General Report - Session 1A: Laboratory Testing

Rapport de Spécialistes - Session 1A : Essai en laboratoire

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ABSTRACT
Ninety three papers were submitted to Session 1A on 'Laboratory Testing'. A wide number of different laboratory techniques and tests are covered by these papers. Most of the emphasis is given to stress history, large strains, consolidation, basic soil properties, triaxial testing, cyclic loading, test interpretation, soil models and non-standard soils. Each paper is briefly reviewed herein. For ease of reference, a summary table and list of papers submitted to the session is provided in the Appendix at the end of the report.

RÉSUMÉ
Quatre-vingt-treize papiers ont été soumis à la session 1A sur le laboratoire. Un certain nombre de différentes techniques de laboratoire et des essais sont couverts par ces documents. La majeure partie de l'emphase est indiquée à l'histoire d'effort, aux grandes contraintes, à la consolidation, aux propriétés de base de sol, à l'essai à trois axes, au chargement cyclique, à l'interprétation d'essai, aux modèles de sol et aux sols non standard. Chaque papier est brièvement passé en revue ci-dessus. Pour la facilité de la référence, un tableau synoptique et une liste de papiers soumis à la session est fourni dans l'annexe à la fin du rapport.

1 INTRODUCTION

Ninety three papers have been submitted for this session on 'Laboratory Testing' and these come from 39 countries around the world. The geographical balance of the papers is relatively similar from each of the ISSMGE regions: North/South America (24 papers), Europe (27 papers), Africa and Asia (14 papers), and Australasia (28 papers). The subjects addressed by the authors cover a very broad scope and applications, and the papers cover multiple laboratory areas and techniques.

To guide readers to the most relevant papers, a table is provided in the Appendix that shows the main focus of each paper, subdivided into the categories and sub-categories shown below. The number of papers in each category is shown in the brackets below:

- *Feature of soil behaviour:* stress history (19), small strain (12), large strain (41), very large strain (5), permeability (11), consolidation (21), basic properties (60) and cyclic/dynamic behaviour (18).
- *Type of laboratory technique:* sampling (13), triaxial (38), true triaxial/ hollow cylinder (1), resonant column/bender element (13), direct/simple shear (14) and other (57).
- *Main emphasis of paper:* field testing (7), test interpretation (28), soil properties (65), experimental technique (18), soil models (27), special soils (39) and practical implications (26).

The papers range from highly theoretical approaches to practical 'near-market' applications of geotechnical knowledge. The emphasis appears to be on traditional laboratory techniques, such as triaxial and basic characterization tests, and there are relatively few new developments of techniques or interpretations. The spread of new testing approaches (e.g. bender elements) seems to be global and many authors are investigating new geomaterials and conducting tests for the purpose of soil enhancement and waste disposal/reuse.

The papers in this report have been arranged in the following manner under these headings:

2. *Basic Soil Characteristics*;
3. *One Dimensional Strain States*;
4. *Two and Three Dimensional Strain States*;
5. *Permeability and Drainage*;
6. *Unsaturated Soils and Suction*;
7. *Non-Standard Soils*;
8. *Soil Profiles and Field Data*.

Topics have been selected to follow a more or less rational sequence (but not in any order of importance) and do not cover all aspects of laboratory testing; the sections have been confined to the review of the submitted papers. Unfortunately, a number of papers (5) could not be arranged under these topics, but the findings of 88 of the papers are described in the report. The following sections provide a brief review of each paper.

2 BASIC SOIL CHARACTERISTICS

This section includes fundamental geometrical and physical properties that can or have been correlated to engineering properties, derived from classification tests and tests concerning the character, composition and evolution of soil particles and their arrangment. Much of our knowledge of soils is taken from basic laboratory tests, due to access, cost and time, and these forms of test are most often utilised by the consulting industry around the world. These basic tests are used to identify the type of soil, its fundamental state and simple characteristics. Our descriptions are then used in combination with our engineering experience to provide the anticipated behaviour based on our knowledge of the *in situ* state and any changes to the soil mass. Later in the design process, more complex testing is performed to confirm our hypotheses of the materials on the site and for more detailed analytical methods. Some of these basic

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laboratory tests and fundamental aspects of the behaviour of soils are being reinvestigated and new forms of test being added to our portfolio of testing methodologies. This section covers 11 papers that address particle crushing, scale effects, compaction and small-strain stiffness. Many other papers in the session cover these aspects, but these papers in particular have been included since it is the main focus of the work reported.

2.1 *Particle crushing and degradation*

Particle crushing is a fundamental feature of the deformation of particulate materials at medium and high stresses, and plays a major role in the mechanical behaviour of crushable soils at all stress levels. It can cause profound changes in the fabric and the structure of the geomaterial involved (e.g. Bolton, 1999; Hardin, 1985). This process is relevant for many geotechnical problems, e.g. *in situ* testing, pile driving and end bearing resistance, high earth or rockfill dams, and foundation problems associated with calcareous soils. Recent years have seen significant research focused on understanding the crushing behavior of calcareous soils and siliceous soils at high pressures. As the crushing proceeds, the grain-size distribution of the soil undergoes modification, causing changes in porosity and grain-to-grain contacts. The changes in the grain-size distribution play a key role for structural stability, stress-strain behaviour, dilatancy and shear strength of particulate materials (Mitchell & Soga, 2005; Rahma, 1998) and volume change, pore-pressure developments, and variation in permeability. Within this session, five papers cover this area of micromechanics and discuss aspects from fundamental investigations of particle crushing to applied engineering studies of the results of this behaviour.

The papers of *Di Emidio et al.* and *Valore & Ziccarelli* examine the yielding of granular materials subjected to one-dimensional compression and measure the grain breakage at different stages of the tests. One paper describes highly crushable and homogeneous artificial granular materials being compressed to simulate the crushability of natural sands at high stress levels and the other investigates the evolution of characteristic diameters of natural calcareous and siliceous sands. The test results demonstrate that crushing starts before the point of maximum curvature in the void ratio versus logarithm of vertical effective stress curve. Hence the 'yield point' defines the initiation of significant particle crushing.

The stress at the yield point varied depending on the material characteristics. Amongst natural sands, the lowest yield stress value occurs in the carbonate sand and the highest in the silica sand. Breakage was found to increase with the size of the grains. Coarse uniform samples showed higher breakage than uniform fine samples and well-graded samples. The breakage increased with decreasing strain rate or increasing load application time. It is also proposed that the evolution of the grain-size distribution of geomaterial can be represented by a relationship between the absolute value of the decrement of the generic characteristic diameter ΔD_i. This Verhulst type relation accounts for the existence of an upper limit to ΔD_i. The characteristic diameter decreases with increasing effective stress and the existence of an upper bound $\Delta D_{i,max} < D_i$ implies that at high stresses the grains of sand become so mutually coordinated that further crushing becomes negligible.

Lorincz et al. have interpreted the results of crushing tests on sand using grading curves and the grading entropy at the end of each treatment. The grading entropy of soils is calculated from the theory of information (Imre et al, 2008) and is an application of the statistical entropy to the possible grading curves. The grading curve is assumed to be a statistical distribution curve where the probability is a function of the diameter of the particles. This study has investigated the path of the grading curve variation in the entropy diagram, as a geomaterial undergoes degradation. The researchers found that only the entropy increment increased monotonically with an increasing number of crushing treatments. Therefore, the ultimate state can be expected to be characterized by maximum entropy increment and for a grading curve where the relative frequencies of the fractions are equal. This suggests that the optimal and final grading curves have a finite fractal distribution.

An application of the concept of grain crushing has been applied to the degradation of rockfill aggregate in ballast beds of Finnish railway tracks by *Nurmikolu & Kolisoja*. The degradation of these aggregates results mainly from mechanical fragmentation and attrition caused by traffic loads and tamping. The research utilised a cyclic loading apparatus to degrade the aggregate, ensuring that the principal stress direction rotated corresponding to a moving train loading. Long-term cyclic loading tests were conducted varying grain size distribution, aggregate strength, amount of fines and water in the aggregate, loading level and flexibility of the foundation. The ability of the aggregate to distribute loading was found to correlate closely with the ability of the aggregate to resist degradation. The initial grading of the crushed rock bed was found to have a significant impact on the degradation; uniformly graded aggregate beds degraded more quickly than well-graded beds. In the water saturated state, the degradation of the crushed rock aggregate increased dramatically and this has important implications for drainage provisions in railway track beds. Further applied investigations are reported by *Frossard* who describes material scale effects for the shear strength of deep granular fills and slopes based on physical laws from fracture mechanics controlling particle breakage (Bolton and McDowell, 1998). In particular, the static stability of rockfill slopes are addressed and specific design guidelines developed.

2.2 *Compaction methods and soil fabric*

An experimental program using a large triaxial apparatus designed to study the mechanical behaviour of a matrix-type coarse-grained soil (composed of a sandy matrix and angular inclusions) is described by *El Dine et al.* The results obtained show the effect of reinforcement due to the inclusions, with angles of internal friction increasing significantly with the volume fraction of the inclusions. This work has some interesting implications for the mechanical behaviour of materials with a wide range of particle sizes, such as moraines and tills. *Lange & Fanourakis* discuss analyses conducted on different soils to show the differences between vibratory and impact compaction. Standard methods based on the vibratory hammer and impact method were applied. It was found that the vibratory method was more suitable than the impact method for non-cohesive soils and gravels. Cohesive soils reached the maximum compaction at higher moisture contents using vibration as opposed to impact, but at lower densities. In the design and construction of embankments and other similar structures, it is essential that the designer can accurately model the soil mass in its actual compacted state, thus they recommend field densities should be assessed under the most appropriate laboratory methods. *Jimoh* reports the development of a two dimensional mathematical model for the California Bearing Ratio (CBR) of a typical lateritic sub-base material in Nigeria, in terms of the density and moisture. Conventional laboratory compaction and CBR tests were simultaneously conducted on samples of soils obtained from the highway borrow pits. The outcomes of the tests were used for the formulation of relationships of CBR with the resultant of the vectorially combined normalized dry density and moisture content at low compactive and medium compactive energy levels. The development of this type of approach will lead to more rational frameworks for quality control of compaction and geotechnical properties in the field.

2.3 *Small strain stiffness measurement*

Since the seminal paper of Burland (1989), steady progress has been made to develop both theoretical and experimental approaches to measure and predict small-strain stiffness of soils (Jovicic et al., 1996; Lee and Sanatmarina, 2005). This progress has been so rapid that it is now common place to find the mainstream consulting industry employing constitutive models, finite element analyses and laboratory data to describe non-linear stress-strain behaviour of structures such as, retaining walls, tunnels, excavations and foundations at 'working' loads. Academia has continued to broaden and enhance this area and it appears to be maturing, as evidenced by recent publications (e.g. TC29 report on Bender Elements, 2008). It is now typical to have precise strain measurements from laboratory tests that cover the entire range from very small to large strains, which bridge the traditional gap between 'dynamic' and 'static' behavior. In addition, links between *in situ* geophysical methods (e.g. the cross-hole method) and laboratory wave measurements now contribute to our understanding of a range of representative scales from micro to macro. Further examples of this are given in Section 8 on *in situ* soil profiles.

A thorough review of laboratory experimental techniques to determine the shear wave velocity of geomaterials using bender elements has been carried out by *Lohani and Shibuya*. Following on from the TC29 report (2008) on Bender Element testing, these researchers identify the need for a universally accepted base for the shape and frequency of input signal, and a universal definition of arrival time. Inconsistency of these aspects causes problems associated with uniqueness and objectivity, and uniformity in interpretations of stiffness. The authors analyze experimental results from a consolidation test on reconstituted clay samples and discuss the errors associated with different techniques adopted for arrival time determination. Of particular concern to these researchers is the difficulty involved in applying these methods to less well known soils and for new researchers in this field.

A similar study was conducted by *Wicaksono & Kuwano* who performed static and dynamic stiffness measurements consecutively on the same specimen, with a triaxial apparatus combined with dynamic measurement tools (i.e. Trigger Accelerometer [TA] and Bender Element [BE]). The values of shear modulus resulting from static measurement, TA, and BE methods were then compared at different stress levels for specimens of Toyoura sand, Hime gravel, crushed glass, and glass beads prepared under dry and saturated conditions for different isotropic and anisotropic stress states. The study found that the values of shear modulus obtained from dynamic measurements (i.e. using TA and BE methods) tend to be larger than those of static measurements. Dynamic measurement using the BE method yielded lower values of dynamic shear modulus compared to those of the TA method, which was attributed to the effects of bedding error at the interface between the BE and the specimen with gravelly materials (particle size with mean diameter of larger than 1 mm). Finally, for the evaluation of shear modulus obtained from the triaxial test under anisotropic conditions, the authors suggested the adoption of rigorous anisotropic small strain assumptions.

Pender et al. present laboratory test results for a complete stress-strain curve for specimens of Auckland residual clay. This work was conducted using an older technique (Cuccovillo & Coop, 1997) that has been revisited for small strain application, where three high accuracy LVDTs were positioned around the periphery of the specimen to measure axial strains over a gauge length of 100mm. The authors addressed the problems associated with the end effects in conventional testing, by fixing the cap against rotation, thus ensuring the same axial compression across the specimen. Quality of the experimental technique was also found to be paramount and they ensured excellent specimen end preparation, where a thin layer of plaster was applied and a trimming mould was used to ensure the ends were parallel. Using these experimental technique refinements, they were able to get very good quality axial strain data.

3 ONE DIMENSIONAL STRAIN STATES

The prediction of the behaviour of soft soils from thin one dimensionally loaded laboratory specimens to thick *in situ* soil layers is one of the key research topics in understanding clay compressibility and consolidation. Issues of the effects of mineralogy, disturbance, loading state and rate, saturation and viscous behaviour are also a central part of this research area, and many of the 11 papers in this section address aspects of these questions.

3.1 *Compression and volume change*

Tiwari & Dhungana evaluated the geotechnical properties of different soil specimens prepared by mixing various proportions of quartz, smectite, and illite. The liquid limit, plastic limit, and volume change behavior in terms of compression and swelling indices were measured. The results show that plasticity index and liquid limit depend on the proportion of smectite and total clay content; a parabolic relationship could be observed between the liquid limit and proportion of smectite. Likewise, the volume change properties also depended on the proportion of smectite. Another parabolic relationship was observed between the compression index and proportion of smectite, whereas a linear relationship was observed between the liquid limit and compression index. The results show that we can estimate the coefficient of consolidation, and compression and swelling indices of a soil mass with reasonable accuracy with liquid limit and proportion of dominant clay mineral.

Chae et al. describe the compressibility of marine clays off the southern and western coasts of Korea. To evaluate the effect of disturbance on the compressibility, a series of laboratory consolidation tests were performed on specimens obtained by large block sampling and piston sampler. The large block samples appear to have better quality than the piston samples; the volumetric strains of large block samples ranged from 1.0 to 4.5% for OCR of 1.65 - 2.22; that of piston samples range from 1.4 to 11.7% for OCR of 1.23 - 2.13. The magnitude of pre-consolidation pressures obtained from the various consolidation tests on the large block samples was dependent on the types of sampler and test method. The pre-consolidation pressure obtained from Rowe-cell tests on large block samples is about 1.3 times larger than that of piston samples and the pre-consolidation pressure evaluated from incremental loading consolidation tests on large block samples is 1.1 times larger than that of piston samples. Correlations for compression index of large block samples are suggested considering the effect of disturbance during specimen preparation.

Shi & Lok have conducted an experimental investigation of the variation of shear wave velocity of reconstituted Macau marine clay during consolidation using bender elements installed in an oedometer. From the results of deformation and the simultaneously acquired shear wave velocity, the variation of shear wave velocity during the consolidation process was closely studied. The increase of shear wave velocity reflects the transfer of load from the pore water pressure to skeletal stresses during the consolidation process. Based on the experimental results, relationships between shear wave velocity and vertical effective stress, and between shear wave velocity and void ratio were proposed. It was observed that the value of shear wave velocity drops slightly immediately upon loading, after which V_s increases approximately linearly with increasing average degree of consolidation from. After the completion of primary consolidation, V_s continues to increase due to aging effects.

Stanciu & Lungu have designed a new oedometer device, to decrease induced testing errors that occur with the classical oedometer. The new test is performed directly on the soil specimen removed from boreholes without sampling. The stress-strain and stress-voids ratio curves are obtained on samples with a partial lateral confined strain, under a stress state close to the one *in situ*. In addition, the new oedometer device provides the ability to perform a plate load test and obtain the stress-settlement curve, based on the vertical subgrade modulus and by correlation with the soil modulus. By comparative studies of the obtained results in both classical oedometer and new oedometer, the soil modulus E and correction factors M_0 of the oedometer modulus M from the classical test, $E = M_0 \times M$, are established together with new approaches to correct the classical compression – voids ratio curves.

Juarez-Badillo presents a very simple theoretical equation given by the Principle of Natural Proportionality for the compressibility of geomaterials. This is applied to experimental compression data obtained by Bridgman (1939) for thirty-nine substances from 0 to 100,000 kg/cm². Independently of polymorphic transitions, the compression response of the natural solid substances presented in this paper is described by this simple theoretical equation with constant natural internal pressures i and constant natural coefficients of compressibility $\gamma < 1$. The natural coefficients of compressibility γ varied between 0.037 and 0.317 and the values of the internal pressure i varied between 2,428 and 127,044 kg/cm^2. The equation is such that when the pressure σ tends to ∞ the volume tends to zero, but due to the polymorphic transitions, all liquids and solids tend to volume zero at finite values of the pressure σ.

Lee et al. have tried to identify the effect of wetting on the long-term compressive settlement of railway track bed filling material, which comprised mixed soil and aggregate, depending on compaction and grading conditions. Consequently, the settlement under fully-submerged conditions reached a maximum of 0.73%, and a repeated settlement was monitored when moisture content was increased repeatedly in a manner that reproduced rainfall infiltration. In contrast, in the case of materials without fine fractions or compacted in a wet condition, the settlement caused by 'setting' was relatively low. Hence, when it comes to embankments requiring a strict allowable residual settlement, the rock aggregate material needs to be compacted in a wet condition and should remain exposed to the natural environment for a year at least, so as to previously induce the settlement by rainwater or freezing and thawing conditions.

3.2 *Consolidation and time effects*

Van Impe et al. presents the laboratory setup and some preliminary results of large strain consolidation testing on several types of dredging and industrial waste sludge. This was designed to investigate the impact of additives, specifically coagulants and flocculants, on the consolidation behaviour of mineral sludges. Large strain consolidation parameters are determined using an adapted version of the well-known seepage consolidation test setup (Imai 1979). Interpretation of the test results is based on an iterative calculation using large strain consolidation theory as presented by Abu-Hejleh (1992). Preliminary results on mixtures of gypsum-slurries with and without flocculant have indicated that the flocculant induces a structural change in the material. This structural change is shown as an increased permeability over the full range of stresses. The testing protocol and the determination of an improvement factor should allow optimising (economically) of the type and concentration of an additive.

Kawabe et al. performed drained constant-rate-of-strain one-dimensional compression tests at different strain rates with and without large unload/reload cycles and many sustained loading (SL) stages, as well as standard consolidation tests, were performed on reconstituted and undisturbed soft clays. Significantly rate-dependent stress-strain behaviour of *Isotach* type, not due to delayed dissipation of excessive pore water pressure, but due to the viscous properties of clay, was observed. The creep axial strain rate at SL stages while otherwise the effective axial stress was increasing at positive axial strain rates was always positive. The creep axial strain rate at SL stages while otherwise effective axial stress was decreasing was basically negative, whereas it was positive immediately after load reversal from primary loading. Irrespective of the signs of current effective axial stress rate and creep axial strain rate, primary loading and reloading are defined by $\dot{\varepsilon}_a^{ir} > 0$, while unloading by $\dot{\varepsilon}_a^{ir} < 0$. These trends of behaviour are simulated by the non-linear three-component elasto-viscoplastic model.

The non-uniqueness of end-of-primary (EOP) void ratio (volumetric strain) versus effective stress relationship has been demonstrated by Degago et al. using experimental measurements that have been determined by others to support the uniqueness concept. Detailed studies of data with direct comparisons of results from thin and thick specimens using a consistent EOP criterion have showed that the EOP void ratio is dependent on the thickness of the specimen. Hence, the EOP void ratio versus effective stress curve of a thicker specimen is larger than for a thinner specimen. The formulation of creep in the isotaches concept gives a non-unique EOP void ratio-effective stress relationship. This study illustrates that the measured results can be calculated, by the same set of input parameters for the thin and the thick specimen, using a soil model that is based on the isotaches concept.

Mesri & Huvaj-Sarihan have revisited the well known Asaoka method, which they describe as a useful tool for interpreting and extrapolating field observations of settlement. The graphical procedure to estimate end-of-primary (EOP) settlement and coefficient of consolidation is simple, however, mathematical deduction of the method by Asaoka is not. The Asaoka method is deduced using simple algebra for one-dimensional compression with and without vertical drains. The Terzaghi theory of one-dimensional consolidation, and the Barron equal strain theory of consolidation modified to include effects of smear, well resistance and vertical water flow through soil, are used. The Asaoka graphical procedure is applied to settlement observations at Skå-Edeby test area I with three spacings of sand drains and area IV without vertical drains. The EOP settlements determined by the Asaoka procedure for the three sectors of area I, with three different vertical drain spacings, are comparable to values interpreted using the Casagrande procedure. The EOP settlement estimated using the Asaoka method for area IV without vertical drains is quite similar to those observed for area I with vertical drains, in spite of the fact that EOP consolidation for area I – 0.9 m was reached in less than 2 years whereas the EOP settlement of 107 cm for area IV requires about 38 years. In other words, the settlement observations for area I and observed settlements for area IV extrapolated using the Asaoka method, support the concept of EOP settlement independent of the duration of primary consolidation. The Asaoka method is not recommended for predicting secondary settlement.

3.3 *Ko conditions*

Federico & Elia have described a study that investigates the link between the at-rest earth pressure coefficient K_{0NC} and Poisson's ratio ν (for normally consolidated soils) based on the connection between the effective friction angle ϕ' and its mobilized proportion ϕ'_{mob} in the process of one-dimensional compression. After considering the existing correlations between these two parameters, the comparison with experimental data leads to both the validation of the existing theoretical K_{0NC} equation coming from the BRICK model (Simpson, 1992) and the proposal of an equivalent empirical K_{0NC} equation, derived without any assumptions. The same connection between ϕ' and ϕ'_{mob} leads to interesting correlations, one theoretical and one empirical, between ϕ' and ν for normally consolidated soils. No laboratory data in terms of pairs (ϕ',ν) have been found at all in literature, and, therefore, experimental validation of these correlations is necessary.

4 TWO & THREE DIMENSIONAL STRAIN STATES

The determination of shear strength and post-peak behaviours of soils are of considerable importance, since they provide the basis for yield and failure criteria for design and constitutive models, and are useful for comparing laboratory tests and field observations. Despite the development of true-triaxial and hollow cylinder (e.g. Vaid et al., 1990) devices able to test a very wide range of stress paths, the triaxial, simple shear and direct shear test are still the most widely employed method to study these aspects of soils. This section reports the findings of 21 papers covering tests with static and cyclic triaxial and shear tests covering pre-failure, post-failure and failure behaviour, appraisal of testing techniques and interpretions, and new theoretical developments derived from test data to create constitutive and working engineering models for two and three dimensional strain states.

4.1 *Time independent behaviour*

4.1.1 2D behaviour: shearing and large strains

Various studies have revealed significantly more landslides and related failures occurring in Central Nepal compared to other parts of the country. *Bhandary & Yatabe* present research with the aim of understanding the shear characteristics of clay material in landslides along this road network. A total of 31 locations of landslides and failure sites were investigated for field verification and soil sampling. The collected samples were then tested in a ring shear apparatus for peak and residual shear strength parameters and in an x-ray diffractometer for mineralogical composition to reveal the influence of chlorite and mica-like weak minerals on the shear strength of landslide clays. The ring shear and mineralogical tests revealed that the landslide soils in the target area have comparatively high angles of internal friction and possess high composition of chlorites and micas as main constituent minerals, especially in phyllitic zones. An analysis of the influence of chlorite and mica content on the frictional resistance of collected samples indicated that the soil strength decreases significantly with the increase in chlorite and mica composition. The sheet-like mineral structure of micas gives them a greater water absorption capacity and illite (i.e. hydrous micas) particles tend to disaggregate considerably in water causing reduced particle-to-particle attraction and lesser frictional resistance.

Although many flowslides can be explained using static liquefaction or instability behaviour of sand under undrained conditions, some of failures can occur under drained conditions. Recent laboratory studies on Changi sand by *Wanatowski & Chu* under axisymmetric conditions have shown that sand can become unstable under completely drained conditions. To date, most of the experiments on the instability behaviour of granular soils were carried out under axisymmetric conditions. In this paper, experimental data obtained from plane-strain tests are presented to illustrate the unstable behaviour of sand under both undrained and drained conditions. When loose sand was tested under an undrained condition using the plane-strain apparatus, undrained instability was found to occur. Contractive and dilative sand specimens can become unstable under a drained condition. Both of these findings are consistent with the experimental results obtained under axisymmetric conditions. The instability line based on yielding conditions is the same for both drained and undrained tests and defines the lower bound of all the possible unstable states regardless of the drainage conditions. A framework formulated by the authors for axisymmetric conditions using the modified state parameter $\overline{\psi}$ and the CSL can now be extended to plane-strain conditions.

Tsutsumi & Maqbool have investigated the effects of confining stress, particle size and uniformity coefficient on local deformation characteristics of a dense clean sand and compacted well-graded gravel in drained plane strain compression tests with image analysis. As a result of the plane strain compression tests on dense Toyoura sand under the confining stresses over a range from 800 to 2400 kPa, the peak principal stress ratios decreased with the increase in the levels of the confining stress. When the confining stress was below 800 kPa, almost the same peak principal stress ratios were obtained. Strain softening behavior was observed clearly in all the tests on Toyoura sand, while no significant decrease in the mobilized strength of compacted Chiba gravel after the peak stress state was observed. After the peak stress state, in the specimens of Toyoura sand, the local maximum shear strain concentrated on the zone where the shear band was fully formed. For Chiba gravel, the local strain accumulated not only at the location of the full shear band, but also at the other zones where significant strain localization was observed even before the peak stress state. In addition, the thickness of the shear band of Toyoura sand was approximately 2 - 3 mm, while that of Chiba gravel was much larger. It was inferred that the above differences in the post-peak behavior of these materials are affected by their different strain localization properties.

4.1.2 3D behaviour: strength, dilatancy and critical states

Kalantary et al. have investigated the dilative behaviour of a crushed rock samples tested in a large triaxial apparatus under different confining pressures and the dependency of dilatancy angle on material characteristics and test condition was studied. Abrasion and point load tests were also carried out to evaluate hardness and compressive strength of the aggregate. It was noted that under low confining pressures samples from various sources exhibited different amounts of dilation. Crushed rock samples with higher grain hardness exhibited greater dilatancy under equal confining pressures. It has been re-affirmed that the dilatancy angle varies considerably during loading and is very much dependent on the confining pressure. It has further been shown that the amount of dilation is directly related to particle strength and its resistance to abrasion for angular shaped particles in rockfill masses. Stronger geo-materials tend to dilate more under a constant (low) confining pressure than less strong rockfills. This has been attributed to the resistance of the grain to crushing and breakage (see Section 2). Thus, increasing particle breakage causes reduction of the dilatancy angle. The particle resistance to crushing and breakage is very much dependent on the strength and hardness of the grain.

The effective shear strength of overconsolidated soils without cementation or aggregates of particles is frequently described in terms of the cohesion and the angle of internal friction. An alternative, that is more consistent with the physical behaviour of these materials when sheared and which is strictly related to the volumetric strains, makes use of the angle of dilatancy and the effective angle of friction. *Maranha et al.* have interpreted the results of different types of soil tests, focusing on the procedures to correctly evaluate the angle of dilatancy. Some cases are presented and discussed. Explicit expressions for the angle of dilatancy at failure have been derived for the drained triaxial compression, simple shear and plane strain biaxial tests.

Sadrekarimi & Olson present drained and undrained triaxial compression and ring shear tests that were used to define the critical state line of a silty sand sampled from the Mississippi River. All specimens were prepared by pluviating the dry sand through air. The results show that both drained and undrained (or constant volume) triaxial and ring shear tests reach critical state at similar shear displacements prior to the onset of particle damage in the ring shear tests. A unique critical state line can be defined for these states. At larger shear displacements only possible in the ring shear tests, considerable particle crushing happens and dominates the sand behavior and only after very large shear displacements (> 750 cm) particle crushing ceases to continue and a complete particle rearrangement is reached. At this state, the stresses and volume of the sand become constant which corresponds to the critical state of the crushed sand. A unique line can also be drawn for this state. These unique critical state lines indicate that they are not influenced by the drainage conditions and shearing modes.

Rahman & Lo have previously reported that void ratio is not a good state variable for sand with fines. Thus, the equivalent granular void ratio, e^* has been proposed to resolve this problem. The Steady State data points in e^*-log(p') space can be described by a single trend irrespective of fines content, f_c, provided $f_c \leq$ TFC. This single trend line is referred to as an equivalent granular steady state line, EG-SSL. However, whether the EG-SSL can be used within the context of critical state soil mechanics (CSSM) for predicting undrained behaviour has to be investigated. An equivalent granular state parameter, ψ^*, defined using EG-SSL as the reference is proposed in this paper. It is found that ψ^* can successfully predict undrained responses of sand with fines in undrained shearing.

The friction angle of sands is computed by Bolton (1986) as the sum of the critical state friction angle and a dilatancy term which is a function of mean effective pressure and void ratio. Critical state is reached when dilatancy vanishes, either due to volume change (in drained shear) or effective pressure change (in undrained shear). Therefore, equating Bolton's dilatancy term to zero yields, at least theoretically, an implicit relationship between mean pressure and the critical state void ratio of sands. It is found that this relationship yields unrealistic results, mainly because Bolton's expression is of a phenomenological nature and was not intended to be used for this purpose. In this paper, *Sfriso* proposes a modification to Bolton's dilatancy term. It is proved that the modified expression has the capacity to predict both the peak friction angle and the critical state void ratio for any void ratio and effective pressure within the range of engineering interest, which is accurate enough for routine analysis and can be used to predict the undrained strength of loose sands.

4.2 *Time dependent behaviour*

4.2.1 Cyclic loading and liquefaction

While the cyclic behavior of sand without initial static shear has been studied extensively, there is still not a general consensus regarding the initial shear effect. *Yang et al.* present an experimental study of the initial shear effect on cyclic liquefaction behavior of sand, focusing mainly on very loose sand. The data base produced is able to improve current understanding and to clarify the existing uncertainty. A new concept, termed as threshold α, is proposed along with the use of zero reversal line to better characterize the effect of initial static shear stress. A series of cyclic triaxial tests were performed on two types of sand to investigate the effect of initial static shear on liquefaction resistance. It was found that the failure mode of loose sand is characterized by sudden, run-away deformations and this characteristic is regardless of whether stress reversal occurs or not. The presence of initial static shear at small levels is always beneficial for cyclic liquefaction resistance but may become detrimental at higher static shear stress levels. There exists a threshold α above which cyclic liquefaction resistance tends to drop with increasing α. The threshold α is a function of initial states in terms of relative density and effective confining pressure.

Increase in cyclic strength due to aging of sands is reflected in the higher number of cycles necessary to reach liquefaction. *Moffat & Ormazabal* report results from cyclic triaxial tests on reconstituted and undisturbed block samples from the Ovejeria tailing dam. Observations on the change of the cyclic stress ratio caused by aging effects during a period of time between 0 to 5 months enable the characterization and comparison on the cyclic behavior on remolded specimens and *in situ* samples. Preliminary observations indicate that cyclic strength of undisturbed samples obtained directly from the tailing dam cannot be compare directly with the strength of reconstituted specimens by moist tamping with the same age.

The effect of large cyclic and creep loading on peak strength of compacted gravel was investigated by *Maqbool & Koseki* who performed a series of four triaxial compression tests using a large scale apparatus. To measure the major principle stress σ_1, a load cell is located just above the top cap inside the triaxial cell in order to eliminate the effects of piston friction. The major principle strain ε_1 was measured not only externally, but also locally with three pairs of vertical local deformation transducers (LDTs). Minor principle strain, ε_3 was measured by three pairs of horizontal local deformation transducers. Chiba gravel was used as the test material. The specimens were prepared by employing automatic dynamic compaction. During monotonic shearing (after large cyclic, as well as creep loading stages) sudden increases in the shear stress level without any increase in axial strain was observed. From this study, it is concluded that if the gravel is compacted to a certain degree, there will be no significant effect of large cyclic or creep loading history on its peak strength.

One of the frequent problems for roads is rutting or permanent deformation accumulated on the pavement surface. *Perez & Garnica* have presented some research relative to permanent deformation and resilient modulus for clayey soils. This paper presents results on permanent deformation obtained from compacted samples of a silty soil. The results show how the accumulation of permanent deformation is influenced if the load is applied in steps or if the maximum stress level is applied. Finally, curves of permanent deformation of the same soil are used to demonstrate the suitability of the natural law model to fit experimental data. It is suggested that permanent deformation in subgrade soils can be limited if the stress level is controlled during compaction.

Through observations of soil skeleton structure, including structure, overconsolidation and anisotropy, *Nakai et al.* have proposed a new elasto-plastic constitutive equation, named SYS Cam-clay model. The proposed model accounts for the decay of structure, the loss of overconsolidation, and the appearance or disappearance of anisotropy accompanying the processes of plastic deformation of overconsolidated soil in a highly structured state. This soil skeleton structure concept is not only applicable to clay, but also can be applied to sand. Loosely compacted sand with a high specific volume has a high degree of structure and a low overconsolidation ratio, and conversely, densely compacted sand with a low specific volume has a low degree structure and high overconsolidation ratio. The structure upgradation process was clarified based on the results of undrained cyclic shear tests for medium dense sand using triaxial testing apparatuses. Based on the results, it was possible to model structure upgradation by applying the new model. As a result, it is possible to not only describe the cyclic mobility behavior of sand, but also to describe the characteristic structure degradation of highly structured clay (high ductility in which degradation under compression occurs easily under low stress ratios, but does not occur easily under shear for stress ratios approaching the critical state).

The liquefaction potential of sand-silt mixtures has been investigated by *Ghalandarzadeh & Ahmadi*. The purpose of this study is to reveal the effect of silt on resistance to liquefaction of sandy specimens by means of a series of load-control cyclic triaxial tests. These tests were conducted on sand-silt mixtures in various fine contents. In addition, the anisotropic behavior of the sand-silt mixtures was studied in this research by exploring the effect of the initial shear stress and stress reversal. The effect of stress reversal was studied by introducing a new parameter RC. By increasing the fine content, the liquefaction resistance of the sand-silt mixtures decreases. The critical silt percent in which the liquefaction resistance has the least amount is 25%. By further increasing the silt content, the liquefaction resistance increases; however, it is always less than the liquefaction resistance of the pure sand. The liquefaction resistance of the anisotropically consolidated sands in compression mode increases by decreasing the amount of (K) and increasing the amount of RC. The anisotropically consolidated sands in extension mode were not liquefied, and they were collapsed due to the tension fracture.

Verdugo & Santos have evaluated the liquefaction resistance of thickened tailings (Robinsky, 2000). Accordingly, a comprehensive series of monotonic and cyclic triaxial tests were performed on reconstituted samples. A wide range of confining pressure was used, from 0.1 to 3 MPa. The results show that the cyclic stress that causes 100% of pore pressure built up is not much affected by the level of confining pressure, which clearly differs from what has been observed in natural sandy soils. On the other hand, the results indicates that re-saturated thickened tailings, although increases their density during drying, they may still develop the phenomenon of liquefaction during severe earthquakes. Nevertheless, the post-liquefaction strength is rather high.

Determining the liquefaction potential of a soil is critical when designing with natural soils or evaluating a liquefaction mitigation technique. Therefore, using a suitable liquefaction criterion becomes critical especially in the case of non-traditional soils where the cyclic behavior of the soil can be different from that of natural soils. Mohtar has compiled results from the literature to address the applicability of using the 5% double amplitude strain criterion for liquefaction with the recent growth in testing non-traditional geo-materials. A compilation of data in the literature on the different criteria used to define liquefaction is presented in this paper. The results consistently show that for traditional soils, using initial liquefaction, 1%, 2%, 5% or even 10% double amplitude axial strain would result in very small changes in the measured cyclic resistance using cyclic triaxial testing in the laboratory. However, for non-traditional soils where the soils have been treated with different grouts (bentonite suspensions, colloidal silica or sodium silicate), one should be more careful with selecting the liquefaction criterion. While some of these soils would still exhibit cyclic response similar to that of traditional soils, the response of others can be significantly different.

Yamada et al have conducted a study with triaxial tests to examine the changes in anisotropy taking place during liquefaction and to investigate the effects of the anisotropy developed during liquefaction on reliquefaction behavior. A distinctive characteristic of reliquefaction behavior of soils is that there are instances where the phenomenon of a sharp decrease in liquefaction resistance occurs, in spite of increases in soil density caused by drainage of water after liquefaction. This suggests the existence of factors other than density that sway the liquefaction resistance of soils. The study has found that during liquefaction, continuous and orderly changes in anisotropy are repeated with rapidity. Because of this, anisotropy exists in various states of development when liquefaction ends. Furthermore, the developed anisotropy remains without fading even after drainage. As the level of developed anisotropy increases, liquefaction is facilitated because behavior resembling that of looser sand is exhibited when sand is subjected to shear in a certain direction. In cases where, because of being subjected to liquefaction history, the anisotropy has developed to appreciably higher levels than before liquefaction, the sand exhibits behavior resembling that of extremely loose sand in spite of increased density. As a result, its liquefaction resistance decreases significantly.

Yasuhara & Murakami report on the effect of drainage history on post-cyclic monotonic undrained shear behavior of non-plastic silt investigated using cyclic and subsequent monotonic undrained triaxial tests, following a testing procedure proposed by the authors in which cyclic loading is carried out under stress-controlled conditions and subsequent monotonic loading is conducted under strain-controlled conditions. The results of these tests show that, if the silt did not experience further undrained cyclic loading, the stiffness returned to the original value after once undergoing drainage from full or partial dissipation of excess pore pressures generated during undrained cyclic loading. This characteristic differs greatly from the behavior of cohesive soils, which tend to exhibit stiffness and strength improvement. On the other hand, the post-cyclic undrained strength increased independently of the period at all stages of dissipation of excess pore pressures when drainage was allowed after undrained cyclic loading, depending only on whether liquefaction took place before drainage started. These characteristic features of post-cyclic undrained behavior of non-plastic silt resemble those of cohesive soils including plastic silts and clays, which implies that deformation of silty soil ground during and after earthquakes is more important than ground failure.

4.2.2 Creep, viscous and rate effects

Martinez-Vasquez & Diaz-Rodriguez describe a study of the creep effects on the stress-strain-time behaviour of Mexico City lacustrine sediments. The studied site is localized in Central Park and soil specimens were obtained from 7.3 and 22.6 m depth. The paper describes the results of 8 creep tests; isotropically consolidated specimens to consolidation pressure σ'_o= 80 kPa; the creep stages causing sustained stress were applied for over 10,000 minutes for different stress levels (D). The test results show that the influence of creep in the destructured range ($\sigma'_y/\sigma'_o > 1$) is not important at low shear stress levels, D. Creep rupture was not present in these tests. The post-creep strength does not show a tendency to increase or decrease by comparison with a reference strength before σ'_y. For Mexico City lacustrine sediments, soil structure and their implications play a very important role before creep behaviour.

Juarez-Badillo & Hernandez-Mira have applied the general theoretical equations given by the principle of natural proportionality to describe experimental data contained in the basic paper 'Rate-Dependent Undrained Shear Behavior of Saturated Clay' by Sheahan, Ladd and Germaine (1990). The paper describes results from 25 K_o consolidated-undrained triaxial compression tests on resedimented Boston blue clay using a computer-automated triaxial apparatus. Specimens were consolidated to four overconsolidation ratios, and for each OCR, undrained shear was performed using four axial strain rates. The proposed theory was found to model these tests in a reasonable manner and the study suggest that this may be accomplished for other materials subjected to similar test states.

Lade has made observations of time effects in triaxial compression tests performed on crushed coral sand with constant strain rate, creep tests at different stress levels, and stress relaxation tests initiated at different stress levels. Observations from these experiments show that strain rate effects are negligible for crushed coral sand. Further, the observed stress relaxation behavior was not in "correspondence" with the measured creep behavior. It is concluded that sands do not exhibit viscous effects, and their behavior is indicated as 'nonisotach'. Thus, there are significant differences in time-dependent behavior patterns of sands and clays. In another investigation on Antelope Valley sand, the measured responses in creep and stress relaxation tests and in constant strain rate tests exhibited similar behavior to the crushed coral sand, but with smaller discrepancy between the creep and stress relaxation tests. An explanation for these non-viscous and dissimilar effects for the different sands is proposed and relates to interparticle friction, grain crushing, and grain rearrangement. Grain crushing is a time dependent phenomenon and this accounts for the time dependency observed in granular materials. Additional experimental research is required to understand the behavior of sand and to develop a more correct constitutive framework for the time-dependent behavior of sand.

5 PERMEABILITY AND DRAINAGE

Piping failure is among the most common failure modes for embankment dams. It is often related to the potential of the embankment material to de-flocculate and erode in the presence of water. Soil erosion is therefore one of the main factors affecting the safety and serviceability of earth structures. Recent catastrophes that have occurred clearly show the great vulnerability of embankments and dikes to internal erosion and overtopping. Sensitivity to erosion of these earthworks is strongly dependent on soil texture (especially, the presence of fine clay particles) and on sensitivity to dispersion and is therefore very difficult to predict. Likewise the flow behaviour and permeability of engineered fills, glacial tills, mudflows, debris flows, residual soils, and colluvial deposits, which have a structure consisting of a soil matrix and large dispersed particles mixed in the matrix, has received little attention in soil mechanics. The three papers in this section cover these issues.

Elsharief & Amin present the results of a laboratory testing program to study the effects of dry density, moisture content and curing time on the erodibility and dispersivity of two alluvial deposits from the Nile for use as dam core material. Samples were prepared in the laboratory at different moisture and density conditions, and tested for dispersivity and erodibility using the pinhole test. Identical specimens were prepared, cured for different periods of time extending up to 18 months and tested. The results show that the erosion resistance of the slightly dispersive soil (A) improved with an increase in dry density, when the moisture content is wet of optimum and with curing time for specimens with lower density and moisture content. However, the highly dispersive soil (B) did not show significant improvement of its erosion resistance, either with increase of its density or with increase in curing time. Pham et al. have also considered the sensitivity of soils to erosion, using the Hole Erosion Test, which they found to be an efficient and convenient laboratory test. They also conducted *in situ* tests with the Mobile Jets Erosion Test. Their study provides comparative tests between these techniques and attempts to bridge the gap between the two approaches.

Gutierrez conducted a study to evaluate the effect of dispersed large particles on the permeability of sand-gravel mixtures. Constant head permeability tests were carried out on samples made of a matrix of Ottawa sand (D_{ave} = 0.725 mm) and dispersed particles with an average diameter of 11.1 mm. The percentage by volume of gravel in the mixtures was varied between 0% and 14%. The hydraulic conductivity of these mixtures was found to be affected by the presence of the oversized particles and was found to decrease as the percentage by volume of the oversize particles increased, where the large particles were uniformly dispersed through the samples. In contrast, if the oversized particles were arranged in clusters in the samples, their hydraulic conductivity varied depending on where the clusters were located. If the clusters were in the mid-section of the samples, the hydraulic conductivity was higher than for samples with the clusters placed elewhere When the clusters of oversized particles were located at the top or bottom of the samples, their hydraulic condutivity was smaller than that measured in samples with no oversized particles. It was concluded that Darcy's law does not seem to apply in the samples with clusters. The water flow in the spaces between the particles forming part of the clusters moves at higher velocities making the flow turbulent instead of laminar.

6 UNSATURATED SOILS AND SUCTION

Historically, the analyses of geotechnical problems have been dominated by solutions developed in classical soil mechanics where the soil is considered completely saturated or dry, conditions that make the analyses less complicated. However, in many geotechnical problems, the engineer has to deal with unsaturated soils which properties are complex due to the fact that two fluids are involved in their performance (water and air). One of the main concepts in unsaturated soils theory is 'suction', which can be determined in the laboratory or field. The amount of water in soil, is often expressed in terms of the degree of saturation, S_r, which plays an important role in defining many soil properties, such as strength and permeability. The eight papers in this section address the measurement of suction and saturation, modelling and testing of unstaurated soils, and the application of unsaturated soil theories.

Orense et al. have proposed a novel method to directly measure the degree of saturation of a continuous region of soil. From photographic images taken at various soil moisture contents, the colours of the images were converted into numerical values which were related to known degrees of saturation. Their method was validated through vertical seepage tests, where good agreements were obtained between saturation found from tensiometers and that estimated from the proposed method. From the test results, it appears to be feasible to measure the degree of saturation of the ground by image processing. The relation between degree of saturation and luminance value can be expressed in terms of a second degree function. With this method, contour diagrams of degree of saturation can be produced, making it possible to visualize the propagation of the saturated region. Moreover, not only the flow of water, but also the movement of air can be evaluated under drained and undrained conditions with this method.

A study of the relationship between soil resistivity and suction is presented by Perez et al. By conducting a careful literature survey in the area of soil science, they have determined that density, degree of saturation and volumetric water content can all affect the resistivity. The results shown in this paper show the effect of water content and dry density on resistivity and demonstrate that as the resistivity increases, the suction also increases for a constant dry density. Whilst, not finding a definitive relationship between suction and resistivity, the authors conclude that further research will fulfil this need.

The main objective of the paper by Chembeze was to assess the level of saturation of soil by measuring the velocity of seismic compression waves using bender elements. The value of Skempton's porewater parameter B was correlated with the velocity of the P wave (V_P) for a number of samples. The author suggests that this may provide a fast and convenient alternative to the standard 'B' test, conducted prior to testing triaxial samples in the laboratory. Wang & Dong report on wave-based characterizations of residual soils to assess the response to bonding effects, yielding, and the influences of weathering. These features were captured in the following relationship between velocity (V_s) and stress(σ'): $V_s = \alpha(\sigma'/1kPa)^{\beta}$. When bonding effects prevail, including capillary suction and precipitated fines or salts around contacts under unsaturated conditions, a higher α value and a lower β exponent were found to be measured, i.e., the soil structure is stiffer and less sensitive to changes in the stress state. Saturation was found to destroy those apparent bonds, which in turn weakens the soil skeleton and increases the compressibility. Thus, a lower α factor and a higher β exponent were found. Weathering effects led to a decreasing trend in α values, suggesting that a looser packing or a more opened structure and softer particles are formed in response to higher degrees of weathering. Similarly, Hatanaka & Masuda describe a series of field and laboratory tests on a sandy soil, where wave velocities have been used to assess the behaviour. They have found that after sand compaction, the primary wave velocity and the degree of saturation of the *in situ* sandy soil decreased due to the injection of air bubbles into the ground. They also observed that the liquefaction strength of the partially saturated sand before and after sand compaction was much higher than that of fully saturated sand. The effects of the size and roundness of soil particles and relative density on the relationship between degree of saturation and primary wave velocity were minor, but the effect of the confining stress on that relationship was though to be significant. Based on these test results, a method to inject air bubbles into the ground may be an effective method to reduce sand liquefaction.

6.1 *Modelling unsaturated soil behaviour*

Hoyos et al. present the results of a preliminary series of triaxial compression and triaxial compression tests conducted on compacted silty sand under constant-suction states. The experiments were conducted using a novel, servo-controlled, true triaxial (cubical) apparatus capable of testing specimens of unsaturated soil under controlled-suction states and for a wide range of stress paths. The equipment is a mixed-boundary type device, with the specimen seated on top of a high-air-entry ceramic disk and between five flexible (latex) membranes on the remaining sides of the cube. The cell features two independent pore-air (u_a) and pore-water (u_w) pressure control systems. Target suction levels are induced and kept constant during testing using the axis-translation technique. Results from suction-controlled tests under axisymmetric conditions ($\sigma_2 = \sigma_3$) were used for calibration and fine-tuning of the original elasto-plastic, critical state based framework postulated by the Barcelona Model (Alonso et al. 1990). Matric suction was found to exert a noticeable influence on the stress-strain-strength behavior under multiaxial stress states. Numerical predictions of the experimental stress-strain response of silty sand under axisymmetric conditions, using the Barcelona Model, were reasonably accurate.

For small compressive stress ranges (less than tens of kPa) and particularly in the tensile stress regime, the Mohr-Coulomb criterion often can not be used for representing the behavior of sand. *Kim et al.* have investigated the relationship between cohesion and tensile strength, using uniaxial tensile and direct shear tests carried out in moist sands. They have found that for direct tensile tests for water contents in the range of $0.5 < w < 1.0\%$, the tensile strength of moist sand is not zero. For the direct shear experiments with water contents less than 1%, a small apparent cohesion due to interlocking between the soil particles was observed in nominally 'dry' sand. An additional apparent cohesion component due to capillary forces was also observed. Based on these experiment results, a simple relationship between tensile strength and apparent cohesion at low moisture and stress levels was proposed using a power law equation. For sand behavior under low compression regimes or undergoing tensile failure, it may be important to consider this non-linear behavior.

Finally, *Sassa & Watabe* present a study in the new cross-disciplinary research field of 'Ecological Geotechnics'. Recent findings about the physics involved in intertidal sediments made it possible to closely investigate the linkage between the geophysical environment and benthic ecology in tidal flats. The results of a comprehensive set of field and laboratory experiments have demonstrated that waterfront suction, voids, and shear strengths, which are relatively unexplored in soil mechanics, and the associated geophysical environments govern the performance of basic living activities of benthos (organisms which live on, in, or near the seabed), such as burrowing and self-burial. These findings will enable engineering design and management for preservation and restoration of habitats with diverse benthic activity.

7 NON-STANDARD SOILS

Issues of sustainability are now at the forefront of many political agendas and disposal of waste materials has become less acceptable for society. Reduction of the use of landfill and of virgin materials is also being encouraged in various ways. Reuse of previously marginal land and different waste streams has become popular; twenty-two of the twenty-seven papers in this part of the report deal with usage of waste as a 'geomaterial' or enhancement of the properties of poor soils with various admixtures. In the literature, a wide range of soils have properties that have been extensively described. Due to various new geological and climatic regions being considered for construction activities, large numbers of other soils still require their geotechnical properties to be identified. The latter part of this section describes researchers investigating other novel geomaterials, such as tropical residual soils, volcanic ashes and diatomaceous soils, to assess their responses to basic laboratory tests and compare this to standard geotechnical frameworks of mechanical behaviour.

7.1 *Geotechnical properties of waste materials*

The storage of waste phosphogypsum (hydrated calcium sulphate), which is a byproduct of fertilizer production represents a significant challenge around the world. Two papers in this section address this issue. *Dapena et al.* have conducted characterisation and mechanical tests of phosphogypsum to assess its suitability for slopes and roadwork fills. Their findings indicate that solubility of the calcium sulphate limits the utilisation of this material in slopes to a maximum calcium sulphate content of 20% and other elements in the phosphogypsum have the potential to contaminate water in the surrounding area. The transportability of dissolved chemicals is also a feature of the paper by *Jdidia et al.*, who describe a project to confine deposited phosphogypsum fill to prevent, partially or totally, heavy metal pollution using an impervious cutoff wall made from a bentonite-cement mixture. Methodologies and guidelines are presented in both papers based on the physical and mechanical properties determined.

The design and management of tailings and other mine waste storages requires the determination of the physical, mechanical and hydraulic characteristics of the waste, to predict both the storage filling operation and its reclamation. *Villar et al.* present the results of an extensive laboratory program to obtain geotechnical parameters for different mining wastes. They suggest that certain effects of the testing technique utilized for the geotechnical characterization can be significant and recommend the use of the production fluid used for the tailings, rather than water as described in many testing standards, to avoid any mis-classification of tailings. An investigation of the use of a mixture of red sand (from bauxite mining) and recycled car tire grains and powders as a fill material, is described by *Mardesic et al.* The geotechnical properties of this new material were investigated by conducting a series of standard laboratory tests including sieve analysis, compaction, permeability and shear strength. Testing indicated that under compaction, the unit weight of red sand-tire mixtures decreases with an increase of tire content, and less tire powder is required to achieve the same reduction than tire grains. The permeability of red sand-tire mixtures used was found to be above 1×10^{-6} m/s, which is generally considered to be adequate for drainage materials. The addition of tire grains and powders to red sand generally decreased the ultimate shear strength and stiffness, but also provided higher strain hardening and decreased dilatancy. Adding up to 30% tire-grains to red sand seemed to give satisfactory geotechnical engineering properties for stability of embankments and slopes.

Preliminary tests were conducted by *Disfani et al.* on pure recycled glass and biosolids, and on blended samples to determine their geotechnical parameters. Particle size distribution, compaction tests and direct shear tests were undertaken on the pure and blended materials. The shear strength characteristics of the mixture and its relation to the percentage of each component were analysed. It was concluded that the mixtures take advantage of the frictional resistance of the coarser recycled glass particles and the cohesive strength of the finer particles, which are mostly from the biosolid grains.

The results indicated that these mixtures have satisfactory shear strength characteristics, which may provide them with excellent potential to be used as embankment fill material in roads.

One area of concern for geotechnical engineers is the potential variability of the behaviour of many of these waste materials. Santos et al. investigated recycled construction and demolition waste through characterization tests, compaction, pH and direct shear tests, and conducted statistical analyses of the chemical and geotechnical parameters. The results showed that whilst the recycled construction and demolition waste has a high compositional variation, there is a low variation of its properties and therefore a high level of confidence to justify its use in a range of geotechnical applications. Recycled concrete aggregates have also been assessed by Inui et al. for road base construction (RCA) using both analytical and experimental studies. This work concentrated on evaluating the leaching of Cr(VI) from the recycled aggregates. It was found that exposure to wetting-drying, freezing-thawing and abrasion, increased the amount of Cr(VI) leached from RCA. The data also suggested that the Cr(VI) leaching potential in the field can be conservatively estimated using conventional batch leaching.

Kim et al. evaluated the mechanical behavior of composite geo-materials (CGM) and unreinforced lightweight soils. The CGM consisted of dredged soil, cement, air-foam and bottom ash. The unit weight was found to be strongly dependent on the air-foam content, as well as the bottom ash content. Unconfined compressive strength and the stiffness of CGM increased with bottom ash content, due to the angular shape of bottom ash and the pozzolanic reaction. Unconfined compressive strength of CGM also increased with curing time. The 28-day strength of the CGM was approximately two times the 7-day strength. The stiffness of the CGM was greater than that of unreinforced lightweight soil due to the reinforcing effect of the bottom ash. In contrast, the geotechnical properties of Portuguese processed steel slags (ISACs) were tested by Gomes-Correia et al. to evaluate the appropriateness of their use in transportation infrastructures and earthworks. The laboratory results were compared with values specified in the Portuguese standards for natural aggregates and with values found for natural aggregates of various geological origins. All laboratory results show that processed steel slags could be used in geotechnical works, and particularly in transportation infrastructures. Interestingly, the two ISACs tested demonstrated better mechanical properties than standard, unbound, granular base, coarse materials.

7.2 *Enhancement of soil properties with admixtures*

Various admixtures are currently used to enhance the mechanical and flow properties of clay and sand soils. Historically, Portland cement and lime have been used for this purpose. More novel admixtures are now being introduced into the geotechnical community and the papers in this sub-section show the wide range of stabilizing materials used.

Two papers focus on improving the behaviour of sandy and granular soils. Viana da Fonseca et al. tested the characteristics of two soils, Osorio sand and Botucatu residual sandstone when stabilized with Portland cement. The results of unconfined compression strength tests show that the voids/cement ratio, (as represented by absolute volume of voids divided by absolute volume of cement), provides a very consistent framework for the engineer to select the amount of cement and the compaction energy appropriate to provide a soil-cement admixture with the strength and stiffness required for foundations and subgrades of railway platforms. The sensitivity of strength and stiffness properties of silty-sands, from granitic residual soil are discussed by Rios Silva et al. Their unconfined compression strength results support the conclusions from the preceding paper that an index based on void/cement ratio seems to be adequate for the strength analysis of these mixtures. Stiffness values obtained in the unconfined compression tests showed the same trend obtained for strength indicating that there is a similar influence in both stiffness and strength. Triaxial tests showed two different stiffness responses depending on the cement content. Highly cemented samples increase in stiffness with the stress level, while for low cement samples the stiffness decreases, showing that structure provided by cementation breaks down as the confining pressure increases.

Artificial cementation was also created by four groups of researchers using Portland cement and various clays. Trhlikova et al. added 4% Portland cement to kaolin clay and compared the mechanical behaviour of the material with pure reconstituted kaolin clay. The aim of this laboratory study was to obtain suitable mechanical behaviour for calibration, evaluation and further development of constitutive models. Using triaxial testing, it was shown that the large-strain behaviour is comparable to the behaviour known from experiments on natural clays. Measurements from bender elements and local LVDT transducers indicated a significant influence of structure on G_{max}. Based on laboratory experiments, a new expression that relates very small strain shear modulus to the current degree of bonding, overconsolidation and mean stress was developed. Tsuchida et al. adopted a similar approach, by trying to reproduce aging effects in clay due to cementation. Again a small amount of portland cement was mixed with slurries of three marine clays under controlled temperatures. By carrying out a series of consolidation tests, it was observed that the quasi-overconsolidation characteristics of natural marine clays 5,000-100,000 years old were reproduced in the laboratory by consolidating and curing for 2 weeks.

Flores & van Impe have also investigated the strength and compressibility of kaolin clay after treatment with Portland cement at dosages varying from 5% to 20%. A number of samples were prepared in the laboratory and were allowed to cure under controlled conditions. The shear and compression behavior of natural and cement-treated kaolin clay samples was assessed with triaxial compression testing and oedometer tests. The results of these tests showed that the behavior is strongly influenced by the cement content and the stress level. The cemented soils behaved initially in a very stiff manner, despite the fact that their void ratio was higher than non-cemented soils. As the stress level increases, interparticle cementation was assumed to breakdown and a collapse of the cemented soil structure occurred. The stress level at yielding was found to be a function of the cement dosage. To create a rational framework for much of the aforementioned behaviour, Jongpradist et al. have presented a physical parameter, termed the ‘state parameter’. This can appropriately represent the dependency of the undrained shear behaviour of cementitious-material admixed clays with different mixing components and shear stress levels. The new parameter is the difference between the total effective void ratio at the current state and that of steady state. The total effective void ratio, combines together the effects of the curing time, the equivalent cement content and the total clay water content representing the structural matrix of material, where the mean normal effective stress represents the state. By comparison with the results of isotropically consolidated undrained triaxial compression tests, important features of the behaviour are found to be captured by this new state parameter.

The treatment of soils with lime is a common technique for the construction of pavement base layers and to support shallow foundations. Consoli et al. noted that there are no dosage methodologies based on rational criteria in existence for the estimation of unconfined compression strength. Hence this study was designed to quantify the influence of the amount of lime, the porosity and the moisture content on the strength of a lime treated clayey soil. The results show that the unconfined compression strength increased approximately linearly with increase in the lime content. The reduction in the porosity of the compacted mixture was seen to greatly improve the strength. The voids/lime ratio, defined by the voids volume of the compacted mixture divided by the lime volume, was also shown to be a more appropriate parameter to evaluate the unconfined compression strength of the soil-lime mixtures studied. Long term investigation of lime treated soil is rarely reported, however Kitazume & Takahashi have monitored two deep mixed columns of *in situ* quicklime treated soil for more than 27 years. Laboratory tests were carried out on one of them at 11 and 27 year curing periods. The unconfined compressive strength, wet density, water content and calcium content at 11 and 27 years reveal that the treated soil cured for 27 years has gained three times the strength of original treated soil, whilst the wet density of the soil had been almost constant during the same period. The elastic modulus has decreased by 20% in the last 15 years and the calcium content has also decreased 5% over the same period. Lindh & Ryden examined test methods to evaluate the durability of stabilised soils (using lime and slag) with respect to freeze and thaw properties. This paper also shows a methodology to evaluate the effects of these different binders and their possible interactions. The stabilised soils were found to have a lower resistance against frost compared to concrete and the only binder that had a significant effect on the frost properties was the slag.

In recent years, researchers have been reporting new forms of soil binder, both pozzolanic and non-pozzolanic, and the last four papers of this sub-section describe some of these novel materials and techniques. Mgangira has utilised synthetic polymers to enhance the abrasion resistance of sands in wearing course materials for unpaved roads. The effectiveness of the synthetic polymers with respect to abrasion resistance was found to be dependent on the sand properties, defined by the particle size distribution, particle structure texture and on the plasticity characteristics measured on the material fraction passing the 0.075 mm sieve. The type of polymer and the the application rate was also found to play a role. Zumsteg et al. have investigated soil conditioning to improve the performance of clay soils in tunnels. The addition of suitable foam and polymer agents was found to lead to enhanced properties of the clay at various points of the tunneling process. The paper also introduces a new vane shear device, which allows the measurement of shear strength of the clay mixtures under pressure and with different vane velocities. A strong pressure and rate dependency of the shear strength and a large effect of polymer type could be observed.

Three-dimensional alumino-silicates with rigid hollow structures, known as zeolites are now being utilised for their pozzolanic properties and their ion exchange capabilities. Osman & Al Tabbaa have conducted an experimental study to verify the improvements in the behaviour of cement-based grouts containing zeolites in aggressive environments. Their paper focuses on the durability of soft clays stabilised with cement-bentonite and cement-zeolite grouts. Their testing has shown that clays stabilised with cement grouts are susceptible to sodium sulphate solution, sulphuric acid solution and freeze/thaw cycles. The incorporation of bentonite in cement-based grouts reduces the stabilised clay resistance to sulphate attack and acid attack. The replacement of half of the cement content with zeolite significantly enhanced the sulphate resistance of the mix. Takeda & Sato report data on a new type of clay liner incorporating zeolite, doromite, hydrotalcite and sludge. These additives have both cationic and anionic exchange capacity, hence the liner has distinct advantages for heavy metal control and other contaminants. The study investigated the physical properties, compaction characteristics, permeability, leachate behaviour and cone index of this new type of clay liner material. The trafficability of the material and the permeability were found to be suitable to satisfy legal requirements and given the surface properties should produce an excellent new liner option for landfills and waste disposals.

7.3 *Characterisation of novel soils and geomaterials*

Three papers within this sub-section address the geotechnical behaviour of tropical residual soils weathered *in situ*. Saprolitic silty soils of acidic rocks, which occur extensively in tropical regions, were investigated by Boscov et al. for use as liner materials with bentonite addition and compaction at modified energy. Initially, the optimum bentonite content was determined considering the mixture permeability. Compressibility, shear strength and expansibility were also determined for the natural soil and the soil-bentonite mixture. A test liner was built in a waste disposal site to consider practical construction aspects. The bentonite addition was found to reduce the soil permeability and ensure conformity to specification limits, without significantly modifying other geotechnical properties. Ampadu & Dzitse-Awuku propose a new, more economical method for field testing in the developing world, to determine the bearing capacity of foundations on lateritic soils. Their study investigated the correlation between the bearing capacity of a plate test and the dynamic cone penetrometer test. The testing of allophane clays derived primarily from the *in situ* weathering of volcanic ash are described by Builes et al. To evaluate the anisotropy of allophone clays, these researchers conducted a series of experiments to evaluate the cohesion in terms of the inclination angle (δ) of the samples, using the direct shearbox test. From the test results, the cohesion showed decreases in its original value, until it reached the approximate angle of δ=60°, at this point the cohesion reached a value near 40% of its original value. From this point, the cohesion increased linearly until an inclination of δ=90°. At this position, the cohesion reached a value near 40% above its original value. The cohesion variation was interpreted to be due to nanotube clusters, which could be found in the soil following the geological formation of this particular soil.

During the recent Holocene, a series of volcanoes spilled their volcanic materials on to the Los Andes buttress in Columbia. Marin-Nieto et al. present the main physical properties of these soils, and particularly those of the lahares and ashes, with different degrees of weathering. The volcanic ashes were found to behave generally like silty soil, when geologically young and then, following physico-chemical weathering processes, are transformed into clay soils. The young ashes, are found to be inherently unstable when they are remolded and are very difficult to compact. The clays are found to have high plasticity with high to very high strength, low sensitivity and good workability. These do not change their behavior when they are remolded.

Diaz-Rodriguez & Lopez-Molina have evaluated the influence of diatomaceous microfossils on the cyclic response of clayey soils. Their paper presents the experimental results of a series of cyclic simple shear tests using an artificially prepared mixture of kaolin and diatom microfossils. The tests were carried out on normally consolidated and overconsolidated samples. The cyclic behavior of artificial diatomaceous soils is complex and depends on several factors such as diatomite content, shear stress ratio, shear strain, and OCR. The results suggest that for high stress ratios, diatoms microfossils control the cyclic behavior, where their rough surfaces and intricate geometry increase interlocking effects and consequently the strain resistance. However, at low stress ratios, the interaction between particles of kaolin and diatom microfossils may have a negative contribution, causing a decrease in the resistance. The contribution of diatoms is smaller for lower vertical effective stresses; with higher diatomite contents and stress ratios, the microfossils contribute to strain resistance.

8 SOIL PROFILES AND FIELD DATA

This section describes seven papers that review geotechnical properties from a combination of laboratory and *in situ* tests. A number of these relate to soft clay and silt sites (both on and offshore). Coupling the results of *in situ* and laboratory tests is shown to aid interpretation, improve spatial resolution and confirm results. These papers show researchers and engineers clearly synthesising effective groupings of methods to most efficiently characterise their sites for design.

Barros et al. describe the results obtained from an extensive laboratory investigation of Brazilian marine clays at eight sites in the Campos and Sergipe-Alagoas basins. Grain size analyses, Atterberg limits, oedometer tests, isotropically consolidated undrained compression and K_0-consolidated undrained compression triaxial tests, direct simple shear and resonant column tests were carried out in samples from 56 cores. In some of CIUC triaxial tests, maximum shear moduli (G_{max}) were determined by using bender elements inserted into the specimens. The SHANSEP technique was also used in the investigation to study the undrained behavior of the marine clays. The results of the investigation show that these soils show a large variability of void ratios (0.9 to 4.2), plasticity indexes (5 to 70%) and clay fractions (5 to 80%). The position of these soils on a plasticity chart lie slightly above and parallel to the "A" line. The OCR values were in general smaller than 2, but in three fields there are higher values. The relationship between C_c and water content obtained is very similar to those found in the literature and the very similar s_u/σ'_{vo} values from CK_0UC and DSS tests obtained suggest that Brazilian marine clays present a very small degree of anisotropy. A correlation of G_{max} with confining pressure and void ratio for the normally consolidated condition is also presented. Puech et al. present a paper on a similar area, where they consider the geotechnical requirements for the design of deep water oil and gas structures and outline the specific properties of the sediments encountered on the continental shelf. They present the objectives for site investigations and discuss current state-of-the-art laboratory and *in situ* tests, with particular focus on the complementarity between these approaches. They recommend strategies for this process and emphasize judicious combination of data to give access to the required engineering parameters.

Westerberg & Andersson present research on the strength and deformation properties of Swedish fine-grained sulphide soils from the Gulf of Bothnia, with the objective of improving the prediction of long term settlements of structures. The authors have observed that due to the varved structure of these sulphide soils, undrained shear strengths may vary between centimetre thick layers when conducting fall-cone tests. They suggest that temperature and rate effects must be considered when conducting direct simple shear tests and triaxial tests for these materials. To obtain 'undisturbed' samples for testing, the sampling and handling procedure in the field must be conducted with great care and with suitable equipment. Due to the silt and organic content, sulphide soils are very sensitive to disturbance and sample handling damage.

Leoni has also investigated the behaviour of Post Pampean Formation high plasticity clays and silts, which were deposited in fresh fluvial water and in marine environments. These deposits are up to 30 m in thickness and have been characterized by means of *in situ* and laboratory tests. The results were modelled by means of the Cam-Clay constitutive model and a procedure is described for the prediction of the undrained shear strength of the soil. The reported data will be used in a large-scale projected to be constructed in this soil. It is concluded by the authors that the proposed methodology allows an approximation of stress parameters in normally consolidated clays of the Post Pampeano Formation in a very simple way.

Complex geotechnical investigations were performed by Ivsic et al. at the location of a long bridge in the southern Adriatic. Marine sediments at the sea bed are very soft to soft, high plasticity clay with silt, to a depth of 60m, where overconsolidated clay with fragments of lime and shells was found. The depth of base lime rock varies along the bridge from the surface at the coast, to 100m under the sea bed. Potential seismicity at this location is significant. Comprehensive dynamic testing was performed to establish the representative seismic soil profile; vane shear, seismic cone penetrometer and piezocone tests were performed to a depth of 25m, as well as downhole testing to a depth of 80m. Classification tests, compressibility and strength tests were performed in the laboratory and undisturbed specimens were tested in the resonant column apparatus, double specimen direct simple shear device (DSDSS), and in the triaxial apparatus with bender elements. The effects of mean effective stress and excitation characteristics have been investigated in all of the tests. The compilation of the investigation results is presented in the paper. Values of shear modulus obtained from all the laboratory tests and from wave velocity measurements are compared taking into account shear deformation and show very good agreement.

Kataoka et al. have studied the soil properties of lake bottom sediments containing shallow methane hydrates in Lake Baikal, Russia. The tested samples were collected from mud volcanoes and reference sediments in the same area. From the results, it was found that the reference samples have no marked differences in soil properties compared to other sediments obtained from different sea-bottom areas. On the other hand, the strengths and shear modulus of the mud volcano samples obtained were lower than those of the reference samples. It is proposed that sedimentary layers have been disturbed by gas and water upwelling from underground and pressure release during sampling. The authors recommend that when methane hydrates are recovered using methods that involve temperature rise or pressure decrease, the resulting dissociation of methane hydrates may lead to reduction in strength and stiffness of sediments, which need to be accounted for in design.

The Gateway Upgrade Project in the State of Queensland, Australia, is the largest road and bridge infrastructure project in the state's history. Look & Wijeyakulasuriya present a statistical analysis of intact rock strength properties of the sub-horizontally interbedded sandstone stratum underlying the main river span of the bridge. These findings were then compared with an analysis based on additional borehole data captured during construction. Boreholes at each socket location have shown signification variation of ground conditions between piles, even for the same pier location. Given the data variation, an appropriate statistical density function was recommended for statistical modeling to assess the reliability of the design. Using the probabilistic models identified, the study has undertaken to rationalize the design rock strength input model adopted for socket design. The impact of rock strength anisotropy on the design UCS was also investigated. The implications of using the design UCS with various probability distribution models to satisfy limit state material characterization requirements are briefly discussed. The assumption of normality in the data distribution was shown to have the potential to significantly affect the design values.

9 SUMMARY

Wood and Yudbhir (1989) stated that laboratory testing is not conducted in a void, but with some intended purpose. The laboratory testing reported herein seems to suggest that global dissemination of many advanced laboratory techniques has occurred in recent years and much excellent work has been done on a number of significant geotechnical problems. However, only relatively modest developments in new laboratory techniques and approaches seem to have happened over the same period. Analytical and experimental techniques have developed to the point where sufficient sophistication has occurred to allow a wide range of applications to be satisified. As always our major issues still relate to the difficulty of practical application of data, with complexity of the stress fields, spatial material property variations and load paths, and making rational choices of appropriate parameters and laboratory tests. Much of the emphasis of the papers in this session appears to be on new soils and reuse of new waste materials. It is possible that challenges associated with these novel geomaterials will ultimately lead to new experimental methods and interpretations to further enhance our portfolio of standard laboratory tests in the future.

REFERENCES

Abu-hejleh, A.N. & Znidarcic, D. (1995). Desiccation theroy for soft cohesive soils. *Journal of Geotechncial Engineering*, 121, 6, 493-502.

Alonso, E.E., Gens, A. & Josa, A. (1990) A constitutive model for partially saturated soils. *Geotechnique*, 40, 3, 405-430.

Bolton M.R., Mc Dowell G.R. (1998). On The Micromechanics Of Crushable Aggregates– *Géotechnique*, 48, (5), 667-679

Bolton, M.D. (1986) The strength and dilatnacy of sands. *Geotechnique*, 36, 1, 65-78.

Bolton, M.D. (1999). The role of micro-mechanics in soils mechanics. In: M. Hyodo and Y. Nakata (Eds.). *Proc. of IWSC'99.* Yamaguchi University, Japan, 58-82.

Bridgman, P. W. 1948. The compression of 39 substances to 100,000 kg/cm^2. *Proc. Am. Acad. Arts. Sci.* Vol. 76, No. 3, pp. 55 - 69.

Burland, J. B. (1989). Small is beautiful – the stiffness of soils at small strains, Ninth Laurits Bjerrum Memorial Lecture, *Canadian Geotechnical Journal*, Vol. 26, pp. 499-516.

Cuccovillo, T. & Coop, M. R. (1997). The measurement of local axial strains in triaxial tests using LVDTs, *Géotechnique*, Vol. 47, No. 1, pp. 167-171.

Hardin, B. O. (1985). Crushing of soil particles. *Journal of Geotechnical Engineering,* Vol. 111, No. 10, pp. 1177-1192.

Imai, G. 1979. Development of a new consolidation test procedure using seepage force, Soils and Foundations, Tokyo, Japan, Vol.19, No.3, pp.45-60.

Imre, E , Rózsa, P; Lőrincz, J (2008) Characterization of some sand mixtures. *Proc. 12th IACMAG*, 2008 Goa, India. 2064-2075.

Jovicic, V., Coop, M.R., Simic, M. (1996). Objective criteria for determining G_{max} from bender elements. *Geotechnique*, Vol.46, No.2, pp357-362.

Lee J-S, and Santamarina, C. (2005). Bender elements: Performance and signal interpretation. *Journal of Geotechnical and Geoenvironmental Engineering*. Vol.131, No.9, pp1063-1070.

McDowell, G. R. & Humphreys, A. (2002). Yielding of granular materials. *Granular Matter*, Vol. 4, pp. 1–8.

Mitchell, J.K & Soga, K. (2005). *Fundamentals of Soil Behavior*. Third edition. J. Wiley & Sons, New York.

Ramha, A. (1998). Modélisation du comportement du milieu granulaire en fonction de l'écrasement des grains. *Canadian Geotechnical Journal*, 35, 517-523.

Robinsky, E. I. (2000). Sustainable development in disposal of tailings. Tailings *and Mine Waste* 00. Colorado, USA, A.A. Balkema, Rotterdam: pp. 39-48

Sheahan, T.C., Germaine, J.T. and Ladd, C. C. (1990). "Automated triaxial testing of soft clays: an upgraded commercial system."*Geotechnical Testing Journal,* ASTM, 13(3), 153-163

Simpson, B., (1992). "Retaining structures: displacement and design", *Geotechnique*, **42**(4), 541-576.

TC29 Report, (2008). *International parallel test on the measurement of G_{max} using bender elements organized by TC-29.* http://www.jiban.or.jp/e/tc29/BE_Inter_PP_Test_en.pdf.

Vaid, Y.P., Sayao, A., Hou, E., and Negussey, D. (1990). Generalised stress-path dependent soil behaviour with a new hollow cylinder torsional apparatus. *Canadian Geotechnical Journal*, 27, 601-616.

Wood and Yudbhir (1989) *General Report Session 1*: Recent developments in laboratory strength and deformation testing. XII ISSMGE Conference, Rio de Janiero, 2303-2339.

APPENDIX

List of papers submitted to this session:

1. *27 Years' investigation on property of in-situ quicklime treated clay*, M. Kitazume & H. Takahashi.
2. *A 2D mathematical model for the CBR of a road sub base in Ilorin, Nigeria*, Yinusa A. Jimoh.
3. *A comprehensive view of measuring soil stiffness with bender elements,* T. N. Lohani, S. Shibuya.
4. *A countermeasure to liquefaction by reducing the degree of saturation of in-situ sandy soils*, M. Hatanaka, T. Masuda.
5. *A new methodology of determination of soil compressibility*, A. Stanciu & I. Lungu.
6. *A unified state parameter for modeling undrained shear behaviors of cementitous material admixed clay*, P. Jongpradist, S. Youwai & W.Kongkitkul.
7. *An investigation on the dilative behavior of crushed rock,* F. Kalantary, S. Jahangiri Maamouri.
8. *At-rest earth pressure coefficient and Poisson's ratio in normally consolidated soils*, A. Federico, G. Elia.
9. *Behavior and geotechnical properties of lahares and volcanic ashes in the Baba River Valley, Ecuador.*, L. Marín-Nieto & E. Herbozo-Alvardo, J. R. Rivera-Guapulema & M. J. Avecillas-Andrade.
10. *Changes in anisotropy during liquefaction and effects on reliquefaction resistance produced by developed anisotropy associated with liquefaction*, S. Yamada, K. Sato & T. Takamori.
11. *Characterisation of Post Pampean clays*, Augusto José Leoni.
12. *Characterístics of phosphogypsum for utilisation in roadwork fills,* Enrique Dapena, Fernando Pardo de Santayana, Esther Díaz Flores.
13. *Checking the saturation on sandy tropical soil samples in laboratory using the seismic waves*, Saturnino D. L. Chembeze.
14. *Comparing Vibratory and Impact Laboratory Compaction Methods*, D.P. Lange, G. Fanourakis.
15. *Comparison of aging effects on cyclic shear strength of undisturbed and remolded tailing sands*, R. Moffat, M. Ormazabal.
16. *Comparison of strain localization properties of dense clean sand and well-graded gravel in plane strain compression tests*, Y. Tsutsumi, S. Maqbool.
17. *Comportement mécanique de sols grossiers à matrice*, B. Seif, El Dine, J. Canou, J.-C. Dupla, Y. Kazan.
18. *Crack propagation velocity of granite by impact splitting tests*, T. Tamano & M. Kanaoka, K. Takehara, N. Mizutani.
19. *Creep behaviour of an undisturbed lightly overconsolidated clay,* Martínez-Vasquez, J.J., Díaz-Rodríguez, J.A.
20. *Creep, stress relaxation, and rate effects in sand*, P.V. Lade.
21. *Crushability of granular materials at high stress levels*, G. Di Emidio, R.D. Verástegui Flores, W.F. Van Impe.
22. *Cyclic behavior of diatomaceous soils*, J.A. Díaz-Rodríguez, J.A. López-Molina.
23. *Defining the critical state line from triaxial compression and ring shear tests*, A. Sadrekarimi, S.M. Olson.
24. *Degradation of ballast and crushed rock subballast in Finnish railways*, A. Nurmikolu & P. Kolisoja.
25. *Design charts for single piles under lateral spreading of liquefied soil*, Alexandros Valsamis, George Bouckovalas, Emmanouil Drakopoulos.
26. *Determination of consolidation parameters of dredging and industrial waste sludge*, P.O. Van Impe, L. Barbetti & W.F. Van Impe.
27. *Development of a new type of impervious material of final landfill with heavy metal adsorption*, M. Takeda, K. Sato.
28. *Dynamic testing of marine sediments at the Pelješac bridge site*, T. IvšićI. Vrkljan, S. Zlatović, R. Mavar.
29. *Ecological geotechnics: Performance of benthos activities controlled by suction, voids, and shear strength in tidal flat soils*, S. Sassa & Y. Watabe.
30. *Effect of cement-zeolite grouts on the durability of stabilised clays*, A. A-M Osman, A. Al-Tabbaa.
31. *Effect of Disturbance on the Compressibility of Marine Clay in Korea*, Y.S. Chae, W.J. Lee, N.J. Yoo, S.J. Yu, J.K. Kim.
32. *Effect of initial static shear on cyclic behavior of sand*, J. Yang, H.Y. Sze & M.K. Heung.

33. *Effect of silt percents on liquefaction potential and anisotropic behavior of saturated sand-silt mixtures*, Ghalandarzadeh, A. Ahmadi.
34. *Effect of stress level on permanent deformation for fine-grained compacted soils and the re-evaluation of the natural proportionality model*, N. Perez, P. Garnica.
35. *Effects of density, moisture content and curing time on dispersivity and erodibility of two River Nile deposits*, A. M. Elsharief, H. Amin.
36. *Effects of drainage on improving post-cyclic behaviour of non-plastic silt*, K. Yasuhara, S. Murakami.
37. *Effects of large cyclic and creep loading on peak strength of compacted gravel in triaxial compression tests,* S. Maqbool, J. Koseki.
38. *Effets d'échelle dans la résistance au cisaillement des remblais granulaires et dans la stabilité de grands ouvrages en enrochements*, E. Frossard.
39. *Entropy concept to explain the particle breakage*, J. Lorincz, E. Imre, L. Kárpáti, P. Q. Trang, Gálos, M, G. Telekes.
40. *Environmental suitability of recycled concrete aggregates used in geotechnical applications*, T. Inui & T. Katsumi, M. Kamon.
41. *Equivalent granular state parameter and undrained responses for sand with fines*, M. M. Rahman & S. R. Lo.
42. *Érosion des sols : deux essais complémentaires*, T.L. Pham, M. Duc, C. Chevalier, P. Reiffsteck and S. Guédon.
43. *Evaluation of the 5% double amplitude strain criterion*, C. S. El Mohtar.
44. *Experimental study of variation of shear wave velocity of Macao marine clay during one dimensional consolidation*, X.T. Shi, M.H. Lok.
45. *Experimental study on mechanical characteristics of composite geo-material for recycling dredged soil and bottom ash*, Y. T. Kim, W. J. Han, H. S. Kang, J. S. Lee.
46. *Formulation et propriétés d'un coulis en bentonite ciment*, Mounir Ben Jdidia & Zouheir Bouarada & Mehrez Khmakhe.
47. *Fundamental factors for the strength control of lime treated soils,* Nilo Cesar Consoli, Luizmar da Silva Lopes Junior, Samir Maghous, Fernando Schnaid.
48. *Geotechnical characteristics of recycled glass-biosolid mixtures*, M. M. Disfani, A. Arulrajah & V. Suthagaran, M. W. Bo.
49. *Geotechnical properties of a silt-bentonite mixture for liner construction,* M.E.G. Boscov, V. Soares & F.D. Vasconcelos, A.A.P. Ferrari.
50. *Geotechnical properties of Brazilian marine clays,* J. M. C. Barros & R. M. S. Silveira, C. S. Amaral.
51. *Geotechnical properties of red sand mixed with tire grains and powders,* T. Mardesic, M.A. Shahin & H.R. Nikraz.
52. *Influence of laboratory techniques on the geotechnical characterization of mining and industrial wastes*, Lúcio Flávio de Souza Villar, Tácio Mauro Pereira de Campos, Roberto Francisco Azevedo, Jorge Gabriel Zornberg.
53. *Influence of mineralogical composition on geotechnical properties,* B. Tiwari & I. Dhungana.
54. *Inherent anisotropy in allophane clay in Colombia*, M. A. Builes, D. V. Gomez, A. A Millan.
55. *Instability behaviour of Changi sand in plane-strain tests*, D. Wanatowski, J. Chu.
56. *Liaisons Structurelles des Argiles Gonflantes pendant l'Humidification,* H. Ejjaaouani.
57. *Liquefaction resistance of thickened tailings of copper mines*, Ramon Verdugo, Eloy Santos.
58. *Long-term settlement of railway embankment caused by repeated wetting and creep*, S.J. Lee, I.W. Lee, J.U. Lee.
59. *Mathematical characterization of rate-dependent undrained shear behavior of soils*, E. Juárez-Badillo.
60. *Mathematical characterization of the compression to 100,000 kg/cm² of thirty-nine substances*, E. Juárez-Badillo & S. Hernández-Mira.
61. *Measurement of soil suction using soil's resistivity*, N. Perez, P. Garnica, N. Landaverde.
62. *Measurement of the degree of saturation of ground by image analysis*, R.P. Orense & N. Kikkawa, N. Yoshimoto.
63. *Mineralogical influence on ring shear strength of landslide materials from Lesser Himalaya and Siwalik zones in Central Nepal*, N. P. Bhandary, R. Yatabe.
64. *Model tests for bearing capacity in a lateritic soil and implications for the use of the dynamic cone penetrometer*, Samuel I.K. Ampadu, D. Dzitse-Awuku.
65. *Modeling unsaturated soil behavior under multiaxial stress states*, L.R. Hoyos, A. Laikram, D. Pérez-Ruiz & A.J. Puppala.
66. *Modelling of cementation bonds in clay – laboratory and numerical model*, J. Trhlíková, D. Mašín & J. Boháč.
67. *Modulus of subgrade reaction for foundations on clay from unconfined compression tests,* Nick Barounis, Trevor L.L. Orr, Paul H. McMahon, Aristides Barounis.
68. *Portuguese steel slags. A new geomaterial*, A. Gomes Correia & S. Ferreira, A. Roque, A. Cavalheiro.
69. *Pressurized vane shear test for soil conditioning* ,R. Zumsteg, S. Messerklinger & A.M. Puzrin, H. Egli & A. Walliser.
70. *Properties controlling the resistance to abrasion and erosion of stabilized sandy soils using non-traditional additives*, M.B Mgangira.
71. *Rate-dependent behaviour of clay during cyclic 1D compression*, S. Kawabe, W. Kongkitkul, D. Hirakawa, F. Tatsuoka.
72. *Relationship between cohesion and tensile strength in wet sand at low normal stresses*, T-H. Kim, J.-M. Nam, J.-M. Yun, K.-I. Lee & S.-K.
73. *Reproduction of structure due to aging of marine clay by addition of small amount of cement*, T. Tsuchida, T. Hirahara, M. Takenobu.
74. *Small strain stiffness of uniform granular materials based on dynamic and static measurements*, R.I. Wicaksono and R. Kuwano.
75. *Small-strain stiffness of Auckland residual clay,* M.J. Pender, N. Kikkawa, R.P. Orense & A. Ibrahim.
76. *Soil properties of the shallow type methane hydrate-bearing sediments in the Lake Baikal*, S. Kataoka, S. Yamashita & T. Suzuki, T. Kawaguchi.
77. *Statistical Analysis of Geotechnical Parameters of Recycled Construction and Demolition Waste (RCDW)*, E.C.G Santos, O.M. Vilar, A.P. Assis.
78. *Statistical models for reliability assessment of rock strength*, B. Look, V. Wijeyakulasuriya.
79. *Strength and stiffness properties of mixtures of granitic soil-cement*, S. Rios Silva & A. Viana da Fonseca, N. C. Consoli.
80. *Strength properties of sandy soil-cement admixtures,* António Viana da Fonseca, Rodrigo Caberlon Cruz, Nilo Cesar Consoli.
81. *Stress-strain behavior of artificially cemented Kaolin clay*, R.D. Verástegui Flores & W.F. Van Impe.
82. *Structure upgradation concept applied to cyclic mobility of sand and high ductility of natural clay*, K.Nakai, M. Nakano & A. Asaoka, T. Kawai.
83. *The Asaoka method revisited*, G. Mesri & N. Huvaj-Sarihan.
84. *The effect of different binders on freeze durability of stabilized soil,* Per Lindh, Nils Rydén.
85. *The evolution of grain-size distribution of sands under 1-D compression*, C. Valore & M. Ziccarelli.
86. *The experimental determination of the angle of dilatancy in soils,* J. R. Maranha, E. Maranha das Neves.
87. *The friction angle and critical state void ratio of sands*, Alejo O. Sfriso.
88. *The hydraulic conductivity of sands with dispersed oversized particles,* J.J. Gutiérrez, L.E. Vallejo, C.I. García.
89. *The non-uniqueness of the end-of-primary (EOP) void ratio-effective stress relationship*, S.A. Degago & G. Grimstad, H.P. Jostad, S. Nordal.
90. *Training of geotechnical engineers in Albania*, Prof.Dr.Luljeta Bozo.
91. *Undrained shear strength and compression properties of Swedish fine-grained sulphide soils,* B. Westerberg, M. Andersson.
92. *Une stratégie de reconnaissance géotechnique pour les argiles grands fonds*, A. Puech, D. Borel, E. Palix, S. Po.
93. *Wave-based characterizations of soils derived from rock weathering*, Y. H. Wang, X. Dong.

Paper #	Feature of soil behaviour								Type of laboratory technique						Main emphasis of paper					
	SH	CY	SS	LS	VLS	P	C	B	S	T	THC	RC	DS	O	TI	SP	ET	SM	SS	PI
1	●			●				●	●	●				●		●			●	
2								●						●	●	●				
3					●			●	●				●			●			●	
4		●	●	●					●	●		●				●				●
5							●							●	●		●			●
6				●				●		●						●		●		
7				●				●		●				●					●	
8							●							●	●			●		
9	●							●						●		●			●	
10	●	●		●						●					●	●				
11	●						●	●								●		●		
12						●	●	●		●				●		●			●	
13								●		●		●		●		●				
14								●						●		●				●
15		●		●				●	●	●						●			●	●
16																				
17				●				●		●				●		●				
18		●	●		●									●	●		●			
19				●				●	●	●				●	●		●			
20				●				●		●				●		●			●	
21				●			●	●						●	●	●			●	
22		●		●									●		●			●	●	
23				●	●			●		●			●					●		
24		●						●	●				●			●				●
25																				
26					●		●	●						●		●	●		●	
27						●		●						●		●			●	
28	●		●	●					●	●		●	●			●			●	●
29	●							●						●		●			●	
30								●		●				●		●			●	●
31	●						●	●	●					●	●	●				
32		●		●				●		●				●	●	●				
33	●	●		●						●					●	●				
34		●							●							●	●	●		●
35						●		●								●				●
36	●	●		●						●						●				
37		●		●				●		●									●	
38								●										●		
39								●							●			●		
40						●		●						●		●			●	
41				●				●		●						●		●	●	
42						●		●									●			
43		●								●					●			●	●	
44		●		●			●					●		●	●		●			
45				●				●		●						●		●		
46						●		●											●	
47				●				●		●								●	●	●
48				●				●					●			●			●	
49				●		●	●					●	●						●	●
50	●		●	●				●		●										●
51				●		●		●		●						●			●	
52								●					●						●	●
53			●									●				●	●		●	
54	●		●	●				●		●									●	
55				●									●			●	●	●		●
56	●							●								●				
57		●		●				●		●								●	●	●
58							●	●						●		●				●
59				●						●					●			●		
60				●			●								●			●		
61								●							●	●	●			
62						●		●						●	●	●	●			
63						●		●								●			●	
64		●		●				●								●	●			
65	●			●							●					●	●	●		
66			●	●						●		●			●			●	●	

Paper #	Feature of soil behaviour								Type of laboratory technique						Main emphasis of paper					
	SH	CY	SS	LS	VLS	P	C	B	S	T	THC	RC	DS	O	TI	SP	ET	SM	SS	PI
67										●				●		●		●		
68								●						●		●			●	●
69					●			●						●			●		●	●
70								●						●		●			●	●
71		●		●			●							●	●	●		●		
72				●				●					●	●		●		●		
73	●						●			●				●		●			●	
74	●	●	●	●								●		●		●			●	
75			●	●						●				●	●		●		●	
76	●		●						●			●				●			●	
77								●	●				●			●			●	●
78								●		●				●	●			●		●
79								●		●		●		●		●			●	●
80				●				●		●				●				●	●	●
81				●				●		●		●				●			●	●
82	●	●		●			●	●		●								●		
83							●											●		●
84								●		●		●		●					●	
85							●							●	●		●	●		●
86				●						●			●		●			●		
87							●								●	●		●		
88						●		●	●					●		●				
89							●							●	●	●				●
90																				
91	●						●	●					●	●		●			●	
92	●	●					●	●	●	●			●	●				●		
93			●				●							●			●	●		

KEY:

(a) *Feature of Soil Behaviour*: stress history (SH), cyclic/dynamic (CY), small strain (SS), large strain (LS), very large strain (VLS), permeability (P), consolidation (C), basic properties (B).

(b) *Type of Laboratory Technique*: sampling (S), triaxial/UCS (T), true triaxial/hollow cylinder (THC), resonant column/bender element (RC), direct/simple shear (DS), other (O).

(c) *Main Emphasis of Paper*: test interpretation (TI), soil properties (SP), experimental technique (ET), soil models (SM), special soils (SS), practical applications (PI).