing of porous sandstone***
[K.A. Issen], T.A. Dewers and D.J. Holcomb

16:15 – 16:35 **Break** ***Coffee & Tea in Heritage Hall***

Numerical Issues in Capturing Localization ***Mount Temple A***
Chair: R.I. Borja

16:35 – 17:00 ***Are problems involving non controllable geomaterials computable?***
[R. Chambon]

17:00 – 17:25 ***FE-calculations of a deterministic and statistical size effect in granular bodies including shear localization***
[J. Tejchman], J. Gorski

17:25 – 17:50	***Localization analysis of a three-invariant geomaterial model with isotropic and kinematic hardening: analytical and numerical insights*** [C.D. Foster] and R.A. Regueiro
17:50 – 18:15	***An elasto-viscoplastic model for diatomaceous mudstone and numerical simulation of compaction bands*** F. Oka, S. Kimoto, [Y. Higo], H. Ohta and T. Sanagawa

19:30 – 22:00	**Welcome Reception**	***Western BBQ Dinner at Brewster Dance Barn***

Thursday, May 29th, 2008
Day 2

Physical Models and Lab Experiments	*Mount Temple A* Chair: F. Oka

8:30 – 8:55 *An analytical and experimental study of the post-peak response of hierarchical structures*
[Z. Chen] and J.F. Labuz

8:55 – 9:20 *Fabric and particle shape dependency of suction and its influence on strength anisotropy of moist sand*
[P. Guo]

9:20 – 9:45 *Experimental characterization of instability: Effects of fabric and shear-volume coupled deformation*
[S. Sivathayalan], A M. Yazdi and P. Logeswaran

9:45 – 10:10 *Phase transformation, critical state and liquefaction*
[X.S. Li] and X. Li

10:10 – 10:35 *Experimental and numerical modelling of diffuse mode of failure in very loose sands*
[F. Laouafa], A. Daouadji and F. Darve

10:35 – 10:55 **Break**	***Coffee & Tea in Heritage Hall***

Numerical Issues in Capturing Localization	*Mount Temple A* Chair: R. Regueiro

10:55 – 11:20 *Stability of steady creep of thermally driven slides*
[I. Vardoulakis] and E. Veveakis S.A.

11:20 – 11:45 *Fracture modelling using the Discrete Finite Element method*
[D. Chan] and G. Bala

11:45 – 12:10 *Reproduction of a compaction band in DEM simulations*
[G. Marketos] and M. Bolton

12:10 – 12:35 *Compaction localization and grain crushing in porous sandstone: constitutive modeling, microstructural evolution and discrete element simulation*
[T-F. Wong]

12:35 – 14:10 Lunch ***Tom Wilson Restaurant***

Geomechanics Applications ***Mount Temple A***
Chair: D. Peric

14:10 – 14:35 ***A multiphase numerical analysis of the strain localization of unsaturated embankment associated with seepage flow***
[F. Oka], S. Kimoto and S. Yamazaki

14:35 – 15:00 ***CIP-based numerical simulation of soil/snow avalanche***
[K. Oda], A. Yashima, K. Sawada, M. Goshima, S. Moriguchi, A. Sato and I. Kamiishi

15:00 – 15:25 ***Performance of SPH method for deformation analyses of geomaterials***
[H. Nonoyama], A. Yashima, K. Sawada and S. Moriguchi

15:25 – 15:50 ***Cyclic mobility of sand and its simulation in boundary value problems***
[F. Zhang], T. Nakai, Y.J. Jin, B. Ye and K. Noda

15:50 – 16:15 ***Deformation and failure processes in geologic materials at scales from grains to basins***
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16:15 – 16:35 Break ***Coffee & Tea in Heritage Hall***

Degradation and Internal Erosion ***Mount Temple A***
Chair: F. Nicot

16:35 – 17:00 ***Piping erosion: testing and modelling***
[S. Bonelli]

17:00 – 17:25 ***Natural processes and strength degradation***
[J. Graham] and M. Alfaro

17:25 – 17:50 ***Pore-fluid induced degradation of soft rocks***
[M. Gutierrez] and R. Hickman

17:50 – 18:15 ***Fluid injection in granular media***
[H. Huang] and R. Wu

19:30 – 22:00 Dinner ***Sun Room***

Friday, May 30th, 2008
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Micromechanical Origins of Instability using Discrete or Micromechanical-Continuum Approach	*Mount Temple A* Chair: R. Nova

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[F. Darve], F. Prunier, L. Sibille and F. Nicot

8:55 – 9:20 *The concept of loss of sustainability in granular materials*
[F. Nicot], L. Sibille and F. Darve

9:20 – 9:45 *Investigating instability conditions in granular materials with different initial densities by means of a micro-structural constitutive model*
[P-Y. Hicher] and C.S. Chang

9:45 – 10:10 *Failure in granular materials in relation to material instability, fabric and plastic flow issues*
[R. Wan], M. Pinheiro and Q. Li

10:10 – 10:35 *Glimpses of the promise of micromechanics in modeling granular materials*
[A. Tordesillas]

10:35 – 10:55 Break *Coffee & Tea in Heritage Hall*

Thermal/Mechanical/Chemical Interaction and Coupled Processes	*Mount Temple A* Chair: A. Rechenmacher

10:55 – 11:20 *Shear heating in localized shear zones: Incipient slip instability and dynamic slip propagation*
[D.I. Garagash]

11:20 – 11:45 *A chemo-thermo-mechanically coupled analysis of ground deformation induced by methane hydrate dissociation*
[S. Kimoto] and F. Oka

11:45 – 12:10 *Geomechanical behaviour of gas hydrate sediment mixtures*
[J.L.H. Grozic]

12:10 – 12:35	***Local behavior of pore water pressure in the specimen during plane-strain compression test of soft rock and its numerical simulation*** [M. Iwata], A. Yashima and K. Sawada

12:35 – 14:10	**Lunch**	***Tom Wilson Restaurant***

FREE AFTERNOON

Saturday, May 31st, 2008
Day 4

Soil-Machine Interaction: Numerical Analysis and Analytical-Based Models — ***Mount Temple A***

Chair: H. Muhlhaus

8:30 – 9:20 ***A review for numerical tools employed in soil dynamics and soil-machine interaction***
[M.I. Alsaleh]

9:20 – 9:45 ***Simulation of earthmoving operations using method of corrected smooth particle hydrodynamics (CSPH)***
[J.G. Gaidos]

9:45 – 10:10 ***Modeling processes involving soil-wheel interaction***
[J.P. Hambleton] and A. Drescher

10:10 – 10:35 ***Analysis of deformation and damage processes in soil-tool interaction problems***
[J. Maciejewski] and Z. Mroz

10:35 – 10:55 **Break** — ***Coffee & Tea in Heritage Hall***

Soil-Machine Interaction: Numerical Analysis and Analytical-Based Models — ***Mount Temple A***

Chair: G. Viggiani

10:55 – 11:20 ***Dynamic effect of ground looseness on hydraulic shovel performance***
M.G. Lipsett and [R.Y. Moghaddam]

11:20 – 11:45 ***A semi-lagrangian reproducing kernel formulation for modeling earthmoving operations***
[J.S. Chen], P. Guan, H. Teng, J. Gaidos, K. Hofstetter and M.I. Alsaleh

11:45 – 12:10 ***Concurrent multiscale computational modeling of particle to continuum length scale mechanics in unbound dense, dry particulate materials***
[R.A. Regueiro]

12:10 – 12:35 ***A micro-mechanical study of the interaction of liquefied granular soils with structural elements***
[M. Zeghal], T. Dessalegn, C. Medina, and U. El Shamy

12:35 – 14:10	**Lunch**	***Tom Wilson Restaurant***

Fracture Mechanics and Grain Crushing		***Mount Temple A*** Chair: W. Wu
14:10 – 14:35	***Concept of mesh scalability in mesh-dependent FEM simulations*** [A. Dyskin] and A. Caballero	
14:35 – 15:00	***Negative Poisson's ratio in geomaterials*** [E. Pasternak] and A. Dyskin	
15:00 – 15:25	***Micro and macro-structural size effects for damage in brittle materials*** [C. Dascalu] and G. Bilbie	
15:25 – 15:50	***Modelling undrained behaviour of granular materials at high stresses*** [A. Daouadji] and P.-Y. Hicher	
15:50 – 16:15	***From self organisation to congestion in comminuting granular systems*** [I. Einav], O. Ben-Nun, A. Tordesillas and Y.Z. Cai	

16:15 – 16:35	**Break**

Experimental exploration of shear banding		***Mount Temple A*** Chair: K. Issen
16:35 – 17:00	***Kinematics of granular mixtures subjected to shear*** [K.M Hill], J. Zhang and F. Yi	
17:00 – 17:25	***Shear banding in a brittle material*** J.J. Riedel, Q. Lin, C.-S. Kao and [J.F. Labuz]	

Closure

17:25 – 18:15	***Discussion***

19:30 – 22:00	**Closure Banquet**	***Alpine Room***

ABSTRACTS

CRITICAL PLANE APPROACH TO ANALYSIS OF FAILURE CRITERIA AND DAMAGE EVOLUTION RULES IN ANISOTROPIC GEOMATERIALS

Z. Mróz[a] and J. Maciejewski[b]

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Numerous geomaterials such as rock and soil exhibit structural anisotropy related to material fabric elements such as crack pattern, bedding, layering, contact arrangements, etc. The fundamental problem is associated with the specification of effective properties of the representative material element, accounting for microstructure and defect distribution. The present work is aimed at derivation of failure criteria for materials with anisotropic microstructure, such as crack pattern, microlaminate structure, or grain contact arrangement. The assumed density distribution function specifies the microstructure is used in deriving the failure criteria and damage evolution rules for specified deformation histories.

The state of a material is described by the damage density distribution on the physical planes. The critical plane approach is used with account for damaged and intact area fractions. The maximum of failure function is specified for all potential failure planes and critical plane orientation is determined. The derived failure condition is applied to study strength evolution for triaxially compressed specimens with varying orientation of principal stress and damage tensor axes. Also a general stress state is considered and the representative failure condition is derived.

The damage evolution rule is next considered by assuming crack growth on a physical plane to be induced by the local strain increment. The failure condition is then affected by damage growth both in stable and post-critical states. The presented approach can be applied to study damage growth on contact interfaces and in material plane elements.

The application of derived damage rules and failure criteria to particular cases is discussed. In particular, the limit states are specified for several engineering cases, such as embedded anchor pull out, passive thrust on retaining walls and plane foundation.

References

[1] S. Pietruszczak and Z. Mróz, "Formulation of anisotropic failure criteria incorporating a microstructure tensor", Computers and Geotechnics., v. 24, 105-112, 2000.

[2] S. Pietruszczak and Z. Mróz, "Formulation of failure criteria for anisotropic frictional materials", Intl. J. Num. Anal. Meth. Goemech, v. 25, 509-524, 2001.

[3] Z. Mróz and J. Maciejewski, "Failure criteria of anisotropically damaged materials based on the critical plane concept", Int. J. Num. Anal. Meth. Goemech, 26, 407-431, 2002.

[4] Z. Mróz and J. Maciejewski, "Failure Criteria and Compliance Variation of Anisotropically Damaged Materials", Lecture Notes in Applied and Computational Mechanics v. 9, Ed. J.J. Skrzypek and A. Ganczarski; 75-112, Springer Verlag, 2003.

MODELLING OF NONCOAXIAL VISCOPLASTIC DEFORMATIONS IN GEODYNAMICS

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We give an outline of a constitutive relationship for transversely isotropic elastic-viscous materials. The formulation is intended either for materials with fine internal layering, which can be described by a single director orientation or in the context of non-co-axial plasticity. This constitutive model is specifically designed for geological deformation problems involving very large deformations. Although there are more general descriptions possible, this formulation is, in fact, very broadly applicable to crustal rocks, where the preponderance of layering arises from deposition of one rock type onto another under gravity. We revisit the basic finite element formulation for viscous materials and demonstrate how the standard element vectors and matrices can be extended to include emergent or pre-existing anisotropy. We explore scenarios from global to internal buckling in nonlinear finite element studies. The director formulation can also be used to define a preferred plane for slip to occur given the local stress field. The simple-shear viscosity and the deformation can then be iterated to ensure that the yield criterion is always satisfied. We also explore the emergence of transverse anisotropy in connection with the formation of melt bands in viscous materials assuming McKenzies (1984) model for partially molten rock.

EXPERIMENTAL AND NUMERICAL VALIDATION OF THE ENERGY BALANCE APPROACH TO THE SHEAR BAND PROPAGATION IN SOILS

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Progressive and catastrophic failure in soils has been commonly associated with the phenomenon of the shear band propagation. This is a challenging topic both in terms of understanding and modeling. Discontinuities, moving boundaries, scale effect are just some factors complicating the analysis. It is not surprising, therefore, that numerical simulations of the phenomenon of the shear band propagation bear a number of intrinsic problems.

An alternative to the numerical modeling could be a simple analytical approach, based on clear mechanical principles and, naturally, free of the mesh-dependency problems. It could facilitate a better understanding of the phenomenon and serve as a benchmark for numerical simulations. In particular, Puzrin and Germanovich [2] proposed to extend the fracture mechanics energy balance approach of Palmer and Rice [1] to model catastrophic shear band propagation in an infinite slope in granular materials with zero shear strength. Although the model is one-dimensional, its experimental validation and numerical simulations are difficult due to the catastrophic nature of the shear band propagation, which is a dynamic problem. Nevertheless, this simple model helped to explain both quantitatively and qualitatively some peculiar phenomena related to evolution of tsunamigenic landslides.

In general, everything based on the energy balance makes an impression of a fundamental approach and it is relatively easy to forget that there are many rather restrictive assumptions involved. Needless to say, the ultimate proof is always the experimental validation.

Unfortunately, for the shear band propagation, physical modeling is also a challenge: unstable catastrophic propagation takes place very fast, while the stable progressive propagation has been observed only in very few experimental setups. One of these setups is a trapdoor test. Though the typical trap door test results have been extensively presented in the literature, not many successful attempts have been undertaken in modeling the rate of the shear band propagation in these tests. Another setup allowing for the progressive shear band propagation is a novel shear blade test. In spite of the completely different geometry of the two tests, the energy balance approach produced similar analytical solutions, which have been shown to provide a better fit to the experimental data than the corresponding numerical simulations.

References

[1] A.C. Palmer and J.R. Rice, "The growth of slip surfaces in the progressive failure of over-consolidated clay", Proceedings of the Royal Society London A, 332: 527-548, 1973.

[2] A.M. Puzrin and L.N. Germanovich, "The growth of shear bands in the catastrophic failure of soils", Proceedings of the Royal Society London A, 461: 1199-1228, 2005.

A SIMPLE METHOD TO CONSIDER DENSITY AND BONDING EFFECTS IN MODELING OF GEOMATERIALS

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A simple method to describe stress-strain behavior of structured soils under normally and over consolidated states in general stress conditions is presented. Based on an idea that structured soils are formed due to a kind of bonding effects between soil particles, a simple elastoplastic model is formulated by extending subloading t_{ij} model (Nakai and Hinokio, 2004). Firstly, a new interpretation of subloading surface concept for describing the influence of density and/or confining pressure is shown. Then a method to take into consideration the effect of bonding on the soil behavior in constitutive modeling is developed. By introducing this method for considering bonding to the subloading t_{ij} model, the stress-strain behavior of structured soils can be described. The validity of the proposed model is checked through numerical simulation of oedometer tests and drained and undrained shear tests on structured clays. Fig. 1 shows the calculated e–ln p relations of the clay with the same initial bonding effect represented by variable ω_0=0.2 but different initial void ratio. Figs. 2 and 3 show the calculated effective stress path and stress-strain curves of the same clays under undrained triaxial compression and extension tests. These calculated results describe well the typical features of the behavior of structured soils.

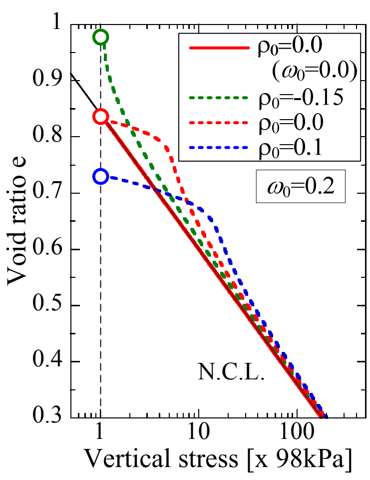

Fig. 1 Calculated results of oedometer tests

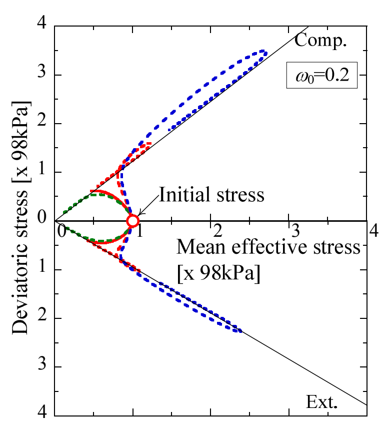

Fig. 2 Calculated effective stress path in undrained tests

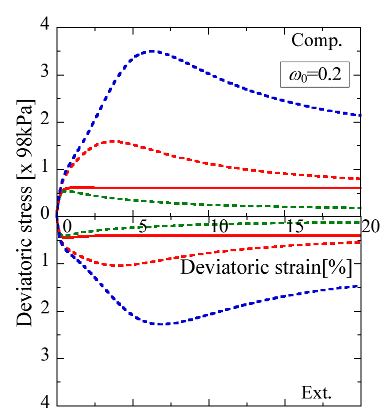

Fig. 3 Calculated stress–strain curves in undrained tests

References

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COMBINING X-RAY CT AND 3D DIGITAL IMAGE CORRELATION FOR STUDYING LOCALIZED DEFORMATION IN STIFF CLAY UNDER TRIAXIAL COMPRESSION

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A set of drained triaxial compression tests on specimens of a stiff natural clay (Beaucaire Marl) were recently performed under tomographic monitoring at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, using an original experimental set-up developed at Laboratoire 3S-R, Grenoble. Complete 3D images of the specimens were recorded several stages throughout each test using X-ray micro tomography. Such images were subsequently analyzed using an in house 3D Volumetric Digital Image Correlation software. Full-field incremental strain measurements were obtained, which allow detecting the onset of shear strain localization and its timing relative to the load peak. We identified different features of localized deformation, including fractures, and characterized their spatial and temporal development in relatively complex 3D patterns. Volumetric Digital Image Correlation revealed patterns which could not be directly observed from the original tomographic images, because the deformation process in the zones of localized deformation was note necessarily associated to density changes.

COMBINING X-RAY CT AND 3D DIGITAL IMAGE CORRELATION FOR STUDYING STRAIN LOCALIZATION IN GRANULAR MATERIALS

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A set of triaxial compression tests on specimens of a granular material (Hostun sand) were recently performed with concurrent synchrotron x-ray micro-tomography (at European Synchrotron Radiation Facility (ESRF) in Grenoble, France) using an original experimental set-up developed at Laboratoire 3S-R. Complete 3D tomography images of the specimens were recorded at several stages throughout each test with a sufficient spatial resolution to observe individual grains and thus characterise the deformation at different scales (the macro (sample), meso ("continuum") and micro (grain) scales) whilst still maintaining the mechanical pertinence of the test. The analysis of this deformation at different scales is possible through digital image correlation (DIC) approaches. However, the DIC analysis of these data requires new approaches to handle the discrete nature of the media being studied, of the mechanisms involved and of the acquired images. To this end new 3D-volumetric DIC methodologies have been proposed. Initial results from this analysis are promising and work is on-going to fully assess the proposed approaches and subsequently to analyse the full data set. Results will be presented from this analysis with the aim of highlighting the mechanics of localised deformation in granular media.

IMAGE ANALYSIS OF DIVERSIFIED GEOMETRICAL PATTERNS OF SHEAR BANDS ON GRANULAR MATERIAL ENGENDERED BY BIFURCATIONS

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Granular material under shear deformation exhibits diverse and characteristic geometrical patterns. To avoid such diversity, extensive experimental efforts were undertaken to make granular material specimens as uniform as possible, but all have been fruitless. It has been a long-standing paradox that the patterns of shear bands are so diversified that every test appears to be unique, even when conducted under identical conditions. The frustrating and surprising aspect underscored in this case is that experimental efforts to make specimens as homogeneous as possible elicit unpredictable responses, which are designated later as the chaotic explosive increase of possible bifurcation states.

To resolve that paradox, the authors investigated the shear behavior from a completely new viewpoint: pattern formation by symmetry breaking bifurcation. By contrast, most studies on strain localization and the formation of shear bands have been conducted up to now from the viewpoint of mechanics of solids. By virtue of the new viewpoint, the authors have succeeded in untangling the mechanism of shear behavior. The major findings are twofold:

1) A chaotic explosive increase of possible post-bifurcation states is an underlying mechanism to diversify geometrical patterns of shear bands.

2) The geometrical pattern of granular material is engraved by the evolution of bifurcation with a diamond-like diffuse-mode breaking uniformity, followed by further bifurcation, mode-jumping, and the formation of shear bands through localization.

The methodology used in this paper is a synthesis of theoretical, numerical and experimental studies, the foundations of which were developed by the authors as follows:

1) A creative methodology of image analysis based on the group-theoretic bifurcation theory [1] to extract bifurcation modes from digitized image data of deformation field on the specimen [2].

2) Numerical bifurcation analysis of soil deformation based on FEM [3].

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GRAIN COLUMN EVOLUTION IN SHEAR BANDS IN SAND

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It is well known that force chains, or columns of grains, form the primary mechanism for shearing resistance in granular media. In sands, under conditions of localized straining, such as in shear bands and in laboratory-simulated fault gouge, preliminary data suggest that evolutions in macro-scale response result from evolutions in the behaviors of these columns (e.g. [1]). Thus, better understanding of the physics of these fine scale features is likely to enhance predictive capability. We present experimental observations of the kinematic signatures of grain column activity within shear bands in sand. The kinematics are calculated from local displacement data obtained at grain-scale intensity from Digital Image Correlation (DIC) analyses performed on images of sand specimens undergoing plane strain compression. Previous research has revealed spatial fluctuations in magnitudes of various strain and displacement components along the length of a shear band: the patterns manifested in these spatial fluctuations, we have argued, are the kinematic signatures of grain column activity [2]. Herein, we track the evolutions of the spatial patterns reflected in these data, and thus the evolution of grain column activity, throughout softening and critical state. Specific questions we are currently addressing relate to the "lives" of the grain columns. For instance, locally computed volumetric data indicate that spatially fluctuating dilative activity during softening transitions to spatially fluctuating contraction during critical state. Could the former be associated with grain column buildup, and the latter grain column collapse? If so, what happens after grain column collapse? Or, are neighboring columns continually building up and collapsing throughout softening and critical state? These questions are targets for ongoing investigation, and up-to-date results will be discussed in the presentation.

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LOSS OF CONTROLLABILITY IN PARTIALLY SATURATED SOILS

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A new model for partially saturated soils is formulated. The model is based on the concept of energy conjugated generalised stress variables. A convenient expression for effective stresses for partially saturated soils is given. It is shown that the saturation index acts as an extensive variable (generalised strain), the corresponding intensive variable (generalised stress) being the effective suction (suction multiplied by the porosity of the specimen). Several comparisons with experimental data show that the model is able to capture well the essential features of the behaviour of partially saturated soils.

The controllability of generalised loading tests is then considered. In particular tests at varying water content are considered. It is shown that instability phenomena, such as collapse at constant loading, can be described by the theory of controllability.

The practical applicability of such results is envisaged, with reference to the destructive flow slides of Sarno and Quindici (wetting induced pyroclastic soil liquefaction).

LOCALIZATION ANALYSIS WITH STRAIN-GRADIENT EXTENDED HYPOPLASTICITY

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Granular materials show scale dependence in the post-localization regime. The description of this phenomenon lies beyond the capability of conventional constitutive models. We present an extension of the hypoplasticity theory by introducing the second-order gradient of the strain rate into the constitutive equation. The strain-gradient extension is aimed at the adequate modeling of the shear band formation in the post-localization regime. It is proved analytically that the proposed extended model produces finite-thickness shear-band solutions if and only if the stress state is a post-bifurcation state for the original non-gradient model. The problem of pure shear with an initially inhomogeneous distribution of the void ratio is solved numerically as an example to substantiate the theory. The numerical calculations show that the thickness of the shear band is invariant to the width of the initial inhomogeneity which induces the shear band.

STRAIN LOCALIZATION IN ELASTIC-PLASTIC COMPOSITES SUBJECTED TO PLANE STRESS LOADING

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In this contribution we quantify the role of fibers in inhibiting the onset of strain localization in elastic-plastic fiber reinforced composites subjected to plane stress loading. A macroscopic tangent stiffness tensor is developed by consistently homogenizing the contribution of fibers in a representative volume element (RVE). It describes the class of composites that is characterized by elastic fibers, which reinforce an elastic-plastic matrix. A mathematical description of the elastic part of the tangent stiffness tensor contains the information about the fiber orientation, volumetric fiber content and it's the uniaxial tensile modulus of the fiber.

The solution for the hardening modulus at the onset of strain localization is obtained from the spectral properties of the macroscopic acoustic tensor. A critical hardening modulus is subsequently obtained by finding the maximum hardening modulus with respect to the orientation of a discontinuity surface, whereby the later is expressed in terms of the unit normal. Solutions are further illustrated on the examples of Drucker-Prager and von Mises yield criteria. Different stress states including biaxial tension and compression, uniaxial tension and compression and pure shear are ranked according to the efficiency of fibers in suppressing the strain localization for these stress states. Furthermore, effects of the fiber orientation and volumetric fiber content on suppressing the onset of strain localization are evaluated as well as the effects of fiber on the orientation of the discontinuity surface. Finally, the solutions are compared with previously published solutions for the elastic-plastic fiber reinforced composites subjected to plane strain loading.

In summary, the analytical solutions have demonstrated that fibers consistently inhibit the onset of strain localization in elastic-plastic fiber reinforced composites subjected to plane stress loading.

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FLUTTERING INSTABILITY IN GEOMATERIALS

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The possibility of having a complex conjugate pair for the acceleration speed of a discontinuous front of non-uniform deformation in solids was apparently first remarked by Rice (1976) and it was coined as "fluttering instability" as the mathematical form of the complex conjugate pair of the eigenvalues closely resemble those for the case of Hopf bifurcation of wind-induced vibration of slender-structures. Although this topic has subsequently been explored mathematically by some researchers, except for the liquefaction interpretation given by Bigoni and Willis (1994) there has been no physical meaning attached to this mathematical possibility. Whether fluttering instability of solids actually occurs in nature? If yes, in what form? There are fundamental issues remain to be addressed. This paper presents the mathematical prediction of the possibility of fluttering instability for two pressure-sensitive dilatant geomaterials: the Rudnicki-Rice (1975) model and Chau-Rudnicki (1990) model. Fluttering instability is searched within the physical range of the parameters, and potential implication on periodic pattern of non-uniform deformation in solids is proposed. Motivated by recent studies for compaction band, it was argued by Issen and Rudnicki (2000) that both or either dilatant factor and pressure-sensitive coefficient can be negative if a two-yield surface model is used to interpret the failure yield surface of rocks. Therefore, we also allow for such possibility of parameter selection in the present study. Finally, it is speculated that fluttering instability can actually manifest itself in nature and can account for many regular patterns of deformation observed in rocks, soils and other materials.

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INVESTIGATION OF STRAIN LOCALIZATION IN CASTLEGATE SANDSTONE

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Deformation bands in high porosity sandstone are tabular structures, consisting of a zone of localized shear and/or volumetric strain. Prior theoretical works have suggested that the strain localization framework of Rudnicki and Rice [1] could be applied toward predicting deformation band formation in high porosity sandstone. However, this application is largely untested because only a few suitable data sets currently exist. This work evaluates localization predictions using results from a suite of tests conducted on Castlegate sandstone, covering a wide range of mean stresses, including brittle, ductile and transitional behavior. Observed failure modes included dilating shear bands (low mean stress), compacting shear bands and compaction bands (intermediate mean stress), and no localization (high mean stress).

Values for the friction factor (local slope of the yield surface) and dilation coefficient (negative of the ratio of the increments of plastic volume and plastic shear strains) are determined from plastic strain data, and used to calculate predicted band angles (angle between band normal and direction of maximum compression). For tests exhibiting dilatant response, the yield surface is a contour of constant plastic shear strain, while for compactant response, a yield surface cap (contour of constant plastic volume strain) is employed. Additionally, elastic moduli were found to depend on stress (non-linear elastic) and plastic strain (elastic-plastic coupling).

Accounting for elastic-plastic coupling, when determining plastic strains, affects values of the friction factor and dilation coefficient, thus affecting localization predictions. Predicted band angles, when accounting for elastic-plastic coupling, are typically lower than those when coupling was not considered. Additionally, predictions for the coupled approach demonstrate better agreement with observed band angles; in particular, compaction bands are predicted for tests where compaction bands were observed. To our knowledge, this is the first work in which localization theory has successfully predicted the occurrence of compaction localization in experiments, using experimentally determined constitutive parameters.

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ARE PROBLEMS INVOLVING NON CONTROLLABLE GEOMATERIALS COMPUTABLE?

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Usually it is assumed that solution of the initial boundary value problem solved by numerical methods is unique. In fact this assumption is often implicit since this point is almost never discussed. Unfortunately it is difficult to prove such a theoretical result. Difficulties of reproducibility of experiment as well as multiplicity of solutions of numerical problems found when they are searched demonstrated that geomaterials behavior induces loss of uniqueness problems before complete degraded or failure states.

On the other hand the controllability condition as defined initially by Nova is clearly related with the well posedness (existence and uniqueness of solution) of some particular problems. General results show that it can be clearly related with the positiveness of the so called second order work (3). In the case of non controllability, for some boundary value problems, several solutions can be exhibited (1). Moreover, contrary to a well admit illusion the use of enhanced models does not solve the problem and non uniqueness has been also exhibited (2), (4).

The proposed contribution discusses this important topic and practical consequences of such paradoxical results and aim to give some insight of a new paradigm for geomechanics and computational geomechanics.

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FE-CALCULATIONS OF A DETERMINISTIC AND STATISTICAL SIZE EFFECT IN GRANULAR BODIES INCLUDING SHEAR LOCALIZATION

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One of the most important properties of the behaviour of many engineering materials is a size effect phenomenon, i.e. experimental results vary with the size of the specimen. In the case of granular bodies, the shear resistance increases with decreasing specimen size and increasing mean grain diameter during many experiments including strain localization. Similarly as in quasi-brittle materials, two main size effects can be defined: deterministic (energetic) and statistical. The first one is caused by strain localization which cannot be appropriately scaled during laboratory tests. A statistical effect (called also a stochastic effect) is caused by the spatial variability/randomness of local material strength. Up to now, the size effects are still not taken into account in the specifications of most of design codes for engineering structures.

The numerical investigations of size effects in granular bodies are described for 3 different boundary value problems including shear localization: shearing between two very rough boundaries [1], plane strain compression [2] and strip foundation. To describe a mechanical behaviour of a cohesionless granular material during a monotonous deformation path in a plane strain compression test, a micro-polar hypoplastic constitutive model was used. It includes particle rotations, curvatures, non-symmetric stresses, couple stresses and the mean grain diameter as a characteristic length. In the paper a deterministic (energetic) and statistical size effect are carefully analysed. The deterministic calculations were carried out with a uniform distribution of the initial void ratio for different geometrically similar granular specimens. To investigate a statistical size effect, in order to reduce the number of realizations without loosing the accuracy of the calculations, a Latin hypercube method was applied [1]. Truncated Gaussian random fields of the initial void ratio were generated in granular specimens. They were generated using a conditional rejection method for a weakly and strongly correlated random fields. The results show that the statistical size effect is significantly stronger than the deterministic one. The shear resistance decreases with increasing specimen size.

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LOCALIZATION ANALYSIS OF A THREE-INVARIANT GEOMATERIAL MODEL WITH ISOTROPIC AND KINEMATIC HARDENING: ANALYTICAL AND NUMERICAL INSIGHTS

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Geomaterials exhibit a number of complex mechanical behaviors under deformation, including dependence on triaxial stress state, Bauschinger effect, strain-rate, and porosity. Effectively capturing these responses requires complex constitutive models. The Sandia Geomodel is one constitutive model that has been developed to capture the above-mentioned behaviors, and several others.

The complexity of such constitutive models, however, makes closed-form solutions of bifurcation conditions difficult to determine. Furthermore, bifurcation conditions for strong and weak discontinuities, and sometimes whether the material in the band unloads elastically (discontinuous bifurcation) or continues to load plastically (continuous bifurcation).

This presentation covers the derivation of different bifurcation conditions for the small strain case. A numerical technique is then adapted to detect the onset of localization, along with the critical directions of the localization. Results are discussed, including how nonassociativity, rate dependence, Bauschinger effect, and third invariant affect the onset of localization within the context of this model.

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AN ELASTO-VISCOPLASTIC MODEL FOR DIATOMACEOUS MUDSTONE AND NUMERICAL SIMULATION OF COMPACTION BANDS

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It is known that compaction bands of porous rock occur as perpendicular or very slightly inclined deformation bands with respect to the most compressive stress direction with volumetric compression under relatively high lateral confining pressure.
Experimental study of diatomaceous mudstone has been done to observe compaction bands in the laboratory. In the tests, distributions of local strains are observed and evaluated on the surface of the specimens by use of an image analysis technique [1]. Diatomaceous mudstone is a highly structured and porous soft rock. The aim of the present study is numerical simulation of compaction bands of diatomaceous mudstone. At first, an elasto-viscoplastic model considering microstructural degradation [2] has been applied to the behavior of the diatomaceous mudstone during the triaxial tests. It is found that the elasto-viscoplastic model can well reproduce the stress-strain relations and the dilatancy of diatomaceous mudstone. Then numerical analyses of a series of triaxial compression tests under drained conditions has been carried out using the elasto-viscoplastic model and Biot's type of two-phase mixture theory [3]. In the analysis, we have adopted the finite element method with updated Lagrangian method to simulate strain localization behavior during the triaxial test. The simulated results are compared with the experimental results and the mechanism of the development of compaction bands is discussed. In addition, the differences in density between the specimen before and after the shear test are measured by a microfocus X-ray CT scanner.

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AN ANALYTICAL AND EXPERIMENTAL STUDY OF THE POST-PEAK RESPONSE IN HIERARCHICAL STRUCTURES

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Much research has been conducted over the recent decades to understand the structural hierarchy as observed in many biological systems at various scales. However, there is a lack of understanding on the scale effect related to hierarchical structures, although tremendous efforts have been made in investigating the size effect on the failure responses of engineering structures. Especially, the existing multi-scale modeling approaches are limited in predicting the failure evolution due to interacting cracking systems. Based on the discontinuous bifurcation analysis, it is known that the transition from continuous to discontinuous failure modes is characterized by the onset of localization. As can be found from the open literature, two different kinds of approaches have been proposed to model and simulate the evolution of localized failure, namely, continuous and discontinuous ones. Decohesion and fracture mechanics models are representative of discontinuous approaches, in which strong discontinuities are introduced into a continuum body such that the governing differential equation is well-posed for given boundary and/or initial data. On the other hand, nonlocal (integral or strain gradient) models, Cosserat continuum models and rate-dependent models are among the continuous approaches proposed to regularize the localization problems, in which the higher order terms in space and/or time are introduced into the strain-stress relations so that the mathematical model remains well-posed in a higher order sense for given boundary and/or initial data. Usually, only weak discontinuities in the kinematical field variables are allowed in the continuous approaches; i.e., the continuity of displacement field must hold in the continuum during the failure evolution. There are certain kinds of applicability and limitation for different approaches, depending on the scale of the problem and the degrees of discontinuity considered. To better understand the onset and evolution of failure in hierarchical structures, hence, it seems to be necessary to integrate continuous approaches with discontinuous ones. As an intense area of research over the past few decades, many efforts have been made to investigate experimental, analytical and numerical aspects of softening/damage with localization. However, nothing has been done to explore softening with localization in the hierarchical structural system that consists of members connected in both serial and parallel settings. Since softening with localization characterizes the failure evolution from a continuum viewpoint, a combined analytical and experimental study on the structural failure response with truss members in parallel connection has therefore been performed, and major findings and future work will be presented in this workshop.

FABRIC AND PARTICLE SHAPE DEPENDENCY OF SUCTION AND ITS INFLUENCE ON STRENGTH ANISOTROPY OF MOIST SAND

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Fabric is an important factor in describing the behaviour of granular materials, since it is quantity reflects the interaction as well as the connectivity among particles and hence the internal kinematical constraint during deformation. Even though particle shape is believed to be a contributing factor, the fabric of granular materials is generally characterized by the distribution of particle contact normal, or equivalently by the distribution of branch vectors on the statistic meaning. It has also been shown that fabric should be taken into account in describing the behaviour of unsaturated granular materials. Since the liquid bridge between particles varies with the local geometry at particle contacts and particle shape, it is expected that particle shape may have certain impact on capillary cohesion in addition to the distribution of particle contact or branch vectors. Consequently, the directional variation of suction and its influence on the strength of unsaturated sand is likely to be affected by particle shape.

An experimental investigation is conducted to provide evidence of directional variation of suction and its influence on the strength of unsaturated sand composed of rounded and angular particles. A series of tests are first carried out to obtain the soil-water characteristic curves of sand compacted using different methods. The experimental data reveal that, in addition to the density of sand, sample compaction methods have noticeable influence on suction of unsaturated sand at low degrees of saturations, which indirectly shows that suction in unsaturated sand varies with fabric of the material. The influence of fabric on suction becomes negligible when the degree of saturation exceeds a certain limit, depending on the representative size of particles.

The directional variation of shear strength for unsaturated sand is examined using a modified direct shear box, in which the shear stress can be applied in directions making different angles relative to the bedding plane. Specimens compacted to a constant dry density at different moisture contents (or degree of saturation) are tested by applying shear stresses parallel or normal to the bedding plane. The experimental data show that the variation of shear strength of unsaturated sand with moisture content is likely affected by particle shape when shearing direction is changed, which suggests that the anisotropic effect of suction on unsaturated sand behaviour may vary with particle shape.

In addition to the experimental study, microscopic analysis is performed to characterize the importance of particle shape for unsaturated sand. The attracting force of the liquid bridge between elliptical grains is calculated by taking into account local geometric properties at the contact points, and the results show that the aspect ratio of particle change the directional variation of net inter-particle forces and hence the effective stress in the ensemble of grains. However, it should be pointed out that the current experimental work should be improved in the future work owing to the well-known shortcomings of direct shear box test.

EXPERIMENTAL CHARACTERIZATION OF INSTABILITY: EFFECTS OF FABRIC & SHEAR-VOLUME COUPLED DEFORMATION

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Strain softening behaviour of saturated sands has been assessed in the laboratory using reconstituted specimens with the objective of further understanding the factors that influence the triggering of instability, and subsequent deformation. The main focus of the results presented herein is to evaluate the effects of (1) the microstructure of the soils, and (2) shear-volume coupled deformation on instability. Specimens reconstituted by different techniques, but to the same density and stress states, have been shown to exhibit dramatically different stress-strain, and failure characteristics. These differences occur on account of the microstructure (fabric) of the soil specimen. The fabric that ensues upon water deposition has a cross-anisotropic structure, which leads to direction dependent response. The minimum shear strength in such soils is dependent on the porosity, confining stress and the loading mode. On the other hand, wet tamped specimens, which are widely used in experimental studies and have generally formed the basis of critical state theories in granular soils, exhibit much lesser level of anisotropy. Experimental studies on strain softening instability in the past have typically been limited to conventional tests. Recently, instability and liquefaction potential have been studied under proportional strain paths [1, 2] following the pioneering work of Chu et al [3]. Actual loading scenarios, however, would generally involve nonlinear strain paths. Such loading is fairly common in several in-situ problems primarily on account of natural heterogeneity. Different pore-pressure boundary conditions that exist in-situ may give rise to such deformation during, and/or following earthquake and other forms of loading. An experimental study has been undertaken to assess instability phenomenon in sands subjected to shear-volume coupled deformation. Two types of nonlinear strain paths (termed partial drainage paths, and expansive drainage paths) are simulated in this study to better represent the shear-volume coupled loading scenarios, compared to the proportional strain paths. The nature of the stress increment vectors was evaluated as a function of the current effective stress state, and strain increment vectors. Systematic variations in peak deviatoric stress, and the effective stress ratio at the peak-state were noted as the rate and magnitude of volumetric deformation varied. However, the effective stress ratio at the instant of peak excess pore pressure (which generally corresponds to the minimum strength state) was found to be unique regardless of the loading mode, and initial state.

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PHASE TRANSFORMATION, CRITICAL STATE AND LIQUEFACTION

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Phase transformation, critical state failure, and flow liquefaction are commonly observed responses of granular materials. While it is generally accepted that a soil ultimately fails with a unique internal structure, it has also been observed, from the undrained tests, that the ultimate states are not necessarily associated with a unique critical state line in the e–p plane. Undrained loose specimens, especially for those subjected to triaxial extension, may easily approach a kind of ultimate states known as flow liquefaction, which is characterized by a nearly zero confining pressure and a very low residual strength. Upon liquefaction, the soil's e–p state is usually distinctly off the otherwise defined critical state e–p line. This presentation will explain, with definite microscopic analyses, why a reasonably dense granular material possesses a phase transformation state; why a loose specimen may liquefy, satisfying the macroscopic definition of the critical state failure but in fact staying far away from the critical state, and why a triaxial compression may pass through a phase transformation state and then approach the critical state but a triaxial extension may lead to flow liquefaction without attaining that supposedly unique ultimate state.

EXPERIMENTAL AND NUMERICAL MODELLING OF DIFFUSE MODE OF FAILURE IN VERY LOOSE SANDS

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The mechanical behaviour of granular materials or more generally, non-associated elasto-plastic materials could exhibit a relevant sight: they can lose their "strength" before they reach the plastic limit criterion (Mohr-Coulomb for instance). This appended at a bifurcation point of the response of the material. The localisation of the strains has thoroughly been studied last decade but the diffuse mode of failure of such materials still needs to be studied.

In this paper, the diffuse mode of failure is investigated from an analytical and numerical point of view. Thus starting with homogeneous stress-strain fields, we firstly demonstrate that the second order work criterion makes it possible to define the material bifurcation domains in the stress space. This one is located strictly inside the plastic limit surface in plane strain condition or in axial symmetry condition. Of course various bifurcation modes such as diffuse modes or localized modes could coexist. The numerical part of this paper will focus only on the first mode of bifurcation, described by the second order work criterion, using incrementally piece-wise linear model and thoroughly non-linear constitutive model.

Classical experimental results usually show an “unstable domain” based only on the concept of “instability line” which is obtained from conventional undrained triaxial tests. We will show experimental evidences carried out on sand samples which confirm this theoretical study. Moreover, several experimental tests were carried out on very loose sand samples; under undrained triaxial compression tests, constant shear drained tests and quasi constant shear undrained tests, to highlight the influence of the stress increment (stress rate) directions.

We show that numerical modelling and experimental results are in a very good agreement to point up the paramount role of the stress increment (stress rate) directions inside the bifurcation domain regardless the stress path followed during the loading program.

STABILITY OF STEADY CREEP OF THERMALLY DRIVEN SLIDES

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Here we study the problem of creeping landslides accompanied by heat production due to friction on their base (called thermally driven slides). The landslide is usually modeled using a rigid block that slides over a clayey zone of finite width and a thermal softening and velocity strengthening constitutive law for the friction coefficient of the basal clay material. For the most part of the considered process the applied shear stress is practically constant. During the considered process a regenerative feedback can develop. The question we address here is if the effect of strain-rate hardening can counterbalance the effect of temperature softening and if steady creep can exist [1] and if it is stable. We notice that if steady creep does not exist or if it is unstable then thermal runaway occurs [2]. Thermal runaway is described by an unsteady heat diffusion-generation equation. The unsteady solutions may lead to finite time instabilities, i.e. to life-time estimates of the creeping landslide.

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FRACTURE MODELLING USING THE DISCRETE FINITE ELEMENT METHOD

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Discrete element method (DEM) is used in solution problems in many discontinuum problems. However, the method suffers several drawbacks such as the difficulties in calculating stresses and strains, the determination of the properties for the discrete elements and imposing boundary conditions. The discrete finite element method (DFEM) combines the advantages of continuum and discontinuum modeling. The method is based on continuum formulation which calculates stresses and deformation of the continuous medium. However when fracture or parting occurs in the material, the discrete approach is used to calculate the motion of individual part of the structure. This allows effective modeling of large deformation of material at the same time addresses the short coming of the DEM approach. In this presentation, the development of the DFEM is presented and applied in solving simple and complex geotechnical engineering problems.

REPRODUCTION OF A COMPACTION BAND IN DEM SIMULATIONS

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Compaction bands are thin localized zones that accommodate only compactive strain and no shear and have been documented in a variety of materials [1]. The current study will focus on porous sandstone, where the micromechanism for compaction banding is grain breakage and crushing, as this is considered to have very important applications for the hydrocarbon extraction industry. For example, compaction bands are impermeable barriers that can inhibit flow, and can be formed as a consequence of the extraction process. Further, they can be associated with well bore instability and borehole breakouts [2]. However key questions remain as to the initiation and propagation of such bands, as well as to the necessary material conditions for their formation.

Discrete Element Method (DEM) simulations of a bonded granular material with crushable particles were conducted [3] and will be shown to reproduce a localized (discrete) compaction band. The initiation and propagation of this compaction band will be presented, providing insight into the development of this instability. The strength of the cementation bond and the fragmentation mode for the grains will also be shown to affect the observed behavior with some simulations not displaying the brittle peak associated with compaction banding. Hence, insight into the necessary material conditions for crushing localization can be obtained.

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COMPACTION LOCALIZATION AND GRAIN CRUSHING IN POROUS SANDSTONE: CONSTITUTIVE MODELING, MICROSTRUCTURAL EVOLUTION AND DISCRETE ELEMENT SIMULATION

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Since strain localization can significantly influence the stress field, strain partitioning and fluid transport in many geological and geotechnical settings, it is important to have a fundamental understanding of its mechanics. Laboratory investigations in sandstones with porosities ranging from 13% to 28% indicate that development of discrete compaction bands is commonly associated with stress states in the transitional regime from brittle faulting to ductile flow.

Important insights into the mechanics of compaction localization have been gained from the continuum analysis of its inception as a bifurcation in the constitutive response of a porous medium. Critical conditions for the onset of localization and orientations of the shear and compaction bands can be derived as functions of the constitutive parameters. While bifurcation analysis provides a very useful framework, it has an intrinsic limitation in that the continuum analysis only addresses the onset of constitutive instability in an initially homogeneous material but not the subsequent propagation behavior of the compaction localization or development of their geometric complexities. In particular this continuum approach cannot explain why compaction bands may preferentially develop as an array of many discrete bands or as one or two diffuse structures that widen laterally.

To address these questions it is necessary to consider a micromechanical model accounting for microstructural heterogeneity and damage evolution related to grain crushing. We develop a discrete element model of porous sandstone that is idealized as a bonded assembly of circular disk subjected to three damage mechanisms. First, the bonds are assigned finite tensile and shear strengths and once either of these threshold stresses is exceeded grain cohesion is lost. Second, relative movement among grains may occur if the bond has been broken and the shear stress exceeds the frictional resistance. Third, intragranular cracking may develop if one of the normal contact forces exceeds a threshold. This third mechanism mimics grain crushing, and it automatically triggers two additional damage processes: the impacted grain undergoes a shrinkage of its radius (typically by ~1%) and breaks off the bond. This numerical model captures key failure modes associated with the brittle-ductile transition with increasing confinement. It also underscores the critical role of grain-scale heterogeneity in controlling the development of compaction localization. Our simulations indicate that the development of discrete compaction bands is promoted in a relatively homogeneous granular aggregate, while diffuse band growth and distributed cataclastic flow are preferred modes of compaction in a more heterogeneous system. To interpret the former result, an Eshelby inclusion model was proposed to estimate analytically the local stress perturbations due to pore collapse in a homogeneous aggregate.

A MULTIPHASE NUMERICAL ANALYSIS OF THE STRAIN LOCALIZATION OF UNSATURATED EMBANKMENT ASSOCIATED WITH SEEPAGE FLOW

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In recent years, many disasters due to floods have occurred around the world. In some cases, river embankments have been failed due to seepage and overflow. In the present study, multiphase deformation analysis of river embankment has been carried out using an air-soil-water coupled finite element method considering the unsaturated seepage flow. A numerical model for unsaturated soil is constructed based on the mixture theory and an elasto-viscoplastic constitutive model. As for the stress variables in the formulation of unsaturated soil, we use skeleton stresses and suction simultaneously. The skeleton stresses are used instead of the Terzaghi's effective stress for the saturated soil and the suction is incorporated through the constitutive parameters of the model. The collapse behavior, due to a decrease in suction, is expressed with the shrinkage of the overconsolidation boundary surface, the static yield surface, and the viscoplastic potential surface. The theory used in the analysis is a generalization of Biot's two-phase mixture theory for saturated soil. An air-soil-water coupled finite element method is developed using the governing equations for multiphase soil based on the nonlinear finite deformation theory, i.e., updated Lagrangian method. Two-dimensional numerical analyses of river embankment under seepage conditions have been conducted, and the strain localization associated with seepage flow has been studied. From the numerical methods, strain localization behavior has been well simulated by the proposed method and the applicability of the method is confirmed.

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CIP-BASED NUMERICAL SIMULATION OF SOIL/SNOW AVALANCHE

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In order to predict a flow area of soil/snow avalanche, numerical method based on fluid dynamics has been proposed. In the CIP–based numerical method the geomaterial or snow is modeled by Bingham fluid with the consideration of the Mohr-Coulomb failure criterion [1]. Therefore, the cohesion c and the internal friction angle φ are the material parameters for flow media. In this research, full depth avalanches really happened in Niigata prefecture, Japan are simulated using CIP-based numerical method. The parameters used in simulations are obtained from former research [2]. In order to investigate the applicability of the proposed method to snow avalanche simulation, the travel length of snow avalanche observed is compared with that obtained by the simulation.

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PERFORMANCE OF SPH METHOD FOR DEFORMATION ANALYSES OF GEOMATERIALS

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In a numerical analysis of geotechnical engineering, the behavior of the geomaterials can be simulated by introducing suitable constitutive models using the Finite Element Method (FEM). There are, however, still some problems for the large deformation prediction. The excessive distortion of the finite element mesh and numerical instability arise when FEM is used to solve a large deformation problem. In this research, deformation analyses of geomaterials using Smoothing Particle Hydrodynamics (SPH) method [1] are carried out. SPH method is a kind of meshless Lagrangian method. Recently, SPH method is used in a variety of fields like fluid dynamics or solid mechanics [2]. In this paper, the analytical accuracy and stability of SPH method are investigated for deformation analyses of geomaterials which are assumed to be solid or fluid.

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CYCLIC MOBILITY OF SAND AND ITS SIMULATION IN BOUNDARY VALUE PROBLEMS

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In this paper, behavior of cyclic mobility of sand under undrained conventional triaxial test was investigated in detail. Special attention was paid to the influence of cyclic loading rate on the stress-strain relation in the region when cyclic mobility happens under cyclic loading process. The behavior was simulated with dynamic finite element analysis (Ye et al, 2007) based on a new constitutive model proposed by Zhang et al (2007). The model can describe the mechanical behaviors of soils under different loading conditions, in which new type of evolution equations for the development of stress-induced anisotropy and the change of overconsolidation of soils are proposed. By combining systematically the above two evolution equations with the evolution equation for the structure of soil, the newly proposed model is able to describe not only the mechanical behavior of soils under monotonic loading, but also the behavior of soils under cyclic loading with different drained condition. Special attention is paid to the behavior of sand subjected to cyclic loading under undrained condition. That is, for given sand with different densities, very loose sand may liquefy without cyclic mobility, medium dense sand will liquefy with cyclic mobility while dense sand will not liquefy, which is just controlled by the density, the structure and the anisotropy of the sand. A suitable model should uniquely describe this behavior without changing its parameters. A series of undrained conventional triaxial tests on Toyoura Sand were conducted under different loading rates and the behavior of element test was simulated with FEM in boundary value problem (BVP).

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DEFORMATION AND FAILURE PROCESSES IN GEOLOGIC MATERIALS AT SCALES FROM GRAINS TO BASINS

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Sediments and sedimentary rocks display a wide range of deformation and failure processes and structural styles that reflect their porous and granular nature, variable loading conditions and loading rates in active depositional settings, and complex chemical/mechanical water-sediment-rock interactions. A basic understanding of these multiscale deformation and failure processes is a prerequisite for successful energy and water resource management and natural hazard mitigation. This paper will cover some of the engineering and geoscience research activities conducted at Stanford University focusing on theoretical, numerical and computational aspects of deformation and failure processes in sediments and rocks across a wide range of scales. "Multiscale" in the present context refers to the physical scale of the problem of interest, which may range from granular scale controlling the behavior of small sediment samples tested in the laboratory, to basin scale encountered in the simulation of faulting and folding of rocks, as well as in the studies of mountain building. I will present some advanced numerical techniques that my group uses to model the complex deformation and failure processes from micron-scale to kilometer-scale. An example includes preserving the numerical resolution of a centimeter-scale rock fracture superimposed over a kilometer-scale rock fold.

PIPING EROSION: TESTING AND MODELLING

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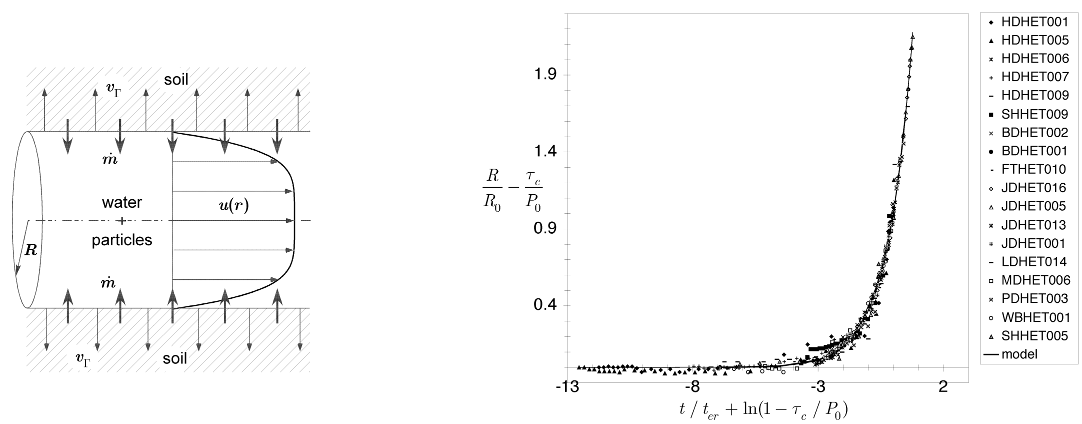
A process called "piping", which often occurs in the soil at water retaining structures (earth-dams, levees and dykes), involves the formation and development of a continuous tunnel between the upstream and downstream sides. Starting with the bulk equations for turbulent flow and the soil/water interface equations with erosion, we derive simplified models after few hypothesis, asymptotic developments and dimensional analysis. It is established here that the product of the coefficient of erosion and the flow velocity is a significant dimensionless number: when this number is small, the kinetic of erosion is low, and the particle concentration does not have any effect on the flow. This finding applies to most of the available test results. Theoretical and experimental evidence is presented showing that the evolution of the pipe radius during erosion obeys a two-parameters scaling law. The first parameter is the critical stress. The second parameter is the characteristic time of piping erosion which is a function of the initial hydraulic gradient and the coefficient of erosion.



(a) (b)

Fig. 1. (a) Axisymmetrical flow with soil erosion and transport of the eroded particles. (b) Hole erosion tests with a constant pressure drop, test (symbols) versus model (continuous lines), scaling law of the radius as a function of time.

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NATURAL PROCESSES AND STRENGTH DEGRADATION

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Much of the testing done in geotechnical laboratories examines the peak strengths of clays. For numerical modeling, attention must also be paid to deformation characteristics, volume changes, and pore fluid pressures, including gases. It is also worth noting that there are many applications in geotechnical practice in which shear strengths may decrease with time or with other physical processes. Projects that have functioned safely for many years may become unsafe.

The paper outlines a number of the authors' field and laboratory projects in which strengths have decreased significantly as a result of natural physical processes. These include rainfall, swelling in expansive clays, wetting-drying, freezing-thawing, heating, changes in pore fluid chemistry; and viscosity and strain-rate effects. Reductions in strength related to these processes will be considered as 'degradation'. Some involve physical disturbance of the macrostructure or microstructure of the clay, while others involve electro-chemical changes in 'bound' water attached to the clay particles.

Projects that will be examined briefly include failure of a highway cut following heavy rainfall; large ongoing settlements of a highway embankment on organic silty clay; ongoing failures due to leaching of gypsum beneath a water-retaining dike; effects of heating on undrained shear strength; and reduction of wave protection of limestone riprap due to freeze-thaw fracturing.

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PORE-FLUID INDUCED DEGRADATION OF SOFT ROCKS

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Porous rocks are known to behave differently when saturated with different pore fluids. The behavior of these rocks varies with different pore fluids and additional deformation occurs when the pore fluid composition changes. In this article, we review the evidence that behavior in porous rocks is pore fluid dependent, present a constitutive model for pore fluid dependent porous rocks, and present a compilation of previously published data to develop quantitative relationships between various pore fluids and mechanical behavior. The model proposed is based on a state parameter approach for weathering and has similarities to models previously proposed for weathering-sensitive rocks, in that the values for parameters that characterize material behavior vary as a function of weathering. Comparisons with published experimental data indicate that the model is capable of reproducing observed behavior of soft rocks under a variety of loading conditions and changes in pore fluid composition.

FLUID INJECTION INTO GRANULAR MEDIA

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The process of fluid injection into granular media is relevant to many practical applications such as fluidization of packed beds for material processing, hydraulic fracturing and water flooding in unconsolidated and highly permeable sedimentary rocks. While the fluidization process in a finite domain with hydrostatic pressure as the initial condition has been extensively studied for many decades, hydraulic fracturing and water flooding in granular materials with fluid injected into an infinite domain under in situ stress state emerged only recently and remains a challenge. In particular, conditions of fracture initiation and propagation in such materials are not well understood.

In this work, fluid injection from an inlet into a two-dimensional rectangular domain under a biaxial stress state was investigated numerically using a discrete element code PFC2D. Fluid flow in the domain is modeled using a fixed coarse grid scheme while the mechanical deformation of the particle assembly was simulated using the discrete element method with the soft contact approach. Results indicated that three types of flow patterns can be identified: i) fixed bed flow; ii) formation of a stable cavity; iii) propagation of an unstable cavity. In the limit of inertia-governed (still laminar) flow, the induced cavity is finger-like with a nearly constant width, whereas in the limit of viscosity-governed flow, the cavity tends to grow more in the width direction rather than the length direction. A criterion of the critical injection velocity as a function of material properties and the far field confinement for transition between flow patterns was proposed. The scaling relationship between the material properties and the confining stress was verified numerically.

3D BIFURCATION ANALYSIS IN GRANULAR MATERIALS

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It is now well recognized that non-associated materials, like granular materials, can develop various types of bifurcations before reaching the plastic limit condition of Mohr-Coulomb [1]. Second order work criterion gives a lower bound for all these bifurcations if we except flutter type instabilities. Until now only specific loading spaces have been considered for this criterion (axisymmetric conditions [2], plane strain conditions [3]) and it is proposed in this paper to take into account general 3D conditions.

The equation of the boundary of the bifurcation domain according to second order work criterion is established in 3D principal stress space. This criterion has a directional nature and elliptical cones of unstable stress directions are exhibited.

In a second part the failure mode associated to second order work criterion is investigated through a discrete element method [4]. It is shown that the instability develops by divergence, exponentially growing strains, burst of kinetic energy and a diffuse mode of failure.

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THE CONCEPT OF LOSS OF SUSTAINABILITY IN GRANULAR MATERIALS

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Failure is one of the most debated notions since many decades in geomechanics. On the one hand, the discrete nature of granular materials does not make it easy to define the notion from a phenomenological point of view. On the other hand, this notion is essential for civil engineers since projects have to be designed so as no failure is expected to occur.

In this talk, we consider the failure mode related to the creation of kinetic energy, without change in the control parameters (loss of sustainability of an equilibrium state). We show how the vanishing of the second-order work is a suitable criterion to detect the occurrence of such a failure mode. This result is derived in the general context of large strains, without any assumptions on the constitutive relation of the material. Thus, a discrete element method is used, and it is checked that a brutal collapse of a granular assembly occurs when the incremental loading direction is related to a negative value of the second-order work. Other typical examples, corresponding to standard geotechnical tests, are finally commented through this approach.

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INVESTIGATING INSTABILITY CONDITIONS IN GRANULAR MATERIALS WITH DIFFERENT INITIAL DENSITIES BY MEANS OF A MICRO-STRUCTURAL CONSTITUTIVE MODEL

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Numerous experimental results have shown the development of instabilities in granular materials, characterized by a sudden collapse of the specimen before reaching the plastic limit. Different stress and strain paths have been investigated such as undrained triaxial tests or constant deviatoric stress path. Most of these experimental studies concern very loose sand subjected to isochoric loading, leading to the phenomenon called "static liquefaction". However, several results on dense sand have shown that instable states could also be obtained, depending on the strain and stress paths followed during testing. Theoretical studies have shown that Hill's sufficient condition of stability is able to describe material instabilities in granular assemblies. It leads in particular to the definition, for a given material in a given initial state, of a bifurcation domain strictly included inside the plastic limit. This has been demonstrated in the framework of different constitutive formulations, including non-associated elastoplasticity.

A constitutive modeling method for granular materials based on particle level interactions has been developed based on homogenization technique. The deformation of a representative volume of a granular material is generated by mobilizing particle contacts in all orientations. The stress-strain relationship can be derived as an average of the mobilization behavior of these local contact planes. In the model, a simple elastic-plastic behavior is assumed on each contact plane. The elastic part is based on the Hertz-Mindlin's contact formulation, while the plastic part is based on a Mohr-Coulomb friction law with an isotropic hardening assumption and a non-associated flow rule. For the whole packing, a critical state behavior is assumed at large deformations and the friction angle on each plane is related to the actual void ratio compared to the critical void ratio at the same state of stress. A strain softening behavior can therefore be obtained for dense materials. On the whole, the model requires a limited number of parameters, which can easily be determined from conventional triaxial testing. Comparisons between numerical simulations and experimental results show that the model can accurately reproduce the overall mechanical behavior of loose and dense granular assemblies.

In this paper, a numerical analysis of the conditions of the vanishing of the second-order work is performed. It demonstrates that the model can predict the appearance of cones of instable directions inside the plastic limit. Different stress and strain paths are investigated: isochoric loading tests, constant deviatoric stress paths, strain controlled loading with constant volume change rate. Special attention is given to the influence of the initial density on the instability condition for a given granular material.

FAILURE IN GRANULAR MATERIALS IN RELATION TO MATERIAL INSTABILITY, FABRIC AND PLASTIC FLOW ISSUE

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This presentation examines the emerging roles of instabilities in characterizing various modes of failure in geomaterials. It is now fully recognized that it is not sufficient to solely analyze the failure of geomaterials in the conventional manner as a limiting state, but it is also important to study the causes leading to failure. Micromechanical in character, these causes are often subtle and relate to local instabilities such as inter-granular slippage, overriding, buckling of internal force chains and grain crushing that may appear prior to a failure limit. We first examine Hill's stability criterion as a means to detect diffuse failure and discuss about issues of invertibility and controllability in kinematically (or mixed loading) controlled tests such as in an undrained triaxial test. From a physical view point, starting from an equilibrium state, we seek various directions of perturbations in the velocity field for any unstable states that may drift from equilibrium and thereby allow a spontaneous change of potential energy into kinetic energy. This criterion, which is based on the sign of the second-order work, is employed to capture the existence of material instability well inside classical plastic limit surface. We briefly investigate the phenomenon of instability using an elasto-plastic model with the consideration of fabric (micro-structural) changes. The postulate of flow rule is another subject matter which will be discussed here. Through discrete element analysis, we show that a flow rule does not exist (i.e. postulate fails) in general three-dimensional conditions, but only subsists under two-dimensional conditions. We also attempt to find any relationship that may exist between the loading history and the nature of the incremental plastic response.

GLIMPSES OF THE PROMISE OF MICROMECHANICS IN MODELLING GRANULAR MATERIALS

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In a four part presentation, we report on recent developments from bifurcation and failure studies for cohesionless granular materials. We present a new method for the development of micromechanical constitutive laws expressed solely in terms of particle scale properties (part 1). The formalism enables a transfer of information from the contact scale, across multiple length scales in the mesodomain, to the macroscale, within the framework of Thermomechanics. A crucial element of this formulation is the use of the Discrete Element Method to identify key mesoscopic instabilities, i.e. confined buckling of force chains, and the subsequent modeling of the evolution of such self-organized mesostructures via Structural Mechanics (part II). We then present a model of shear banding in the context of a one-dimensional bifurcation problem (part III). In this analysis, we use a model from part I and distinguish limitations of the bifurcation treatment versus those of the constitutive model. Finally, results from a finite element analysis of strain localization in solid-structure interaction systems, implemented using ABAQUS, are presented to highlight predictive capabilities of the new constitutive model in more complex boundary conditions (part IV).

SHEAR HEATING IN LOCALIZED SHEAR ZONES: INCIPIENT SLIP INSTABILITY AND DYNAMIC SLIP PROPAGATION

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Shear heating is ever present in localized shear zones. Under conditions when diffusive transport away from the shear zone is limited, changes in temperature caused by shear heating persist and may trigger variety of material specific processes which alter the apparent macroscopic constitutive response. Examples of temperature triggered processes which lead to apparent weakening of sheared material include, but not limited to pressurization of interstitial fluids (Lachenbruch, JGR 1980), flash heating of asperities (Rice, JGR 2006), and thermal gouge collapse (Sulem et al., Soils Found. 2005). This apparent weakening of a shear zone is usually attributed to dynamic stages of slip (localized shear), as in propagating earthquake rupture or landslide where the heating can be substantial. Contrary to dynamic slipping, incipient stages of slip instability are normally considered to be driven by frictional weakening, i.e. shear heating has little effect unless the ambient slipping rate is significant (Segall and Rice, JGR 2006).

Effects of shear zone weakening due to thermal fluid pressurization on (1) incipient slip instability, and (2) later stages of dynamic slip propagation as a self-healing pulse are studied. Problem (1) is discussed in the framework of a single-degree-of-freedom (spring-slider) model that includes effects of dilatancy and frictional weakening. In this system de-pressurization of pore fluid due to dilatancy can stabilize otherwise frictionally unstable slip, resulting in episode(s) of elevated, yet aseismic, slipping rate (Rudnicki and Chen, JGR 1988; Segall and Rice, JGR 1995). Under this circumstances, pressurization of pore fluid due to shear heating when included in the analysis, often drives otherwise stable slip at elevated rates to the ultimate instability.

When dynamic slip is considered, Problem (2), the origin of the self-healing mode of shear rupture is usually attributed to the experimentally based rate and state dependence of dry friction. We show here that the thermal pressurization of pore fluid alone can lead to existence of self-healing slip pulses for assumed simplistic friction description (constant friction coefficient). The obtained solution allows to explore the scaling of the dynamic rupture's extent, its propagation velocity, total slip, and associated energy release with respect to the shear zone thickness, remote loading, pertinent material parameters. For example, the maximum slip duration in the pulse (dislocation rise time) is simply proportional to the timescale for hydro/thermal diffusion over the thickness of the shear zone (proportionality coefficient is increasing function of remote loading). In the view of bounded rupture propagation velocity, the latter necessarily constrains the maximum spatial extent of the rupture pulse.

A CHEMO-THERMO-MECHANICALLY COUPLED ANALYSIS OF GROUND DEFORMATION INDUCED BY METHANE HYDRATE DISSOCIATION

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There are several problems to be solved during the production of natural gas from methane hydrate. These mainly relate to (1) the exploration of high quality deposits containing methane hydrate, (2) investigation of methods for producing of gas, and (3) study of effects of gas production on the environment. The third one includes the ground deformation due to the extraction of methane hydrate and the leakage of gas. When we produce gas from the marine sediments, extensive subsurface deformations may lead to a sea bed slide, while the leakage of gas affects the marine water environment and subsequently contributes to global warming.

In the present study, we have developed a simulation method based on the chemo-thermo-mechanically coupled analysis in order to predict ground deformation, due to the dissociation of methane hydrates. With this method, the phase change from hydrates to fluids, the flows of pore water and gas, the mechanical behaviour of the solid skeleton, and heat transfer can be simultaneously solved. The numerical method is based on the finite element method using an updated Lagrangian formulation, in which the conservation of mass for water and gas phase, the conservation of momentum for total phase, and the conservation of energy are simultaneously solved. In the present study, the average skeleton stress, which is determined from the difference between the total stress and the average pore fluid pressure, is used for the stress variable in the constitutive model. An elasto-viscopalstic model for unsaturated soil is adopted for the constitutive relation of soil skeleton by introducing the suction effect in the hardening rule. In addition, the strength of the soil strongly depends on the saturation of the hydrates in the void, since hydrates work as bonds between soil particles.

Using the proposed method, we have numerically analyzed the dissociation process for the heating and the depressurizing methods. It has been predicted that ground deformation is caused by the generation and dissipation of water and gas during the dissociation.

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GEOMECHANICAL BEHAVIOUR OF GAS HYDRATE SEDIMENT MIXTURES

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Gas hydrates are crystalline solids (clathrates) in which gas molecules are encaged within lattices of hydrogen bonded water molecules. Hydrates are stable under specific conditions of low temperatures and high pressures. Perpetrations to this delicate system can induce hydrate dissociation resulting in increased pore pressures, volume expansion, and generation of gas bubbles; all which have the effect of reducing soil stability. Understanding and quantifying this geomechanical behaviour is necessary to accurately model reservoir response during gas production from hydrate reserves and is required as an input into any analysis of submarine slope stability in which gas hydrates are being considered.

Because the environment in which natural gas hydrates form make them difficult to study in situ, laboratory systems which simulate in situ conditions are necessary to further our understanding of the fundamental properties of gas hydrates. To that end, a geotechnical gas hydrates research laboratory housing a specialized high pressure, low temperature triaxial apparatus has been constructed at the University of Calgary. Modeling the dissociation behavior of hydrates in porous sediments also requires mathematically expressing the thermodynamic-chemical equilibrium that exists within the system, mass and energy balance, fluid flow and heat transfer mechanisms, and the boundary conditions, etc. that are governing the problem. Results from experimental and theoretical studies to date indicate that the dissociation of only a small amount of gas hydrate (approximately 6 to 8% void occupancy) leads to dramatic reductions in the effective stress and soil failure.

LOCAL BEHAVIOR OF PORE WATER PRESSURE IN THE SPECIMEN DURING PLANE-SRAIN COMPRESSION TEST OF SOFT ROCK AND ITS NUMERICAL SIMULATION

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In order to understand the mechanical behavior of soft rock, many laboratory tests on sedimentary soft rock have been conducted in which the influence of the intermediate principal stress was not taken into account. However, in predicting the precise behavior of soft rock, the influence of intermediate principal stress always plays an important role. Therefore, in this study, a series of plane-strain compression tests on sedimentary soft rock were carried out. The saturated specimens were used for all tests. The plane-strain apparatus used in this research has a special feature in which the pore water pressure in the specimen can be measured. From the laboratory tests on soft rock, it was found that the pore water pressure distribution in the specimen was not uniform. In this research, the plane-strain compression tests were regarded as the model experiments and the behavior of the local pore water pressure in the specimen was investigated.

On the other hand, in order to determine the material parameters for a proposed constitutive model [1, 2], a series of drained/undrained triaxial compression tests and creep tests were carried out. Finally, three-dimensional finite element analyses of the plane-strain compression tests as model experiments are carried out based on parameters obtained from triaxial tests.

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A REVIEW FOR NUMERICAL TOOLS EMPLOYED IN SOIL DYNAMICS AND SOIL-MACHINE INTERACTION

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Researchers at Caterpillar have been using Finite Element Analysis (FEA), Mesh Free Models (MFM) and Discrete Element Models (DEM) extensively to model different earthmoving operations. Multibody dynamics models using both flexible and rigid body have been used to model the machine dynamics. The proper soil and machine models along with the operator model can be coupled to numerically model an earthmoving operation. The soil-machine interaction phenomenon has been a challenging matter for many researchers. Different approaches, such as FEA, MFM and DEM are available nowadays to model the dynamic soil behavior; each of these approaches has its own limitations and applications. To apply FEA, MFM or DEM for analyzing earthmoving operations the model must reproduce the mechanical behavior of the granular material. In practice this macro level mechanical behavior is not achieved by modeling the exact physics of the microfabric structure but rather by approximating the macrophysics; that is using continuum mechanics or/and micromechanics, which uses length scales, that are larger than the physical grain size. Different numerical approaches developed by Caterpillar Inc. researchers will be presented and discussed.

SIMULATION OF EARTHMOVING OPERATIONS USING METHOD OF CORRECTED SMOOTH PARTICLE HYDRODYNAMICS (CSPH)

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The objective of this research is the continued evolution of CSPH [1,2] as a suitable Mesh Free Method, for the prediction of earthmoving implement forces and overall soil motion for earthmoving operations in fine-grained cohesive soils. In this collocation formulation, balance of linear momentum is expressed in strong form and solved, together with the continuity equation, at each mesh free point using an adaptation of the CSPH method. The present approach however, reformulates stabilized nonconforming nodal integration [3] and recasts it as a stabilized gradient operator, suitable for use in a CSPH setting. This non-local vector operator, formed using linear Moving Least Squares (MLS) shape functions, is then employed whenever spatial derivatives are needed. Kernel support size and particle neighborhood both vary as the deformation progresses.
The constitutive model for the cohesive soil, couples rate independent plasticity and isotropic damage mechanics in the operator-split formulation of reference [4]. Discrete fracture is simulated for particle neighbors that meet fracture criteria by altering their respective MLS shape functions and re-assembling the stabilized gradient operators. This process is reflected in the irreversible conversion of interior particles to boundary particles, with the accompanying presence of newly established surface normals, and ultimately leads to the creation of new boundary surfaces associated with the fragmenting soil. Contact between the earthmoving implement and the soil fragments and contact among the soil fragments themselves are both handled through a penetration based penalty method that uses the surface normals of the newly fractured surfaces.
Demonstration example results for 3D simulations of a scaled blade cutting clay type soil and a scaled bucket excavating clay type soil are shown. These results capture soil plasticity coupled with damage evolution, soil fragmentation at the end-state of damage and contact of soil fragments with the both the earthmoving implement and other fragments. These industrial applications of CSPH help to highlight the strengths of this method in the study of fragmenting media.

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MODELING PROCESSES INVOLVING SOIL-WHEEL INTERACTION

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Approaches for modeling the process of a wheel rolling over soil are of interest in numerous engineering applications, including performance of earth-moving machinery and assessment of land damage caused by off-road vehicles operating in forests, parks, and wetlands. In these problems, predicting the soil deformation induced by a wheel is critical. Numerical simulations based on the finite element method (FEM) are being used increasingly to study soil-wheel interaction. Such simulations have been successful when the soil is cohesive, although difficulties arise when the material is frictional, including numerical instabilities and unrealistic material behavior. In this paper, FEM is used to simulate indenting and rolling wheels on frictional/cohesive soils, accounting for the large soil deformation. Emphasis is placed on adequately capturing the soil response using relatively simple soil constitutive models. Essential differences resulting from associated and non-associated material models are presented. Key differences between two-dimensional and three-dimensional simulations are discussed. Data from lab-scaled experiments on the soil displacement field beneath a wheel, obtained using particle image velocimetry, are presented to validate the theoretical results and enrich the understanding of soil-wheel interaction.

ANALYSIS OF DEFORMATION AND DAMAGE PROCESSES IN SOIL-TOOL INTERACTION PROBLEMS

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The processes of interaction of earth-working machines with soils are related to large inelastic deformation inducing soil structure variation with dilatancy, compaction and critical states developing during the process. The effects of hardening, softening, strain localization in shear or tensile rupture bands accompany the machine tools operation in the cohesive soil. The aim of this presentation is to provide a simplified incremental analysis of some typical processes, such as soil cutting, digging, filling, compaction, etc. by applying constitutive models relevant to the type of process. The aim of analysis is to predict the deformation modes, forces interaction and energy required for the process, and also to generate optimal process control in order to minimize some parameters of soil-tool interaction

The classical soil plasticity is based on a perfectly plastic model with the Coulomb yield or Drucker-Prager conditions. The limit analysis theorems valid for the associated flow rules then provide the foundation for different methods of assessment of limit loads and safety factors of geotechnical structures. However, for soil tool interaction processes, more refined models are needed accounting for large localized deformation of soil and configurations changes. The models of material softening, hardening and critical state are introduced and applied in the analysis of soil deformation. The incremental equilibrium analysis is applied with account for softening and hardening effects and generation of periodic flow mechanism occurring during tool motion. For the analysis of soil compaction, the multisurface hardening model has been applied with account for material memory effects.

The theoretical predictions are confronted with ample experimental data obtained in laboratory testing of soil-tool interaction problems. The typical processes considered in the paper are:

(i) monotonic tool motion inducing progressive soil deformation: soil cutting, excavation, digging, wedge, punch and pile penetration;
(ii) controlled tool motion with the objective to minimize energy dissipation required for the process execution, the wear of tools and its effect on analyzed deformation mode is clarified;
(iii) soil compaction induced by a moving roller with the analysis of cyclic compaction and related soil cracking effects.

DYNAMIC EFFECT OF GROUND LOOSENESS ON HYDRAULIC SHOVEL PERFORMANCE

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Dynamic effects can adversely affect the performance of earthmoving equipment. These effects can be part of the machine itself, such as looseness in joints and controller faults, or dynamics of the working environment, including hard digging conditions and soft ground.

This work uses a model-based approach to solve for the ground reaction forces in a dynamic model of a hydraulic shovel. Although the mechanical system is controllable under specified control parameters for firm ground conditions, the frequency-response function of the machine on an elastic foundation makes it prone to oscillation. In certain types of operation, such as excavating oilsand, deformation of the ground under the tracks has been observed to exacerbate the effect.

A dynamic model of a shovel will be discussed that includes the soft ground condition as well as possible faults on the joints and mechanical components. Due to the difficulty of acquiring all required data from a real model, an idealized model of the machine has been developed for in-depth laboratory studies of soil-machine interaction and the effects of faults and cracks on the entire performance of the system. Soil-machine interaction and faults model will be included in this model and effective parameters of the system will be identified. These dynamic parameters will be used for later experiments on an instrumented full-scale hydraulic shovel.

This paper examines the dynamics of soil-machine interaction and suggests operating strategies to minimize oscillation in soft ground conditions. It also discusses the application of fault tolerant control to avoid high stresses in the system.

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A SEMI-LAGRANGIAN REPRODUCING KERNEL FORMULATION FOR MODELING EARTHMOVING OPERATIONS

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Soil motion during an earth-moving process typically exhibits extensive plastic deformation in conjunction with prevailing failure mechanisms. Finite element methods have not been successfully applied to the analysis of earthmoving processes primarily due to their inability to effectively model such large deformation and the resulting damage evolution in earthen materials. Alternatively, meshfree methods have been developed to inherit main advantages of finite element methods while at the same time overcome main disadvantages of finite elements caused by the mesh-dependency. One successful application of meshfree methods is in large deformation problems based on a Lagrangian reproducing kernel particle method [1]. The Lagrangian reproducing kernel formulation that considers evaluation of kernels based on particle distance measured in the undeformed configuration is, on the other hand, inadequate in modeling earthmoving operations due to the regularity requirement of deformation gradient. In this work we propose a semi-Lagrangian reproducing kernel formulation which performs kernel evaluation using distance measure defined in the deformed configuration to circumvent the limitation of Lagrangian reproducing kernel formulation. This approach allows the neighbors to be redefined during the deformation process, and avoids the need for inverse mapping from deformed to undeformed configurations. Since semi-Lagrangian kernel does not conserve material covered under the kernel support, a kernel convective effect resulting from the material diffusion is derived, and a nodal mass correction algorithm is introduced. Several stabilized nodal integration methods [2, 3] are proposed for semi-Lagrangian discretization, and stability analyses of these methods are performed. Numerical simulation of earthmoving operations is carried out to demonstrate the effectiveness of the proposed methods.

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CONCURRENT MULTISCALE COMPUTATIONAL MODELING OF PARTICLE TO CONTINUUM LENGTH SCALE MECHANICS IN UNBOUND DENSE, DRY PARTICULATE MATERIALS

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The talk will discuss the latest progress for a project on concurrent multiscale computational modeling of unbound dense, dry particulate materials, such as sands and gravels. The approach involves coupling discrete element (DE) particle regions to finite element (FE) continuum ones, and bridging the particle to continuum mechanics within an equivalent micromorphic inelastic continuum constitutive model and balance equations. The goal is to use higher-resolution materials models (DE particle mechanics) for regions that experience large relative particle motion and flow, while coupling to a lower-resolution FE micromorphic continuum representation (but higher resolution than standard continuum) in regions where the particulate material behavior is more like a solid continuum. We would like the numerical simulations to be independent of the location of this coupling/overlap region.

Based on current computational limitations, it is not feasible to simulate the heterogeneous, localized deformation, and flow response in the engineering application of interest using a pure particle-based materials modeling approach (such as DE simulation), in turn motivating a multiscale modeling approach. The challenge is how to couple particle and continuum regions properly from a computational mechanics perspective to minimize fictitious numerical DE/FE boundary effects (for quasi-static and dynamic loading), and how to allow one region to transition to the other – and vice versa – through the bridging mechanics, while all done adaptively within a computational framework. An experimental collaboration on micro-computed-tomography of particle system deformation provides data for calibration/validation of the multiscale modeling approach.

A MICRO-MECHANICAL STUDY OF THE INTERACTION OF LIQUEFIED GRANULAR SOILS WITH STRUCTURAL ELEMENTS

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The dynamic response of saturated granular soils exhibits complex interaction mechanisms in the presence of structural elements (such as pile foundation or machine tool). This response has been investigated extensively over the last decades using full and small scale tests, theoretical studies and numerical simulations. Most of these simulations rely on continuum formulations and the use of the finite element method. Nevertheless, some of the mechanisms of saturated granular soil response are heavily dependent on the particulate discrete nature of these soils and are still not fully understood.

A coupled continuum-discrete model is used in this study to analyze the response and interaction of saturated granular soils with structural elements. A Lagrangian discrete element method (DEM) formulation is used to model the soil solid phase as an assemblage of particles. The fluid phase is idealized using an Eulerian formulation based on averaged Navier-Stokes equations. The interphase momentum transfer is quantified using established relationships. A continuum formulation is employed to model structural elements using the finite element (FEM) technique. The soil discrete elements and structural finite elements interact in a nonlinear frictional fashion at their interface. Numerical simulations were conducted to investigate the dynamic response of a saturated soil-pile foundation system. The conducted simulations provided valuable information regarding the interaction of liquefied soil with structural elements.

CONCEPT OF MESH SCALABILITY IN MESH-DEPENDENT FEM SIMULATIONS

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Finite element modelling of fracture processes is usually based on the introduction of special elements capable of accounting for stress singularities at the crack tip. When extensive crack propagation and/or multiple crack formation and interaction are involved, this type of modelling requires non-uniform meshes and, in many cases, re-meshing. An existing alternative approach is to model fracture evolution as successive breakage of finite elements in a uniform mesh. This alternative is attractive as it can model complex fracture structures in a natural way, free from the uncertainties in the identification of the criteria of crack propagation; however, the price to pay is the mesh dependence of the solution. Instead of fighting the loosing battle of mesh-dependence we propose to incorporate it in the computations. In the case of fracture modelling we quantify the dependence of the relevant stresses in the finite element at crack tip upon the element size; when the dependence approaches a power law with the required accuracy, we call the mesh scalable. If the mesh is scalable and the exponent and pre-factor are known we can scale the results of the computations to the size relevant to the scale of the microstructure of the material. We illustrate this approach with 2D examples of single straight cracks under tensile and shear tractions applied either to the external boundary or to the crack faces. We show that combining the stresses at the crack tip computed using a set of similar meshes of different densities with the crack tip asymptotics allows accurate recovery of the stress intensity factors.

NEGATIVE POISSON'S RATIO IN GEOMATERIALS

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Thermodynamically admissible negative Poisson's ratios are mainly found in specially engineered artificial materials. In nature, the negative Poisson's ratios where only confirmed in some highly anisotropic crystals like a cubic crystal of Pyrites FeS2 and only in certain directions. The results of the analysis of ultrasonic logs in boreholes indicate that negative Poisson's ratios may exist in some rocks in the Earth's crust. This is usually associated with Budiansky's (1965) result which predicts negative Poisson's ratios for large enough concentrations of pores. This conclusion is however an artefact of the algebraic self-consisted method; more accurate methods do not confirm it. Accurate interpretation of the results of ultrasonic measurements requires an understanding of the micromechanical nature of the negative Poisson's ratio effect and its influence on the mechanical behaviour of geomaterials.

Many geomaterials belong to a class of particulate materials whose microstructure consists of cemented grains, pores and cracks. We consider a homogenisation scheme that computes the effective characteristics of a particulate material and determine the combinations of parameters which result in negative values of Poisson's ratio. We show that the presence of conventional pores and cracks reduces the negative Poisson's ratio effect; only a special type of cracks with restricted sliding can increase this effect.

MICRO AND MACRO-STRUCTURAL SIZE EFFECTS FOR DAMAGE IN BRITTLE MATERIALS

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We present a new procedure to construct micro-mechanical damage models able to describe size effects in solids. We use homogenization based on two-scale asymptotic developments to describe the overall behavior of a damaged elastic body starting from an explicit description of elementary volumes with micro-cracks. An appropriate micro-mechanical energy analysis is proposed leading to a damage evolution law that incorporates stiffness degradation, material softening, size effects, uni-laterality, different fracture behaviors in tension and compression, induced anisotropy. The model also accounts for micro-crack nucleation and growth.

The new approach is illustrated on numerical tests in the case of brittle damage. Extended finite elements are used for the numerical modeling of macro-crack initiation and growth. The influence of the micro- and macro-structural size parameters on the failure initiation and growth is pointed out.

MODELLING UNDRAINED BEHAVIOUR OF GRANULAR MATERIALS AT HIGH STRESSES

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Static liquefaction occurs when the shear stress within the granular material decreases under undrained conditions and induces collapses when correct control variables are used. Although this condition is not necessary as collapses can occurs under drained conditions or even for dry materials, it is usually studied under closed drainage. Few experimental studies have been performed at high stresses for such type of test. Hence, the few constitutive relations written and evaluated along drained paths at high stresses are not evaluated along undrained paths.

Numerical simulations of undrained tests for dense sand at high stresses obtained by an elastoplastic strain-hardening model are presented. The constitutive relations are based on an original idea which makes dependent the critical state line (CSL) on the evolution of the material due to grain breakage. As grain breakage occurs during isotropic consolidation and shearing, the position of the critical state line in the (e, log p') plane is assumed vary to due to grain crushing.

The comparison between numerical results and experimental data show that the introduction of this new concept inside an elastoplastic model can accurately reproduces the material behavior. Comparison is also made between numerical simulations obtained by the model with and without grain breakage. As the dilatancy tendency vanishes, the pore pressure continuously increases with the effective mean pressure. It is found that the peak in the q-p' plane is reached for a lower value for the model with grain breakage which implies that the instability occurs before and becomes close to the experimental value. The axial strain corresponding to this peak is correctly simulated. The behavior of dense sands at high stresses is similar to the behavior of loose sands under low stresses. It is also found that the stress ratio corresponding to the instability line for dense sands at high stresses is close to the value usually found for the same material at a lower density.

FROM SELF-ORGANISATION TO CONGESTION IN COMMINUTING GRANULAR SYSTEMS

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Confined loading of brittle granular systems manifests several transitions and lifecycles of deformation. During continuous monotonic confinement of an initially gas-like set of elastic perfectly-brittle granules, the first transition occurs when the short-uncorrelated force chains are being replaced by a long-correlated network of force chains. This is often referred to as the jamming transition. Thereafter, the granules act as a collective solid-like entity, and contact laws fully govern the constitutive behaviour. In brittle systems, beyond a certain point, further monotonic confinement leads to the crushing of particles, which triggers un-jamming, reorganisation of fragments, followed by re-jamming. These lifecycles continue until the confined comminution is congested, i.e., particles are being self-cushioned against further crushing. Beyond the congestion point, the motion is once again fully governed by the contact laws, and experiments suggest that a power law determines the grain size distribution. We see the presence of the power law grain size distribution as a hint of fractal, self-similarity, and a self-organised criticality process.

The objective of this project is to investigate the connection between power-law distributions with self-similarity and self-organisation, using two extreme discrete model approaches: (a) a crushable distinct element model, and (b) a new conceptual self-organised criticality (SOC) model. The logic behind the first model is physically driven from the complete rigorous computational description of the Newtonian mechanics of round particles, their interaction, motion and fragmentation. The second model is approached via an inverse philosophy: to describe the system in the simplest way, using a set of organisation rules of long and crushable spaghetti-like particles. Using this concept it becomes attractive to study the emergent properties that the complex system presents. The idea is to explore points of convergence between these models. If both systems derive certain similar patterns, then to a first order, these patterns may be explained using the simple logic that defines the SOC model. The results will be further discussed in the context of the recent energy framework of breakage mechanics and the concept of granular compactivity. Some traditional assumptions of soil mechanics will be reviewed with respect to uniaxial compression experiments.

KINEMATICS OF GRANULAR MIXTURES SUBJECTED TO SHEAR

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New retroreflector tracer particle technology provides the potential for simultaneous 3-D translational and 3-D rotational movements within granular materials. However, the size and material density of the tracer particles are likely different than typical matrix particles whose movement they are designed to measure. Particles of different sizes and densities tend to segregate which indicates that the tracer particles will likely not perfectly trace the movements of the particles of interest. Therefore, effective use of the retroreflector tracer particles to predict movement of the bulk material requires a systematic understanding of how their relative movement depends on relative size and density of the tracer particles.

We experimentally and computationally study the movements of individual components within binary mixtures in two differently sheared systems, one, a free surface gravity-driven shear band and the other, an internal shear band driven by slow, steady forcing. In addition to somewhat different relative (segregation) velocities depending on the nature of the shear band, we report that the mean variance of the velocities differs for components, a difference that may be understood through a combination of momentum considerations and a geometrically motivated model.

SHEAR BANDING IN A BRITTLE MATERIAL

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Closed-loop, servo-controlled compression tests were conducted to investigate the development of shear banding in Berea sandstone. The experiments were performed with a Vardoulakis-Goldscheider type plane-strain apparatus, designed to allow the shear band to develop in an unrestricted manner. Dilatancy and friction were evaluated at three confining pressures, and several tests were halted in the strain-softening regime.

Thin section microscopy and digital image analysis provided direct observations of the shear band. Porosity increase within the shear band was 4-8 grain diameters wide and associated with intragranular microcracks; increased porosity did not extend beyond the tip of the shear band. Thin sections for optical microscopy were prepared from specimens where deformation localized and softening occurred, but the shear band was not fully developed; the specimens remained intact and the shear band was well preserved. Care was taken in handling the specimens by potting them in hydrostone to facilitate cutting the specimens in half; then the blocks were quenched in low viscosity, blue epoxy to increase the visibility of porosity and to preserve the structure of the material during slide preparation. The thin-sections were examined under reflected and transmitted light at magnifications ranging from 4x to 52x. Photographs were taken with a digital camera mounted on the microscope.

The shear band seemed to initiate at a stress concentration, either the corner of the specimen or, when present, an imperfection (a 3-mm diameter hole) introduced in the specimen. From displacement measurements and acoustic emission locations, it was concluded that the shear band initiated around peak stress and then propagated in the softening regime until the test was stopped. All the specimens showed similar deformation mechanisms along the shear band. Microcracking among individual grains was the dominant failure mechanism. The intensity of grain cracking within the shear band was greatest near the corner of the specimen and decreased as the surface was traced towards the center of the specimen. Areas of high crack density also appeared to have the greatest amount of grain size reduction and there seemed to be a larger amount of pore space. The shear band also propagated through regions where grain fracturing was not observed; in these locations the shear band transected grain contacts.

A numerical code was written to provide an efficient means for analyzing the relative porosity of epoxy-impregnated thin sections. The code was set up to receive a digital image. The colors of most concern were blue, the color of the epoxy filling the pore spaces, and white, the color of individual grains composing the matrix of the sandstone. The bitmap image used three parameters, R, B, and G, to define the color of each pixel, with a value between 0 and 255. The intensity of the R channel consistently defined the boundary of grain and pore space and was the channel used to differentiate blue pore space from the white grains composing the matrix, Fig. 1.

The areas of increased porosity, 4-8 grain diameters wide, did not extend beyond the tip, which was determined by the last observable intragranular microcrack. An absence of notable porosity change in the immediate vicinity of the tip suggested that a porosity increase was not detected prior to microcracking. The porosity change that corresponded to the shear band was observed in areas with high densities of intragranular microcracks. Therefore, it seemed that the localized porosity increase was related to the evolution of microcracks after the initial inception of the shear band.

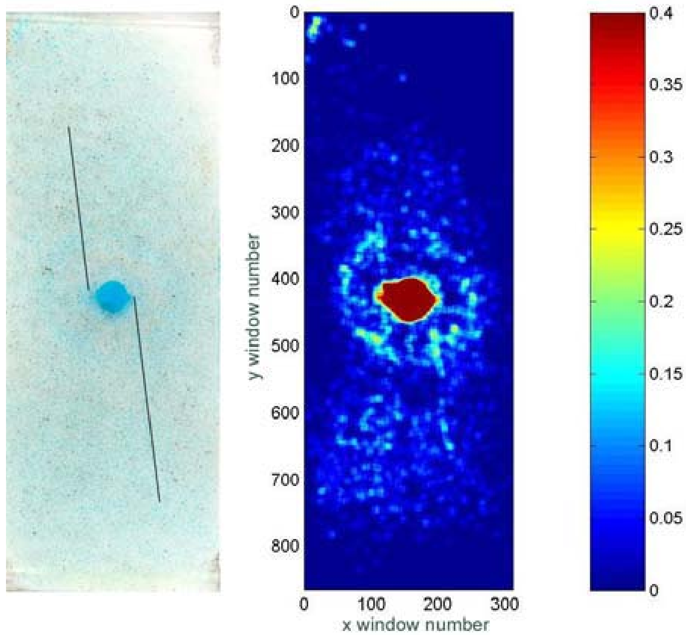

Figure 1. Shear band in Berea sandstone at 5 MPa confinement

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