CLOSING REMARKS AT THE CONFERENCE ENTITLED, *"FROM EXPERIMENTAL EVIDENCE TOWARDS NUMERICAL MODELLING OF UNSATURATED SOILS"*, HELD ON SEPTEMBER 18 AND 19, 2003; VENUE: BAUHAUS-UNIVERSITAT, WEIMAR, GERMANY

By Delwyn G. Fredlund

The field of unsaturated soil mechanics has been propelled forward by a variety of concerns brought to the fore by societal demands. In the 1960s, a series of international conferences was convened to better understand the behavior of expansive soils. As a result of these conferences, geotechnical engineers became aware of the significant role played by soil suction. Consequently, the volume change behavior of expansive soils began to be viewed in terms of changes in soil suction. Later, there was considerable interest in studying landslides precipitated by a reduction in soil suction as a result of excessive rainfall over a period of time. In the 1980s, society began to demand greater accountability with regard to our stewardship of the environment. The need for accountability provided a great impetus for research into the movement of water and chemicals through the unsaturated portion of the soil profile. Another application that provided an incentive to better understand unsaturated soil behavior was the need for adequate handling of radioactive wastes from nuclear power plants.

Over a period of about 30 years, the theories and formulations for unsaturated soil mechanics have been put forth and verified through numerous research studies. Unsaturated soil mechanics is now sometimes referred to as "Nonlinear Soil Mechanics" and it is interested that our understanding of unsaturated soil behavior has paralleled the development of computational ability to make numerical solutions available for geotechnical engineering practice.

At the close of this conference, I would like to provide a few comments in response to 4 questions that have been placed before me by the Organizing Chairman, Dr. Tom Schanz. I will attempt to answer these questions by taking into consideration research studies around the world over the past few years. These questions are as follows.

1.) **What are the major landmark contributions in the last five years relative to the field of Unsaturated Soil Mechanics?**

The past few years have indeed bore witness to a number of significant major landmark contributions in the area of unsaturated soil mechanics. I couldn't help thinking back to the time when Dr. Harianto Rahardjo and I completed the writing of the book entitled, "Soil Mechanics for Unsaturated Soils" in 1993. No sooner was the book completed than we realized that it had some shortcomings. It had shortcomings because some significant landmark developments were emerging in unsaturated soil mechanics. Our book attempted to take the classic areas of *saturated soil mechanics* and extend these areas to embrace *unsaturated soil behavior*. The book focused primarily on the areas of i.) seepage, ii.) volume change and iii.) shear strength. For each of those areas, the book presented, i.) theory, ii.) methods of measuring he soil properties and iii.) application of

the theory to engineering practice, for unsaturated soils. While the book provided an extension of the classic theories into the unsaturated soil range, implementation of unsaturated soil mechanics proved to be difficult due mainly to the cost of measuring unsaturated soil properties. However, engineers are problem-solvers and geotechnical engineers began to find ways whereby unsaturated soil mechanics could be implemented into routine geotechnical engineering.

As a result of extensive research in unsaturated soil mechanics, the soil-water characteristic curve, SWCC, emerged as a means for estimating unsaturated soil property functions. I would say that research into techniques for estimating unsaturated soil property functions has been one of the most significant research contributions in the last 5 to 10 years.

There are also other significant landmark contributions that have also been made. Significant progress has been made in developing elasto-plastic models for unsaturated soils; however, we need to realize that there is still need for more research on comprehensive elasto-plastic models that incorporate wetting and drying paths along all total stress loading paths. The models should be verified for a wide range of soils (e.g., sands, silts and clays) prepared as either initially remolded materials (e.g., compacted) or initially undisturbed. Consideration also needs to be given to the variations in soil model behavior that might occur in the occluded air bubble stage (near saturation), the desaturation phase between the air entry value and the residual suction stage, as well as the stage beyond residual suction conditions.

Significant contributions have been made by geotechnical engineers in the measurement of soil suction. There is great need for both "direct" and "indirect" means of measuring soil suction *in situ* and in the laboratory. The advances in the direct measurement of matric suctions beyond one atmosphere are to be hailed as a significant breakthrough. At the same time, it is important to be transparent regarding the limitations of this technology. Further research should be undertaken to more fully understand the factors that affect the longevity of such suction measurements. The advances in the use of "indirect" methods such as TDR and TC (i.e., Thermal Conductivity) are also worthy of mention particularly because of their ongoing functionality with limited maintenance over long-term monitoring.

2.) What are the deficiencies we are facing today?

I believe that one of the primary deficiencies in unsaturated soil mechanics is the lack of comprehensive case histories where sufficient state variables have been measured in the field in order that an assessment can be made regarding the accuracy of the proposed theories for unsaturated soil behavior. We need to see the "Observational Method" used over and over again relative to the assessment of unsaturated soil behavior. It is interesting to note that the present Chairman of the TC6 Committee on Unsaturated Soils (Professor E. Alonso) has made a special plea for detailed case histories involving unsaturated soils.

I also believe that there is still need for more research into the measurement of matric suction *in situ* and in the laboratory. Limitations in the measurement of soil suction result in a deficiency to the overall implementation of unsaturated soil mechanics.

There have been numerous formulations that have been proposed in the research literature associated with elasto-plastic type soil models. While these formulations are encouraging to see, it is advantageous to have the models eventually formulated on a sound continuum mechanics basis, if at all possible. In other words, it is preferable that there be a clear distinction when using empiricism in the description of state variables for the models, as opposed to following the requirements of classical continuum mechanics. I would note that reference was made at this conference to a "constitutive stress" for an unsaturated soil. Such a reference is an oxymoron in the sense that "stress" is a state variable and the word, "constitutive" must link together state variables. The use of the word "effective stress" for unsaturated soils is also "constitutive" in character and therefore interjects empiricism at the onset of subsequent formulations. Researchers may choose to deviate from all the classical concepts of continuum mechanics in some of their formulations but it should be realized that these constitute deficiencies that we face as researchers in unsaturated soil mechanics.

3.) Which major questions are still open ended?

I believe that models for unsaturated soil behavior need to be more clearly developed in relation to their position along the soil-water characteristic curve, SWCC. Just as there is a soil behavior models for a saturated soil; likewise there may need to be separate models (or at least, somewhat differing models) developed for soils in the desaturation zone (i.e., between the air entry value and the residual suction value) and the residual zone. In other words, there is evidence that the behavior of an unsaturated soil in the residual zone may be significantly different from its behavior in the desaturation zone between the air entry value and the residual value.

The fundamental physical characteristics of an unsaturated soil in the "residual suction" range need to be further studied with respect to volume change, shear and seepage behavior. For example, liquid water flow most likely ceases in the residual zone and only water vapor flow is of consequence. Therefore, the permeability function (or hydraulic conductivity function) should not be mathematically extended into the residual soil range when using empirical estimation techniques. This subject requires further research. Likewise, research is also required for the volume change and shear strength behavior of unsaturated soils in the residual soil range.

Research needs to be done regarding the required accuracy for the assessment of unsaturated soil property functions for various types of problems. In other words, estimation techniques may be suitable for certain types of problems but may be unsuitable for other problems. There needs to be guidelines made available to practicing geotechnical engineers.

4.) Which are the goals for the next 5 years

I believe that one of the primary goals of the researcher engineers should be studies related to the implementation of unsaturated soil mechanics into routine engineering practice. There is a need to demonstrate in detail the implementation procedures that are to be used by practicing geotechnical engineers. There needs to be protocols (or standards of practice) established for acceptable engineering practice in order that engineers can be protected from excessive litigation associated with unsaturated soils problems.

There should be a review of all near-ground-surface geotechnical problems in order to develop engineering protocols for numerous types of problems. In so doing, it may be possible for some empirical practice procedures to be put onto a more reliable and theoretical basis.

Further attention needs to be given to the quantification of climatic conditions at specific engineering sites. In particular, more research is required on soil-atmosphere models that predict the actual evaporation at a site. As well, there is need for procedures for assessing runoff and infiltration into highly fractured, near-ground-surface soils. These procedures should be somewhat standardized to produce consistency and reliability in engineering practice.

In closing, I want to express my gratitude to Professor Tom Schanz and all his co-workers for the excellent conference that has been held. The organizers have drawn upon research from a variety of disciplines and geographic locations. In so doing, the conference proceedings provide a valuable addition to the unsaturated soil mechanics literature.

Delwyn G. Fredlund