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14. ABSTRACT This is a two-part research program that focuses on the fundamentals of unsaturated soil mechanics. The funding agreement was for three years with one no cost extension. This report is the final project report. The aim of the first part was to modify the MIT method to measure rapid and continuous soil moisture characteristic curves under drying conditions so that the wetting curve can also be obtained with computer					
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Project Summary:

Characterization of Shear Strength of Unsaturated Soils and the Role of Soil Moisture Characteristic Curves

Proposal Number 45730-EV

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Objectives

The first objective was to develop a fundamental model for soil strength based on a micromechanics description of the system (water and particles) in order to understand the physics of unsaturated particulate media. The model will incorporate the effects of soil moisture content and water tension in calculations of inter-particle forces, and then use particle packing considerations to compute continuum effective stresses. This model will rely on the Soil Moisture Characteristic (SMC) curve (i.e. soil water content – matric suction relationship) to analyze the effective stress and to predict its changes as a function of wetting and drying.

The second objective was to develop technology to perform precise measurements of SMC curve and the strength of unsaturated soils. State-of-the-art equipment and techniques, developed at **MIT**, will be used to obtain continuous drying SMC curves rapidly. New methodology and equipment will be devised, building on the existing technique, to obtain continuous wetting SMC curves. For the measurement of shear strength of unsaturated materials, an automated triaxial cell with direct suction measurement and control will be designed and manufactured.

The third objective was to obtain high-quality data from a systematic study undertaken to understand factors controlling unsaturated behavior and strength. These data will be used to evaluate the micromechanical model. Experiments will be performed on increasingly complex geometries of porous media, ranging from uniform manufactured spheres to well graded natural silt, in order to examine the factors which critically affect unsaturated soil behavior.

Approach

The impact of water on the mechanical behavior of unsaturated porous materials is difficult to quantify for a number of reasons. The negative water pressure provides individual bridges between particles. The interparticle force due to these bridges, strengthens the particle contact against shear stress. Assemblages of particles then form structures that ultimately provide the global strength of the material to external loading. The strengthening due to the water tension is an additional factor that must be considered along with particle size, particle shape, packing density, stress conditions, etc. For these reasons, we have simplified the problem and focus on uniform spherical particles at one density and one water content. The approach is then to upscale a micromechanical model for the suction induced effective stress and then verify

this prediction with experimental observations comparing saturated and unsaturated strength measurements.

- *Model for effective stress increment*— The model is built on two essential components. First is the attraction force between two particles due to the suction and interfacial tension of the water surrounding the contact point. This water is commonly termed a pendular ring. The second component is to combine individual contact forces to obtain an average increment in effective stress. This was solved using a range of uniform packing geometries for mono-sized spheres. The solutions of this analysis provide an average increment in effective stress for each packing geometry as a function of particle size, water content and packing geometry. The method provides a means to compute effective stress but does not predict the particle contact strength.
- *Characterization of soil moisture characteristic relationship*— An unique experimental capability has been developed at MIT to measure a continuous response between the water content of an unsaturated particulate material and the water tension in the pore space. This technology is used to characterize the relationship for several materials including the glass beads. In fact, CRREL is supplying materials for such characterization and this results are being used for immediate Army applications. These relationships are particularly important to model predictions of strength as a function of changes in water content.
- *Measurement of effective stress increment*— Triaxial testing is used to measure the strength envelop of uniform glass beads deposited at one density. The equipment was developed at MIT and is completely automated with internal force measurement and has a tensionmeter incorporated into the base. Tests were performed on both saturated and unsaturated glass beads. Comparison of the two envelops provides a back calculation of the mobilized increment in effective stress due to the water tension. The provides a means to directly compare model prediction with experimental measurement for one rather simplified particulate system.

Significance and Army Value

The vast majority of near surface land based sediments around the World exist in a partly saturated condition. This applies to most sands, clays, and organics that are exposed to the atmosphere. The unsaturated layer (vadose zone) varies from a meter to tens of meters. This upper layer is extremely dynamic and plays an important role in energy and vapor transport to the atmosphere. The mechanical behavior (strength and compressibility) of this layer controls vehicle mobility. Changes in the moisture condition of sediment can have a very dramatic impact on the bearing capacity. Understanding the interaction of the sediment layer with the atmosphere and linking this understanding to a predictive model of the bearing capacity would provide a powerful predictive mobility tool to the Army.

Accomplishments

- A model framework has been developed that is based on a micromechanical representation of the sediment. The model applies to granular materials with low water contents in which all the moisture is contained in pendular rings between contacting particles. A relationship for the interparticle force was derived for spherical particles. This contact force was then combined with uniform particle packing combinations to derive effective stress increments. The model provides an means to compute the effective stress increments created by water tension as a function of particle size, particle packing, and moisture content.
- Considerable progress was made in developing the technology (procedures and equipment) to measure the continuous soil moisture characteristic curve. In particular, the improvements have increased the measurement repeatability and now allow more accurate determination of the specimen void ratio. A design is in place for building equipment to measure the wetting curve but this has not yet been fabricated due to funding constraints.

- A series of triaxial compression tests have been performed on saturated and unsaturated specimens of uniform glass beads from two suppliers. These measurements have been used to evaluate the model predictions over a range of effective stress levels. The experimental increment in effective stress is inferred by comparing the strength of the saturated and unsaturated specimens. This experimental value is much larger (5 to 10 times) than the model prediction. This difference was expected and implies that the strength increase associated with water tension is more effective than the increase caused by externally applied boundary stress.

Technology Transfer

- November 2004 met with Berney and Peters at WES during first PI review meeting to discuss potential collaboration with work at the station. Exchanged technical papers but had little follow-up.
- December 2005 traveled to CRREL and presented ARO sponsored research to group of in house scientists. Met with Cole, Grant and Melloh to discuss possible collaborations. Have worked with Melloh relative to SMC determinations. She has provided extra funding through ARO and has supplied samples to MIT for testing.
- September 2007 met again with Berney and Peters at WES during last PI review meeting to discuss research results. They expressed interest in work and have end use for the technology. Berney is sending samples to MIT for SMC testing but unlikely to have substantial funding.
- June 2007 Toker conducted public defense of thesis and submitted thesis to MIT library. Thesis contains extensive description of theory and experimental measurements.
- October 2007 traveled to CRREL and presented summary of ARO sponsored research.
- April 2008 review meeting at MIT with program manager Russell Harmon to provide findings for research. Provided him with Power Point Presentation for internal ARO use.

Impact of Research

- Toker, N.K., Germaine, J.T., and Culligan, P.J. (2003) Comment on “Cavitation during Desaturation of Porous Media Under Tension,” by Dani Or and Markus Tuller, *Water Resources Research*, 39(11).
- Toker, N.K., Germaine, J.T., Sjoblom, K.J., and Culligan, P.J. (2004) “A New Technique for the Rapid Measurement of Continuous Soil Moisture Characteristic Curves,” *Geotechnique*, 54(3), 179-186.
- Toker, N.K. (2007) “Modeling the Relation between Suction, Effective Stress and Shear Strength in *Partially Saturated Granular Media*,” *MIT PhD thesis*, June
- Toker, N.K., Sjoblom, K.J., Germaine, J.T., and Culligan, P.J. (2005) “Improvements and Reliability of the MIT Tensiometers & Studies on Soil Moisture Characteristic Curves,” Poster session Soil and Rock America, Boston, MA
- Adulhadhi, N. (2006) attended Forth International Conference on Unsaturated Soils, Carefree, AZ.
- 3 MIT graduate students worked on the project (one earning a PhD degree).
- 5 MIT undergraduate students worked on the project.