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Editorial
Soil mechanics at the grain scale: issue 1

The physical processes governing the mechanics of soils remain rather mysterious. Examples of obvious practical significance include the effects of cyclic loading; the influence of creep and rate effects; and the extent to which localisation and instability should inform an assessment of peak strength. In the past, the modelling of soil behaviour has largely been phenomenological at the macro-scale and based on the data of soil element tests. A prominent example is the framework of critical state soil mechanics (CSSM) and the cam clay model of elasto-plastic soil behaviour (Roscoe *et al.*, 1958; Schofield & Wroth, 1968). The outstanding strength of CSSM lay in its ability to combine the recoverable and irrecoverable volumetric and deviatoric stress–strain data of clays in triaxial tests within a mathematical model that used only four parameters. This was also widely perceived as its main weakness. Engineers who conducted different classes of test, or who tested different classes of soil, drew attention to the importance of phenomena that lay outside the CSSM framework: undrained cyclic loading could lead to the liquefaction of sands; creep in conjunction with transient flow led to errors in predicting the consolidation settlement of clays; the compressibility of sands was evidently non-linear on a linear-logarithmic plot; and the dramatic drop to residual sliding friction that accompanied the formation of polished slip surfaces in clays led to controversy over the selection of safe angles for slopes.

The reactions of soil modellers to such observations ranged from the generation of much more elaborate constitutive models with 20 or more parameters, to the development of a multitude of phenomenological models that dealt separately with one class of specialised data. Researchers taking the elaborate route often achieved a pleasing representation of a wide range of behaviour simultaneously, but at the expense of raising immense obstacles to communication and practical application through the lack of obvious physical meaning in their many parameters. How might those many parameters change if the representative soil sample changed its composition? Those taking the specialised route could generally match the particular data they focussed on, but the decision-maker could hardly know whether that particular facet of behaviour would be pre-eminently important in the application of interest. In a sense, both approaches to phenomenological modelling amount to curve-fitting, and both raise the question ‘Am I looking at the right curve?’.

One way of raising confidence is to take the route adopted in materials science and to enhance stress–strain data through micro-structural images and micromechanical modelling. Although Rowe (1962) based his stress-dilatancy theory on granular propositions rather than actual micro-measurements, many readers found the theory easier to visualise than the rival CSSM models. It took the advent of discrete element modelling (Cundall & Strack, 1979) to facilitate extended granular simulations, including those which linked stress-dilatancy and CSSM in the context of grains which could both rearrange and crush (Cheng *et al.*, 2004). The association by Skempton (1964) of the residual friction of clays with the reorientation of platelets parallel to a surface of continuing sliding, was originally an appeal based on the photography of ‘polished’ slip surfaces. Later, it became possible to confirm that impression by scanning electron microscope (SEM) imaging (Müller & Schlüchter, 2001). Such images fix themselves very effectively in the minds of engineers. It is not surprising, therefore, that discrete-element method (DEM) simulations and microscope images appropriate to a variety of soils and processes form the backbone of papers published in these themed issues.

The challenge is to clarify the processes that have given rise to common soil types in terms of their current microstructure, and especially to track changes in that microstructure during the gamut of natural or man-made activities that require geotechnical data for their design and control. Successful research along these lines should lead to justifications for the selection of test methods, and to the definition and clarification of macroscopic and microscopic parameters and mechanisms best suited to the prediction of small-strain stiffness, kinematic yielding, plastic hardening, critical states, rate and time effects, localisation, fracture and flow. This in turn should lead to the availability of correlations between these fundamental modelling parameters and elementary soil classification and index tests, offering decision-makers a priori estimates of future performance before more expensive element-testing has been commissioned. Designers would then be able to focus appropriately on potential threats – whether of seismic liquefaction, internal erosion, creep, anisotropy or progressive failure – in the knowledge that they were not wasting their clients’ ground investigation money.

Initial impetus in this direction was gained through international symposia organised at Yamaguchi University by Professor Masayuki Hyodo. The potential value of this new initiative was recognised by the International Society for Soil Mechanics and Geotechnical Engineering when it acceded, at the turn of the new millennium, to Professor Malcolm Bolton’s proposal to set up a technical committee, TC 35, which has the mission ‘Geomechanics from micro to macro’ with the acronym GM^3. Subsequently, working groups began to meet both in Japan and in the UK. Seven annual meetings have taken place of the UK GM^3 travelling workshop, and there have been an increasing number of international workshops and conferences dedicated to this theme.

This burgeoning of international research activity was reflected in the 100 abstracts submitted initially to the call for papers on ‘Soil mechanics at the grain scale’ by *Géotechnique*. When the *Géotechnique* advisory panel agreed to publish themed issues, it was decided that these should be substantially different from symposia in print. Unlike the latter, which tend to gather state-of-the-art papers, these occasional issues were intended to ‘inform readers of new and emerging developments’ (Atkinson, 2008). The subjects covered in the submitted abstracts ranged from experimental to numerical research, and originated from institutions all over the world. The final selection of 18 papers reflects this variety, and hopefully makes an exciting read. They report studies of the influence of soil fabric, grain shape and roughness, interparticle creep, localisation and many other potentially significant micro-mechanical aspects of soil behaviour. Furthermore, through an agreement with Professor Mingjing Jiang of Tongji University who is organising the next TC35-sponsored conference, IS-Shanghai 2010, some of these papers will also be presented for oral discussion on that occasion, as well as being open to written discussion in *Géotechnique* in the usual way.

This first issue offers information about mechanisms occurring at the grain scale during phenomena observed at the meso-scale that are generally poorly understood and neglected by constitutive modellers, such as the non-uniformity of stresses and strains in single-element tests. The second issue will report work on those characteristics of the grains that may be responsible for soil behaviour, such as particle size and shape, particle breakage and inter-particle friction.

In this issue, significant advances are reported in sensing and imaging technologies, and in computer performance, combined with techniques borrowed from other areas of science such as medicine or chemistry. This technology permits better spatial resolution (a few microns) in tracing the movements of individual grains during a test. Hall *et al.* (2010) and Hasan & Alshibli (2010) used X-ray micro-computer tomography with synchrotron sources to characterise the three-dimensional kinematics of individual sand grains within shear bands. They were able to detect grain translation and rotation as well as particle contacts and orientation during triaxial testing of sand specimens. Force chains developing within specimens emerge as a significant factor accounting for meso-scale phenomena such as the evolution of the mobilised strength. For example, the evolution of critical states can be linked to micro-mechanisms such as the buckling and collapse of the force chains (Hasan & Alshibli, 2010; Rechenmacher *et al.*, 2010; Thornton & Zhang, 2010). It is interesting to see that such observations are made during experiments as well as in numerical simulations using the DEM.

The enhanced performance of computers is increasingly allowing researchers to match experimental research with DEM simulations: Li & Yu (2010) applied DEM to study the effects of stress rotation and the non co-axiality of stresses and strains, while Wang & Gutierrez (2010) looked at the effects of scale and geometry on shear bands in direct shear tests. The advantage of these simulations lies chiefly in the information which can be obtained on the evolution of contact force distributions, and also the possibility to repeat tests in exactly similar conditions, bypassing the uncertainties associated with sample variation (Thornton & Zhang, 2010). But they have generally relied on simple particle shapes (spherical in most cases) and simplified inter-particle reactions (linear elasticity or Hertz–Mindlin) that may or may not be sufficient to represent soils. Nevertheless, results from these DEM simulations may lead us to question our interpretation of single-element tests (to what extent is the measured parameter an outcome of the testing method?) and our use of continuum constitutive models.

So far, these advances in experimental and numerical research have benefited simple granular materials such as sands. Clays are different by nature, the definition of a particle itself not being clear. More traditional techniques such as scanning electron microscopy and mercury intrusion porosimetry remain significant sources of information when trying to understand compressibility, or in identifying changes in particle orientation during testing (Delage, 2010; Hattab & Fleureau, 2010), but there are still advances to be made to understand phenomena such as sensitivity and structure degradation, for example. The papers in this issue are therefore opening up new avenues of research rather than coming to immediately applicable conclusions.

Of course, a sceptic might question the use of knowing what is happening to soil grains. Our reply must be that this research will ultimately validate or improve our approach to soil characterisation as well as the numerical models, discrete or continuum, which lie at the heart of geotechnical engineering. This is evident in our second issue, published next month, in which the papers deal with what could be qualified as more fundamental aspects of soil micro-mechanics, such as particle morphology, inter-particle contacts, inter-particle friction and particle breakage, but still within the context of their wider application to large-scale problems.

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