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Technical session 1d: Modeling

Séances techniques 1d: Modélisation

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1 INTRODUCTION

Constitutive models and numerical analysis (based mostly on the finite element method) are two underpinning elements of geotechnical modelling. Referring to the so-called Burland triangle (1987), modelling in fact represents one apex that interacts with the two other apices representing ground profile and soil behaviour respectively. The papers submitted in this modelling session mostly addressed constitutive issues, with only a few being devoted to physical modelling and numerical modelling of geotechnical structures. Even though, there is a session on Prediction and Performance, one would have liked to see a good mix of the two kinds of papers. Among the variety of topics covered on constitutive modelling, principal themes covered include rate effects in clays, cyclic loading of soils, strain localization, and the role of microstructure on sand behaviour. These are very relevant topics that need to be studied as they impact on important practical applications such as soil liquefaction and the long term deformation and performance of soil structures. Papers in numerical modelling essentially covered the analysis of 'non-conventional' problems such as soils reinforced with inclusions, cyclic rocking of shallow foundations due to lateral forces and vibro-driving of piles.

Despite the outburst of activities in the development of powerful constitutive laws and numerical algorithms for their integration into numerical models, these have not much impacted on the way geotechnical analysis is carried out in practice. There must be various reasons as to why this is happening and why is there such a gap between theory and practice. The closing of the gap is certainly a challenge in the area of modelling in geotechnical engineering, besides addressing more technical issues that focus on high order effects such as strain localization, microstructure and rate dependency in soil behaviour.

The general report presents a succint review of the papers submitted to this conference session, while at the same time refers to other important contributions within the theme published elsewhere. The papers can be categorized as follows:

<u>Constitutive Modelling</u>

- Clays – viscous effects, cyclic loading, strain localization, shrinkage and dessication.
- Sands – microstructure, fabric, packing, bonded grains and liquefaction.

<u>Numerical Modelling of Geostructures</u>

- Earth dams, reinforced soils, foundations, vibro-driving of piles, cyclic rotation of foundations, settlement of foundation soils containing inclusions.

2 CONSTITUTIVE MODELLING

There are two main approaches to constitutive modelling, namely phenomenological and micromechanical. Phenomenological approaches are based on the classical theory of plasticity, or alternatively, hypoplasticity, a less popular, but yet very flexible and elegant formulation. For the avid reader, it is herein recalled that hypoplasticity is an extension of hypoelasticity (Truesdell, 1955, and Truesdell and Noll, 1965) in that rate objective, frame invariant non-linear stress and strain rates constitutive functions are developed without the need of introducing any flow rule or yield surface, nor the decomposition of strain into elastic and plastic parts as in elasto-plasticity. On the other hand, micromechanical models look into the sub-scale where grain particle kinematics and statics are described and upscaled to the macro-scale. Furthermore, there is a class of models which marry continuum concepts with micromechanics (continuum-micromechanics) by introducing higher gradients in the field variable to make it locally in-homogeneous. Hence, these introduce a length scale than can be related to grain size, see Cosserat based as well as higher gradient plasticity models, as summarized in Vardoulakis (2000).

Overall, phenomenological models have been very successful in capturing most salient behavioural features of soils, but for describing accurately second order effects such as strain localization, a precursor to failure and damage, micromechanical or continuum-micromechanics approaches are needed. Some of the papers in the modelling session touched on this topic as more powerful analytical, numerical as well as experimental techniques become available. Related to strain localization problems are issues of well-posedness, existence, uniqueness and stability of constitutive relationships, but these were not addressed in the session.

2.1 *Rate effects*

<u>Gudehus</u> interestingly revisits the hypoplasticity framework to describe the behaviour of two main classes of soils, mainly sand-like rate independent and clay-like rate dependent soils. These are coined as *Psammoids* and *Peloids* (greek words[1]) referring to the particular grain contact aspects, viz. hard and soft contacts for sands and clay particles respectively. Hard contacts are inclined to give rise to macroscopic rate-independent behaviour, while soft contacts are favourable to time-dependent like behaviour. This time-dependency (viscosity) trait at the grain contact level is called *argotropy*[2]. Other descriptors of greek origin of soil behaviour are *barotropy* and *pyknotropy* which refer to pressure and density dependencies respectively. Gudehus effectively demonstrates how the two classes of soils can be

[1] Psammos=Greek for sand; pelos=Greek for clay.
[2] Argos=Greek for slow.

unified under the framework of hypoplasticity, especially addressing the viscous properties of clays.

Acosta-Martinez, Tatsuoka and Li further along argue that viscous properties of clay soils are important in geotechnical practice due to the fact that geotechnical design requires limit states such as the satisfaction of serviceability, especially in the long term. It is seen that creep occurs as early as during the primary consolidation phase, and not after the end of primary consolidation, as commonly thought of. Phenomena such as delayed dissipation of pore water pressure are a pure reflection of the true material viscous properties. The paper presents tests performed on both drained triaxial compression and one-dimensional compression tests on clay with stepped strain rates to highlight rate sensitivity and confirm isotach behaviour. Isotach behaviour refers to a unique stress-strain-strain rate relationship for a given soil as experimentally revealed by Leroueil et al. (1985) for Batiscan clay. Generally speaking, isotach behaviour is observed in clays and not in sands. In the paper, rate sensitivity of material behaviour was confirmed in tests performed on both reconstituted and intact 'Japanese' clay specimens. It was found that the rate of strain induces a stress change proportional to the instantaneous stress. The proportionality constant is a function of the ratio of new and original strain rates. A non-linear three component rheological model as developed by Di Bennedetto et al. (2002) is used to analyze the data.

Jastrzebska and Lupiezowiec investigate rate effects on the cyclic behaviour of clays as a function of over-consolidation. A bounding surface plasticity with a kinematic hardening rule is formulated. Amendments are made to the modified cam-clay model and the hardening rule by incorporating the rate effects through a term that includes the rate of change of preconsolidation pressure. Creep and rate effect phenomena can be accounted for in the model. The kinematic hardening rule is modified and the elastic core is made variable in the bounding surface plasticity formulation so that a sharp change in the hardening modulus can be captured when unloading within very small strain intervals. This is a feature that is revealed in the experimental results and that is quite difficult to properly model when dealing with cyclic loading. Higher rates of loading normally give rise to a higher strength for both normally and overconsolidated clays. From a practical view point, the developed model will be useful in analyzing soil-structure interaction problems in the cyclic loading regime in which small strains and various rates of loading are involved.

Oka, Kodaka, Kimoto and Ichinose present an interesting paper that investigates strain localization in clay as a function of strain rate and specimen slenderness ratio in three dimensional stress states. This paper distinguishes itself from previous studies which were focused mainly on plane strain and axi-symmetric stress/strain states. The displacement field in every single test is analyzed using techniques such as particle velocimetry tracking (PVT), Ohmi and Li (2000) and Adrian (1991), so that concentrated zones of strain localization can be accurately revealed. Numerical simulations of the experiments are also performed using three-dimensional finite element calculations with coupled flow/deformation. Elasto-viscoplasticity as developed by the authors is used as constitutive model. The calculations seem to reproduce quite well observed strain localization features of clay behaviour. Most importantly, it is observed that the higher the loading rate is, the thinner the shear band becomes. Also, higher strain rates lead to higher shear strengths (deviatoric stresses). In the strain softening regime, the strain rate effect is less pronounced with the deformational behaviour being mainly dictated by the fully developed shear bands. When slender specimens are used, instability in the form of buckling occurs and gives way to multiple shear banding that result into softening behaviour at large strains. As expected, the shear strains (local) in the shear band are much higher that the global strains imposed on the specimen.

Siddiquee, Islam, Hoque, and Tatsuoka next demonstrate that rate effects are also possible in pressure-sensitive and cohesionless soils under cyclic loading. The adopted approach is standard in that it uses a backbone curve (hyperbolic equation) to describe monotonic loading, and then applies the Masing's rule to construct subsequent hysteretic stress-strain curves cycles based on the backbone curve. For simplicity, the model employs isotropic hardening combined with the Masing's rule for describing unloading/reloading cycles. Creep aspects of the deformation are also incorporated by using an analogical three-component model as described by Di Bennedetto et al. (2002) and coined as the new-isotach model. Visoplasticity is formulated according to Duvaut-Lions theory based on an overstress concept, and similar to the more commonly used Perzyna model. Creep effects in drained sand behaviour are successfully modelled. It has been observed by several researchers that sands exhibit time-dependent behaviour. In particular, in drained condition, the creep strains develop in time under a specified effective stress in triaxial compression (cf. Lade 1994). These creep strains induce material hardening that depend on the initial density and applied effective pressure. In undrained loading, inelastic strains develop in time and may significantly affect the respective undrained effective stress path. With time dependent pore pressure build-up, delayed failure eventually occurs whenever the instability point is reached. On the other hand, for strain controlled deformation processes, the stress path exhibits a strain rate sensitivity - the higher the strength is at a higher strain rate. It should be noticed here that the effect of strain-rate softening is not and cannot be addressed by a Perzyna-type model; see di Prisco et al. (2000).

The Reporter points to the avid reader to two recent papers, Augustesen et al. (2004) and Liingaard et al. (2004), that discuss in very general terms the issue of time dependent behaviour in both clays and sand as well as their modelling.

2.2 *Structured soils*

Katsuki and Nakata investigate the behaviour of structured soils with bonded particle contacts. Interparticle bonding is regarded as additional contact forces acting at the grain level that leads to an extra frictional or a compressive/tensile resistance. At the macroscopic level, these interparticle bonding forces give rise to new internal stresses that superimpose onto existing ones to give a so-called true stress. These internal stresses can be regarded the same way as suction operates in a partially saturated soil. A model is worked out in axi-symmetric stress/strain conditions and assuming fabric isotropy within the framework of critical state soil mechanics. The limiting compressive behaviour of bonded sand is described by a normal compression line (NCL) that plots parallel and above the unbonded one. As such, the compression behaviour of a bonded sand starting from an arbitrary state (void ratio and mean effective stress) follows a curve that cuts across the NCL of the unbonded sand and bends over to reach asymptotically the same NCL as debonding occurs at higher mean stresses. The model leads to the determination of yield and plastic potential, as well as an evolution law for the decaying of internal stresses due to bonding. The whole model uses the concept of sub-loading surfaces (Hashiguchi, 1989). The constitutive model gives results that are very comparable with experimental ones for weakly bonded carbonate sands.

Masin, Herbstova and Bohac present the constitutive modelling of special materials with evolving internal structure as a result of environmental loads as an illustration. This occurs when materials formed of blocky coarse materials (clay lumps) with a high porosity (40-45%) are freshly dumped into landfills. With time, due to precipitation and external stresses, weathering of the reference material occurs and the initial voids slowly get filled with fine materials so as to form a double porosity material. A constitutive model is developed for such a double porosity material based on the critical state soil mechanics framework. Basically, the model considers the material to be cemented with a proper description of chemical degradation of the interparticle bonds. Just like in the previous paper that was presented by Katsuki and Nakata, the NCL for the structured (double porosity) material plots above the NCL of the reference material due to its higher porosity. During increased compression, plastic straining of the double porosity material causes gradual closure of the intergranular voids so that ultimately, the mechanical behaviour of the composite soil is governed by the characteristics of the reference material. The modified Cam Clay model framework is used together with an evolution law for the degradation of intergranular porosity.

Korhonen, Korhonen, Lojander and Koskinen further describe the behaviour of a special Finnish clay with peculiar characteristics. Murro clay is a highly anisotropic and bonded soft silty clay with a relatively low shear strength of 25 kPa. The availability of extensive laboratory test (oedometer, and drained/undrained triaxial stress paths) data combined with field data concerning the settlement of an embankment make it very suitable for a comprehensive constitutive study including model calibration. The literature abounds in the constitutive description of the anisotropic behaviour of clay, see among others, Dafalias (1986), Dafalias and Herrmann (1982), Al-Tabbaa and Muir Wood (1989 and Whittle and Kavvadas (1994), which use elasto-plasticity, bounding surface as well as kinematic hardening concepts. The presentation of the paper is somewhat confusing in the sense that there is some ambiguity in the modelling approach. The forms of the yield function and the plastic potential are first chosen based on yield locus and stress dilatancy equations proposed by other authors in the literature. The next obvious step is to check whether the experimental data (yield stress points, stress ratio versus shear strains, and volumetric strain versus shear strain) fit well with the analytical forms of the yield function and plastic potential. This was actually done (no details shown) in the paper, but what was confusing is that in addition to the plasticity equations, the data was fitted independently with other functionals, and it was claimed that these fits were better than the results obtained from plasticity calculations. One normally either uses empirically fitted function derived from a particular data set, or adopts the framework of plasticity which is more general, but not both at the same time. The presented work seems to be incomplete as it needs to address important issues such as anisotropy development, cyclic loading, among others. As a matter of fact, there is a complete study on the behaviour of Murro clay described in Karstumen et al. (2005) where the importance of anisotropy is highlighted *vis à vis* that of destructuration in the light of a test embankment case study on the same problematic clay.

Oda and Matsui present the study of an interesting clay, here described as quasi-over-consolidated, for which the current effective stress is less than the consolidation yield stress, although there has been no change in overburden stress according to geological history. While this clay should be defined as normally consolidated in geological terms, there is a slight overconsolidation that is probably caused by diagenesis such as effects of cementation or ageing among clay particles. These clays are of the Pleistocene age and found in the Osaka bay area. Their studies are relevant to the calculation of long term settlements of large scale reclaimed structures such as offshore manmade islands like the Kansai airport, off the shores of Osaka city. The principal characteristic is that remarkable secondary consolidation occurs even at a stress level less than the preconsolidation yield stress. Long term consolidation tests on these clays performed at constant strain rates show a delayed phenomenon in that deformations start to be only prominent after a given time. This is attributable to time dependent effects arising from the grain skeleton level. It is also found that the consolidation behaviour depends on the drainage length. If the drainage length is short, primary consolidation rapidly proceeds so that secondary consolidation is obtained, even for stress states below the pre-consolidation yield stress. For longer drainage paths, the primary consolidation is affected by time dependent properties of the solid skeleton, which exacerbates compression. Hence, long term residual settlements may become very large, even if the applied stresses are smaller than the pre-consolidation yield stress. These experimental observations are reproduced using an elasto-viscoplasticity model based on sub-loading surfaces (Hashiguchi, 1989).

2.3 *Cyclic loading*

Allotey and El Naggar review a number of soil models dealing with cyclic loading. Reference is made mainly to those ones which empirically relate the degradation of the stiffness of the load/reload curves to a number of parameters such as, among others, the number of cycles, the stress/strain amplitude as well as stress/strain level. The traditional cyclic constitutive models based on elasto-plasticity are unfortunately not covered, while empirically based ones are favoured. It is argued that the traditional cyclic models are normally built upon ideal experimental conditions such as constant amplitude loading. Under general conditions, varying loading amplitudes are encountered and extrapolations are therefore needed. The paper points out assumptions made in various degradation models and discusses issues of linear/non-linear fatigue. This literature review on cyclic soil models was done in the context of analyzing the dynamic response of structures such as piles in saturated soils.

Park, Byrne and Wijewickreme describe a constitutive model that can address the phenomenon of rotation of principal stress directions, as well as plastic unloading with dilation during cyclic loading. It is well recognized now that principal stress direction rotation plays a determinant role in sand behaviour under stress reversal loadings. Another constitutive behaviour that is connected to this issue is the non-coaxiality of plastic strain increments with principal stress directions; see for instance the works of Papanichos and Vardoulakis (1995) as well as Hashiguchi and Tsutsumi (2001). While the topic discussed in the paper is of considerable interest in the study of the cyclic behaviour of materials, the modelling ideas were unfortunately not well communicated. The avid reader is forced to consult other directly related publications for a better understanding of the ideas put forward in the paper.

Gajan, Kutter, and Thomas describe the rocking behaviour of a shallow footing when subjected to dynamic and slow cyclic lateral loads. Experiments in a 20 g centrifuge are performed to put in evidence the nature of the moments and deformations. The rocking motion of the footing produces a phenomenon of rounding at the contact surface in the foundation soil. In other words, during the first half of a cycle, the heel of the footing lifts off and causes yielding. Yielding at the heel produces more settlements in the next half cycle. The net effect is a gap forming beneath the footing so that the contact beneath the footing and the foundation soil rounds off. As the contact area decreases, this phenomenon causes a stiffness degradation in the moment-rotation curve, while the moment carried by the footing remains virtually constant. This means that the associated energy dissipation increases so that the shaking demand on the building is reduced. However, settlements increase and tend to stabilize in subsequent cycles (shakedown condition). An analytical model is developed based on simple statics. The model gives very reasonable results comparable with experimental data. The model has three parameters: friction angle, vertical stiffness, and rebounding ratio of the soil. It would have been interesting if the authors had discussed about the mechanisms of dilatancy, fabric changes and ratcheting effects in the foundation soil as it experiences various cycles of loading. England et. al. (1997) have shown that ratcheting effects are intimately linked with the dilatancy response of granular materials as well as the stress/strain amplitude involved in the cyclic loading.

3 MICROSTRUCTURAL ISSUES

Yang, Lacasse and Forsberg describe the characterization of sand-silt and gravel-sand mixtures as a binary mixture where the material behaviour is controlled by the finer fraction. For instance, the static or cyclic liquefaction behaviour of the mixture is governed by its finer fraction, and hence the determination of the porosity/void ratio should be based on the fines content. It is found that there is a critical fines content which describes the transition from the coarse fraction dominated behaviour to the-fine fraction one. Physical phenomena related to fines content in water saturated cases are described in Kovacs (1981) and Vardoulakis (2004). In petrophysical analysis, the porosity of the mixture is determined from the porosities of the clean coarse and fine materials together with the volume fraction of the fines. Hence, hydraulic conductivities can be determined from some correlation. Some corrections can also be made to account for the relative size distribution and packing within each fraction. For geotechnical modelling, there is a so-called intergrain state characterized by a TFC (Transitional Fines Contents) line of demarcation below or above which the mixture behaves fundamentally as a sand or a fine material. In dealing with a mixture of grains of different sizes and packing, it is important to work with grain contact aspects, hence in terms of the contact density, which is reflective of the soil mixture microstructure. The void ratio of the mixture is corrected by a factor which accounts for contact density. The same concept has been applied to acoustic properties of soils. It seems that there is a unique relationship between compressional/shear wave velocities and *corrected* void ratio for various clay contents based on a set of limited data. However, this finding has to be confirmed by looking at other soils. If true, this would mean that basic acoustic properties of sediments can be rendered objective with the use of a corrected void ratio that embeds the notion of contact density/microstructure. Consequently, the shear wave velocity of a mixture of sand/silt at various fine contents should the same at constant contact density, i.e. at *corrected* void ratios.

Jung, Chung and Kim recognize the discrete nature of granular materials and as such incorporate this feature into a macroscopic constitutive law through micromechanical analysis. The description of microstructure and how it relates to macromeasures through homogenization techniques has been widely covered in the literature; see for instance, pioneering works of Oda (1972), Chang (1993), Emeriault and Cambou (1996). In the current paper, non-linear contact laws are established at the grain level and the resulting bulk material modulus is derived as a function of fabric for the simple case of cross-anisotropic elasticity. In order to describe changes in microstructure during deformation history, a fabric evolution which is purely deviatoric in nature is introduced. The numerical simulations afforded by such a formulation seem to give the same trend as experimental ones. The non-linear contact stiffness produces the elastic pressure dependency in isotropic stress conditions, while both fabric anisotropy and contact stiffness nonlinearity govern the shear behaviour of the granular material. However, no contact loss, gain or particle rotation was considered in the analysis.

Wan, Guo and Al-Mamun present an interesting discussion on the intertwining roles of fabric and dilatancy on the shear strength behaviour of a granular material such as sand. The authors point out that it is important to account for fabric information when characterizing a sand, given that it governs its propensity to dilate, hence its strength. For instance, it is well recognized now that the shear strength as determined from conventional triaxial tests is very much dependent on the initial fabric created from the method the sample was prepared, namely wet tamping or air pluviation, As such, natural soils display a wide range of responses, from stable hardening to unstable softening like behaviours, depending on their initial fabric. These issues are further investigated in an experiment that involves the testing of an analogue 2D material comprised of photoelastic particles. Various rates of dilatancy (contractancy) are applied to the specimen so as to explore the deformational and fabric properties of the material with the appropriate fabric changes. It is shown that the mechanism by which materials derive their strength is reflected in the way stresses/forces are carried by the microstructure. A spontaneous flow type of behaviour with softening is obtained whenever extreme dilation rates are imposed on the material. This is due to the local buckling of force chains at the micro level, which has been demonstrated in previous works such as those of Oda and Iwashita (2000), Oda and Kazama (1998) and Satake (1998). Interestingly, the same material is shown to behave in a stable hardening fashion whenever a moderate dilation or a compaction rate is applied to it. Clearly, the strength of soils is a function of the dilation rate applied to it, and is not bounded by the undrained (zero volumetric strain rate) and drained cases. A good example is the case illustrated in this paper in which slow cyclic rotation of a retaining wall imparts both fluctuating strains and rotation of principal stress directions to the granular backfill. Unstable material behaviour in the form of granular flow may be triggered under some special conditions.

4 REINFORCED SOILS

Gaszynski and Gwozdz-Lason talk about the philosophies of modelling any physical phenomenon. Here, the topic of reinforcing soils with gravel columns is discussed. The paper points out approximations made in a model, in particular, temporal and spatial approximations. In the case of a soil reinforced with columns, a systematic approach is proposed whereby the effect of one column is first analyzed followed by the case of several columns with a goal to study group effects and optimize the column spacings to arrive at a certain targeted bearing load. Also, in the modelling processs, any effort to include the method of construction should be considered. For instance, construction variables can be incorporated in the form of a transition zone between a column and the adjacent soil so as to highlight the consolidation aspects.

Rospars, Bourgeois, Humbert, and de Buhan tackle the analysis of soil reinforced by means of rigid columns (actually piles), a topic akin to the one reported in the previous paper. The necessity for such a method of soil reinforcement arises when an embankment is constructed on a soft substratum. The loads are distributed over a uniform mat made of gravel and then transferred to a series of rigid inclusions (piles) to transfer the loads to a hard stratum, while also taking lateral loads from the adjacent soft soil. The authors propose a modelling technique similar to the theory of mixtures where various phases overlap so as to approach the problem from a continuum mechanics viewpoint (cf. Truesdell and Toupin, 1960). Soil and inclusions (rigid columns) are considered as two distinct phases that interact together. In a next step, homogenization of the phases proceeds through the principle of virtual work. Basically, at each continuum point, both phases are present. Interaction between the phases is done by way of relative displacements. While the model is restricted to elasticity, it is quite elegantly developed and should be amenable to more realistic non-linear soil behaviour. Furthermore, model implementation in any finite element code appears to be straightforward.

5 OTHER APPLICATIONS

El Ouini presents a classic analysis of dam foundation deformations with a comparison of numerical results with field measurements. It is recalled that challenges pertain to the modelling of the proper geology, construction sequence and material behaviour. Different material models were used in conjunction with the coupling with water flow. Some of the field data such as lateral movement and foundation settlement are approximately matched, but the model needs to be improved in order to provide more confidence in prediction. The intent is to use such as model to predict the future behaviour of the dam and foundation as a function of reservoir impoundment.

Le Thiet, Canou and Duplau describe the phenomenon of the fluidization of a cohesionless soil by means of vibration excitation. Applications are in the area of pile (or sheet piles) driving during vibration, while the associated theoretical work has been described by Schmieg and Vielsack (1986). Test prototypes are performed in a calibration chamber where various parameters affecting vibro-driving are investigated. For instance, initial density, grain size distribution, water saturation, frequency and amplitude of the vibration excitation are considered. As expected, it is found that a large vibration amplitude causes the most effective driving. However, the practical limitation lies in the considerable power rating of the vibrating equipment required in a field situation. The Reporter feels that the paper should have touched on some mechanical aspects of vibro-driving. For instance, it is known that the dilatancy properties of the soil play a major factor in the process. Although ratcheting effects may be a driver force, the use of high amplitude of vibration may cause grain crushing.

Nyambayo and Potts model crack formation and closure in shrinkable soils due to dessication. This occurs due to changes in rainfall and an evapotranspiration process. It is important to model such phenomena because they lead to large fluctuations in permeability. The aim is to develop a crack-permeability model which can be implemented in a stress-deformation-fluid model. The work adopts a simple linear relationship between the logarithmic of permeability and minor effective principal stress. The initial permeability increases linearly to a final value that is conditioned by the development of fully grown cracks and the associated pattern. The paper demonstrates that the proposed cracking and closure (dessication) model performs well and gives more realistic results than a more simplistic model based on linear permeability against mean effective stress model. However, it remains to be seen whether it can model hysteresis effects produced in the opening/closure of cracks. The weather data is an important input that has to be worked into the finite element model which computes stress, strains and pore pressures in a coupled fashion. Permeability are changed as discussed previously, while cracking is predicted based on a simple zero minor principal stress criterion. The paper should have made mention of a similar problem in unsaturated soil mechanics that deals with the vadose layer, the first few metres of the soil subjected to fluctuations in moisture content. The modelling of the vadose layer, at least from the moisture transport viewpoint, is well-known in geo-environmental engineering where soil covers need to be designed for mine or municipal waste facilities; see for instance, Newman et al. (2002).

Rechenmacher, Medina-Cetina and Ghanem present an interesting approach to measure 'local' fields such as displacements in a deforming specimen applying digital photogrammetry techniques on a stereo pair. This technique is not new, but was first used by the Desrues and Duthilleul (1984) in the analysis of strain localization. However, in the current paper, the main objective is to use this information to compare the local field measurement with the ones predicted by a finite element calculation. As such, through an inversion process, the spatial distribution of material and state parameters is found is such a way that it minimizes the error between experimental and computed displacement fields. This leads to the determination of a statistical distribution of material parameters, instead of a unique value as done in practice. Currently, the work has only proceeded with the calibration of material behaviour based on elasticity, but the extension to more complex models remains to be seen. It is found that the higher the variability of soil properties, the smaller the difference between actual and measured displacement fields. However, in the plastic deformation regime, a random spatial distribution of material properties may lead to strain localization, which may complicate the calibration proposed. The whole computational procedure is set within the framework of so-called stochastic finite elements; see Ghanem and Spanos (1991).

6 CONCLUDING COMMENTS

The Reporter makes the following comments to set the scene for discussion at the technical session. In doing so, this will hopefully provide guidelines for future contributions on the theme.

- There is currently a prevalence in the development of increasingly sophisticated constitutive models as more complex material behaviours need to be captured. These new constitutive models require a large number of material parameters that are difficult to determine experimentally. There seems to be an enormous gap between constitutive model developers and practicing engineers, since advanced constitutive models have currently limited use in design. The models may be viewed to be too theoretical and devoid of simple physics. However, the Reporter feels that the root of the problem lies in the current engineering curriculum being somewhat antiquated. It has to be updated and revitalized with an emphasis on modern techniques in mathematics, physics and mechanics.

- More emphasis should be placed on physical modelling, which has been barely touched upon in the papers submitted in this session. Physical modelling should be the starting point of any research endeavour and a paradigm within which the physics of the problem is incrementally developed in tandem with modelling. On the other hand, it is found that current theoretical developments of models are becoming very involved so that laboratory testing techniques have reached a level of sophistication that may obscure the original objective, i.e. the description of material behaviour through simple physics and intuition. The measurement of physical phenomena requires increasingly higher resolution in both space and time so that the analysis and interpretation of results may be rendered complex.

- There is a need for carrying out more benchmarking activities in order to verify systematically the performance of constitutive models in real or idealized boundary value problems where non-homogeneous stresses and strains develop throughout the entire medium. Pertinent geotechnical problems involve soil-structure interaction with cyclic loading, for instance.

- The determination of material parameters is problematic. There was only one paper in the session that addressed this issue in a systematic manner, combining photogrammetric techniques and finite element modelling. More emphasis should be placed on this issue in future endeavours, especially as constitutive models become more complex. The systematic determination of material model parameters and their physical significance should make the use of advanced constitutive laws more attractive to the practitioner.

In closing, the Reporter wishes to point out that the evaluation and discussion of the papers may contain some misunderstandings or errors in interpretation, for which he sincerely apologizes. There may, of course, be other opinions on the points put forward for discussion in the technical session.

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