ABSTRACTS: DEM I

Particle-size distribution shape effect on critical state behavior of sand – Mingdong Jiang and Zhongxuan Yang, Zhejiang University

In this paper, a three-dimensional (3D) discrete element method (DEM) is applied to study the critical state behavior of idealized granular assemblages, in which various PSD shape parameters are considered, including mean particle size (D50), the coefficient of uniformity (Cu), the coefficient of curvature (Cc), and the coefficient of size span (Cs). Numerical triaxial tests are carried out by imposing axial compression under constant mean effective pressure condition. A unique critical state stress ratio in p’-q plane is observed. However, in e-log p’ plane the CSL shifts downward, as the grading becomes more widely distributed, i.e. the increasing size span (Cs). Additionally, a decrease in the coefficient of curvature (Cc) would also move the CSL downward but with negligible rotation. However, it is found that the variations of the mean particle size (D50) and coefficient of uniformity (Cu) do not affect the position of CSL in e-log p’ plane.

Suffusion-induced deformation and microstructural change of granular soils: a CFD-DEM coupling perspective – Zheng Hu (Zhejiang University), Zhongxuan Yang (Zhejiang University) and Yida Zhang (University of Colorado Boulder)

Behavior of granular soils subjected to suffusion is a classical but not yet fully understood problem. During suffusion, fines contents in the soil matrix are gradually eroded due to the continuous action of seepage flow. This paper presents the first micro-macro investigation on suffusion in internally unstable soils using the fully coupled computational fluid dynamics and discrete element method (CFD-DEM) method. The code couples the interaction between soil particles and seepage flow via momentum exchange terms between the two phases. The loss of fines and the volumetric strain of the soil skeleton during suffusion process are observed. In addition, the microstructure evolution is tracked via statistical descriptors such as coordination numbers and contact forces. A parametric study indicates that the initial fines content of soil packing and hydraulic gradient of seepage flow can significantly influence the initiation and development of suffusion erosion. The corresponding evolution of contact force, coordination number and fines content reveals the micro mechanisms of suffusion erosion, which is useful for future upscaling and continuum-based modeling attempts.

Modeling of Soil Erosion Caused by Pipeline Leakage in Shanghai Using A Coupled CFD-DEM Method – Ye Lu (Shanghai University), Yong Tan (Tongji University) and Xiao Jiao Li (Shanghai University)

In recent years, lots of ground settlements and cave-in cases were reported in China. Forensic investigations indicated that many cases were caused by leakage of pipelines. In metropolitan areas of Shanghai, pipelines are usually buried less than 4 m below ground surface (BGS) and the natural water table level is located at 0.5-1.0 m BGS. When a pipeline with gravity flow (water supply or
sewage) breaks, the soils surrounding the pipe can be washed into the pipe, which result in settlements or ground surface cave-in in the end. In order to explore the process of soil erosion and migration of soil particles in case of pipeline leakage, a coupled computational fluid dynamics (CFD) and discrete element method (DEM) were used in this study. The flow field of ground water was computed using FLUENT module in ANASYS, and soil strata were modeled in Particle Flow Code (PFC3D). The computed flow field was imported into PFC3D and coupled computation was performed. A series of numerical simulations were conducted to investigate the soil erosion process and influence of following factors: ground water table levels, opening size and locations of pipeline leaks. Finally, some conclusions were reached on the basis of numerical analyses.

**Deformability of idealized polydisperse granular materials: DEM simulation** – Jizhong He (Tongji University), Fang Liu (Tongji University), Mingjing Jiang (Tianjin University & Tongji University), and Gang Deng (China Institute of Water Resources and Hydropower Research)

This paper investigates the effect of the grain size distribution (GSD) on deformability of assemblies of spherical particles using the distinct element method. The GSD is modeled by a normalized beta function, which allows variation of the size span (from nearly monodisperse to highly polydisperse) and the shape (from approximately linear to strongly curved) of GSD. A series of triaxial compression tests are simulated on a set of assemblies with varying GSDs under different packing fractions and confining pressures. The compressibility under isotropic loading and deformation modulus during shearing are examined for various GSDs. The results show that the size span and the shape of GSDs affect the packing conditions of the assemblies but have negligible influence on the compressibility and deformation modulus of the assemblies under the same packing conditions. A unique correlation is found between the deformation modulus and the mechanical coordination number, which can be estimated from the effective void ratio.

**A conceptual model of critical hydraulic gradient for piping considering friction resistance** – Hui Tao (The University of Akron) and Junliang Tao (Arizona State University)

Piping is a major cause for failures of embankment dams and levees. Recently, the fundamental mechanism of piping was investigated using coupled Computational Fluid Dynamics (CFD) and the Discrete Element Method (DEM). The numerical simulation results not only reveal the evolution of soil fabrics and contact forces when piping progresses, but also have implications for the development of a conceptual model of piping resistance. A series of CFD-DEM simulations were conducted to evaluate the effects of various soil parameters on the critical hydraulic gradient. Inspired by the numerical results, a simple conceptual model of piping resistance was developed considering equilibrium of a soil column at hydraulic critical state, considering soil specific gravity, initial void ratio, sample aspect ratio and friction coefficients. This model highlights the effect of friction on critical hydraulic gradient, which is not included in the classic Terzaghi formulation.
**ABSTRACTS: GROUND IMPROVEMENT**

**Microscale visualization of Microbial-Induced Carbonate Precipitation (MICP) processes by different treatment procedures** – Yuze Wang (University of Cambridge), Kenichi Soga, (University of California, Berkeley), Jason DeJong (University of California, Davis) and Alexandre Kabla (University of Cambridge)

Microbial-Induced Carbonate Precipitation (MICP) is an innovative subsurface improvement technique for enhancing the strength and stiffness of soils or controlling their hydraulic conductivity. Various treatment procedures have been applied in previous MICP studies, but the MICP processes occurring during these different procedures are poorly understood. In this study, microscale experiments were conducted by using synthetic porous models called microfluidic chips to investigate the MICP processes occurring at the microscale during different treatment procedures (one-phase treatment, two-phase treatment, and modified two-phase MICP treatment). During one-phase treatment, bacterial suspension and cementation solution were mixed and then injected together. During two-phase treatment, bacterial suspension (Phase 1) was injected, after which bacteria were allowed to settle and attach to the porous medium before proceeding with the injection of cementation solution (Phase 2). For the modified two-staged injection, bacterial suspension was mixed with CaCl2 solution prior to injecting this mixture (Phase 1), followed by the injection of cementation solution (Phase 2). The microscale experiments revealed how different treatment procedures influence the interactions between bacteria and chemicals, their interactions with flow, the formation and development of calcium carbonate precipitates, and the correlation between the distribution of bacteria and precipitates. The choice of MICP treatment procedure influenced the MICP process and affected the morphology of carbonate precipitates. The results presented in this paper suggest that the visualization of the MICP processes during the different treatment procedures using the microfluidic technique can improve our understanding of the fundamental mechanisms of MICP and consequently help improve and tailor the MICP treatment procedure for different applications.

**Reinforcement Effect on Air-Booster Vacuum Preloading for Improvement of Dredged Fill** – Huayang Lei, Yao Hu, Shuangxi Feng and Yingnan Liu, Tianjin University

The effectiveness of vacuum preloading is a very important aspect of the improvement effect of dredger fill. This paper offer the technique of air-booster vacuum preloading to reinforce dredged fill. Comparing tests of the conventional vacuum preloading and the air-booster vacuum preloading are performed to investigate reinforcement effect of the dredged fill. The test results indicated that the reinforcement effect of air-booster vacuum preloading is more superior than the conventional vacuum preloading, which the air-booster vacuum preloading can increase surface settlement and vane shear strength, decrease the final pore pressure and reduce the clogged drainage boards. In addition, the results of microstructure also demonstrate that the pores of air-booster vacuum preloading is less than that of conventional vacuum preloading, and the microstructure is more dense.

**Particle-based visualization of ground behavior caused by grout injection by means of a transparent soil** – Daiki Takano (Port and Airport Research Institute, Japan), Yoshihisa Miyata
Compaction grouting (CPG) is an in-situ grout injection technique used to improve the liquefaction resistance of loose sandy ground by densification and increasing lateral confining pressure. The present study investigates ground response during grout injection using a particle-based visualization technique with a transparent granular soil. The injection process was simulated using models placed in a geotechnical centrifuge. During each physical model test, the movements of target particles were captured by a video camera and analyzed using the Particle Tracking Velocimetry (PTV) technique. The particle movements are used to examine the influence of pile spacing on ground movements during injection grouting. The test results show that different soil deformation modes occur during grout injection depending on the pile spacing.

Effect of different biopolymers on the soil mechanical behavior – Antonio Soldo and Marta Miletic, Auburn University

One of the most popular processes to enhance soil strength is chemical treatment using additives like cement, but its use raises a number of environmental concerns such as CO2 emissions, groundwater contamination, prevention of vegetation growth, etc. Therefore, the demand for bioinspired and sustainable soil improvement alternatives is increasing. The main aims of this research are: i) the development of eco-friendly, biopolymer-based soil improvement techniques, and ii) experimental and computational investigation of their effect on the shear strength behavior. To achieve these objectives, five different types of biopolymer additives were used: xanthan gum, guar gum, chitosan, beta 1,3/1,6 glucan, and alginate-calcium chloride solution. Improvement of the soil shear strength by biopolymer reinforcement was experimentally investigated by conducting unconfined compression, indirect tensile, and triaxial tests on the plain and biopolymer-modified soil specimens. The additional testing variables were a percentage of biopolymers added, and the specimen curing time. Furthermore, a constitutive model that can capture a stress-strain response of elastic-plastic biopolymer modified soil is developed and implemented. The biopolymer-soil composite is described by a non-associated non-linear Drucker-Prager hardening plasticity model. Several unconfined compression tests on the unreinforced soil as well as on the biopolymer-modified soil were modeled. It was found that the presence of biopolymers significantly improved the mechanical behavior of the soil. These findings agree closely with the experimentally observed response. The experimental and numerical results showed that most types of biopolymers significantly enhanced the engineering soil properties. Furthermore, the addition of xanthan gum proved to be the most effective solution and provided plenty of potential for future sustainable engineering.

Geogrid-stabilized Aggregate Base Stiffness: Laboratory Characterization and Modeling for Mechanistic Pavement Analysis – Yong-Hoon Byun (Kyungpook National University), Issam Qamhia (University of Illinois at Urbana-Champaign), Erol Tutumluer (University of Illinois at Urbana-Champaign) and Mark Wayne (Tensar International Corporation)
Geogrids provide mechanical stiffening in a pavement base course to effectively increase bearing capacity and prevent excessive deformations under vehicular loading. Lateral restraint is the primary stabilization mechanism associated with the interlocking of aggregate particles in the geogrid apertures. The objective of this paper is to present findings from a recent laboratory study which could successfully quantify local stiffness enhancement of aggregates through micromechanical interlocking provided by two different types of geogrids and apply these findings in the modeling of the resilient response characteristics of geogrid-stabilized base course composite systems thus considering the mechanically stabilized layer stiffness profiles as sublayers in a pavement elastic layered macro-modeling approach. Using three pairs of bender elements as shear wave transducers, the horizontal stiffness profiles were determined above mid-heights of aggregate specimens where two types of geogrids with rectangular and triangular shaped apertures were installed. For the two geogrid types, the shear modulus profiles estimated from shear wave measurements decreased as the distance from the geogrid location increased. The stiffness increase near the geogrid with the triangular aperture was greater than that near the geogrid with rectangular aperture. Considering the variations in shear moduli with distance from the geogrid location, the local stiffness enhancements provided by the two geogrid types were evaluated as the mechanical stabilized layer characteristics and assigned to resilient modulus profiles in a constructed geogrid-stabilized aggregate base course layer in flexible pavement mechanistic analysis and modeling. The results of the modeling simulation, which fully cover the applications of geo-mechanics principles from micro to macro in research and practice, will be presented to show the effect of geogrid base stabilization on the computed pavement resilient responses for the two geogrid types. The modeling approach for the base course sublayers or geogrid influence zones based on the stiffness characterization will be demonstrated for use in the mechanistic analysis of the geogrid-stabilized pavement systems.

Effect of particle shape on unbounded aggregate-inextensible steel grid interaction evaluated using bench-scale rutting apparatus – Sangy Hanumasagar (Georgia Institute of Technology), Prashanth Vangla (Georgia Institute of Technology), J. David Frost (Georgia Institute of Technology) and Mark H. Wayne (Tensar International Corporation)

The current study investigates the effect of shape characteristics of coarse aggregates on macroscopic rutting behavior of unbound aggregate layer systems in flexible pavements. The improvement in rutting behavior achieved with stabilization using a steel grid is also presented. The rutting tests are conducted using a newly developed laboratory rutting apparatus with a rolling-wheel loading system, which closely simulates the field pavement conditions. For this study, totally three uniformly graded aggregate materials and one inextensible steel grid are chosen. The three aggregate materials are similar in gradation, but differ in their shape properties such as sphericity, roundness and roughness. These shape parameters are precisely quantified using image-based computational methods. By assessing the permanent deformation behavior of the aggregate materials with and without grid stabilization under rolling load conditions, the influence of properties like shape and roughness can be clearly understood. Results from the testing program clearly established the influence of aggregate morphology on their rutting behavior and the effectiveness of grid stabilization even with low-quality rounded aggregates. Further, the placement of grid in the upper-half of the base layer was observed to consistently reduce the surface rutting properties of the tested specimens.
ABSTRACTS: CLAY/FLUIDS

The effect of electro-chemical properties of fluids on clay structure and sedimentation – Yeong-Man Kwon (Korea Advanced Institute of Science and Technology), Ilhan Chang (University of New South Wales) and Gye-Chun Cho (Korea Advanced Institute of Science and Technology)

In micro-mechanical aspects of fine grained soil, interaction between clay and pore fluid determines overall behavior of soil such as strength, permeability, adsorption capability etc. Previous studies and theories have suggested that clay particles form different structure depending on the electro-chemical properties of fluids such as pH, ion concentration, electrical conductivity, permittivity and water content etc. Thus, it is very meaningful to investigate the influence of electro-chemical properties of fluid on initial structure of aqueous phase clay and correlation between initial structure of clay and sedimentation behavior of clay. To observe these clay structure, it is necessary to use electron microscope due to small clay particle size (in the range of nanometer). This study analyzes effect of fluid electro-chemical properties (sodium chloride concentration, polyelectrolyte concentration) on clay sedimentation. Additionally, clay structural changes were visually observed by scanning electron microscope (SEM) to identify microstructure of clay. Results indicated that electro-chemical properties of fluid affect initial clay structure and structural differences occurs distinct sedimentation results. Sodium chloride concentration in pH of 6.0 forms dispersed structures and results in lower settling velocity and higher sediment density. e-Polylysine forms face to face flocculated structure and results in higher settling velocity and higher sediment density.

Variation of electrical conductivity of bentonite with porosity and pore fluid conductivity – Thu Thi Do (Chonnam National University), Ewusi-Wilson Rodney (Chonnam National University), Changho Lee (Chonnam National University), Hyunwook Choo (KyungHee University) and Woojin Lee (Korea University)

The porosity (i.e., void ratio) is a very important parameter to access the behavior of fine-grained soils. Because the electrical conductivity of soils is strongly related to the porosity, a series of experimental measurements using the four terminal electrodes system were performed in this study to investigate the quantitative variation of electrical conductivity of the bentonite as a function of pore fluid conductivity and porosity. The measured electrical conductivities of the bentonite with porosity shows two distinguishable behaviors with the electrical conductivities of pore fluid: the variations of the measured electrical conductivities of the bentonite can be assessed by pore water conductivity and/or surface conductivity according to the values of pore fluid conductivity. The magnitude of the surface conductivity of tested bentonite is back-calculated based on the measured values and index properties of the bentonite. The relation between porosity and electrical conductivity of the tested bentonite is proposed in this study.

Experimental and Numerical Investigation of Micro-Mechanics of Particle-Fluid Flow and Transport – Ingrid Tomac, Daniel Fjaestad and Luo Lan, University of California San Diego

This paper investigates micro-mechanics of particle-fluid and particle-wall interactions for prop-pant flow and transport in narrow fractures. Small and large-scale experiments are performed in
the lab to better understand role of particle-particle interactions on slurry agglomeration, settling and transport velocity. Experiments include coarse, medium and fine sand with up to 60% particle volumetric concentration in a 2-mm wide fracture. Particle Image Velocimetry (PIV) is used for analysis of velocities of individual particle and group particles and their relative paths, collisions and agglomerating in viscous Newtonian fluid. The displacement vectors show the movements of group of particles and global velocity trends of the observed area. The results from this experimental study indicate dependency of settling velocity on particle size and shape, as well as the dependency of different size of particle or agglomerate particles. The slurry settling velocity depends on the relationship between settlement, particle concentration and occurrence of particle agglomeration. Large-slot experiments investigate effect of particle, fluid and flow parameters on horizontal slurry transport regime in the narrow fracture. Analogies with sediment transport theories are found to be useful but do not completely comply with obtained results. The measured results, including vertical velocities and displacement vectors of singular particle and agglomerated particles, were compared with previously published theoretical and empirical relationships. Forming of particle agglomerates during settling, caused by frequent particle-particle and particle-wall collisions and interactions, changes the overall settling velocities predicted by the previous experiments in larger slots. Previously performed numerical analysis using the Discrete Element Method coupled with computational fluid dynamics (DEM-CFD) is shown to quantitatively and qualitatively synthesize obtained results.

Clogging and Reduction of Hydraulic Conductivity due to Colloidal Deposition: Geochemical Impacts – Jongmuk Won and Susan Burns, Georgia Institute of Technology

Understanding the underlying mechanisms of clay colloid deposition in porous media is critical in all geotechnical applications that rely on filtration. Deposition of particles in the filter medium can result in clogging, which significantly decreases the hydraulic conductivity of the filter medium. There are three main mechanisms for deposition of clay colloids in saturated porous media: straining, attachment, and detachment. Attachment and detachment are a function of the interaction energy between clay colloids and the filter bed material, and are governed by the size of the clay colloids and solution chemistry. Therefore, understanding the interaction energy is critical in the prediction of clay colloid transport. This experimental study used batch kinetic adsorption tests to investigate the impact of solution chemistry and mass ratio on the interaction energy and attachment between kaolinite and silica particles. Data demonstrated that the short term attachment coefficients were not sensitive to ionic strength; however, long term attachment is a strong function of ionic strength and d50, with attachment increasing as ionic strength increased and median particle size decreased.

A new paradigm for the compression behaviors of cohesive soils – Yuan Guo and Xiong (Bill) Yu, Case Western Reserve University

The classical soil mechanics characterize the mechanical behaviors of soil with a set of empirical experimental parameters. Such approach gains popularity due to its simplistic nature in geomaterial characterization and inherent variabilities of the geomaterials, which provide consistent solutions to engineering practice problems. However, in the opinions of the author, geotechnical researchers should not just be satisfied with such a heuristical approach. We believe that a more
universal predictive geotechnical mechanics can be initialized starting from formulating a set of fundamental parameters. We demonstrate this ideology on the compression behaviors of clay. The interparticle force model is calibrated with interparticle force curve by Atomic Force Microscope (AFM) curve measurement. The interparticle force model is implemented into the discrete element model (DEM). The DEM model are firstly calibrated and validated with controlled experiments. It is then used to simulate the behaviors of Kaolin clay subjected to different loading paths in the consolidation experiment. The effects of particle shape and topology are also analyzed with the model. The results show that behaviors such as compression branch, swelling branch, and overconsolidation pressure are reproduced with the model and compare favorably with the experimental data. The overconsolidation pressure remembered by the clay is related to the van de watts force between clay particles. The memory is also facilitated by the shape of clay particles. Fundamental characterization of interparticle force model together with computational model provides a new approach to predict the engineering behaviors of clay and to identify the related parameters. This shows the promise of a new set of science based toolsets integrated with holistic computational model to study the engineering behaviors of cohesive soils.

Nanoscale stick-slip behavior of Na-montmorillonite clay – Babak Abbasi (Washington State University), Balasingam Muhunthan (Washington State University), Iman Salehinia (Northern Illinois University) and Hussein Zbib (Washington State University)

Clay minerals are plate-like particles that play a critical role in problems involving swelling, deformation, and failure. Fundamental understanding of these phenomena and the parameters that influence them requires studies at the nanoscale. The nanoscale mechanism of the sliding of clay sheets at different states of hydration and hydrostatic stress is studied here using molecular dynamics in an isobaric-isothermal ensemble. The hydration state was varied to lie within the range of crystalline swelling (0 - 400 mgwater/gclay). Under hydrostatic pressures as high as several GPa, the mobility and the molecular structure of water are comparable to super-cooled water. Examination of the molecular structure of interlayer water, number of hydrogen bonds, and their configuration during shear loading show evidence of stick-slip phenomenon similar to those found in thin films. The nanoscale cohesion and friction angle of the layers were calculated using the Mohr-Coulomb failure criterion and found to be in good agreement with previous studies.
ABSTRACTS: CONTINUUM/FEM

Numerical analysis of the plastic zone in drained soil around a pressurized cylindrical cavity under biaxial stress – Fernando Patino Ramirez and Chloe Arson, Georgia Institute of Technology

Understanding the nature of stress and deformation distribution around cavities is fundamental to improve the design and construction of underground structures, such as drainage systems, tunnels and geological storage facilities. This paper focuses on the problem of cylindrical cavity expansion in a drained elasto-plastic soil under biaxial stress conditions, which, to this date, has no closed form solution due to the mathematical complexity that arises from the absence of axis-symmetry. We analyze the sensitivity of the size and shape of both the cavity and the Elastic-Plastic (EP) boundary to soil mechanical parameters. Geometric indexes are stored in an output database after each Finite Element (FE) simulation. A feature selection algorithm automatically ranks the soil parameters according to their predictive nature, and calculates the error made if one of the parameters is dropped out of the model. Results show that the friction and dilation angles have little influence on the size and shape of the cavity or the EP boundary. The geometry of the cavity is mostly influenced by the elastic modulus, while that of the EP boundary is mostly controlled by the Poisson’s ratio. Although the present analysis is restricted to cases when the cavity and the EP boundary both keep elliptical during the pressurization process, results provide useful insights for the development of new analytical or semi-analytical solutions for the problem of cavity expansion in drained-biaxial stress conditions.

Predicting the behavior of an embankment using an elastic visco-plastic model with industry standard data and a large scale undisturbed specimen – Pankaj Baral, Buddhima Indraratna and Cholachat Rujikiatkamjorn, University of Wollongong

Predicting the behaviour of embankments on soft soil in terms of settlement and excess pore water pressure has been practiced for many years and it is still a challenging exercise for geotechnical engineers. Soft soil possesses time-dependent stress-strain behaviour due to its viscous nature and this visco-plastic behaviour affects the long term settlement and dissipation of pore water. In this paper the behaviour of embankments is predicted using an elastic visco-plastic model (Indraratna et al., 2018) with a non-Darcian flow function (obtained from the radial consolidation of large scale undisturbed specimen); this elastic visco-plastic model has been developed by coupling the basic radial consolidation equation developed by Barron with Bjerrum’s time-equivalent (Bjerrum, 1967) concept that incorporates Yin and Graham’s (1989) visco-plastic parameters. The settlement and excess pore water pressure obtained from this model are then compared with pre-existing models as a Class C prediction for the Ballina trial embankment. This proposed elastic visco-plastic model gave better results in terms of settlement and pore water pressure with the field data, although the excess pore water pressure that did not dissipate after a year or so is mainly due to the biological and chemical clogging of piezometers in acid sulphate soil (ASS) terrain.

Local macro-element model of rigid monopiles in sand – Ritesh Gupta (Universite Grenoble Alpes, CNRS), Christophe Dano (Universite Grenoble Alpes, CNRS) and Stéphane Grange (Universite Lyon, INSA-Lyon, GEOMAS)
Macro-element modelling has gained significant importance over conventional finite element modelling in recent times, due to its computational ease and readily available information for numerical parametric studies and engineering concept design. This paper presents a ‘local’ macro-element for rigid open-ended monopile in sand, under cyclic loading for offshore wind turbine applications. It is inspired by the macro-element developed for deep foundations by Taciroglu et al., 2006. The local macro-element model is an assembly of a non-linear spring model representing pile-soil interface friction, combined p-y & t-z soil-pile interaction behavior along pile shaft; and q-z behavior at pile base of monopile. Simplified cyclic loading scenarios approximately representing the wind and wave loading has been utilized in the computations; with consideration to standard ultimate and serviceability limits criteria. The pile head response observed from the model under static monotonic and cyclic loading shows the qualitative potential of the macro-element model. The model response results are further utilized to report significant differences between the previously studied ‘flexible pile’ and our ‘rigid pile’ behaviors in sand under combined loading.

**Finite element analysis of cement-treated ground under micro failure and macro yield conditions** – Hideto Nonoyama (National Defense Academy, Japan), Yoshihisa Miyata (National Defense Academy, Japan) and Daiki Takano (Port and Airport Research Institute, Japan)

A cement treatment technique is often used to improve the bearing capacity of soft-soil foundations. Predicting the effects of such an improvement is important for deciding on the volume of cement and the improvement area. In this research, a finite-element method with particle discretization that can consider the micro failure and macro yield conditions of the treated soil is proposed. Its validity is examined by simulating laboratory strength test results.

**Considerations in the reliability evaluation of the effective stress analysis of a two-dimensional embankment model** – Tadashi Kawai (Tohoku University), Motoki Kazama (Tohoku University), Natsuki Adachi (Takenaka Corporation), Jong-Kwan Kim (Korea Institute of Civil Engineering and Building Technology) and Toshihiro Noda (Nagoya University)

Since the ground is usually regarded as a continuum body comprised of inhomogeneous materials, numerical analyses are indispensable for evaluating the behavior of the foundations and soil structures in detailed designing processes. However, as yet no unified method or procedure has been established for the systematic and objective checking of the calculated results. In this paper, through the data processing of the results of an effective stress analysis, a frame image to validate the calculated results for a two-dimensional embankment model is discussed. Firstly, the general issues about the validation of FEM results in geotechnical engineering are summarized, then a two-dimensional effective stress analysis of an embankment model was conducted to classify the elements to separate in a several groups based on their behavior. Finally, suggestions are made regarding the kind of laboratory tests which should be conducted to evaluate the reliability of the calculated results.
Granular Micromechanics: Paradigm for Continuum Modeling of Geomaterials – Anil Misra, University of Kansas

Continuum modelling remains an attractive choice for describing the mechanical behavior of geomaterials particularly for problems that are computationally intensive, such as problems in which path and rate dependency are paramount. Granular micromechanics provides a paradigm for continuum modeling of geomaterials that captures at the macro-scale (>10^6 grains), the influence of grain-scale parameters. This short paper delineates the progressive development of the granular micromechanics approach and discusses its advantages, particularly in relation to other possible methods for modeling geomaterials. The discussion is illustrated with experimental evidence and describes the recent applications of the granular micromechanics approach to path-dependent and rate-dependent behavior of geomaterials.
Mechanical characteristics of methane hydrate-bearing sands containing various fines – Yang Wu (Guanzhou University), Masayuki Hyodo (Yamaguchi University), Koji Nakashima (Yamaguchi University), Shintaro Kajiyama (Yamaguchi University) and Yukio Nakata (Yamaguchi University)

A series of triaxial compression tests were performed to investigate the influences of fines and porosity on mechanical characteristics of hydrate-free sands and methane hydrate-bearing sands. The test results indicate that an increase in fines content within methane hydrate-bearing sands greatly improves peak shear strength and promotes dilation behavior. The inclusion of fines particles into sand grains alters the internal microstructure of sand matrix and the hydrate formation pattern in the pore space between sand grains and fines particles. The grain-scale structure of methane hydrate-bearing sediment is proposed to examine the effect of fine contents.

Creep behavior of methane hydrate bearing sand under triaxial compression loading – Yukio Nakata, Shintaro Kajiyama, Masayuki Hyodo, Norimasa Yoshimoto, Shotaro Hiraoka, Ryo Shimamoto and Koji Nakashima, Yamaguchi University

Research and development related to methane hydrate (hereafter referred to as MH) is being progressed in order to prepare for its production in Japan. In fact, in 2017, an offshore production test was carried out to investigate the validation of methane gas extraction from the sea bed for commercial purposes (MH21 Research Consortium). The extraction of MH as methane gas is mainly performed using a depressurizing method, in which the MH layer is depressurized to a point outside of its stability region.

A series of triaxial shear tests were performed on artificial MH bearing sands using temperature-controlled high-pressure triaxial shear testing apparatus developed by Hyodo et al.(2013). It is assumed that MH production will occur over a long period and the dissociation of MH not only leads to a change in properties of the MH-bearing sand but, as pressure propagation gradually occurs, the stress on the sand also changes.

However, there has been little research carried out regarding the compressive creep behavior of MH bearing sand and this property is an important characteristic for the prolonged production of MH. This is because the compression of the MH bearing sand causes the decrease of the permeability and reduces the production rate. Therefore, a series of the creep tests using the triaxial compression apparatus has been carried out for MH bearing sand under various stress conditions.

Strength and deformation behavior of methane hydrate bearing soil under different b values using DEM – Jie He (Tongji University) and Mingjing Jiang (Tianjin University & Tongji University)

Methane hydrate bearing soils (MHBS) are a kind of natural soil deposit. The influence of the intermediate stress ratio on its mechanical response is not well understood, especially in regards to relations between macro-micro responses of MHBS. The objective of this paper is to investigate the influence of the intermediate stress ratio on the mechanical behavior of pore-filling type of MHBS under the condition of a constant mean stress p. The distinct element method (DEM) can
be used by modeling MH particles as agglomerates of spheres cemented together and filled into the pores of soil skeleton based on the specific MH saturation of pore-filling type of MHBS. The numerical samples were then subjected to shear deformation for different b values under a specific MH saturation. The macro behavior and micro response were shown by the relationship between the stress ratio and the fabric structures.

**Macro-micro response of pore-filling type of methane hydrate bearing soil under in simulated true triaxial tests of constant minor principal stress** – Jie He, Tongji University

More and more resources have invested into studying the mechanical characteristics of MHBS to realize commercial exploration as a type of energy reserve. The effect of different values of intermediate stress ratio b under the same constant minor principal stress on Methane hydrate bearing soils (MHBS) is not well understood, especially in regards to relations between macro-micro responses of MHBS. The distinct element method (DEM) can be used by modeling MH particles as agglomerates of spheres cemented together and filled into the pores of soil skeleton to form pore-filling type of MHBS. Then the numerical specimens were then subjected to shear deformation for different b values under a specific MH saturation. The macro-micro responses were shown to investigate the influence of the intermediate stress ratio on the mechanical behavior of pore-filling type of MHBS under the constant minor principal stress.

**Characterization of coal combustion residuals in engineering practice** – Longde Jin, Andrew Fuggle, Grant Martin and Gregory Hebeler, Golder Associates

The coal-fired electric power generation industry historically managed the long-term storage of coal combustion residuals by sluicing these generally sand- and silt-sized materials into impoundments. These materials present significant challenges when assessing their engineering parameters as the materials are not typical of traditional geo-materials and the standard methods for interpretation are generally inadequate. High-quality undisturbed sampling of these materials is also very difficult, which leaves in-situ testing as one of the primary characterization tools. One approach is to develop site-specific relationships for interpreting cone penetration test (CPT) data. This approach combines the ability of the CPT to provide a good indicator of material behavior and a near-continuous vertical profile, with other supporting data from supplemental in-situ and laboratory tests, to estimate engineering parameters for design. A flexible approach is encouraged, which takes into account all available data within accepted theoretical frameworks.
ABSTRACTS: PARTICLE/CRUSHING I

3D Finite Element Modeling of Individual Sand Particles Behavior at High Strain Loading
– Siavash Amirrahmat and Khalid Alshibli, University of Tennessee

Fracture is a common failure mode of sand particles when they are exposed to high strain rate (HSR) loading conditions such as blast, impact, or projectile penetration. The constitutive behavior and the failure mode of sand particles are influenced by the loading rate; therefore, a particle-scale constitutive model is necessary to address the effects of HSR loading and particle fracture within a sandy material. To that end, a special Kolsky test (i.e., a HSR 1D compression test), 3D x-ray computed tomography (CT), and finite element methods were employed in this study to investigate the failure mode of individual natural sand particles when they are subjected to a HSR loading. Individual particles were first imaged using CT technique followed by testing them using Kolsky bar at an approximate strain rate of $10^4$/second. The fragments of fractured particles were collected and imaged using synchrotron micro computed tomography (SMT) for further evaluation of the fracture mechanisms within individual particles. A brittle fracture model was adopted to perform 3D Finite element (FE) modeling to capture the fracture of individual sand particles. 3D CT images of the particles were used to generate 3D meshes with similar morphology as the actual sand particles and the particles were loaded similar to Kolsky experiments. The paper introduces the constitutive model and briefly discusses the calibration and the validation of the simulations. It investigates the effect of loading mechanisms on fracture of particles.

The construction and commissioning of a new inter-particle loading apparatus for the micromechanical behavior of railway ballast – Cacin Po Ying Wong, Ben Boorman and Matthew Coop, University College London

Relatively little is known about the contact mechanics of ballast particles, yet it is a key input into DEM of ballast, which is becoming increasingly common. A new inter-particle loading apparatus has therefore been constructed to examine these mechanics. This is able to apply loads or displacements at a contact between two ballast or small rockfill sized particles along three orthogonal axes. The apparatus has been constructed for low compliance and high accuracy of the loads and displacements, using a new type of capacitive proximity transducer. Preliminary tests gave highly variable data, but a softer response than expected in normal loading, indicating that the contact morphology must play a significant role.

A level set-based method of constructing Set Voronoi diagrams and its application to granular materials – Reid Kawamoto (University of Tsukuba), Edward Ando (Université Grenoble Alpes) and Takashi Matsushima (University of Tsukuba)

This paper presents a new method to construct Set Voronoi diagrams, a variant of Voronoi diagrams, using level set functions. This method does not require the discretization of particle surfaces, rather, it uses level set functions representing particle geometries directly, and also does not require overlapping particles to be eroded. The method is then applied to a simulation of 3-D particles undergoing triaxial compression using the level set discrete element method (LS-DEM) at three stress states: initial, peak, and residual. From the Set Voronoi diagrams, Set Voronoi cell
volumes are computed and particle-wise volume fractions are found. The evolution of the distributions of these volume fractions and dilations, inside and outside the shear band, is reported, which agrees well with the globally-measured porosities in the reference experiment used to calibrate the simulation.

**Numerical and laboratory evaluation of the fragmentation of a sand in a ring-shear apparatus** – Sebastian Lobo-Guerrero (*AGES Inc.*), Zamri Chik (*University of Malaysia*) and Luis Vallejo (*University of Pittsburgh*)

Granular materials forming part of the gouge in earthquake fault zones are subjected to fragmentation as a result of compressive and shear stresses. Fragmentation caused the granular materials to develop a particle size distribution (psd) that was fractal in nature. In this study, fragmentation is accomplished by the use of a Bromhead’s ring shear apparatus and a uniform sand (d50 = 1.6 mm). The sand was subjected to various combinations of normal and shear stresses that changed the psd from uniform to one that was fractal. The level of fragmentation of the sand was measured by the fragmentation fractal dimension value that changed from 1.4 to 2.3. Also, the peak friction angle decreased as a result of fragmentation from 47 degrees to 27 degrees. Implications of the laboratory results (micro analysis) to the behaviour of a gouge in earthquake faults is outlined. Also, a DEM analysis of the breaking process is presented.

**Discrete element study of morphology effects on fracture of single sand** particles – Zaher Jarrar and Khalid Alshibli, *University of Tennessee Knoxville*

The particulate nature of granular materials makes it essential to study the behavior of these distinct particles to gain a fundamental knowledge of the bulk material behavior and characteristics. Fracture of sand particles greatly influences the constitutive relationships and deformation characteristics of natural granular materials. Discrete Element Method (DEM) is a numerical method that has been widely used to model discontinuous materials. Although particles in DEM are typically modeled as rigid incompressible spheres, several approaches have been proposed in the literature to model fracture of sand particles. This paper presents the results of DEM simulations of unconfined 1D compression tests for 100 particles with various sizes and shapes. Single sand particles were modelled as agglomerates of spheres that are bonded together at their contacts using the linear parallel bond model. The agglomerates match the actual 3D shape of sand particles that were acquired from high resolution 3D Synchrotron Microcomputed Tomography (SMT) images. Effects of morphology (sphericity and roundness) on tensile strength are investigated based on calculated values of the model proposed by Hiramatsu and Oka (1966). Tensile strength values tend to increase as sphericity of agglomerates increases, while no specific trend is observed with variation of roundness. A modification of Hiramatsu and Oka (1966) model is proposed by normalizing stress with respect to sphericity index. The mean tensile strength of all agglomerates calculated from the proposed model is within 5% of the parallel bond strength used in DEM simulations.
**ABSTRACTS: IMAGE ANALYSIS**

**Shape, Fabric, Packing and Compressibility of Sands by SedImaging** -- Junxing Zheng (Iowa State University), Roman Hryciw (University of Michigan) and Andrea Ventola (University of Michigan)

A sediment index, B is defined from the Haar Wavelet Transform decomposition of an image of a sand following deposition through a water-filled sedimentation column. The index reflects the dominant orientation of the particles’ longest axes in the horizontal direction. As such, B correlates with particle dimension ratios, d1/d3 and d1/d2 where d1>d2>d3. For perfect spheres, B=1 and it increases with particle elongation. Index void ratios, emax and emin are observed to increase with an increasing B. Functional equations for the index void ratios are presented. They relate emax and emin to B and the index void ratios of glass spheres. It is also shown that the one-dimensional compression index, CC can be related to B. Equations are presented relating CC to B and the compression index of glass beads at low, medium, and high relative densities, Dr.

**Study of surface fractal dimension of compacted bentonite by image analysis** – Haiquan Sun, David Mašín and Jan Najser, Charles University

Compacted bentonite is very popular material for engineered barriers in high level nuclear waste disposal. The swelling properties are mostly related to the high specific surface of montmorillonite. Fractal dimension is a parameter which may be used to understand the fabric of compacted bentonite. In this paper, the Czech compacted bentonite B75 with dry densities of 1.27 g/cm3 and 1.90 g/cm3 was studied. The environmental scanning electron microscope (ESEM) tests were used to study the surface characteristics of bentonite. The samples were observed under both wetting and drying paths. Pore surface fractal dimension was calculated from microphotos of ESEM observations by box counting method. The analysis of ESEM images showed a complex pore system of the compacted bentonite, which is composed of different pore families. Under low magnifications, more homogeneous structure of aggregates and macro pores was observed. High magnification showed in a detail the structure of the aggregates with smaller pores inside them. Results show that the fractal dimension highly depends on observation scale, applied suction and initial dry density.

**Meso- and macro-scale response of clay-structure interfaces under varying shearing rates** – Hans Henning Stutz (Aarhus University) and Alejandro Martinez (University of California Davis)

Soil-structure interface shear behavior can present significant challenges in geotechnical engineering analyses because it is governed by localized soil deformations. In the past three decades, significant attention has been focused on the interface behavior of sandy soils. However, only a few studies exist that focus on obtaining deformation measurements at the meso- and macro-scales in clayey and silty soils. This paper presents an investigation focused on the influence of varying shearing rate on the stress – deformation behavior of fine-grained soil-structure interfaces. The interface shear tests were performed on normally- and over-consolidated kaolin specimens sheared at different rates. The Particle Image Velocity (PIV) method was utilized in thus study to provide
meso-scale measurements of soil deformation to complement macro-scale measurements of mobilized shearing resistance. The practical relevance of the insights provided in this paper is discussed.

**Discrete frictional wing crack based damage model for salt rock** – Xianda Shen (*Georgia Institute of Technology*), Chloe Arson (*Georgia Institute of Technology*), Jihui Ding (*Texas A&M University*), Fred Chester (*Texas A&M University*) and Judith Chester (*Texas A&M University*)

A Discrete Frictional Wing Crack Damage (DFWCD) model is proposed to simulate the initiation and propagation of inter-granular cracks in salt rock. Damage is defined as the integration of crack densities over the unit sphere. In order to simulate inter-crystalline bonding, a cohesive frictional model is formulated for main cracks. Crack growth is controlled by mode I and mode II fracture mechanics criteria. Since salt crystals are rhomboids, we assume that wing cracks are perpendicular to the main cracks. The tensile normal stress triggers the growth of wing cracks according to a mode I fracture mechanics criterion. The formulated DFWCD model is calibrated against triaxial cyclic loading tests. This model can predict the microstructure development, the nonlinear stress/strain relationship and the stiffness degradation during the cyclic loading.

**SEM experimental study on unified calculation theory of water and earth pressures** – Li-yang Xu, Ri-qing Xu, Yi-hong Zhu and Muhammad Rizwan (*Zhejiang University*)

In order to study the engineering adaptation of unified calculation theory of water and earth pressures in practical engineering. A serial of tests are conducted for unified calculation theory of water and earth pressures from Wang Hong-xin. The soil sample is from Hangzhou Wulin-square underground space development project, and Scanning Electron Microscope (SEM) microstructure research technique was used. In the tests, the parameter \( \xi \), which means pressure coefficient of soil-water coaction, is calculated. Then the active earth pressure can be calculated. After that, relations between the particle diameter and \( \xi \), between the void ratio and \( \xi \), between the thickness of adsorbed water and \( \xi \) are all studied. Finally, the interpretation of unified calculation theory of water and earth pressures was given from the viewpoint of microstructure experiment. The results showed that the parameter \( \xi \) increases with increase of particle diameter and void ratio, decrease with increase of the thickness of the adsorbed water. The unified calculation theory of water and earth pressures can be applied into engineering practice, which realizes transition of water and earth pressures calculation between high permeable sand and low permeable clay.

**Assessment of merits and demerits of angularity measurement techniques using image analysis** – Nimisha Roy (*Georgia Institute of Technology*), Prashanth Vangla (*Georgia Institute of Technology*), Madhavi Latha (*Indian Institute of Science*) and David Frost (*Georgia Institute of Technology*)

Angularity is an important aspect of particle morphology, which can be directly correlated to the mechanical response and strength of granular materials. Many researchers have proposed several direct and indirect methods such as visual charts, analytical formulae and advanced image based techniques for qualitative and quantitative assessment of particle angularity, but no single method has been fully successful in distinguishing all types of particles and in obtaining the accurate value of angularity. However, due to the significant importance of the parameter, researchers have been
using few widely accepted angularity quantification methods. This paper evaluates the conceptual merits and demerits of four of such methods, viz. two conventional methods called Roundness Index and Degree of Angularity proposed by Wadell (1932) and Lees (1964) respectively, and two image based methods called Angularity using outline slope (AI) and Gradient angularity index (GRAD) used in University of Illinois Aggregate Image Analyzer (UIAIA) and Aggregate Imaging System (AIMS), respectively. Based on the comparative assessment, it is concluded that the meso level geometrical features of importance along a particle’s outline need to be distinctly characterized as they are the controlling parameters that contribute to particle angularity and correlate to kinematics and mechanical response of granular materials.
ABSTRACTS: LIQUEFACTION/CYCLIC LOADING

Performances on shear resistance and shear wave propagation of sandy soils in liquefaction and re-liquefaction tests – Guojun Liu, Noriyuki Yasufuku and Ryohei Ishikura, Kyushu University

Cyclic tri-axial system was assembled in laboratory for the liquefaction and re-liquefaction tests. Liquefaction strength of saturated sandy soils were discussed with different relative densities and different deviator stress in the tests. And utilizing of the propagation characteristics of shear wave in different contact force between soil particles, which is represented as effective stress in macroscopic, this study is trying to discuss the performances of shear wave velocity in liquefaction and re-liquefaction tests. Results indicated that the effective stress decreased smoothly and gently during the most portion in the first liquefaction process, on the contrary, the effective stress dropped very fast in the re-liquefaction process even if the soils became denser after re-consolidation process. The velocities of shear wave in most cases was measured at approximate 190m /s after consolidation with the same cell pressure of 100kPa, and approximate 25 m/s was measured when sand was liquefied by different test conditions.

Mechanism analysis on deformation progress of soft clay under cyclic loading – Huayang Lei, Yinggang Xu, Min Liu and Yao Hu, Tianjin University

In this study, a series of triaxial cyclic tests were carried out to study the dynamic deformation properties of soft clay, scanning electron microscope (SEM) tests were proceeded to reveal the micro change of soft clay under cyclic loading. Test results show that plastic strain of soft clay exhibits three stages under different dynamic stress level: stable, progressing, and failure type. Plastic strain increases up to a constant value involving stable type, while for progressing or failure type variation, deformation is divergent. Large pores spread depth and width in undisturbed soft clay and are compressed heavily at early vibration. With continuous cyclic loading, large diameter aggregates are crushed into smaller ones, which slows down the increase of plastic strain. Under high dynamic stress level, weak band among partial densely compacted areas occurs and gradually develop which induces the divergent plastic strain. Dynamic deformation development is summarized into three stages: initial compaction, pore size distribution, and weak band occurrence, which deepen the comprehension of deformation characters of soft clay under cyclic loading.

The effect of dynamic loads on the behavior of non-engineered mudrock backfill materials – Shaymaa Kennedy, Sheffield University

In the UK HS2 rout line come cross south Yorkshire. Mudrock backfill covered wide spread area. In this paper performance of subsoil subjected to dynamic loads were studied. Material of study is Mudrock backfill, a weak rock which response under indicative loading of high speed rail line is unknown. A triaxial cyclic loading machine was conducted to assess the expected mechanical behaviour of mudrock under a range of dynamic loads which could be generated beneath different track constructions. In this paper material of study compacted at optimum moisture content and subjected to cyclic load. Deviatoric stress and stress ratio are discussed in this paper. Stress level are applied to recreate in situ conditions in the laboratory by applying 4 Hz frequency. Cyclic
response is vital to determine the residual plastic strain which is major concern to find out the rate of settlement.

**Insights from numerical analysis of liquefaction-induced building settlement** – Jorge Macedo (*Georgia Institute of Technology*) and Jonathan Bray (*University of California Berkeley*)

A stress-ratio controlled, critical state compatible, bounding surface plasticity soil constitutive continuum model (PM4Sand) is employed to perform dynamic soil-structure interaction effective stress analyses of buildings with shallow foundations affected by soil liquefaction by systematically varying subsurface conditions and building properties while applying a set of ground motions with a wide range of characteristics. During strong shaking, shear-induced soil deformation mechanisms govern building response and volumetric mechanisms are of lesser importance. Large shear strains are localized within the liquefiable layer under the edges of the building. Generated pore water pressures under the building are typically higher during strong shaking, inducing flow away from underneath the building. The shape of the building settlement vs. time curve matches the shape of the normalized standardized cumulative accumulated velocity (CAVdp) slightly better than that of the Arias Intensity (Ia). CAVdp is also estimated with less uncertainty than Ia. Hence, CAVdp is the performed ground motion parameter for estimating liquefaction-induced building settlement. The 5%-damped one-second spectral acceleration brings in additional important earthquake ground motion information. Building settlement is highly dependent on the relative density of the liquefiable layer, and its thickness and depth are also important soil profile characteristics. Building contact pressure is the most important building parameter. Key insights from the large number of SSI analyses are shared.

**Multidirectional cyclic shearing of granular media using discrete element simulations** – Ming Yang (*University of British Columbia*), Mahdi Taiebat (*University of British Columbia*), Patrick Mutabaruka (*Massachusetts Institute of Technology*) and Farhang Radjai (*University of Montpellier*)

Multidirectional shear test provides a physical way to study the complex response of granular soils subjected to cyclic shearing applied simultaneously in two directions on a plane. This test extends the simpler plane strain loading condition simulated by unidirectional simple shear test to a real three-dimensional configuration, and targets the state of loading in many cases experienced in the real field conditions. A number of such laboratory experimental tests have been carried out over the years and are available in the literature. While these tests provide useful physical basis for the stress-strain response of soils in such complex loading scenario, understanding the underlying mechanisms influencing the response, such as fabric and dilatancy, requires detail investigation into the interactions in the inter-particle level. Discrete element simulations can provide numerically driven experiments to be used for detailed analysis of soil rheology when subjected to these shearing within the framework of discrete element modeling. Periodic boundary conditions are applied to minimize the boundary effects that pose limitation to the use of physical tests results. Among the several possible load paths, the ones known as linear, circular/oval, and figure-8 are reproduced using this numerical framework. Variations of stress, strain, contacts, force chain, and fabric can be explored for densely packed polydisperse granular media using these simulations.
ABSTRACTS: CONTACT/INTERFACES

Grain-scale study of pile installation and subsequent axial loading cycles – Jeanne Doreau-Maliocche, Gaël Combe, Jean-Benoît Toni and Cino Viggiani, Université Grenoble Alpes, CNRS

The mechanisms occurring at the grain scale at sand-pile interface during pile installation and axial cyclic loading are analysed quantitatively in a mini calibration chamber, using X-ray tomography and advanced image analysis tools. Grain kinematics, local porosity changes and grains orientations are studied, along with the macroscopic mechanical response of the interface. The test conditions are not representative of real engineering applications, where piles supporting bridges, tidal or wind turbines have to safely sustain severe load-controlled cycles. However, measurements at the grain scale shed light on the mechanisms controlling the macroscopic behaviour of sand-pile interface.

Assessment of Influence of Sand Morphology on Inter-Particle Force and Stress Transmission under Uniaxial Compression Using 3D Finite Element Modelling – Wadi Imseeh and Khalid Alshibli, University of Tennessee

Sand is a granular material composed of discrete particles that have complex morphology and interaction at the particle-scale. Compressive loads imposed at boundaries of a mass of sand are internally resisted by highly stressed particles that form force chains. With the emergence of high-performance computations, research of particle-level interaction in sand is shifting from laboratory experimentation to computational models that can predict materials’ behavior with a high fidelity. The high heterogeneity of sand particles (e.g., variation in morphology, mineralogy, surface texture, etc.) can be incorporated in computational models whereas laboratory experiments are always limited by testing apparatus capabilities. In this paper, in-situ Synchrotron Microcomputed Tomography (SMT) scans were acquired during a uniaxial compression experiment on natural round silica sand and used to build and calibrate 3D finite element (FE) simulations. Sand particles were modeled using isotropic linear elastic tetrahedral meshes that closely match each particle morphology. Similar simulations were also conducted on an analogous virtual assembly with meshes of equal volume spherical particles replacing each sand particle. The major advantages of the conducted FE simulations are their ability to provide estimates (e.g., stresses and contact forces) at multi-scale levels. Namely, nodal contact forces and element stresses were averaged into particle-level estimates. Interestingly, spherical particle simulations showed higher particle-level stresses as well as inter-particle contact forces than actual sand shape particles at the same global axial compression load. Furthermore, spherical particle exhibited a lower coordination number during the simulations due to the absence of surface asperities in particle meshes. This advocates for the significance of particle-level morphology on inter-particle force and stress transmission in granular materials.

How does the plastic nature of contact interactions influence overall stiffness? – Masahide Otsubo (University of Tokyo), Kevin Hanley (University of Edinburgh) and Catherine O’Sullivan (Imperial College London)

This contribution draws on theoretical and empirical understanding of contact behaviour to consider the effects of two aspects of contact yield, namely slip prior to full frictional sliding and
asperity crushing, on the overall material response. The study considers the effects of these particle-scale yields on small-strain stiffness and the dynamic response to small-amplitude stress perturbations. Roughness effects are shown to have a more marked influence on the macro-scale response than partial slip.

**Framework for modeling coarse-grained soil behavior using 3D printed soil analogs** – Alejandro Martinez and Sharif Ahmed, *University of California Davis*

This paper presents the initial developments of a framework for modeling the compression behavior of coarse-grained soil using 3D printed particle analogs. This framework consists of a newly developed normalization scheme for 1-D compression response based on Hertz contact theory. The scheme normalizes the differences in stiffness of the natural and 3D printed particles’ constituent materials. To explore the capabilities of the proposed framework, this paper presents results of 1D compression tests on assemblies composed of spherical particles of constituent materials with Young’s moduli that span over two orders of magnitude (steel, glass and 3D printed resin). These initial results indicate that the stress-strain behavior of the assemblies can be normalized to be independent of constituent material stiffness. The presented framework can be useful for modeling the behavior of natural soil by testing representative 3D printed analogs, provided that the different aspects of the soils, such as particle shape, size, surface roughness and gradation are properly reproduced.

**Deformation behavior around foundation piles in Hasuike clay deposits: Model tests on Kawasaki clay** – Takaharu Shogaki and Daishi Okuda, *National Defense Academy, Japan*

Deformation behavior around the foundation piles in Hasuike clay deposits is examined based on the movement of soil particles in a laboratory model of Kawasaki clay penetrated by a foundation pile. The experiment results are compared with measurements of the changes of natural water content wn and undrained shear strength cu around the pile in the small boat docks section (SBD) of the Miettsu Naval Facility, Japan, to infer the installation method of the cedar foundation piles preserved in the SBD. The deformation around the cedar pile caused by pile penetration increased within the pile diameter range, likely due to the lower water content and higher shear strength caused by increased pore-water pressure and dissipation. The area influenced by pile penetration on site agreed with the affected area in the model clays; thus, based on the field and laboratory wn cu results, the cedar foundation pile was driven into position.

**Interface behaviour of sand and 3D-printed sleeves under axisymmetric shear test condition** – Prashanth Vangla (*Georgia Institute of Technology*), Omar A. Eid (*Golder Associates, Inc.*) and J. David Frost (*Georgia Institute of Technology*)

This paper study the axisymmetric interface shear behaviour of sand and CPT friction sleeves having different surface roughness and diameter. For this purpose three set of sleeves with different diameters were 3D print-ed. Each set of sleeves have three different kinds of textural features ranging from smooth to very rough in-duced on its surface, either due to the inherent resolution of the 3D printer or due to designing and printing of diamond shaped textured elements on the sleeve surface. The spacing of the diamond elements on sleeve sur-face was kept constant for all 3D-printed textured sleeves, implying that the total number of textured ele-ments per sleeve is dependent on the diameter. The macroscopic interface response of sleeves and sand is un-derstood through
surface topographical analysis of sleeve carried out by 3D optical profilometer. Results have shown that surface roughness of sleeves largely influenced sand-sleeve interface shear response. The diameter of sleeves didn’t show any effect on the interface response of smooth, textured and textured micro-rough sleeves except for the large diameter sleeve with textured micro roughness.
ABSTRACTS: DEM II

Influence of Particle Shape on Microstructure of Granular Materials under Gravity – Beichuan Yan and Richard Regueiro, University of Colorado Boulder

The paper presents study of particle shape effect within granular materials in gravitational environments using samples acquired from three-dimensional (3D) discrete element method (DEM) simulations of gravitational pluviation. Three-axis ellipsoidal particles with various aspect ratios are examined for their spatial orientations, and the three-axis probability density functions (PDF) are analyzed before and after pluviation. A complicated data structure, convex hull, is employed to construct tetrahedrons that connect particle centroids, and investigate the internal topology and fabric of particle assemblies composed of various particle shapes. The Qhull-constructed connective tetrahedrons within granular materials may serve as a useful tool to study the geometrical fabric, deformation/failure mechanism and stress distribution over granular materials.

Exploring the effects of randomized particle properties in DEM simulations – Ali Khoubani, Ehsan Yazdani and Matthew Evans, Oregon State University

In discrete element method (DEM) simulations, material properties are typically constant across particles: each individual particle has the same stiffness, specific gravity, and surface friction coefficient. While this is computationally and conceptually convenient, it is not reflective of physical reality. Importantly, variations in simple material properties can serve as surrogates for more complex variations in granular properties, such as shape, mineralogy, and surface roughness, all of which are expected to vary from grain to grain. In the current work, DEM simulations are used to investigate the effects of nonuniform particle properties on assembly response at both the specimen (macro) and particle (micro) scales. Groups of particles with heterogeneous physical properties are isotropically equilibrated and then subjected to applied boundary tractions. The sensitivity of measured macroscale response to microscale particle property variability is investigated. Local heterogeneities in the contact network are used to interpret complexities in macroscale system response.

Parametric Study of the Asteroid Impact at Chicxulub: Integrating Geological Field Observations and Modeling by the Use of Distinct Element Method (DEM) – Tam Nguyen Minh Duong (Texas A&M University), Zenon Medina-Cetina (Texas A&M University) and Jamie Urrutia-Fucugauchi (National University of Mexico)

Inspired by recent site investigations at the Chicxulub crater, this study aims to provide a parametric analysis framework to assess the likely geomechanical conditions associated to the corresponding asteroid impact on Earth. This will be achieved by using geological information from the field and the modeling of the impact by the Distinct Element Method (DEM). DEM is a powerful tool for studying large deformation and localization problems such as impact problems. In this study, the software PFC2D from ITASCA is used to simulate likely asteroid impact scenarios assuming a model scaled down 100 times of the actual asteroid impact size for computational efficiency. The ground conditions prior to impact are replicated based on the actual geological field information. Impact conditions, such as asteroid physical and material properties, are treated as random
variables in this study. The results of this study will provide insights on the asteroid impact consequences from the ground for future event risk assessment on the existing ecosystems.

Two-Dimensional DEM Assessment of the Shear Behavior at Interfaces between Sand and In-Situ Testing Devices – Jiaxing Su, Tianlong Xu and David Frost, Georgia Institute of Technology

Shear behavior at interfaces between geo-materials and soils is critical in many engineering applications, among which in-situ tests serve as the techniques to obtain soil properties and assist for geotechnical designs. This paper presents a series of DEM simulations of the penetrations of three distinct in-situ testing devices: the conventional cone penetrometer (CPT), the K0 stepped blade (KSB), and the penetrometer with multi-friction sleeve attachment (MFA). The comparisons of the results in macroscale between these simulations, such as the tip resistance and shear strength at various interfaces are evaluated. In addition, microscale responses including particle displacements and particle rotations are analyzed and linked to the observations at higher order scales. Our results highlight that given the penetration disturbance, the in-situ measurements are significantly affected, and the magnitudes of the disturbance are correlated to the variation of the penetrometer designs. Consequently, the penetrometer with multi-friction sleeve attachment, which can alleviate the disturbance effects due to tip insertion, provides more robust and reliable measurements in a single sounding.
ABSTRACTS: ROCK/FRACTURES

3D DEM simulations of triaxial compression tests of cemented sandstone – Aigerim Rakhimzhanova (Nazarbayev University), Furkhat Khamitov (Nazarbayev University), Minh Hop Nguyen (Nazarbayev University), and Colin Thornton (University of Birmingham)

Three-dimensional DEM simulations of triaxial compression tests on loose samples, using periodic boundaries, were performed using 5206 frictional elastic spheres at different values of confining pressure and bond strength. The results show that the peak strength and stiffness depend on the bond strength. For a higher bond strength, the material becomes stiffer and the peak stress is reached at a lower strain; the sample exhibits a higher volumetric dilation and less bond breakage. Bond breakage was found to increase with confining pressure. The Mohr-Coulomb strength parameters $c'$ and $\phi'$ were obtained for the numerical samples and correlations between the shear strength parameters and the bond strength were established. The correlations were then used to identify the bond strength to be used for comparisons with experimental results. The stress-strain responses of the numerical samples were found to be in good agreement with the experimental results of the cemented sandstone.

A pore-network model to estimate the shale gas permeability – Di Zhang (New Jersey Institute of Technology), Guo Haohao (Tsinghua University), Jay Meegoda (New Jersey Institute of Technology), Liming Hu (Tsinghua University) and Pengwei Zhang (Tsinghua University)

Amount of shale gas that can be recovered from a shale formation depends on the network that connects pores containing trapped shale gas under high pressure. The shale gas flow is usually due to gas slippage and diffusion whereas flow in traditional laboratory permeability tests are viscosity dominated Darcy flow. Hence the hydraulic conductivity values of shale formations measured using standard laboratory methods may not yield appropriate results. A 3-dimensional nanoscale pore network model was recently developed to simulate dynamic gas flow, and to describe the transient properties of flow regimes. This pore network model accounts for the pore size distributions and low connectivity of shale pores. The characteristics of pore structure of geo materials are controlled by specific parameters: porosity, pore size and pore throat distribution, as well as pore space connectivity. The pore size, pore throat size and coordination number obey normal distribution, and the average values can be obtained from shale reservoir data. The gas flow regimes were simulated using an extracted pore network backbone. This 3-dimensional nanoscale pore network model was validated by extensive laboratory tests that included viscous flow, slip flow and Knudsen diffusion. In this research the 3-dimensional nanoscale pore network model was reconstructed using low pressure viscous flow dominant permeability tests data. Then using this reconstructed 3-dimensional nanoscale pore network, the high pressure slip flow and Knudsen diffusion dominant permeability values were predicted. These predicted values compared well with the measured.

Size Effect and the Ductile-Brittle Failure Mode Transition – Yifei Ma and Haiying Huang, Georgia Institute of Technology

Discrete element simulations of the Brazilian test and the asymmetrical four-point shear test are conducted in this work to show that dependence of the material strengths on the sample size from
the indirect tests could be due to the ductile-brittle failure mode transition. This is an alternative explanation for the size effect in addition to the statistical, deterministic and fractality arguments that have been previously proposed in the literature. A displacement-softening contact model is employed to generate particle assemblies with different strength ratio UCS/UTS. Depending on the UCS/UTS, two types of failure scenarios, i.e., an indentation-type and a fracturing only type can be obtained in DEM simulations. For the indentation-type of failure scenario, the material strengths are observed to decrease with the sample size when the sample size is relatively small. However, the splitting strength from the Brazilian test and the shear strength from the four-point shear test do not appear to depend on the sample size when the failure is in the form of either a center tensile crack or a shear crack along the mid-span.

**Effect of CO2 on the mechanical behavior of synthetic carbonate rocks** – Dinu Arakkal and Marta Miletic, *Auburn University*

The rapid industrialization and following human activities, such as excessive use of automobiles, burning of coal, gases, and oils, have caused an unprecedented increase in the emission of greenhouse gases, especially carbon dioxide (CO2), to the atmosphere causing major challenges such as climate change and global warming. To date, the one technologically and economically feasible solution is the geological sequestration of compressed CO2 in deep underground rock formations. Nevertheless, despite its excellent environmental benefits CO2 capture and storage in underground geological formations faces major challenges in monitoring and verifying that the gases remain suppressed over a long-time period. This is because the injection of CO2 in carbonate aquifers dissolves some of the carbonate rock by forming carbonic acid and hence alters the natural rock mechanical properties, which further affects the safety and efficiency of the geological sequestration process. Therefore, the main aim of this research is the experimental and numerical investigation of the CO2 effect on the mechanical properties of the carbonate rock. In this study, a constitutive model is developed to simulate mechanical response of non-treated and acid-treated carbonate rocks. In addition, the performance of the developed framework is compared with the experimental data. To date, the synthetic rock samples were artificially prepared by thoroughly mixing the desired mass of quartz sand, kaolinite clay and calcite aggregate, followed by the slurry consolidation process. Once prepared, one-half of the synthetic rock samples were then kept in a tank containing acidified formation brine, then tested to determine their altered mechanical properties. The mechanical properties of these non-treated and acid treated rock samples were analyzed using the unconfined compression and indirect tensile tests. The experimental and numerical results showed a good agreement. Furthermore, the experimental results showed that exposure of carbonate rock to acid significantly degraded the mechanical properties of the carbonate rocks due to the breakdown of the mineral structure, with important practical consequences for the sequestration process.

**Micro-Scale Parametric Analysis of Independent Components of a Masonry Wall System** – Miguel Fernando Ortiz Cahun (*Texas A & M University*), Zenon Medina Cetina (*Texas A & M University*) and Luis Enrique Fernandez Baqueiro (*Universidad Autonoma De Yucatan*)
This study presents preliminary results of the modeling of all different testing components of a masonry wall when these components are subjected to unconfined compression: mortar cube, mortar cylinder, and concrete block compression (meso-scale structures), by the use of 2D Discrete Element Method (DEM). The purpose of this investigation is to calibrate the mortar cylinder using DEM model and to perform a parametric analysis for each set of micro-parameters. The micro-parameters’ influence on the model behavior is analyzed, and a broad comparison between micro-properties is presented. The specimen was calibrated with experimental data obtained from experimental tests conducted at Universidad Autónoma de Yucatán (México). Besides the materials’ micro-parameters, the analysis considers other control variables such as shape (cube and cylinder) and the modeling dimension approach (2D and 3D) for the case of the mortar. A parametric analysis is performed to understand the independent influence of each micro-parameter on the macro-behavior of each specimen. PFC 2D by Itasca was the software used to perform the simulations of all compression tests. Results showed difficulties when predicting the stress-strain curve, being able to predict the peak stresses. Results are part of an ongoing study to perform the probabilistic multi-scale calibration of a masonry wall system, from the independent wall components to the full macro-scale system response submitted to lateral cyclic loads.

**Heat Conduction in Fractured Rocks** – Adrian Garcia and Carlos Santamarina (King Abdullah University of Science and Technology)

Mechanical interactions at fracture interfaces affect all forms of conduction in fractured rocks. We explore the stress-dependent thermal conductivity of fractured rocks using the steady-state, divided-bar method within a loading frame (normal stress: 10kPa -to- 3000kPa). One fractured limestone column has clean and smooth fractures; the other includes an interstitial monolayer of carbonate sand to represent gouge-filled fractures. Results show that the thermal conductivity of the rock mass with clean-fractures approaches the thermal conductivity of the intact rock and exhibits only minor stress sensitivity. On the other hand, the rock mass with gouge-filled fractures has a low initial thermal conductivity, and experiences a rapid increase in conductivity during early stages of loading followed by strong hysteresis upon unloading. The observed behavior reflects the role of fracture thermal impedance on the rock mass conductivity, and the underlying evolution of contact coordination across the fracture and void space filling.
ABSTRACTS: UNSAT/SOILS

Microscopic model for saturated-unsaturated particulate soil – Kazunari Sako and Ryosuke Kitamura, Kagoshima University

A versatile model for saturated-unsaturated particulate soil is proposed based on some microscopic mechanical considerations with the probability and statistics. An elementary particulate model is proposed. The pore structure of soil is modeled by a pipe in the model. The diameter and inclination angle of the pipe are adopted as the random variables. The diameter and contact angle at the contact point of soil particles are also adopted as the random variables for particulate soil structure. The probability distribution of diameter of soil particles is obtained from the grain size distribution. The probability distributions of contact angle for particulate soil structure and inclination angle of the pipe for pore structure are assumed to be same and pentagon in shape. The probability distribution with respect to the diameter of pipe in EPM, i.e., the pore size distribution, is derived from the grain size distribution and void ratio obtained from the laboratory tests.

Rapid direct measurement of the soil water characteristics curve and hydraulic conductivity function utilizing the continuous pressurization method under the drying phase – Adel Alowaisy (Kyushu University), Noriyuki Yasufuku (Kyushu University), Ryohei Ishikura (Kyushu University) and Masanori Hatakeyama (OYO Co., Ltd.)

Proper determination of the unsaturated soil hydraulic properties including the Soil Water Characteristics Curve (SWCC) and the Hydraulic Conductivity Function (HCF) are key indices in analyzing the unsaturated hydrological and mechanical soil behavior. However, a simple method that considers short time and high accuracy to concurrently obtain the SWCC and the HCF is still lacking. A novel systematic testing setup and methodology combining the Instantaneous Profile Method and the Continuous Pressurization Method to concurrently obtain the SWCC and the HCF for sandy soils under the drying conditions in a short time is proposed. It took less than 24 hours to obtain a full drying phase SWCC and HCF for sandy soils which is very short in comparison to the time required using the conventional methods. However, a proper calibration function to consider the ceramic disk influence is necessary for accurate determination of the HCF.

Displacement evolution of heater in the THMC China-Mock-up test – Yuemiao Liu, Shengfei Cao, Jingli Xie and Like Ma, Beijing Research Institute of Uranium Geology

In order to simulate the evolution of canister with vitrified waste in underground disposal pit of the high-level radioactive waste (HLW) repository in China, a large scale thermal-hydro-mechanical-chemical (THMC) China-Mock-up test designed as a vertical cylindrical tank filled with compacted GMZ-bentonite was built on 10th September 2010. Six LVDT sensors were installed on the top and bottom of the heater in stead of the canister to monitor its vertical displacement. A maximum upward displacement 7.57mm of the heater was recorded after heating and hydration 1287 days. After more than four years operation, the evolution of displacement and temperature of the heater, as well as the relative humidity and stress in the bentonite indicate that the displacement are controlled by consolidation or volumetric/deviatoric creep induced by weight of heater, thermal expansion and swelling process of bentonite with the heating and hydration. The long-term stability of canister should be considered in the design of the HLW repository.
Microscopic investigation on morphological evolution of pore water in partially saturated sands during triaxial compression – Yosuke Higo, Ryunosuke Kido and Yo Fukushima, Kyoto University

A triaxial compression test for a partially saturated uniform sand was performed and strain localization zones were observed using micro x-ray computed tomography (CT). A series of image analysis of the CT images was conducted to investigate morphological evolution of pore water. Firstly, the CT images were trinarized into three phases: sand particle phase, pore water phase and pore air phase. Voronoi tessellation was applied to the trinarized volumes subdividing the pore space into individual pores, which enables to compute volume and degree of saturation of each pore. Cluster labeling of pore water phase was performed to investigate morphological evolution of pore fluids such as continuity, number of clusters, volume of clusters. The methodologies and the results of these image analyses are presented and microscopic morphological evolution of pore water during triaxial compression is discussed.

Modeling strain localization of unsaturated porous media with chemical effect through a novel non-local method – Xiaoyu Song and Shashank Menon, University of Florida

Strain localization is a ubiquitous failure mode of geomaterials. It has been well recognized that the variation of the chemical property of pore fluid in clay can affect remarkably the hydromechanical behavior of unsaturated soils. In this study, we conduct a numerical study of strain localization in unsaturated clay with chemical effect via the state-based peridynamics theory. The state-based peridynamics is a non-local mathematical reformulation of classical mechanics using integral equations which unites the mathematical modeling of continuum and discrete materials. A recently formulated non-local chemo-plastic constitutive model for unsaturated clay via the constitutive correspondence principle was adopted to conduct the numerical study. Specifically, we investigate the influence of horizon – an intrinsic nonlocal variable in the peridynamics theory on the failure mode of unsaturated clay under the same mechanical and chemical loadings. The numerical results demonstrate that the state-based peridynamics can be used to simulate strain localization in unsaturated clay without any difficulty. The width of shear bands may be correlated to the horizon as shown by the numerical results. Furthermore, the numerical results show that the novel non-local method can simulate both strain localization and diffusive failures of unsaturated clay by adjusting the horizon under the same mechanical and chemical loadings.

Thermal conductivity of Piedmont residual soils from laboratory tests – Fikret Atalay (Georgia Institute of Technology), Nicholas Sianta (Georgia Institute of Technology), J. David Frost (Georgia Institute of Technology) and Helen Heindl (FM Global)

Characterization of thermal properties of soils is a very important component of the design of shallow thermo-active foundations. In this paper, results are presented from a laboratory testing program, where six bulk samples of Piedmont residual soils were collected from several locations around the state of Georgia and their thermal conductivities were measured under varying density and saturation conditions. The composition of the samples ranged from high plasticity silts to low plasticity clays and silty and clayey sands, representing the general range of conditions typically encountered in the Piedmont physiographic region. Thermal conductivity measurements were
made at room temperature during both wetting and drying. A predictive relationship has been de-
veloped based on the test results which allows estimation of the thermal conductivity of Piedmont
residual soils for a given density and composition, and for moisture conditions ranging from dry
to full saturation.
**ABSTRACTS: SPH/MPM**

**Coupled material point method for large scale analysis of soil-water mixture** – Yuya Yamaguchi (*Tohoku University*), Shuji Moriguchi (*Tohoku University*), Kenjiro Terada (*Tohoku University*) and Shinsuke Takase (*Hachinohe Institute of Technology*)

A new solid-liquid coupled material point method is developed with the aim to simulate a large scale collapse process of ground structures such as slopes and embankments caused by seepage flow, which involves a transition process from a solidus to liquidus behavior. The governing equations are formulated based on Biot’s two-phase mixture theory and discretized with different sets of Lagrangian material points that possess soil and water information. The material behavior of solid phase is represented by elast-plastic model, whereas the liquid is assumed to be a Newtonian fluid. In order to improve the robustness and efficiency in comparison with the previous studies, the incompressibility is assumed for pore liquids and continuity equation of two-phase mixture is derived. With treating velocity and pore water pressure as unknown variables, implicit scheme is applied to solve momentum equation and continuity equation. For the discretization in space, we employ B-spline basis functions, which suppress numerical oscillations induced by material points crossing the grid line, without losing the merit of MPM that is suitable for parallel computing with regional division of calculation space. Since MPM also does not require us to search neighboring particles, the computing costs are significantly small applying parallelization at the same time. Several numerical examples are presented to demonstrate the capability of the proposed method to deal with massive behavior of soil-water mixture.

**Relating mobilised internal friction to subnetworks of interparticle contacts** – Adnan Sufian (*Imperial College London*), Adrian Russell (*University of New South Wales*) and Andrew Whittle (*Massachusetts Institute of Technology*)

The interparticle contact network plays a crucial role in the development of shear strength in granular media. Moreover, certain subnetworks play a dominant role in the stress transmission process and this study demonstrates that mobilised internal friction can be uniquely related to particular subnetworks. This was achieved by considering a novel derivation of the well-known stress-force-fabric (SFF) relationship for arbitrary partitions of the contact network. This new partitioned SFF relationship was validated using discrete element simulations of elemental shear tests. A particularly interesting partition considered was the quad-partition comprising subnetworks of (i) strong and non-sliding; (ii) strong and sliding; (iii) weak and non-sliding; and (iv) weak and sliding contacts. Strong contacts are defined as those with an interparticle normal force greater than the mean (and vice versa for weak contacts). Within the partitioned SFF framework, these subnetworks play distinctly different roles in the development of shear strength. In particular, it was observed that the fabric associated with the geometric configuration of strong and non-sliding contacts were the dominant contributor in the SFF relationship, a result which is not apparent when considering the complete contact network. Most interestingly, the geometric configuration of strong and non-sliding contacts can be uniquely related to the stress ratio, a measure of the mobilised internal friction of the assembly. This suggests that partitioned subnetworks should be considered in modelling the mechanical behaviour of granular materials.
Dry granular flow dynamics Comparison between DEM and SPH with mu(I)-rheology model – Siliang Guo, Xiaoyu Jiang and Takashi Matsushima, University of Tsukuba

The present paper focuses on the simulation of dry granular flow using mu(I)-rheology model. First, the performance of the model was tested for steady incline flow by a series of 2-D DEM simulations. It turned out that the effective friction of the flow increases in increasing dispersity of grain size distribution and in increasing intergranular friction. Then, by using the best-fit parameters from DEM results, the SPH simulation with mu(I)-rheology model was carried out for the steady incline flow to validate the simulation method. Finally, the model was applied into a non-steady flow simulation, and a quantitative agreement with DEM simulation was observed.

Granular flow analysis using moving particle simulation method considering soil strength – Kazuhiro Kaneda (Takenaka Corporation) and Tomoki Sawada (Prometech Software, Inc.)

In recent years, many sediment-related disasters have occurred in Japan. To predict sediment flow, we conducted granular flow analysis with the moving particle simulation method, using the viscosity term formulated by the Drucker-Prager model. The program code we used is Particleworks Ver. 6, developed by Prometech Software. The Bingham fluid model, i.e., viscosity depends simply on the shear rate, was introduced in the original program code. And to express the more appropriate plasticity, soil strength was implemented in the constitutive model by using SDK (Software Development Kit) of Particleworks. Plastic viscosity is described as the function of c and Φ. The modified code was applied to various well-known basic and practical problems. At first, simple problems, such as freestanding height and dam brake of the simulations were analyzed to assess the accuracy of the particle method with the model. Subsequently, a simulation was performed of sediment flows on actual slopes to determine the practicality of the modified code.

Effect of initial volume fraction on the collapse of granular columns in fluid – Krishna Kumar (University of Cambridge), J-Y Delenne (University of Montpellier) and Kenichi Soga (University of California Berkeley)

This paper investigates the effect of initial volume fraction on the runout characteristics of granular column collapse in a fluid. Two-dimensional sub-grain scale numerical simulations are performed to understand the flow dynamics of granular collapse in a fluid. The Discrete Element (DEM) technique is coupled with the Lattice Boltzmann Method (LBM), for fluid-grain interactions, to understand the evolution of submerged granular flows. The fluid phase is simulated using Multiple-Relaxation-Time LBM (LBM-MRT) for numerical stability. In order to simulate interconnected pore space in 2D, a reduction in the radius of the grains (hydrodynamic radius) is assumed during LBM computations. A parametric analysis is performed to assess the influence of the granular characteristics (initial packing) on the evolution of flow and run-out distances. The volume of the initial packing is changed to simulate different stress conditions while maintaining the same aspect ratio. The influence of the stress condition on the run-out behaviour is studied for different permeabilities. The granular flow dynamics is investigated by analysing the effect of hydroplaning, water entrainment and viscous drag on the granular mass. The mechanism of energy dissipation,
the shape of the flow front, water entrainment and evolution of packing density is used to explain the difference in the flow characteristics of loose and dense granular column collapse in a fluid.
ABSTRACTS: LABORATORY/IN SITU TESTING

Expression of stress distribution on vane shear test with soil/water coupled simulation – Katsuyuki Kawai (Kindai University), Shunzo Kawajiri (Kitami Institute of Technology), Takayuki Kawaguchi (Kitami Institute of Technology) and Masanori Tanaka (Port and Airport Research Institute, Japan)

Because its principle of testing is simple and clear, the vane shear test is used frequently all over the world. However, differences in undrained shear strength do exist between the vane shear test and laboratory tests such as the direct shear test and the triaxial test. Consequently, a correction coefficient is needed to determine undrained shear strength. These differences are thought to be caused by the localization of stress and/or strain around vane blades upon shearing. In this study, the laboratory vane shear test is simulated using soil/water coupled analysis. Under various conditions the effects of shearing speed, soil properties and vane blade shape are investigated. Simulations reveal that localization is more obvious at a slower shearing speed and on harder materials, and disturbance is dependent on the shape of the vane blade.

Development of substructure pseudo-dynamic testing system considering permeability – Yuki Domoyo and Masaichi Yamada, Nihon University

In this study, the new system capable of taking account of permeability during earthquake ground motion has been developed mainly to simulate ground motion that continues for a very long period of time as observed during the 2011 earthquake off the Pacific coast of the Tohoku region in Japan. When considering liquefaction, conventional practice is to ignore seepage in soil during earthquake ground motion. A particularly notable feature of the system is the ability to analyze liquefiable sand without modeling restoring force characteristics and also to shed light on its seismic response behavior, taking into consideration permeability under different stratigraphic conditions. The newly developed system makes it possible to determine, through pseudo-dynamic testing, the shear stress–shear strain relationship, the behavior of excess pore water pressure and ground surface response acceleration in the case of seepage during earthquake ground motion.

Torsional shear: experiments, models, and application to deep foundations – Alejandro Martinez (University of California Davis) and Armin Stuedlein (University of Oregon)

Laboratory-scale experimental tests on the role of surface roughness on the drained torsional interface shear response of sand are used to illustrate the applicability of a recently-proposed non-linear 1D spring model used to simulate the load transfer and global response of deep foundations subjected to torsion. First, Class A blind predictions of the experimental results are made using fundamental soil parameters to assess the general suitability of the functional form of the spring model. Then, the spring model is fitted to the observed experimental tests to compare back-calculated strength and stiffness parameters to the actual soil parameters to evaluate their physical reasonableness. This element-scale model is then used to simulate the global torsional response of hypothetical drilled shaft foundations after calibrating to back-fitted soil parameters to demonstrate the application of experimental observations derived from the torsional shear test device. The implications of using laboratory tests and analytical models to predict full-scale behavior are discussed with regards to research and practice.
Characterization of a carbonatic deposit across scales – Marika Santagata, Antonio Bobet and Alain El Howayek, Purdue University

The paper discusses a study of a glacio-lacustrine fine-grained carbonatic (CaCO3 = 35%-65%) deposit formed ~22,000 yr BP during the Wisconsin glaciation in south-west Indiana, USA. The investigation involved field tests (seismic CPT and field vane) and laboratory experiments on high quality Shelby tube samples to characterize the compression and shear strength behavior of the soil, as well as its index properties. X-ray diffraction and thermogravimetric analyses (TGA) were used to obtain the mineral composition; optical and scanning electron microscopy equipped with energy dispersive X-ray spectroscopy were employed to examine the microstructure of the soil, including the morphology of select minerals, the biological intrusions present, and the distribution of carbonates within the soil. The paper illustrates how these techniques, which probe the nature of the material at different scales, provide complementary insights into the geologic origin of the deposit, the nature of the structure formed in presence of carbonates, and the observed variation in geotechnical properties.

An acid dissolution method for preparation of contractive fine-grained soil specimens – Christopher Krage (GEI Consultants, Inc.) Jason DeJong (University of California Davis) and Don DeGroot (University of Massachusetts Amherst)

A preparation method was developed using acid dissolution to prepare loose mixtures of nonplastic soil, where silica silt was admixed with varying amounts of ground carbonate soil and prepared using a slurry deposition technique. After establishing target confining stresses in the oedometer, the soil was flushed with hydrochloric acid to alter the soil structure through dissolution of admixed carbonate. This paper presents the preparation procedure and the evaluation of dissolution progress by monitoring settlement, changes to void ratio, pore pressure response, and shear wave velocity using bender elements. Oedometer behavior and shear wave velocity were tracked pre- and post-dissolution to investigate changes to soil behavior between pre-dissolution and post-dissolution conditions. The state parameter was used to track changes in void ratio and confinement stress, where increases in the state parameter from initially dense of critical to slightly loose of critical were also observed for the nonplastic soil subjected to dissolution. The treatment process is extendable to testing scenarios capable of 1D vertical flow (e.g. oedometer, triaxial, simple shear, etc.) for further investigation of effects of post-depositional changes to soil structure.

Influence of material structure on unconfined compressive strength of halite – Amir Salar Moslehy and Khalid Alshibli, University of Tennessee Knoxville

Halite (rock salt) formations are utilized in many applications such as disposal of nuclear waste, the waste of oil drilling operations, and storage of several types of hydrocarbons and gases. However, they possess different compositions and could be formed in various material (crystalline) structures (single crystal or polycrystalline). The material structure of halite has a significant effect on its strength and behavior. Therefore, studying the strength of different types of halite is critical for better understanding of the behavior of the material. This paper investigates the unconfined compressive strength of single crystal and polycrystalline halite using un-confined compression experiments. Halite grains were prepared by grinding natural single crystalline halite blocks to a
grain size of smaller than 0.075 mm. The grains were then deposited into a die and consolidated at a 200 MPa compressive stress. Moreover, some polycrystalline specimens were locked in place while maintaining consolidation stress and were cured at 200°C for a week. The polycrystalline specimens along with cuboidal single crystal specimens were tested using unconfined compression procedure. The deformation behavior and failure modes of the specimens with different material structures are presented and discussed.
ABSTRACTS: PORES/X-RAY CT

Constriction size and frequency in granular filters: A micromechanics perspective – Catherine O'Sullivan (Imperial College London), Thomas Shire (University of Glasgow) and Howard Taylor (formerly Imperial College London)

The constrictions in a granular filter are the narrowest points in the void space. The size of the constrictions control the size of base material that can pass through the filter. Since the work of Terzaghi engineers have developed filter rules based on the idea the filter pore size is related to the 15th percentile particle diameter (D15) (Fannin, 2008). However these filter rules are empirical and the theoretical justifications which consider co-planar packings of spherical disks, are highly ideal. With the advent of micro computed tomography (μCT) and discrete element modelling (DEM) detailed information on the topology of the pore-space can be gathered. In contrast to the particle phase, where individual particles can usually be objectively identified, any partition of the continuous pore space will be subjective (other than the case of regular lattice packings). However, various rational approaches can be applied that segment the pore-space and hence identify and measure individual constrictions.

Development of temperature-controlled box shear test apparatus for X-ray CT scanning – Satoshi Matsumura and Takaaki Mizutani, Port and Airport Research Institute, Japan

This paper describes details of a test apparatus developed to evaluate effects of temperature change on mechanical behavior of soils and to visualize the soils during the temperature change using X-ray CT scanning technique. This paper describes results of freeze-thaw test and subsequent box shear test with X-ray CT images scanned at different moments, i.e. freezing, thawing and shearing, and also describes results of 3-dimensional digital image correlation (3D-DIC) to quantify the 3-dimensional deformation using stacks of the X-ray images.

MicroX-ray visualization of pullout behavior of reinforcement material under triaxial confining stress conditions – Yasuo Sawamura, Koshi Kimura, Ryunosuke Kido and Makoto Kimura, Kyoto University

Reinforced earth walls have high earthquake resistance. In order to adequately evaluate the ductility deforation performance of these walls, it is important to elucidate the detailed soil-structure interaction according to the displacement level of the reinforcement. An experimental device has been developed that can visualize the interior of a soil sample using a microfocus X-ray CT apparatus during pullout tests on the reinforcement placed inside the sample under triaxial confining conditions. To clarify the mechanisms of the pullout resistance of the reinforcement, CT image analyses were performed via pullout tests under different confining pressures. From the results, it was confirmed that the larger the confining pressure is, the larger the maximum pullout force and pullout displacement become. However, although the magnitude of the pullout force and the displacement at the maximum pullout force are different, the deformation process of the ground is almost the same regardless of the confining pressure.

Quantitative analysis of pore tortuosity in three-dimensional porous media – Jie Cao, M. Mahdi Roozbahani, Nimisha Roy and J. David Frost, Georgia Institute of Technology
Tortuosity of pore structure characterizes the convoluted pathways of fluid diffusion and electrical conduction through porous media. Conventionally, a single tortuosity value is defined and resolved by use of semi-empirical correlations, but it is restrictive in capturing the details of the topology of the highly intricate, heterogeneous pore structure. This work develops a voxel-based analysis tool for directly quantifying the spatial distribution of tortuosity within a three-dimensional digital microstructure. Pore space is transformed into a network of discrete pore skeletons that preserve all the essential topological information, and then a shortest-path searching is performed computationally. Comprehensive knowledge of existing tortuous paths available for transport can be identified, allowing a thorough examination on pore-scale transport processes to better predict transport properties. Effectiveness of the tool is demonstrated on an idealized packing structure. Tortuous attributes of the pore structures in two simulated structures with different packing densities, very loose and dense, are characterized to study the packing density effect. Shear-induced evolution in the tortuosity is explored by comparing sheared with unsheared structures for laboratory specimens of Ottawa 20-30 sands subjected to biaxial loading. The discovered broad range of tortuous paths with various lengths as well as spatial anisotropy in the tortuous attribute suggest that the “distribution” representation is more appropriate and effective than using a “single” tortuosity value.

Measurement of fabric in cohesive frictional granular materials using computed tomography
– Saurabh Singh (Indian Institute of Science), Tejas Murthy (Indian Institute of Science), John Miers, (Georgia Institute of Technology) and Christopher Saldana (Georgia Institute of Technology)

Cohesive frictional granular materials (c-phi) exists in nature with varied structure due to different methods of origin/deposition and relative binder content. The structure in c-phi granular materials usually classified in three categories contact bound, void bound, and matrix bound. At low amount of binder, contact bound structure prevail in c- material. With high amount of binder content, c- materials obtain either void bound or matrix bound structure depending on relative amount of binder and granular materials, relative density and relative speed of deposition. Mechanical response of c- materials depends heavily on its structure i.e. arrangement of particles and binder. We investigate the structure of contact bound and matrix bound c- materials, prepared using spherical mono-dispersed glass beads and epoxy as binder, with the help of x-ray computed tomography (XCT). We perform image segmentation using watershed algorithm on the reconstructed XCT scans of these materials to identify different phases (binder, air voids, and glass beads). Further, we quantify the structure and show different aspect of the structure using coordination number, fabric tensor, and distribution density of particles/voids.

An improved pore-network model for porous geo-materials – Haohao Guo (Tsinghua University), Liming Hu (Tsinghua University), Jay Meegoda, (Tsinghua University and New Jersey Institute of Technology), Dongming Yan (Chinese Academy of Sciences) and Di Zhang (New Jersey Institute of Technology)
It is necessary to study the micromechanics of seepage in the porous geo-materials from the microscopic point of view, and pore-network model is a convenient tool to investigate the pore structure properties. Based on 2D images series of the porous media produced from CT or micro-CT technology, the 3D structure can be reconstructed by advanced computational graphics technology. After extracting the particles and pores by appropriate triangulation method, the pore size and connectivity distribution are derived from the extraction, and the seepage is simulated by developed micro-mechanics seepage model using statistical parameters. To increase the precision of the simulation, random connected networks are constructed to find the relationship between connections in network and its statistical parameters, and a generating algorithm is proposed to create corresponding connections with a better accordance to the input parameters. The experimental data of various porous media agreed well with the permeability calculated by numerical simulation, which demonstrates the potential availability and capability of pore-network model in the hydraulic properties study.
ABSTRACTS: BIG DATA

High-Performance Discrete Element Modeling of Free-Field Surface Fault Rupture – Fernando Garcia and Jonathan Bray, University of California, Berkeley

Fundamental aspects of earthquake surface fault rupture propagation through granular media are captured with the Discrete Element Method (DEM). The principle hindrance to the application of DEM techniques to the analysis of large-scale problems is its burdensome computational demands. Earthquake surface fault rupture is a large-scale boundary displacement problem involving orders of magnitude more grains than contained within a standard laboratory test. Therefore, analyses of surface fault rupture using DEM necessitate high-performance computing. Earthquake fault rupture propagation through dilatant granular media is simulated in three dimensions (3-D) using the highly efficient, parallel DEM code LIGGGHTS on a high-performance computing cluster. Particle assemblages are prepared with over 400,000 non-spherical sphere-clusters consisting of over 1 million constituent spheres. The out-of-plane boundaries are periodic, which approximates an in-finitely long model by allowing particles on one boundary to interact with particles on the opposite boundary. Reverse and normal fault ruptures are simulated with fault dip angles ranging from 30° to 90°. Numerical results are shown to compare satisfactorily with experimental fault rupture results. The characteristics of the shear rupture surface are captured using signatures of strain localization including particle rotations. The computational speed-up with LIGGGHTS facilitates performing comprehensive sensitivity analyses to evaluate the effects of grain size and rate of rupture, among other factors.

Development of optimal methodology for rockfall protection walls using discrete element analysis – Hasuka Kanno, Shuji Moriguchi, Kenjiro Terada, Shunsuke Hayashi, Tohoku University

This study aims to propose a methodology that enables us to solve an optimal design problem of rockfall protection walls based on the result of three-dimensional DEM rockfall simulations. For this purpose, we define two functions to quantitatively evaluate the construction cost and the safety of rockfall protection walls. These are formulated as a function of important design parameters, such as width of walls and the horizontal distance between the toe of a slope and walls. By using the functions, we can solve a design optimization problem of the wall that minimizes the construction cost under a given safety constraint. In this paper, the proposed methodology is applied to an example of the optimal design problem on a simple slope model.

Soil Properties: Database + IT-Tool + Lab-on-a-Bench – Marisol Salva, Gloria Maria Castro, Marco Terzariol and J. Carlos Santamarina, King Abdullah University of Science and Technology

Soil data accumulated during the last century and more recent developments in sensors and information technology prompt the development of new geotechnical solutions for soil assessment. We have advanced three complementary tools. (1) The soil properties database has more than 6200 entries extracted from peer-reviewed papers and includes both index and engineering properties. (2) The IT Tool classifies soils according to the Revised Soil Classification System RSCS and operates the database to provide a self-consistent set of soil parameters based on known properties.
Lab-on-a-Bench technology combines cutting-edge sensors and sensing concepts within compact devices and effective laboratory protocols to allow multi-physics soil characterization. These devices maximize the information that can be readily gathered about a soil in order to anticipate its properties through the database and the IT-Tool. We invite colleagues to test the database and ITTool, to contribute multidimensional data, and to participate in Lab-on-a-bench developments.

**Application of 3D pavement data to geotechnical aspects of concrete pavement performance** – Georgene Geary and Yichang (James) Tsai, *Georgia Institute of Technology*

Foundations are integral aspects of pavement performance, especially for concrete pavements. Non-uniform, unstable foundations lead to uneven support and premature pavement distress, typically in the form of cracking or faulting of the concrete pavement slabs. This paper describes a unique 3D Slab-Based Methodology that models cracking patterns in concrete pavement slabs and the propagation of the cracking at the individual slab level at different scales using 3D pavement data. The type and orientation of the cracking can provide insight on the mechanistic causes of the cracking, such as loss of foundation support or excessive internal concrete stresses. Identification of patterns and interpretation of deterioration rates in light of these multi-scale configurations will be illustrated through the use of a case study using several years of 3D pavement data from an actual concrete pavement in Georgia.

**Spatio-temporal statistical characterization of 3D boundary displacement fields observed on a series of triaxial sand specimens** – Yichuan Zhu and Zenon Medina-Cetina (*Texas A&M University*)

Assessing multi-scale behavior of soil specimen in triaxial compression test plays an important role in revealing soil failure mechanisms. However, current research mainly focuses on advanced experimental techniques, or more accurate model representations. The lack of statistical inspection of these mechanical understandings weakens its significance in theory and practice. In this research, we analyzed an ensemble of spatio-temporal data populated from repeating a triaxial compression test on sand specimens under the same experimental conditions. Through statistical characterization, the overall trend and uncertainty of deformation are classified in a Cartesian system. The layered displacement field in vertical direction indicates heterogeneity in the density tends to affect strain localization, and further associated with sample preparation method. Findings from this research can serve as a-priori information for further stochastic simulations, or higher order uncertainty quantification frameworks.

**Machine learning for DEM model calibration based on experimental data** – Rodrigo Borela, Nimisha Roy and David Frost, *Georgia Institute of Technology*

The literature has demonstrated the discrete element method (DEM) to be suitable for the modeling of a variety of problems involving granular media. Several contact laws have been proposed, covering a range of complex particle interactions of physical, chemical and electrical nature. While good agreement between simulations and experimental results can be obtained, a calibration process is necessary to select model parameters, often disregarding whether these generalize to different mechanisms involving the same material. Recent studies have focused on the calibration task, however, a systematic and efficient approach remains lacking, often leading to extensive
parametric studies which are highly inefficient from a computational standpoint. In the present study, a method is proposed to address both issues in the framework of machine learning. First, an algorithm is designed for fast training of DEM models based on a finite difference approximation of Newton’s optimization method. The routine takes a set of experimental results as input and outputs updated DEM model parameters that approximate the response of the material. Subsequently, the model parameters are utilized in another DEM simulation setup to predict the results of tests on the same material but involving different mechanics for the purpose of validation. Finally, an example is presented in which parameters learned from triaxial compression test are validated against that of biaxial compression.
ABSTRACTS: FRICTION ANGLE/SLOPES

DEM analysis on the reinforcement mechanism of the toppling rock slope by bolts – Mingjing Jiang (Tianjin University & Tongji University), Huali Jiang (Tongji University), Youbin Liao (University of Shanghai for Science and Technology) and Sun Liu (Hohai University)

In order to investigate the reinforcement mechanism of the toppling rock slope by bolts, a contact model considering the bond size was introduced to the two-dimension distinct element method (2-D DEM) to simulate the failure processes of the toppling rock slope reinforced by bolts and the unreinforced one based on the gravity increasing method. In addition, the reinforcement mechanism of the toppling rock slope by bolts was analyzed from the macro prospect including the safety factor and failure pattern, which was further illustrated from the micro prospect through the force chains. The results show that: (1) the bolts improve the stability of the slope by enhancing the integrity of local rock; (2) the bolts can share the tension of the rock bridges, which reduces the failure possibility of rock bridges; (3) the bolts decrease the effect of the joints on force transfer and improve the stress state of the slope.

The angle of repose of granular mixtures with a fractal particle size distribution: DEM and experimental analyses – Luis Vallejo (University of Pittsburgh), Zhiqiang Lai (Wuhan University), Jairo Espitia (Universidad de los Andes) and Bernardo Caicedo (Universidad de los Andes)

The angle of repose of uniform in size granular materials is equal to the angle of friction between the particles. However, many deposits of granular materials are not made of uniform size particles but have a particle size distribution that is fractal in nature. Very little is known about the effect that a fractal particle size distribution has on the angle of repose of dry granular mixtures. This angle of repose measures the en masse angle of friction of the granular mixtures made of non-uniform size particles. In this study, the effect that the particle size distribution have on their en masse angle of repose is analyzed using the discrete element method (DEM) and experimentally. Both methods indicated that a fractal particle size distribution had a large influence of the angle of repose of granular mixtures.

Coupled CFD-DEM modeling of interactions between debris flow and multiple flexible barriers – Xingyue Li (Hong Kong University of Science and Technology), Jidong Zhao (Hong Kong University of Science and Technology), Kenichi Soga (University of California, Berkeley)

This paper presents a unified computational framework to simulate the interactions between debris flow and flexible barriers, based on coupled Computational Fluid Dynamics and Discrete Element Method (CFD-DEM). We consider the debris flow as a two-phase mixture of fluid and debris particles and model the two phases respectively with CFD and DEM. The simulation of flexible barriers is accommodated within the same framework by the DEM as a network of bonded particles with remote interactions. Different components are considered for the flexible barriers, such as single wires, double twists and cables, to explore their resisting capacity to debris flow impacts. The total sustained force in the barrier and the load sharing mechanisms by the different components of a flexible barrier are carefully examined. The vulnerability and possible failure patterns of a flexible barrier under debris flow impact is further explored in connection with the maximum sustained force in the barrier.
Effects of repose angle and basal friction angle in granular flow simulations – Shuji Moriguci, Hiroki Okuyama, Kenjiro Terada, Tadashi Kawai and Takayuki Aoki, Tohoku University

The effects of the repose angle and the basal friction angle in granular flow simulations are discussed in this study. These important parameters characterize the flow behaviors of granular materials. A database of the repose angle, which includes data on the relation between the repose angle and distinct element method (DEM) input parameters, was prepared based on the simulated results of the repose angle. A series of DEM simulations was then performed to quantify the effects of the repose angle and the basal friction angle in granular flow simulations. The obtained results indicate that the basal friction angle strongly affects the run-out distance, and that contribution are much stronger than the repose angle. Therefore, due consideration should be given to the basal friction angle when predicting the run-out distance in granular flow simulations.

The effect of initial conditions on the variation of angle of repose simulation using a Discrete Element Method – Shintaro Kajiyama and Yukio Nakata (Yamaguchi University)

Using a Discrete Element Method it is possible to reproduce the slippage of particles, which is difficult to analyze using a Finite Element Method, and furthermore it is possible to acquire the microscopic forces applied to individual particles. However, it is difficult to decide on the parameters to be used, and although many researchers have proposed methods of determination, clear standards have yet to be established. Therefore, in this study, measurements of the angle of repose are simulated in order to investigate the validity of analytical results used in determining parameters. The simulation was performed by changing factors such as the interval from stable condition of the particles to fluidity and the size of the specimen. As a result, from the DEM analysis, it was clear that the angle of repose is normal distributed. It also became clear that a width of box ratio and a lip height of at least a certain value are necessary to reduce the influence of the initial conditions on the angle of repose. Comparing the experiments with the DEM analysis, it was confirmed that under the conditions of this study, if the lip height was more than 8 times in the DEM analysis, the same tendency as in the experiments was obtained. It is clear that the angle of repose tends to decrease as a power function as the bottom width ratio increases.

Effects of grading on the flow behaviors of saturated loess – Fangzhou Liu (Georgia Institute of Technology), Qiang Xu (Chengdu University of Technology), Yixi Zhang (Chengdu University of Technology), Dehao Xiu (Chengdu University of Technology), Kuanyao Zhao (Chengdu University of Technology) and J. David Frost (Georgia Institute of Technology)

The Chinese loess is progressively classified as sandy, silty, and clayey loess based on the fine content, as such aeolian soil distributed from northwest to southeast of the loess plateau of China. We present the study on large-strain behavior of intact and reconstituted samples of clayey and sandy loess based on 1-D compression tests and isotropically consolidated undrained tests (CIU), with the aim of better understanding the effects of structure, initial void ratio, and grading on the mechanical behavior of saturated loess. The results have shown that: 1) the effects of structure are highlighted by the observation of that the critical state line of the reconstituted (CSLr) sample is below that of the intact (CSLi) samples in the v-lnp’ plane for both types of loess; 2) the degree of transitional behavior of reconstituted loess appear to be associated with the silt content, as such
behavior intensifies with increasing silt content; 3) the silt content has strong effects on the tendency of strain-softening under high confining stresses. The implications of the results can be used to analyze the failure mechanism(s) of loess flowslides that exhibited liquefied and fluidized behaviors that are appeared to be concentrated in a few locations across the loess plateau.
ABSTRACTS: PARTICLES/CRUSHING II

Allometric description of granular materials – Yu Feng Su (Florida International University), Sumana Bhattacharya (Florida International University), Chang Hoon Lee (Western New England University), Moochul Shin (Western New England University) and Seung Jae Lee (Florida International University)

Allometry originates from biology, which studies the inter-dependent relationship of body morphology (shape) to size and their coupled influence on various metabolisms of the species. This study is inspired by the concept of allometry and provides the ‘allometric’ perspective upon the 'coupled' influence of particle morphology and size on the behavior of granular materials. A new formula is proposed to allometrically describe the 3D particle geometry, \( M = \frac{(A/V \times L)}{6} \), where the morphology (M) is defined as the surface-area-to-volume (A/V) ratio multiplied by size (L), i.e., M and L are coupled through A/V, and divided by 6 which is the invariant A/V \times L value of sphere. We witness the M value of typical particles found in natural soils and construction aggregates ranges between 1 and 3 on the basis of the Krumbein and Sloss chart. As such the influence of 3D particle morphology can be estimated by leveraging a single value instead of the separately described global form and local angularity in terms of conventional 2D descriptors such as Sphericity and Roundness. This approach also enables a 'holistic' description of both morphology and size distributions that allows for 'unified' plotting in a single space, which provides the valuable information regarding how morphology and size are 'correlated' and their relation to the surface-area-to-volume ratio. Therefore, this study will contribute to the systematic constitutive modeling of the 'coupled' influence of allometric property, compared to the conventional approaches separately considered the influence of either morphology or size distributions.

The interpretation of soil particle crushing by Acoustic Emission Method – Sha Luo, Erdin Ibraim and Andrea Diambra (University of Bristol)

The significance of soil crushing to the mechanical behaviour of granular materials is well identified and of interest to many disciplines, such as geotechnics, geology, geophysics, mining engineering and powder technology. In the field of geotechnics, soil grain crushing frequently occurs if the confining stresses are sufficiently large and such phenomena are significant in a wide range of practical geotechnical applications involving pad foundations, the soil around driven piles and foundations of large offshore structures, embankment and dams, pavement and railway substructures under repeated loadings. However, owing to the specific nature of real geotechnical system scale, the interpretation of the relevant soil physical mechanical parameters and prediction of soil’s particle size distribution are still problematic. Therefore, Acoustic Emission (AE) technique, a non-destructive method, was used to study the occurrence of the soil particle crushing at element laboratory testing scale. As a preliminary work, this paper presents an investigation on the use of the AE technique for the characterization of crushing of individual sand particles under uniaxial compression loading. Silica type soil particles are selected as an example, and it is shown that clear correlations are found between the particle mechanical parameters and the AE signature.

Fractal and optimal gradings and their relationship to internal stability – Emoke Imre (Obuda University), Daniel Barreto (Edinburgh Napier University) and Istvan Talata (Obuda University)
Using statistical entropy principles, any particle size distribution can be characterized by a coordinate pair. These entropy parameters are derived from the entropy formula for discrete distributions and may characterize the grading curves more effectively than simple diameter values (i.e., d50) or the fitting parameters of other functions. The first entropy parameter is a continuous internal stability measure. The second entropy parameter allows the definition of a unique, mean grading curve with finite fractal grain size distribution for each value of internal stability measure. The internal stability rule of the grading entropy theory separates the soils into (transitionally) stable and unstable ones. Also into natural and artificial soils. It is shown that the probability of a stable state could be very low, and stable states can occur since the grading entropy path of breakage and degradation has directional properties.

**Microscopic failure mechanisms of cemented granular materials driven by particle morphology** – Seung Jae Lee *(Florida International University)*, ChangHoon Lee *(Western New England University)* Moochul Shin *(Western New England University)* Sumana Bhattacharya *(Florida International University)* and Yu Feng Su *(Florida International University)*

Cemented granular materials are abundant in nature, e.g., calcareous sediments, and of significant importance in the modern industry, e.g., grouted soil and concrete. Cementation plays a critical role in the behavior of granular materials and even makes an important ‘paradigm shift’ in the understanding of the morphology effect, which may not be reasonably explained in the context of traditional soil mechanics of the ‘un-cemented’ granular materials. The cemented granular materials are commonly composed of the three key phases: constituent particles, binding substance, and interphase region that works as the load-transferring bridge between the particles and the binding substance. This study focuses on how particle morphology affects the interaction of the three key phases and consequently the macroscopic material behavior. To this end, three morphology-driven failure mechanisms are postulated to fundamentally address the influence of angularity at the particle scale that ‘negatively’ impacts the small-strain performance, while ‘positively’ influences the ultimate state properties at a large strain level. This study corroborates the efficacy of the postulated failure mechanisms through a set of systematically performed laboratory tests. The research findings will challenge and complement the existing body of knowledge at the interface of soil and concrete mechanics.

**Grading entropy coordinates and shear stiffness in granular materials** – Daniel Barreto *(Edinburgh Napier University)* and Emoke Imre *(Obuda University)*

This paper discusses the use of grading entropy coordinates as a better descriptor for particle size distributions. Grading entropy coordinates are derived from statistical entropy principles and enable to represent any particle size distribution as a single coordinate pair in a normalized (or non-normalized) entropy diagram. These coordinate pairs contain a lot of information, but their calculation is straightforward. Furthermore, in contrast to common descriptors based on individual particle sizes (e.g. the coefficients of curvature and uniformity cc and cu, respectively), grading entropy coordinates consider the full range and distribution of particle sizes. By establishing a relationship between the grading entropy coordinates and the value of the shear stiffness at small strains as measured by other researchers in resonant column tests we also demonstrate, that in addition of straightforward calculation (based on standard experimental measurements), a physical
meaning can be given to these entropy coordinates. Furthermore, in contrast to other PSD descriptors, a higher degree of sensitivity can be observed on the value of the shear stiffness and its relationship to grading entropy coordinates.

**Applicability of SSE model for railroad ballasts with various water contents and fine fraction contents** – Jiaqiang Yang (Hokkaido University), Tatsuya Ishikawa (Hokkaido University), Takashi Okayasu (Kyushu University), Takahisa Nakamura (Railway Technical Research Institute) and Ippei Kijiya (Railway Technical Research Institute)

Various constitutive models for granular materials have been developed until now. Among them the subloading surface model was modified by assuming an existence of the elastic domain surface inside the subloading surface so as to realistically describe the inelastic deformation behavior of material under cyclic loading. Previous research indicated that the predicted result was coincident well with the test result on railroad ballast settlement. However, the input parameters used in each simulation should be carefully investigated for various materials and loading conditions. In this paper, the reliability of the subloading surface extension (SSE) model is discussed by comparing cyclic triaxial compression test results for railroad ballasts under different water contents and fine fraction contents with the predicted results. The predicted permanent strain of this model agrees well with the experimental results by adjusting input parameters, although some of the predicted values are slightly higher than the experimental values. Thus, the SSE model can be used to improve the performance of mechanical simulation behavior on railway foundation.

**Strength and deformation behavior of the calcareous sand in Nansha Islands, South China Sea** – Mingjing Jiang (Tianjin University & Tongji University), Yangbiao Xie (Tongji University) Banglu Xi (Tongji University)

Calcareous sand is widely distributed on the coral reefs in Nansha Islands, South China Sea, which is commonly used as the backfill material for road embankments and airport runways. Therefore, it is essential to study the strength and deformation behavior of the calcareous sand. For this aim, a series of triaxial compression tests is carried out on two different sizes of samples, i.e., φ39.1 mm×80 mm and φ101 mm×200 mm. Note that the maximum particle diameters are 2 mm in the small sample and 20 mm in the large sample, respectively. The results show that the strength and deformation behavior of the calcareous sand depends on the confining pressure and sample size. The volumetric strain of the sample is mainly caused by the particle rearrangement at a low confining pressure, while the particle breakage becomes the main reason at a high confining pressure. Under the same test conditions, the relative breakage index of the large sample is smaller than those of the small sample.
ABSTRACTS: POSTERS

Calculation of osmotic suction of bentonite external saline solutions – Xiaoyue Li (Shanghai Jiao Tong University) and Yongfu Xu (Shanghai Jiao Tong University)

Bentonites are usually selected as the engineered barrier material of repositories for radioactive waste. The saline solution from surrounding rock fissures can affect the mechanical behaviour of bentonite for the reason that the osmotic suction of bentonite pore water from external solution intruding can act as an additional stress component on bentonite crystal layer. The osmotic coefficient, as the key to calculate the osmotic suction, is usually obtained by measuring the vapor pressure of a solution and that of the pure solvent with a differential manometer in experimental method. Considering that the vapor pressure is affected by many factors such as solute type, concentration, and temperature, it is very complicated to obtain the osmotic coefficient by experimental method. In this paper, the osmotic coefficient is calculated according to the modified Debye-Hückel equations and the calculated results of the osmotic suction is validated by comparing with the experimental data in other literature. In this way, the osmotic suction for different solutions under different temperature can be obtained by calculation.

Maximum shear modulus of crushable natural pumiceous sands – Mohammad Bagher Asadi, Mohammad Sadeq Asadi, Rolando Orense and Michael Pender, University of Auckland

This paper focuses on the maximum shear modulus (Gmax) of natural pumiceous (NP) sands, found in the central part of North Island of New Zealand. These pumiceous sands are highly crushable, compressible and lightweight due to the vesicular nature of the pumice particles, making them problematic from engineering point of view. Several series of bender element tests over a wide range of effective confining pressure (σ′c) and void ratio (e) were performed on different reconstituted NP sands, as well as on hard-grained Toyoura sand. The results showed that the Gmax of NP sands are considerably lower than that of Toyoura sand under similar relative density and σ′c and the effect of σ′c on Gmax is more significant for NP sands compared to Toyoura sand. With respect to Gmax - e relation, the NP sands show Gmax that is less dependent to e, compared to Toyoura sand. The difference in Gmax between crushable and hard-grained sands were then explained in terms of the micro-properties of the particles, especially the occurrence particle crushing, and difference in particle shape and particle size distribution.

DEM analysis on the effect of non-uniformly distributed bond strength on the mechanical behavior of cemented sand – Mingjing Jiang (Tianjin University & Tongji University), Liangkai Qin (Tongji University), Wei Liu (Tongji University) and Banglu Xi (Tongji University)

The cement strength usually distributes non-uniformly in natural cemented sands, since the environmental conditions are different in different position in the ground, in term of the sedimentary condition, stress history and cement type, etc. However, most researches assumed that the cement strength distributes homogeneously in the sample in their Discrete Element Method (DEM) simulation for simplicity, which may lead to unclear difference between the practical and experimental data of the macro and micro behavior. In this paper, a series of isotropic compression tests was simulated with DEM on cemented sands where the bond strength varies in three normal distributions and one uniform distribution. The results show that the specimens with normal distributions
exhibit smaller volumetric deformation, larger structural yield stress and less bond breakage ratio than those in the specimen with uniform distribution at the same mean stress. However, the standard deviation $\sigma$ shows little effect on the volumetric deformation, structural yield stress and bond breakage ratios in the samples with normal distributed bond strength.

**DEM analysis on yielding behaviors of cemented sands under constant stress increment ratio compression tests** – Mingjing Jiang (*Tianjin University & Tongji University*), Jiabin Wei (*Tongji University*), Banglu Xi (*Tongji University*) and Fuguang Zhang (*Tongji University*)

Cemented sands are often encountered in geotechnical engineering, such as in dams and subsoil, where the in-situ soil undergoes constant stress increment ratio (CSR) stress path. Thus, it is of great significance to study the mechanical behaviors of cemented sands under the CSR stress path. In this paper, a series of CSR compression tests was carried out on cemented sands by the three-dimensional Distinct Element Method (DEM), in order to study the effects of cement content and stress increment ratio on the macro- and micro- yielding behaviors. The DEM results show that the cement content can enhance the gross and micro yielding stresses of cemented sands. And there is an optimal stress increment ratio for the maximum gross and micro yielding stress. Moreover, the gross and micro yielding stresses are identical in value at an identical stress increment ratio regardless of cement content.

**3D DEM analysis of the effects of low confining pressure on mechanical behavior of lunar regolith** – Banglu Xi (*Tongji University*) and Mingjing Jiang (*Tianjin University & Tongji University*)

Lunar soil has attracted lots of attention since early years of last century. However, it is difficult and costly to perform various indoor and in-situ geotechnical tests on the Moon directly. The distinct element method seems a promising method since the particular environmental conditions can be easily reproduced. Thus it is important to present a three-dimensional (3D) contact model for high efficiency DEM analysis of lunar regolith. In this paper, a 3D contact model was presented at first which fuses the particle rolling and twisting resistance and van der Waals force together in a simple way. Then a series of triaxial compression tests was carried out under widely different confining pressures from 10 kPa to 200 kPa, aiming to analyze the effect of low gravity condition on the Moon. The results show that the model can well reproduce the mechanical behaviors of lunar regolith, which features low apparent cohesion and high internal friction angle. Moreover, the lunar environmental condition, e.g., high vacuum and low gravity field, will result greater strength and more apparent shear dilatancy of the samples than the terrestrial conditions.

**Exploring the critical state void ratio of grain-coating type methane hydrate bearing sand by the Distinct Element Method** – Mingjing Jiang (*Tianjin University & Tongji University*), Jun Liu (*Tongji University*) and Zhifu Shen (*Nanjing Tech University*)

This study presents a numerical investigation into the critical state void ratio of grain-coating type methane hydrate bearing sand (MHBS) by the Distinct Element Method (DEM). An extended bond contact model accounting for particle-scale mechanisms of grain-coating type MHBS was used to carry out drained triaxial compression tests. The simulations were run until the critical state was obtained and the numerical results show that the void ratio of the grain-coating type MHBS at the
critical state $e_{cr}$ increased when the MH saturation and the value of temperature-pressure parameter $L$ increased. Two empirical equations were proposed for $e_{cr}$ in relation with mean stress, MH saturation and $L$. In addition, $e_{cr}$ obtained in experiments can be well fitted by the proposed equations.

**Study on the Influential Factors of NCPRF Using FEM-DEM Coupling Method and Orthogonal Experiment** – Yaokun Li (*China International Engineering Consulting Corporation*), Xiaolei Han (*China University of Technology*), Jing Ji (*South China University of Technology*) and Zinan Wu (*South China University of Technology*)

With the FDM-DEM coupling method developed previously, this article further studies the effects of different influential factors on the mechanical properties of the Non-Connected Pile-Raft Foundation (NCPRF). A total of 6 influential factors were chosen to design a statistical experiment using Taguchi’s array. Quantitative analysis was carried out on the numerical test results. Main conclusions include: 1) the FDM-DEM coupling method, together with orthogonal experiment is a good way to study the effects of factors on the mechanical properties of the NCPRF 2) the cushion thickness is found to be the most significant factor for the properties of the NCPRF, while particle diameter and pile diameter have some but limited effects on the NCPRF; 3) the quantified significant level of different factors and the tendency of indices vs. factorial levels may be reference for theoretical research and engineering practice.

**Comparison of coupled CFD-DEM method and constant volume method for simulating undrained behavior of dense granular soils** – An Zhang (*Tongji University*) and Mingjing Jiang (*Tianjin University & Tongji University*)

This paper compares a coupled computational fluid dynamics and distinct element method (CFD-DEM) with the constant volume method for simulating the undrained triaxial tests on dense granular soils. The compressible volume-averaged continuity and momentum equations are used with an equation of state relating the fluid density to the pressure in the coupled CFD-DEM method. It is found that the coupled CFD-DEM simulation shows a good agreement with the constant volume method at small strain where shear band has not formed for both methods. However, at large strains, the coupled CFD-DEM simulation can form an obvious shear band in the specimen while the constant volume method shows a relatively uniform deformation, which leads to the difference in the deviatoric stress and pore pressure plots for both methods.

**Evolution of rattling particles in deviatoric shear deformation of granular material** – Zhifu Shen (*Nanjing Tech University*), Guoxing Chen (*Nanjing Tech University*) and Mingjing Jiang (*Tianjin University & Tongji University*)

Granular material such as clean sand in geotechnical engineering is characterized by structured internal defor-mation pattern and some interesting particle arrangement patterns. This study focuses on the evolution of the fraction of rattling particles in deviator deformation until the critical state. Numerical simulations using the discrete element method reveal the presence of rattling particles (with zero or only one contact with neighbor-ing particles) even in a very dense packing system. The results show that the initial fraction of rattling particles depends on sample density and particle size distribution. With the increase of deviator strain, the number and volume fractions
of rattling particles gradually approach a steady critical state from either a loose or a dense starting point. An effective void ratio, which is calculated by treating rattling particles as voids, is found to be a more proper density state parameter than the conventional void ratio. The rattling behavior strongly depends on particle size distribution.
Micro and macro structure evaluation of soft silty clay at low cement content – Usama Khalid and Guan-lin Ye, Shanghai Jiao Tong University

In the past, a lot of research on cement-treated soft clays was carried at high cement content which discussed the variations in geotechnical and microstructural characteristics. However, study on the behavior of soft clays at low cement content is limited. The mechanical and structural characteristics of soft clay with low cement contents can differ from the soft clays treated with traditional cement contents. The aim of this study is to conduct an experimental program on soft silty clay treated at low cement content. Silty clay was treated at 1, 2 and 3% cement content and curried for 7, 14 and 21 days. Scan electron microscope, mercury intrusion photometry and consolidated-undrained triaxial tests were performed to examine the effect of low cement content on micro and macro structure. The results indicate that the effects of low cement content on PSD curves, microstructure, peak deviator stress, pore pressure, stress ratio and M-value are meaningful.

Roughness distribution on sand particles – Ting Yao (University of Hong Kong), Beatrice Baudet (University College London), Sérgio Lourenço (University of Hong Kong)

Surface roughness, the third scale of particle shape, mainly affects the micro-mechanical behaviour of granular materials. Natural sand particles, even of same mineralogy and equal size, are not identical, thus the roughness should be characterized by a statistical distribution function. In this paper, an advanced device, optical interferometry was used to measure the surface roughness of Leighton Buzzard sand (LBS) of different particle sizes. The surface roughness was quantified by flatten root-mean-square roughness (RMSf) with the shape motif method. Weibull function was used to fit the cumulative distribution of RMSf and its suitability to model the distributions is discussed. The correlation between particle size and two parameters (shape parameter and scale parameter) of the function were investigated. Furthermore, a simplified model is proposed to predict the probabilities of RMSf.

Cross-scale characterization of shales by a big data-based statistical nanoindentation technique – Shengmin Luo (University of Massachusetts Amherst), Yunhu Lu (China University of Petroleum Beijing), Yongkang Wu (University of Massachusetts Amherst), Yucheng Li, (University of Massachusetts Amherst) and Guoping Zhang (University of Massachusetts Amherst)

This paper presents a newly developed big data-based statistical nanoindentation technique that provides a viable approach for characterizing the mechanical properties of small-scale individual mineral phases in shales as well as the bulk rock at the macroscale. This novel method employs obtaining massive indentation data using the continuous stiffness measurement (CSM) method with the maximum indentation depth of ~8–10 μm. Results obtained from both shallow depths (e.g., ~0.25 μm) and large depths (e.g., ~4 μm) were processed by statistical deconvolution to determine the mechanical properties of individual phases at different scales, and the depth-dependent mechanical properties were then used to fit a newly proposed surround-effect model that can yield accurate results for the mechanical properties of individual phases at virtually infinitesimal depths (e.g., a few tens of nanometers) as well as the bulk rock (e.g., a few tens of micrometers). As a result, the mechanical properties of individual phases at the nano to micro scales as well as
the bulk rock at the meso scale can be obtained on the same small-sized sample by a single type of experiments.

**A comprehensive parameter for assessment of structural characteristic of natural clays** – Huayang Lei (Tianjin University), Shanghua Lei (Tianjin University), Yingjie Song (Tianjin University) and Mingjing Jiang (Tianjin University & Tongji University)

In this study, a comprehensive parameter termed coefficient of meta-stability Cm was proposed to quantitatively assess the structural characteristic of natural clays. This structural parameter is characterized as easy-obtaining and combines the concepts of the soil stability and soil changeability with a parameter e1. The validity of the parameter was examined by analyzing extensive published data of natural clays in various regions. The results show that highly structural clays do not necessarily require highly strong interparticle bonds. Instead, clays with moderate interparticle bonds and highly instable soil arrangement can be highly structural as well. Clays in Type2 are generally more highly structural than clays in Type1, which is due to the more instable soil arrangement of clays in Type2. The coefficient of meta stability Cm can serve as a powerful tool for successful constitutive modeling of natural clays and thus provide theoretical basis for the engineering practices.

**Experimental study on undrained shear strength of soft clay after cyclic loading** – Huayang Lei, Xiaofang Sun, Jiangyan Miao and Shanghua Lei, Tianjin University

A large number of urban infrastructures have been carried out on soft clay foundation in coastal areas, hence the strength characteristics of soft clay under complex loading is worthy to be studied. In this study, several sets of cyclic tests and undrained triaxial shear tests were performed to observe the change of undrained shear strength of undisturbed soft clay after cyclic loading. Further the influence of CSR, frequency and effective confining pressure on shear strength was studied. Test results showed that the application of cyclic loading accelerated the failure of soil sample, caused a certain level of strength degradation in shear test and increased the internal pore water pressure during shear test. The lower the CSR and frequency was, the higher the shear strength would be. And the increasing of effective confining pressure during cyclic loading had positive effects on enhancing shear strength of soft clay. Moreover, different shear failure standards were discussed, which had great impact on evaluating the strength change before and after cyclic loading.

**Dynamic Characteristics of Soft Clay in Dynamic Stress-Seepage-Coupled Field** – Huayang Lei, Jiangyan Miao and Shuangxi Feng, Tianjin University

To study the dynamic deformation characteristics and permeability of soft clay from Tianjin in dynamic stress-seepage-coupled field, a series of cyclic drained triaxial tests with different osmotic pressures and cyclic stress ratios were conducted. The results show that the development of accumulative plastic strain is divided into three stages: instantaneous stage, attenuate stage and stable stage. And higher cyclic stress ratio and higher osmotic pressure both induce more accumulative plastic strain. Besides, the stress-strain loops get thinner and steeper with increasing cyclic number, which indicates that dynamic elastic modulus increases and soft clay become more resistant with decreasing accumulation rate of plastic strain. The permeability of soft clay mainly goes through
two phases: fast attenuation phase and stable phase, and the reduction degree of hydraulic conductivity of soft clay in the fast attenuation phase could reach above 85%.

**The effect of water on single grain fracture** – Younes Salami (*Euro-Mediterranean University of Fès*), Christophe Dano (*Université Grenoble Alpes*) and Pierre-Yves Hicher (*École Centrale de Nantes*)

The mechanical behavior of a granular medium is closely related to its saturation state. One of the underlying phenomena controlling this dependence is particle breakage. In the presence of water, the strength of a particle is weakened through various physical-chemical processes, which lead to an increase in the intensity of particle crushing. The acceleration of the fracturing of particles results in the distinctive mechanical response usually observed in unsaturated soils. A multiscale experimental study was conducted to establish a causal relationship between the change of saturation and the increased breakage rate. Oedometric tests were used to understand the effects of saturation on the mechanics of the granular packing, while crushing and wedge splitting tests help appreciate the micromechanical origins of this typical behavior.

**Micro - macro modelling of piping progressive failure in river levee** – Kenichi Maeda, Masaya Nishimura and Masato Takatsuji (*Nagoya Institute of Technology*)

A river levee of Yabe River was breached due to piping failure induced by long duration of high water level in the northern Kyushu heavy rain, 2012, in Japan. It was reported that the piping failure was caused by the infiltration in the high permeable foundation ground with sand and gravel under the clay levee body. However, some levees were deformed but not failed even with similar foundation ground. Therefore, the influences of the soil-stratum conditions on the properties of water pressure propagation and water leak and the behaviours of piping failure were investigated by model tests. It was revealed from test results that the piping could not be observed in a single-homogeneous foundation ground with leakage of clean water according, but piping failure was progressed with large amount of water leak and sand volcano in two foundation ground with gravel blow fine sand even under low hydraulic gradient. We proposed a new criterion of piping with the foundation ground strata configuration, average hydraulic gradient and seepage velocity. Moreover, we investigate the mechanical instability of soil and subsequent destabilization of the ground resulting from internal erosion. We aim to throw light upon the processes of seepage failure with internal erosion and piping from the particle (micro) level to the soil system (macro) level as a boundary value problem using DEM and continuum modelling and SPH. Simulations of local seepage failure and internal erosion show the success of this micromechanics approach. From simulation results, when no internal erosion has occurred and the leaked water was clean, the toe slope of the levee becomes swollen and loose, but the levee did not result in a break. When internal erosion has occurred and the leaked water was muddy, then local deformation of the toe slope progresses, and the levee became instable and collapsed.

**Fast contact detection of general irregular-shaped particles** – Zhengshou Lai and Qiushi Chen, *Clemson University*
The discrete element method (DEM) has been widely used to model the behavior of granular materials from a fundamental level. Incorporating irregular-shaped particles into a DEM model necessitates accurate and efficient methods to capture irregular shapes and to detect particle contacts. This work presents an effective approach to represent shapes and detect contacts of general irregular-shaped particles in DEM modeling. In this approach, Fourier series (FS) is proposed to represent particles of irregular shapes, where the support function of a particle shape is derived from Fourier analysis and expressed in closed-form Fourier series. The Gilbert–Johnson–Keerthi (GJK) algorithm is then implemented to detect contacts between particles. The proposed FS-GJK approach is shown to be accurate and computationally efficient when verified and compared to the prevalent Overlapping Discrete Element Cluster-based approach for modeling irregular-shaped particles. The FS-GJK approach can be incorporated into most DEM frameworks as an effective and efficient means to represent general irregular-shaped particles and detect contacts.