Non-intrusive sensors for the hydro-mechanical characterization of unsaturated soils using centrifuge testing

Capteurs non-intrusifs pour la hydro-mécanique caractérisation des sols non saturés à l'aide de tests centrifuges

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ABSTRACT: This paper presents the development of two non-intrusive measurement systems: a water content sensor based on time-domain reflectometry, and soil deformation measurement based on image analysis. Both systems were implemented at the centrifuge permeameter at The University of Texas at Austin. They provide information to characterize the unsaturated flow properties of soil (soil-water retention curve and unsaturated hydraulic conductivity) and the response to wetting of expansive clays. These new monitoring tools aim at providing continuous measurements while minimizing influences – typically caused by the use of intrusive sensors – over the soil response. A special acrylic permeameter cup was designed to hold TDR probes within its walls; the design was complemented with a probe specific calibration. Digital cameras were installed next to the permeameters. To obtain soil deformation measurements, a combination of markers and edge detection algorithms was implemented. A typical result from an expansion test is presented to show the capabilities of these systems; the average error in the water content measured with the GTDR was about 2%, and the image analysis performed accurately even in the presence of clay masking the edges.

RÉSUMÉ : Cet article présente le développement de deux systèmes de mesure non intrusifs: un capteur de teneur en eau basé sur la réflectométrie dans le domaine temporel et la mesure de déformation des sols basée sur l'analyse d'image. Les deux systèmes ont été mis en œuvre au perméamètre centrifuge de l'Université du Texas à Austin. Ils fournissent des informations pour caractériser les propriétés d'écoulement non saturées du sol (courbe de rétention du sol et de l'eau et conductivité hydraulique insaturée) et la réponse au mouillage des argiles expansives. Ces nouveaux outils de surveillance visent à fournir des mesures continues tout en minimisant les influences - typiquement causées par l'utilisation de capteurs intrusifs - sur la réponse du sol. Une cupule de perméamètre acrylique spéciale a été conçue pour contenir des sondes TDR dans ses parois; La conception a été complétée par un étalonnage spécifique de la sonde. Des caméras numériques ont été installées à côté des perméamètres. Pour obtenir des mesures de déformation du sol, une combinaison de marqueurs et d'algorithmes de détection des arêtes a été mise en œuvre. Un résultat typique d'un test d'expansion est présenté pour montrer les capacités de ces systèmes; L'erreur moyenne dans la teneur en eau mesurée avec le GTDR était d'environ 2%, et l'analyse d'image effectuée avec précision même en présence d'argile masquant les bords..

KEYWORDS: Centrifuge, expansive clays, time-domain reflectometry, image analysis, swelling, volumetric water content.

1 INTRODUCTION

Geotechnical centrifuge modeling is used to evaluate the behavior of prototype structures using reduced-scale models. However, in flow problems centrifuge permeameters can be used to accelerate the flow process. In particular, centrifuge tests can be carried out to determine both the soil-water retention curves and the hydraulic conductivity function.

In flow tests, instrumentation is often incorporated to simultaneously determine the volumetric water content and matric suction along the model. Sensors currently available (e.g. TDR, HDU, ECHO, psychrometers) are commercialized in sizes that are comparatively large in relation to that of the soil specimen itself, which possibly impacts the soil response. Furthermore, recent work has shown that even for low plasticity clays, increased stresses due to g-levels induce soil deformations that affect the hydraulic response and analytical interpretations. The expansive nature of highly plastic clays imposes additional restrictions on the selection of sensors to be used during an infiltration process.

The goal of the work presented in this paper is the development of non-intrusive sensors to determine the deformation and volumetric water content of unsaturated soils during centrifuge testing.

The first system developed as part of this study is identified as GTDR. It is a non-intrusive volumetric water content sensor, based on time-domain reflectometry (TDR) technology, which can be incorporated into the walls of the permeameter cell. Although interaction with the acrylic used for the cell reduces the sensor's accuracy, the correlation between the soil apparent dielectric conductivity (Ka) and its volumetric water content was found to remain well defined. Construction and calibration details are presented herein, along with details on its implementation in a centrifuge environment.

The second system was composed of a set of digital cameras with short focal length lenses installed next to the centrifuge permeameter to obtain images of the soil column. The equipment was particularly useful in accounting for the comparatively high stresses and significant space constraints. A simplified testing approach was selected to evaluate soil deformation: markers were placed in the soil, and the algorithm performed local analysis using edge detection techniques to define marker movements.

The results from an expansion test, conducted to characterize the response of expansive clays to wetting, are presented to highlight the significance of using non-intrusive monitoring techniques in centrifuge environments.

2 BACKGROUND

The design included the following requirements: 1) minimize soil-sensor interaction so that volume changes are not constrained and additional deformations are not caused by the sensors; 2) measure a broad range of volumetric water contents; 3) measurements should be as localized as possible; and 4) sensors must fit in a 71mm (ID) acrylic tube.

2.1 *Non-intrusive time-domain reflectometry sensors (GTDR)*

Time-domain reflectometry is a reliable, highly accurate technique for the determination of the volumetric water content of soils (Jones 2002, Tarantino 2008b). The potential of this methodology comes from the TDR system's ability to accurately determine the apparent dielectric conductivity of a soil (Ka), and the strong correlation between this dielectric property and the soil volumetric water content θv (Topp et al. 1980).

However, the TDR probe must be completely embedded in the soil. McCartney (2007) implemented a vertical TDR probe partially embedded in the wall of the acrylic permeameter cup to determine the average water content across a broad range of the sample. The VWC profile was assumed to be constant and an average value was reported. Yet, this example showed the TDR to be a promising solution. In this case, the proposed solution was to incorporate horizontal TDRs with curved prongs.

2.2 *Image analysis*

Measurements of soil deformations using image analysis have been developed through different methodologies. In particular, PIV, a template matching technique (Adrian, 1991), has been widely used and has led to proprietary and open source codes (White and Bolton, 2003). Indeed, PIV has been applied to obtain displacement fields in centrifuge models (Stainer and White, 2013). However, this method was less appealing for testing on expansive clays due to at least two disadvantages. First, the "patch" must remain undisturbed, which can be satisfactorily achieved with coarse grain soils, but is not effective for fine grain soils like clays. This is because clays undergo volume changes, and their structure and texture change in contact with water. Second, defining matches in successive pictures requires much more computational effort than operations like binarization, morphological operations and edge detection. Because of the nature of the tests, displacements are one-dimensional and along the sample axes. Combined with markers, this creates a simple but effective tool to determine soil deformation using image analysis.

3 EXPERIMENTAL AND ANALYTICAL APPROACHES

The large centrifuge facility includes a permeameter with two swinging buckets at a radius of 0.61 m. Centrifuge tests are carried out in two columns of soil simultaneously. Each bucket holds an acrylic tube in which the soil sample is placed. The centrifuge can reach up to 675 rpm, which corresponds to an acceleration of 300 g's. Both measurement systems were incorporated into the centrifuge facility and their designs take into account the additional forces created by centripetal acceleration. In addition to these new systems, the centrifuge permeameter had the following capabilities: 1) a target infiltration rate provided through a rotary joint; 2) a linear displacement sensor at each bucket to monitor the overall deformation of the soil column; and 3) a chamber, located below the column, to measure the outflow rate via a pressure transducer sensor.

3.1 *GTDR*

The volumetric water content sensors (GTDR) were built by incorporating 3-rod probes (CS645) within the sidewalls of the acrylic permeameter (Figure 1). Preliminary tests showed that curving the TDR prongs did not influence the waveforms and, as a result, the measurements. However, the inclusion of sensors in the cup was found to considerably impact the test results. In this case, the pulse was affected in part by the acrylic, the epoxy used to seal the sensor, and in part by the soil.

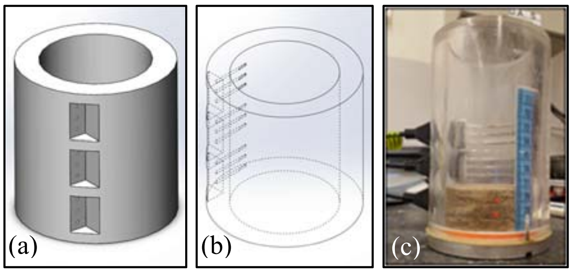

Figure 1. GTDR: (a and b) Solid-works design; (c) implementation

A reduction in travel time and consequently in the equivalent apparent dielectric permittivity was observed from the waveforms. A loss of accuracy could be estimated by comparing the range of apparent dielectric conductivity (Ka) for a given range of water content in the soil between a regular probe and the GTDR. Yet the correlation between the soil apparent dielectric conductivity and its volumetric water content was found to have remained well defined. Although accuracy is lower than that obtained using regular straight probes, the problem of defining a soil-probe-cup specific calibration was changed into defining the appropriate parameters (probe length, offset length, windows length, etc.) for GTDR. A set of probe-specific fitting parameters for each GTDR can be obtained with PC-TDR software (CS). Using these parameters, the apparent dielectric conductivity (Ka) values obtained from a calibration run on a highly plastic clay (Eagle Ford clay) almost matched the one proposed by Topp et al. (1980) (Figure 2).

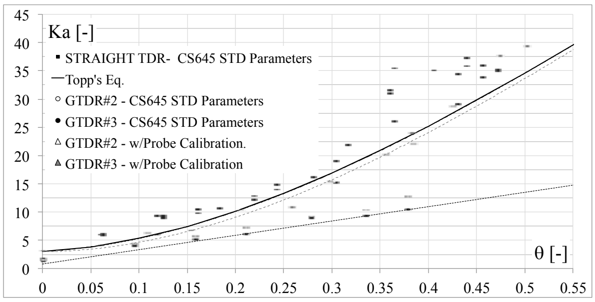

Figure 2. Three different calibration stages of GTDR

Equipment from Campbell Scientific (CS) was installed at the center of the permeameter table to minimize the centrifuge force, including: a pulse generator unit TDR100, a datalogger CR1000, and a multiplexer (Mux) SDM8X50 (Figure 3).

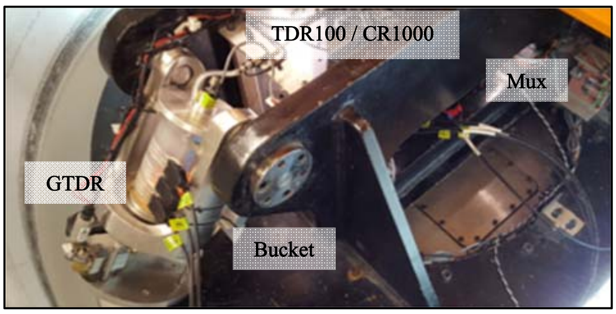

Figure 3. GTDR system within the centrifuge

During centrifuge testing the VWC profile is not constant, for either transient or steady state conditions, along the soil column. In regular arrays, the TDR rods are located perpendicular to the flow direction and the VWC measurement is attributed to a very thin soil layer. In this case, the GTDR covered a significant portion of the column the VWC was an average of the volume of soil being sampled. Waveforms were interpreted using CS firmware built in the datalogger script.

3.2 *Image analysis*

The buckets were instrumented with digital cameras and short focal length lenses (minimum focal distance 60 mm) that remained fixed relative to the acrylic tubes. The support structure and the cameras are shown in Figure 4. LED lights were placed around the permeameter table to provide a uniform diffusive lighting condition.

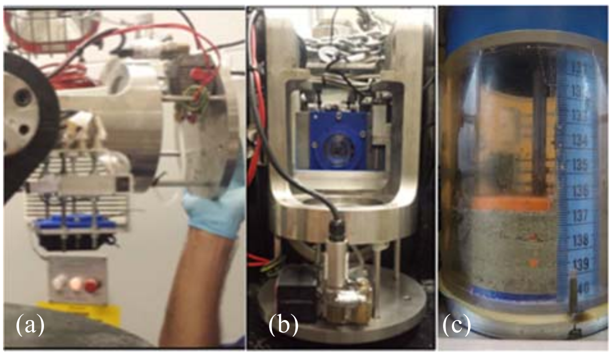

Figure 4. (a and b) Camera mount in the centrifuge bucket, and (c) typical image from an expansion test

An algorithm was designed to measure the displacement of rigid bodies (markers) within the soil column to define a deformation profile, and to monitor the void ratio along the column. Analyses were performed in small local domains to reduce the amount of information and to enhance the contrast between regions of interest. The code was developed in MATLAB using functions from the Image Processing Toolbox. In the analysis proposed, based on edge detection, the markers contours are analyzed to determine the upper and lower boundaries of each marker. Marker movement is defined, in pixels, as the change in position of these boundaries through successive images, and then displacements can be calculated using a local calibration factor (mm/pixel). Finally, the relative movement between the acrylic tube and camera is measured by tracking a fiduciary point in the tube that is not being deformed. Any rigid displacement detected should be added to the displacement of the markers.

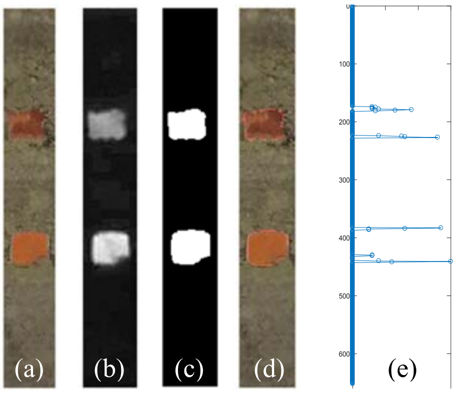

Figure 5. Partial outputs from the image analysis algorithm

An example of the algorithm main steps is presented in Figure 5. First, images were transformed from RGB (a) to the YUV color space. Channel "U" (b) provided an image with a distinctive contrast between the background and markers. This difference is typically reflected as bimodal histograms. Second, images were binarized (c). In general, this process showed a low sensitivity to small variations in the selected threshold value. Third, morphological operators were incorporated to eliminate small imperfections from the binarization process. Fourth, Canny's edge detection procedure was implemented to obtain the edge of the binary images. Images with the detected edges overlaid were created to visually evaluate the success of this process (d). The boundaries were then computed as a number of pixels per row. Peaks were detected, indicating the upper and lower boundaries of each marker (e).

A local calibration factor of 20.7 pixel/mm was obtained along the sample, which indicates a maximum resolution of 48.3 μm/pixel. Additionally an edge-masking effect could be seen when the clay swelled, which caused errors when determining the marker's position. The average height of the marker was calculated to quantify the error.

4 CENTRIFUGE TEST RESULTS AND ANALYSIS

The "hydro-mechanical characterization of unsaturated soils using centrifuge testing" includes two main sets of tests: a) unsaturated hydraulic properties; and b) expansion tests. Both are carried out using expansive clays, but the soil sample size and testing procedure is modified for each case.

In this paper, the result from an expansion test is used to illustrate the accuracy of the non-intrusive sensors and typical results obtained from the tests. Two 30 mm soil samples were compacted in three layers at 15.2 kN/m3 (maximum dry density for the proctor standard test), and a gravimetric water content of 16.5%. A marker was placed at each intermediate layer. The sample was then spun at a constant velocity and water was delivered from the top at a constant rate. Infiltration was sustained until maximum expansion was reached and constant outflow was measured at the bottom.

4.1 *Expansion test results*

The evolution of the global testing variables: soil volume, water content, and degree of saturation are presented in Figure 6. The compression/expansion was monitored with an LVDT from the top, the VWC was measured with a GTDR, and the outflow was collected below the cup.

Different variables can be used to describe the changes in volume of the soil. In Figure 6a, the change in height in millimeters is presented. An initial period was observed where the sample was compressed due to the increased gravitational field. Once the sample leveled out under this loading condition, water was incorporated. Expansion was reported starting from the new condition wherein the sample was densified.

The volumetric expansion is presented in logarithmic scale in Figure 6b. A typical behavior was observed, with an initial "primary" period of rapid growth and a subsequent "secondary" period of a comparatively much smaller constant swelling rate. The threshold between primary and secondary swelling could be defined, thus reducing this process into two linear portions (tp). The intersection of these stages was found to be 70 hrs. At this point 90% of the total swelling was achieved. Same results can be obtained if void ratio is used as a representative variable instead of volumetric swelling.

The evolution of the void ratio with time was compared with the changes in volumetric water content (Figure 6c) and the degree of saturation (Sr) (Figure 6d). The VWC increased rapidly during the primary swelling stage; in this portion the sample is unsaturated; after tp was reached a small change in volume and water content was measured. Finally after 80-90hrs of testing deformation occurs at constant degree of saturation. This time range also matched the time when constant outflow started.

After filtering the sensor data the error in the volumetric water content was about +/-0.02. It can be expected the VWC near saturation to have a higher error since the sensitivity in the calibration is lower between 0.4-0.5. Yet, the error measured in the degree of saturation was about +/-2%.

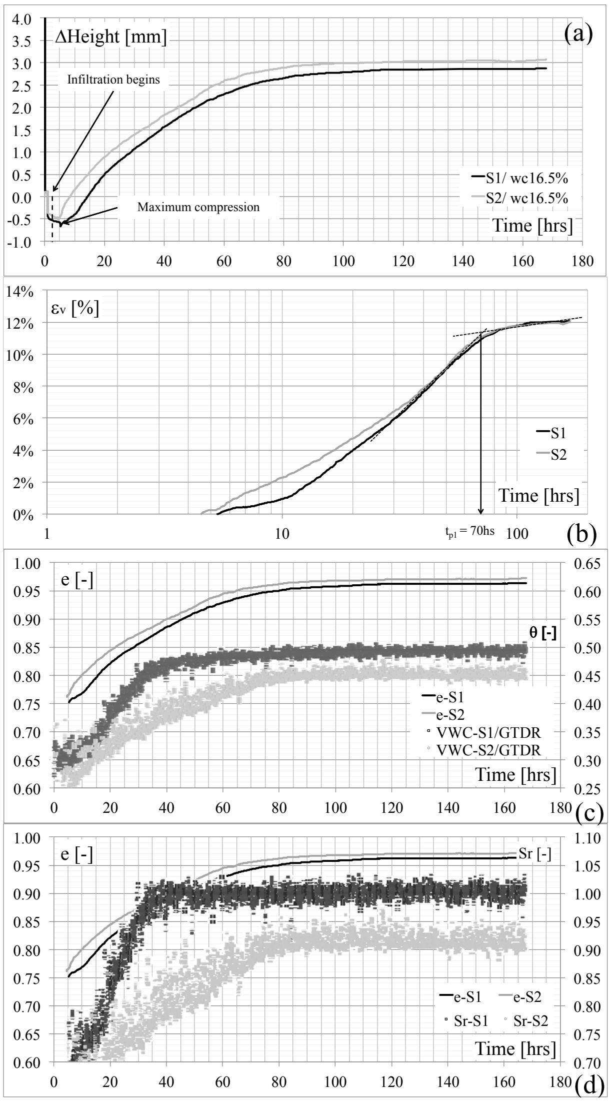

Figure 6. Typical output from an expansion test

4.2 *Image analysis results*

The edge detection algorithm provided information about the movement of the upper and lower boundaries of each rigid body. Physically, the displacement of each marker represents the deformation of all soil located below. While centrifugation may compress the soil, and the markers will move down; clays will swell in contact with water and the markers will move up. A comparison between the algorithm output and naked eye measurements is presented in Figure 7 for a reduced set of eight pictures from the same expansion test. Although handpicked results were only approximate, they showed good agreement with results from the algorithm.

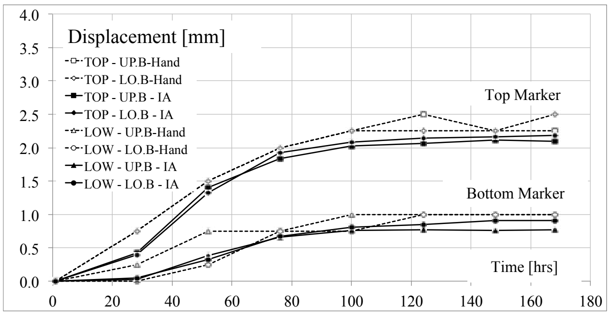

Figure 7. Marker's displacements for a reduced set of pictures

Ideally, the upper and lower boundary measurements should be equal, but the effect of clay edge masking could create differences between them. Typically, masking will be seen first, but not solely, in the upper boundary, as the clay is wetted from top to bottom. The average marker height was calculated. The difference in pixels was less than 5% of the overall movement.

Finally, deformation profiles can be created using this values and the LVDT measurements for a desired time. Additional information can be obtained from this analysis; for example, it can be observed that water did not reached the lower third of the sample before the 30hrs of test since the marker showed no movement.

5 CONCLUSION

Two non-intrusive sensors for monitoring the hydro-mechanical behavior of unsaturated soils were developed and incorporated into the centrifuge permeameter at the University of Texas at Austin. The GTDR sensor measures the volumetric water content of soils without restrictions to soil displacement. A tool set, consisting of inflight cameras and an image analysis algorithm, enabled the measurement of deformation along the soil sample and observation of other features in real time.

The GTDR provided a reliable average measurement of the VWC during the expansion test (+/-0.02); it was observed that the void structure and water content were closely related. The breakpoint between primary and secondary swelling was followed by a reduction in VWC change. Consequently, the degree of saturation remained almost constant after this point. Around this same threshold outflow was observed, changes in both the void ratio and VWC were found to be negligible.

Inflight cameras provided a stable and high-quality image for analysis. The algorithm is simple and benefits from the nature of the centrifuge test – results are obtained in a very short time. Results of an expansion test obtained from a reduced set of pictures showed good performance when compared to measurements carefully taken by hand. Although clay can camouflage the markers, this represents a very small error in displacement.

6 ACKNOWLEDGEMENTS

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