EVALUATION REPORT ON PARALLEL SESSION 2.2 - EXPERIMENTAL UNSATURATED SOIL MECHANICS

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General comments on laboratory and field measurements

Any predictive theory must be tested against it utility. How does the theory compare to sound experimental evidence both in the laboratory and in-situ is the often the first question asked of any theoretician? Whilst field measurements reflect conditions likely to be encountered in practice and are of vital importance, there are often uncontrolled if not uncontrollable parameters affecting the measurements and interpretation of data. Laboratory measurements of soil properties should not be taken as replacing in-situ measurements, but more reproducible data using selected variables is obtained in a controlled laboratory environment.

A number of the papers presented use laboratory triaxial cell set ups. Significant corrections have often to be made to volume and moisture content changes in standard equipment in order to obtain meaningful results. Zero error corrections for the air trapped in the system, bedding errors and, in particular, zero errors for the volume-change indicators are readily identifiable. However, a large number of other potential sources of error exist. The measurements of volume and moisture content change of specimens in the triaxial cell are recognised as problematic. Papers have been presented in this session which highlight these difficulties and that high quality experimental data is a prerequisite to the validation of analytical predictions of soil behaviour. The end-product of experimental research both in the laboratory and in the field must be to develop a better understanding of soil behaviour and, where applicable, to put the knowledge and experimental techniques to practical usage.

The points that emerged from the forgoing are:

Improvement in test data requires new and improved testing techniques and equipment.

Operatives must develop a greater understanding of test strategy.

Technicians performing tests on soils commercially are under pressure to carry out tests rapidly to recognised methods and require robust tried and tested techniques.

Engineers skilled in soil mechanics are required to carry out careful interpretation of test data if meaningful results are to be obtained.

If new procedures are proposed for commercial usage:

The equipment must be sufficiently robust to withstand repeat operations.

The results must be readily interpreted.

Repeatable data must be forthcoming.

There must be minimal error corrections to add confidence to the data obtained.

The significance of the results obtained from the tests in relation to its usage must be apparent.

The presentations
Twelve papers on experimental procedures in unsaturated soils were presented in Parallel Session 2.2. There was also one poster paper that is also considered in the following. The papers cover a wide range of important topics from measurements of water vapour transfer, air conductivity, hydraulic properties in-situ and in the laboratory, through to volume change measurements and improved experimental procedures and equipment.

Session 2.2 was divided into four sets of presentations under the following generalised headings based on the contents of the papers:

(i) Image analysis of degree of saturation and volume
(ii) In-situ testing of degree of saturation and hydraulic properties
(iii) Laboratory investigations of vapour flow, air flow, diffusion and hydraulic properties
Laboratory investigations of theoretical concepts

Prior to each set of presentations an outline of the theme and papers was given and the authors were asked to address questions previously forwarded to them. The presenters were extremely co-operative with skilled presentations followed by insightful discussions. Outlined in the following are the panel's views on the papers along with questions posed, which were aimed at stimulating discussion. Authors were subsequently requested to provide written responses to the questions and where written replies have been received these are included. However, where no written reply has been received only the questions are presented as it is not wished to restrict the authors to the answers provided verbally during the presentations.

(i) Image analysis of degree of saturation and volume
The accurate measurement of the degree of saturation and the relative volumes of the phases are imperative if the behaviour of unsaturated soils is to be fully appreciated and practical problems are to be analysed satisfactorily.

The paper of **Sharma, Mohamed and Lewis** describes the use of image analysis techniques to predict the degree of saturation of unsaturated soils. They compare the results from image analysis of column tests on sand to the degree of saturation calculated from measurements of water content. The paper examines two analysis methods for the images: a linear and an S-shape equation. These convert colour numbers of images over the full height of the columns to the degrees of saturation. The S-shaped equation is shown to better fit the data. They suggest that adopting such a non-destructive approach could facilitate a determination of the dynamic degree of saturation of water in unsaturated soils though they do not attempt this in the tests reported. The following questions were posed and the authors' written replies are included:

Q. Are there limitations in the type of soil or the migrating fluid with which the technique and experimental set up can be used?
A. *There are no limitations hindering the use of the image analysis technique for different types of soil or different liquids. Further detailed results of this investigation will be published in journals.*
Comment: The implication of the reply is that the measurement of contaminant

concentrations may be a feasible measurement which could prove interesting if linked to the dynamic measurements suggested as obtainable.

Q. Does the method require calibration for each soil type and density?
Yes, it requires to be calibrated for each soil. Additionally, the light configurations should be kept the same during the calibration and during the actual experiments.

Q. What is the influence of image distortion using a cylindrical column?
Using a cylindrical column causes some variation in the light intensity especially at the outer edges of the column. However, the light intensity along the middle part of the column was almost the same for saturated columns. This problem was eliminated by processing the middle part of the column image and taking the average colour number in each row.

Q. Please comment further on the use of image analysis to the measurement of the 'dynamic' degree of saturation of water in unsaturated soils mentioned in the paper.
Once a calibration equation is obtained, it can then be used during the flow of water into or from the sand providing that the porosity remains constant.

Q. According to the authors, there was an influence at the base of the column due to shadow effects. While this may well explain measurement discrepancies within this zone (Fig. 6), it is noted that the degree of saturation at the base of the column approaches unity. Another possible explanation is that such a technique cannot adequately capture conditions close to or at saturation. This point would be important when analysing the evolution of an infiltration front. Please comment.
A. *Before taking any images, the light arrangement was adjusted so that the light intensity along the height of the column was uniform. For this reason, the variation in the colour number in the saturated part was attributed to the shadow coming from the base of the column. It can be observed from Figure 1 that the colour varied between 85.5 and 88.5 and from 86 to 94 for tests 1 and 2 respectively. Substituting these numbers in the calibration equations, the maximum differences between measured and predicted degree of saturation is about 5%. Furthermore, using the normalised image, which is produced by subtracting the background image from the actual image, gave better results eliminating any problems of shadow.*

The importance of being able to measure accurately the volume change of soils under test is highlighted by two papers dealing with image processing and volume measurements in the traiaxial cell. The first of these papers is by **Rifa'i, Laloui and Vulliet** who compare and contrast the use of the 'liquid variation (LV method)' and the 'image processing (IP method)' techniques with application to the measurement of volume change of unsaturated soil during consolidation, drying and shearing in triaxal tests. The LV method consists of measuring the variation of the triaxial cell liquid. The IP method consists of measurement of the sample shape by taking photographs through the transparent triaxial cell. Calibration of the cell for the IP method was carried out using a rigid sample so that digital images could be corrected for optical distortion using computer analysis. The authors report various saturated and unsaturated tests on Sion Silt to evaluate the methods and conclude both methods give a good measurement of volume. For saturated soils, when the methods are compared to measurements of water content change using a conventional burette (B method), maximum errors in volumetric strain are typically 4% to 8%. For unsaturated soils the relative maximum difference in volume measurements between the LV and IP methods is assessed as below 8%. The authors were asked to consider the following questions.

Comment on possible difficulties due to specimen deformation not being regular.

In Figure 3a, volumetric strain estimated using the LV method does not attain a constant value. This is not unexpected if one considers perspex water absorption, perspex creep, possible water leakage amongst other influencing factors. It is more surprising that volumetric strain estimated using the IP method also continuously increases. Please discuss.

The second paper dealing with image processing as a method of measuring volume change of unsaturated soils in the triaxial cell is that by **Elkady, Houston and Houston**. Digitised colour images were analysed and corrected for cell distortion effects. These were not computed separately but lumped together and determined experimentally. The paper assesses the effectiveness of the image processing technique in relation to measurements of both axial and radial strains of a rubber specimen. The rubber specimen was first tested under axial load but with no cell or water surround. The results of direct measurement were then compared with photographs analysed using computer programing. Finally the rubber specimen was tested in the triaxial cell and a calibration curve obtained by comparing the photographs with measurements of the specimen internal to the cell. The authors claim good agreement between image processing and the measurements taken. The authors were asked to address the following questions:

Q. The image-processing technique gives excellent results in capturing the specimen deformation profiles. Nonetheless, differences between LVDT "measured" strains and camera "observed" strains, which are reported in Figures 6 and 7, still seems relatively large. The error in the measurement of axial strain, when using the digital camera, seems to be about 20 % of the measured value. Similarly, the error in the measurement of radial strain, when using the digital camera, seems to range from about 10 to about 30 % of the measured value. Is this an "inherent" limitation of image-processing techniques or could some improvement be achieved?

A. *The results presented in Figure 6.0 and 7.0 represent a collective comparison for the axial and radial strains for the whole specimen as well as individual sections within the specimen. Figure 1.0a shows a comparison between the axial strains for the whole specimen. Figure 1.0b illustrates comparison between axial strains for selected sections within the specimen. The results indicate the variation in the image axial strain does not exceed 5%. As an example, if the image processing gives an axial strain of 5%, the actual strain is no less than 4.75% and no more than 5.25%. Similar conclusions were reached from the comparison between experimental and image radial strain for selected sections within the rubber specimen as illustrated in Figure 2a.*

Figure 1a calibration curve for experimental and image axial strain of the whole specimen

Figure 1b Comparison between Experimental and image axial strain for selected sections within the rubber specimen.

Figure 2 Comparison between Experimental and image radial strain for selected sections within the rubber specimen.

Further research on compacted specimens also indicates good agreement between measured and image axial strain, as shown in Figure 3. Further tests were performed on drained specimens to evaluate the image processing as a volume measurement method by comparing the volumetric strain of saturated compacted silty sand samples during compression and shearing obtained from conventional methods (burette method and cell chamber water displacement) with that computed from image radial and axial strains. The results of the tests indicate good agreement between volumetric strains obtained from images and those obtained from conventional methods as shown in Figures 3 and 4.

Figure 3 Comparison of volumetric strains during precompression of compacted silty sand

Figure 4 Comparison of volumetric strain during shear of compacted silty sand

Q. Comment on possible difficulties due to specimen deformation not being regular for real soils.
A. *Due to the irregular deformations in specimen, it is recommended that more than one camera be used to capture images in different directions for determination of radial and axial strains. The authors used two cameras in further research on unsaturated compacted samples and results indicated that there are variations in radial strains that result from images taken from different directions. An average of the imaged strains for at least two directions appears to provide good results for overall sample response. When using the image processing method on real soils, care must be taken to avoid erroneous readings results from warping of the sample membrane. This membrane warping data can be easily detected and removed from the imaged data for determination of strains.*

(ii) In-situ testing of degree of saturation and hydraulic properties

An accurate assessment of the degree of saturation provides essential information on soil conditions and thus behaviour, but also insight into many other applications, not least in appraising contaminant quantities in the ground and in the assessment of coupled flow and deformation problems.

Montrasio describes a method for the in-situ measurement of the degree of saturation S_r at shallow depth. Unfortunately the author could not present the paper but has kindly provided written answers to a number of questions. The primary aim of the research was to allow an assessment of the influence of S_r on slope stability. The method relates the water absorbed into a sponge to the degree of saturation (as opposed to filter paper and a correlation with suction). The method is validated by laboratory tests on five different silts and sands and in-situ measurements in an unspecified soil. The author claims the method as cheaper and quicker than the filter paper method.

Q. Where can further information on the sponge and testing techniques be found?
Actually in an internal report at the University of Parma.

Q. Over what range of degrees of saturation would the method be applicable?
A. *In the range actually taken into consideration i.e. about 0.3-0.8.*

Q. The laboratory tests are on sand and silt. No clays were tested. It is not clear on what material the in-situ tests were carried out. Would the method be applicable to clays and are any results available? (Note: In contrasting the sponge method to the filter paper method, the latter is not usually carried out on sand or silt)
A. *Experimental tests have been carried out only on sandy and silty soils: no information is available on clays. The in situ tests referred to were in a silty soil che si trova.*

Q. Does the author now have comparison results between the 'sponge' method and the tensiometer measurements for the experimental embankment in Viadan?
Yes, actually some comparison have been obtained and are in the processs of publication. The comparisons reveal a good agreement.

Q. The author claims that the method is quicker than the filter paper method and can be used in-situ. Please discuss further.
A. *The asymptote of the q-t curve is reached in a reasonably small time period (about sixty minutes) and this permits a large number of tests even if the measures are derived manually.*

Q. The author assumes that the amount of water absorbed by the sponge can be directly related to degree of saturation of the soil. As water absorbed by the sponge depends on soil suction and not directly on degree of saturation, is there an inherent approximation in the procedure? What is the influence of hysteresis in the soil water retention curve? What is the influence of remoulding of soil in the laboratory? Does the author have experimental evidence addressing these points?
A. *I have to recall that the method has been introduced for practical purposes: the final goal is in fact to monitor the Sr variation in superficial soils potentially at risk of soil-slip. Is my opinion the errors in correlating test results directly to Sr instead of matric suction are not appreciable in this context. But I am firmly convinced that for other purposes the way to interpret the results is in terms of matric suction.*

Q. The technique used to measure the mass of water absorbed by the sponge is not clear. Is the sponge removed, weighed, and then replaced in the cylindrical net? Or is the sponge mass continuously monitored through the precision balance? If so, is the sponge in contact with the soil or does it hang free from the balance?
The sponge is removed and weighted and then replaced in the net.

Q. Is there a typographical mistake on the time scale in Fig. 3? Should the time be expressed in (s/10)?
A. *No. Due to PC problems, the authors decided to express the times in this unusual way to permit manual modifications.*

Q. The author states the equilibrium time for the absorption process does not exceed 60 min. However, equilibrium time seems to be greater than 60 min in Figure 3, 4 and 5. Is there any experimental reason that explains the monotonic increase of water absorption over the entire test duration?
A. No answer given.

Q. Please clarify meaning of "m" (minimum of the upper curves) and "M" (maximum of the lower curves) e.g. Fig. 4.
A. *They represent the minimum and maximum envelope of the experimental points respectively.*

Q. In relation to Fig. 6, the author states that parameters A and B for the first three soils can be considered similar (A=10 and B=18). Accordingly, a single interpolation line is traced to fit data for these three soils. However, there is scatter in the data suggesting errors in the estimated degree of saturation of possibly 40%. Is this the likely error in estimating the in situ degree of saturation?
A. *Referring to the diagram shown in figure 6 I see that for twenty five tests performed the maximum scatter reaches 15-20% for only two tests. I am not able to appreciate the 40% remarked in the question.*

Takeshita and Morii draw attention to the need to measure in-situ saturated and unsaturated soil hydraulic properties for contaminant transport. The authors present the results and interpretation of in-situ Guelph 'constant head' infiltrometer tests on a variable sedimentary sand and gravel. The authors propose a new field method to measure insitu unsaturated permeability using the Guelph infiltrometer coupled with a water content probe (Amplitude Domain Reflectometry). Finite element analysis is used to analyse the axisymmetric flow of an initially unsaturated deposit, which becomes field-saturate during the tests. The authors report 'fairly good' agreement between predicted and measured soil water contents and cumulative flow in-situ. Laboratory permeability tests were also performed with good agreement reported between predicted and measured data. The authors provided the following answers to questions posed:

Q. Outline restrictions on the soil type that can be tested using the Guelph Infiltrometer and why? What is the practical range of pressure head that can be applied?
A: The *Guelph Pressure Infiltrometer consists of a single steel ring inserted into the soil, attaching a Mariotte reservoir. The steady-state infiltration rate is measured during the constant-head infiltration from the single ring into the soils. The practical range of pressure head that can be applied is 5 to 25cm. Steady flow is often attained within 5 min using small rings (10cm diameter) in highly permeable soils, and within 60 to 120 min using large rings (20cm diameter) in low permeability materials. Reynolds & Elrick (1990) reported the range of field-saturated hydraulic conductivity in unsaturated soils that can be measured practically with a Guelph Pressure Ifiltrometer is of the order of*

$5x10^{-2}$ to 10^{-7} cm/s.

Q. How does the assumption of initial hydrostatic pressure affect parameter estimates using the GA (Genetic Algorithms) method?

A. *The distribution of initial pressure head in the unsaturated soil affects parameter estimates using the GA (Genetic Algorithms) method strongly. The results and the analysis of the proposed method are influenced strongly by the distribution of initial pressure head. It should be measured independently by using tensiometers before the beginning of permeability test. In our case, according to the groundwater level information measured by observation wells at this test site, the hydrostatic pressure head was assumed for the distribution of initial pressure head in the unsaturated soil.*

Geoenvironmental engineers rarely appreciate that topsoil may have retention and hydraulic characteristics much different from those of the underlying soil. This problem is of primary importance in infiltration modelling, as the topsoil is the interface between the soil and the atmosphere, i.e. the boundary condition of the infiltration problem. Other factors may influence infiltration rates at a site. While direct root action of plants may be readily perceived as influencing the hydraulic properties of a soil, the potential influence of organic secretions exuded by certain plants is highlighted in the paper by **Fourie, Mathews and Hattingh**. Such exudes counter the encroachment of other plant species. The authors present the findings of a preliminary study of the influence on an aeolian sand in South Africa and they argue that the water repellency of the sand, its water retention characteristics and hydraulic conductivity appear to be altered. Tests were carried out in-situ using a Guelph permeameter and appear to indicate differences in field-saturated permeabilities of sufficient magnitude to be of concern and warrant further investigation. Moisture content profiles were determined using a nuclear density probe. The following questions were asked of the authors prior to the presentation.

Are the authors able to identify what species of plants are most prone to exuding substances that influence permeability and are they specific to South Africa?

To what depth do the authors feel such effects are relevant?

The water content profiles presented in Fig.2 show a basic difference between the sand and burnt forest, on the one hand, and the grassland and woodland, on the other hand. In the former, the increase in water content following rain is concentrated at greater depth. This apparently surprising result could be explained by a retention curve of exudeenriched soil that is higher than that of the “unpolluted” soil (higher in the sense of Fig. 3). In other words, results in Fig. 2 would be consistent with water contents of exudeenriched soil that are greater than that of “unpolluted” soil at given suction. Would the authors agree with this interpretation? If so, could they explain how greater hydrophobicity results in an increase in water content at a given suction?

(iii) Laboratory investigations of vapour flow, air flow, diffusion and hydraulic properties

In a full appraisal of the behaviour of unsaturated soils under changing conditions, or in changing from one equilibrium condition to another, flow criteria (including liquid flow, vapour movement, air flow and diffusion) must be taken into account, together with soil particle movement. Coupled flow and deformation problems are of great significance not least for nuclear waste facilities and other situations where barrier systems are required. Whereas water flow through saturated soils and to a lesser degree through unsaturated soils has received attention by researchers, considerably less work has been done on air, vapour and diffusion transportation and on the driving mechanisms for such change such as chemical and temperature gradients. Darcy's or Fick's laws are usually utilised to describe flow conditions.

Vapour movement is an important means of transport of water within an unsaturated soil and assists in the equalisation of water pressures. It may also play a significant role in the migration of solute contaminants through barrier systems. **Al-Mukhtar** describes a laboratory programme to investigate the diffusion of water vapour through highly compacted, unsaturated specimens of FoCa-smectite and kaolinite. Moisture diffusion experiments were carried out using different concentrations of salt solution to induce different relative humidities, thus a vapour pressure difference across prepared soil specimens. Water adsorption curves were also determined. It was found that vapour diffusivity reduced as suction decreased. The author concludes that the method of measuring water vapour diffusivity is simple and inexpensive and reasonable accurate. It is also concluded that the water vapour transfer coefficient is higher than the hydraulic conductivity at saturation and vapour movement must be taken into account in low permeability barriers. The following are the questions asked of the author:

Can any guidance be given as to the accuracy of the method?
From the microstructural (microscopic) standpoint, is there an explanation of the different behaviour of FoCa-smectite and Kaolinite shown in Fig. 5?

The paper by **Loiseau, Cui and Delage** investigates air conductivity of a heavily compacted bentonite – sand mixture under different suctions. The laboratory air flow tests employed relative humidity (suction) using salt solutions to generate the potential. The authors note that Fick's diffusion law best describes vapour flow and Darcy's advection law best describes liquid water flow. For air flow they note that where the fluid pressure is below 8kPa the use of Darcy's law is sufficiently accurate and Fick's law, which best describes generalised gas movement, where air compressibility needs to be taken into account, need not be applied. The method described is termed the 'tangent' method. The authors state the importance of air permeability in coupled flow related to nuclear waste disposal. The following were the questions asked of the authors:

In nuclear depositories, what is the significance of greater pressures on the air flow and the security of such construction?
Can this work be tied into the migration of other potentially problematic gases (e.g. methane, carbon dioxide, hydrogen sulphide) from landfills or other sources?

DeGennaro, Cui, Delage and DeLaure discuss the effects of air diffusion and some problems concerning the use of the axis translation method and high air entry porous stones. The principle of axis translation allows suction to be established while maintaining positive water pressures thus avoiding the effects of cavitation. However, elevated pressures enhance diffusion effects. The authors report results for oil retention of a specimen of chalk. In the test apparatus, air pressure was applied to the top of the specimen and was elevated above the oil pressure below a ceramic stone at the base of the specimen. The authors report on an investigation of air diffusion through the oil and porous stone and its influence on measurements of displaced oil. The questions posed were as follows:

Do the authors feel that the use of the axis translation technique, which is based solely on stress considerations, and does not take account of the relative volumes of the phases, is valid?

Equation 2 refers to the concentration of air dissolved in water. On the other hand, Equation 4 defines the pressureconcentration relationship of air in the gas phase, i.e. not dissolved in water. Please discuss the inferences of combining Equations 2 and 4.

The paper by **Sorbino and Foresta** presents the results of laboratory determinations of the unsaturated hydraulic properties of pyroclastic soils from two sites bordering the Somma-Vesuvius volcano in Italy. The prime aim was to assess the influence of suction changes as a result of rainfall on the stability in areas of past flowslides. A preliminary characterisation of the relationship between suction and both volumetric water content and hydraulic conductivity is presented of two ash deposits of very low dry density and high porosity. This was achieved by carrying out suction controlled oedometer test, volumetric pressure plate extractor tests and Richards pressure plate tests on 'undisturbed' samples of ashy deposits comprising predominantly silt and sand size particles. Unsaturated hydraulic conductivity was determined by numerical analysis of equations governing transient flow due to change of suction. Amongst the conclusions reached, the authors suggest the hydraulic properties are not influenced by net total stresses up to 20kPa consistent with the non-compression of the soil skeleton at these stresses; these stress levels being appropriate to the zones of flowslides. They also note that seasonal variations in suction as a result of rainfall result in a large change in hydraulic conductivity. The authors were asked to consider the following:

Can the authors comment further on how the strength and flowslide characteristics of the ash deposits is influenced by suction, thus rainfall, and the cover materials?

How do their measurements relate to previous flowslides in the area?

The collapse recorded for the sample with 50 kPa vertical net stress could suggest a possible triggering mechanism for the flowslide, i.e for the generation of positive pore water pressure. Is it a plausible mechanism?

The paper by **Carvalho and Campos** within the poster presentations describes the development of a diffusimeter for measurement of diffusion coefficients in unsaturated soils, particularly in relation to solute contaminant transportation at landfill sites. A desk study revealed a lack of experimental results on transport parameters in unsaturated soils. Sodium chloride and potassium chloride were used as solutes. The soil used was an 'inert' mixture of kaolin, silt and sand with results of tests reported for suctions of 200 and 500kPa. The authors report encouraging results. The diffusion coefficient increases for a decrease in suction to a maximum when the soil is saturated. The authors have kindly presented the following answers to questions:

Q. How might the suction control be improved?

A. *It may be improved by using proper instrumentation. The tensiometers should have a higher resolution for a better suction control. The ones used were designed to support a positive pressure of 7MPa, which makes them very rigid.*

Q. Why were sodium chloride and potassium chloride used in the tests?

A. *They are easy to handle, not very reactive, have a high solubility, and there was information about their properties and diffusion coefficients in literature in order to compare to the obtained results.*

Q. Describe in greater detail the advantages of the system.

A. *(i) The diffusion coefficient in unsaturated soils is a combination of the air and the soil water diffusion coefficient. The axis translation technique influences the diffusion through the air, besides the uncertainty related to the fact that the mechanism of de-saturation and the movement of the soil water it is not clear. The osmotic suction control technique does not disturb the sample during the diffusion process.*

(ii) The equipment is simple, cheap and light. There is no need to use high pressures, which makes the equipment that uses the axis translation technique extremely robust.

(iii) There are two options to use the osmotic control technique in diffusion tests. First, we can apply the pressure to the PEG solution for a finer control of the suction applied to the sample, once the PEG calibration is not precise; or we can use the PEG concentration given by the calibration and monitor the suction. There will be some difference between the expected and the measured suction, however it is being monitored and it is still possible to determine the relation suction to diffusion coefficient. Hence, it is necessary to use an appropriate instrumentation.

Q. Discuss the independent determinations of the diffusion and adsorption coefficients.

A. *The independent determination of the diffusion and adsorption coefficients is possible through a single test proposed by Rowe et al. (1888). At relatively low velocity the hydrodynamic dispersion is equal to the effective diffusion coefficient. In the proposed test, a soil sample is placed in a column and the leachate of interest is placed above the soil. Contaminant is then permitted to migrate through the specimen.*

If the source concentration is allowed to drop with time, the concentration profile obtained in a hypothetical test, differs for different sets of (D, $_dK_d$) used on the simulation, which illustrates the different effects of D and $_dK_d$. Assuming linear sorption, theoretical models can be used to estimate the effective porosity, n, diffusion coefficient, D, and $_dK_d$. This theoretical analysis has been described in detail by Rowe and Booker (1985a, 1987), and has been implemented in the computer program POLLUTE. The values of D and $_dK_d$ are deduced by fitting the theoretical curve to the observed change in concentration with time on the reservoir.

Hence, the experimental procedure used to determine the diffusion coefficient, D and the distribution coefficient K_d, is described bellow:

The concentration of the source leachate is monitored with time.

The effluent concentration is monitored with time (if there is a collection chamber on the equipment – double reservoir method).

Determine the concentration profile along the sample at the end of the test.

Calculate D and $_dK_d$ by fitting theoretical solution to the experimental curves.

The variation in source concentration, c_T, with time provides an initial means of estimating the parameters D and $_dK_d$, however, the variation in the concentration throughout the sample at end of the test provides the primary data for estimating, or checking, these parameters.

(iv) Laboratory investigations of theoretical concepts

An important area of current research, in developing a better understanding of the behaviour of unsaturated soils, is elasto-plastic modelling incorporating the concept of LC yield loci. The paper by **Barrera, Romero, Lloret and Vaunat** presents the results of a laboratory study of the hydro-mechanical behaviour of clayey silt during deviatoric stress application. The tests are analysed within the context of elasto-plastic behaviour. The results of two strain controlled triaxial compression tests are reported. In both tests suction was maintained constant during the shearing stages and both specimens started from the same initial stress state. However, one sample was normally consolidated and the other slightly overconsolidated as a consequence of induced collapse on reduction in suction (or wetting). The results show that induced irreversible volumetric collapse increased the size of the yield surface and increased the tendency of the soil to dilate during shearing. The following questions were asked of the authors:

On what basis do the authors consider the stresses and strain variables conjugate?

If unsaturated soils are perceived as having a bi-modal structure, could there not be two phases of yielding i.e. yielding between the saturated regions and yielding of the saturated regions?

The authors report difficulty in identifying the yield point. If yielding is perceived as more pronounced between the saturated regions perhaps a volumetric parameter related to the air space rather than total volume or water volume might be more indicative of yield?

The research reported by **Miller, Muraleetharan, Tan and Lauder** is aimed at developing a cavity expansion based method of interpreting cone penetration tests and pressuremeter tests in unsaturated soils. They describe the construction of a laboratory calibration chamber and present preliminary results of pressuremeter tests in a prepared bed of silty soil. Radial and axial stresses on the prepared bed of 610mm diameter, enclosed in a rubber membrane, can be controlled independently. Pore air and water pressures can also be independently controlled. In the tests reported a miniature pressuremeter probe was used. Some differences are reported between target and interpreted matric suction but the pressuremeter test is reported as correlating strongly with water content in the soil surrounding each test depth. The authors provided the following written answers to questions:

Q. Do the authors now have further results and for different soils?

A. *Additional results have been obtained for the Minco Silt; however, no new soils have been tested. Minco Silt was selected because it is amenable to matric suction measurement via tensiometers and is easy to process and compact. Furthermore, with Minco Silt, variations in fabric at different compacted moisture contents are not as significant compared to a clayey soil. This is a very important issue for the calibration chamber testing, i.e., influence of differences in fabric resulting from different compaction moisture conditions on soil behavior must be distinguished, to* the extent possible, from the influence of matric suction.

Q. What properties of unsaturated soils may be most usefully obtained from pressuremeter and cone penetration testing and from cavity expansion analysis?

A. *Interpreting the pressuremeter test as an infinitely long cylindrical cavity expansion, and employing certain assumptions, a pressuremeter curve can be used to generate a* *complete stress-strain curve for the soil. A portion of the curve prior to yielding is used to estimate the soil shear modulus and a portion of the curve well beyond yielding is used to determine the limit pressure, which represents the ultimate failure state of the soil. Thus, the pressuremeter yields information for determination of elastic properties and strength parameters of unsaturated soils. For the latter, a soil-water characteristic curve, moisture content, and soil classification is required. In addition, important assumptions must be made, the implications of which are a major aspect of the related research. The pressuremeter curve can also be used to estimate initial lateral stress conditions in the soil, a further subject of the research. Finally, some methods of design using the pressuremeter, for example to predict bearing capacity of shallow foundations, utilize the pressuremeter limit pressure directly. Thus, the research is also examining the use of such methods for unsaturated soils and exploring methods for predicting variations in limit pressure as a function of moisture content based on results of a single pressuremeter test. Again, this requires knowledge of the soil type, moisture content and soil-water characteristic behavior. The research into cone penetration in unsaturated soils is just beginning and is more complex compared to the pressuremeter; however, it is expected that the research will demonstrate the importance of unsaturated soil behavior on the cone penetration process and eventually allow reasonable predictions of strength and stiffness properties to be made.*

Q. The authors say that the annulus around the membrane is filled with air instead of water to avoid water diffusing toward the sample. However, air permeability of rubber membranes is generally greater than that of water, so air is likely to pass through the membrane (and connections) more easily than water. Is the chamber vented to atmosphere throughout the test? If not, is there any control of air pressure inside the sample?

A. *While it is true that air diffuses more easily across the membrane than water, it is also easier to control and detect in case of leaks, except possibly at nearly saturated conditions. If there is a small pinhole in the membrane with compressed air in the annulus, the hole can be readily detected by monitoring the outflow of air from the soil bed. The chamber is designed for pore air control; however, during soil bed preparation and testing with the pressuremeter the soil bed is vented to the atmosphere.*

Q. What is the technique used to determine the soil water retention curves shown in Fig. 6?

A. *The curves in Fig. 6 are wetting curves determined using a constant volume cell with controlled injection of water while monitoring matric suction with a miniature tensiometer. The apparatus is similar to that used with the instantaneous profile method for measuring unsaturated hydraulic conductivity except that the cell is much shorter and only one tensiometer is used.*

Q. When discussing the difference between target and interpreted matric suction, the authors say that instrumentation did not indicate problems. Can the authors discuss the uncertainty further?

A. *This statement was made with regard to the function of the diffused air volume indicator and pore water volume measuring system. These systems appeared to function properly in that the calculation of water volume change determined from burette readings, corrected for measured diffused air volume, indicated a relatively small change in water volume in the soil bed. The water pressure maintained in the pore water control system* *represents the target matric suction while the interpreted matric suction was based on the water content of the soil and the soil water characteristic curve. Since the water content of the soil bed was not effectively changed by the pore water control system over the timeframe in question, the target and interpreted matric suction should be different. The exception would be if the soil moisture content were such that water pressure in the pore water control system and interpreted matric suction coincide. Subsequent measurements with tensiometers in the soil bed support the interpretation of matric suction from the soil water characteristic curves. Additional work in this area is ongoing.*

Q. How did they saturate the 3 bar air entry ceramics? Were these just soaked in water, or was a positive pressure applied?
A. *The stones were submerged in water and chamber pressure applied to the air above the water. After some time water was allowed to flow through each stone.*

Q. Did they try to measure the air entry value of the ceramic by increasing the air pressure inside the chamber without the sample?
A: *No; however, water was forced to flow through each stone, one at a time, in order to check the effective permeability as compared to what it should be for a properly saturated, sealed stone.*

It is wished to thank the authors along with those attending Parallel Session 2.2 for the lively presentations and discussions and in particular for those who found enough time in busy schedules to provide written answers to questions.