

A LOW-COST AUTOMATED SWCC DEVICE AND DATA ANALYSIS PROCEDURE FOR UNSATURATED SOILS EXHIBITING VOLUME CHANGE

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ABSTRACT

Conventionally, a soil water characteristic curve (SWCC) is measured using a pressure plate device; however, this procedure is relatively tedious, and demands manual measurements. A new system has been developed utilizing a low cost single board computer (Raspberry Pi). The following paper discusses both the operational, and practical benefits of this device as it relates to unsaturated soil mechanics. The device continuously measures volume outflow to determine matric suction equilibrium - producing a SWCC with limited user interaction. The SWCC for numerous soils were approximated. A photogrammetric procedure was employed to measure the shrinkage curve and produce volumetric SWCC's as described by Fredlund et al. (2018). The transient outflow steps were then used to approximate the unsaturated permeability and compared to implicit methods. This device provides a preliminary framework for directly and automatically estimating unsaturated hydraulic conductivity for unsaturated soils exhibiting volume change using multi-step outflow measurement.

RÉSUMÉ

Classiquement, une courbe caractéristique de l'eau du sol (SWCC) est mesurée en utilisant un dispositif à plaque de pression; Cependant, cette procédure est relativement fastidieuse et nécessite des mesures manuelles. Un nouveau système a été développé en utilisant un ordinateur monocarte (Raspberry Pi) à faible coût. Le document qui suit décrit à la fois les avantages opérationnels et pratiques de ce dispositif en ce qui concerne la mécanique des sols non saturés. L'appareil mesure en permanence le débit sortant pour déterminer l'équilibre d'aspiration matriciel - produisant un SWCC avec une interaction utilisateur limitée. Les SWCC pour de nombreux sols ont été approximés. Une procédure photogrammétrique a été utilisée pour mesurer la courbe de retrait et produire des SWCC volumétriques, comme décrit par Fredlund et al. (2018). Les étapes de sortie transitoire ont ensuite été utilisées pour estimer la perméabilité non saturée et comparées à des méthodes implicites. Ce dispositif fournit un cadre préliminaire permettant d'estimer directement et automatiquement la conductivité hydraulique non saturée pour des sols non saturés présentant un changement de volume à l'aide d'une mesure du débit en plusieurs étapes.

1 INTRODUCTION

The Soil-Water Characteristic Curve (SWCC) describes a fundamental relationship between volumetric water content and soil suction for a given soil (at a specific void ratio). The SWCC can then be used to predict shear strength (Han and Vanapalli 2016) or unsaturated hydraulic conductivity (Fredlund et al. 1994). The use of unsaturated soil mechanics in practice has become more practical due to increases in computing abilities in recent years (Siemens, 2018). However, the long laboratory time and high cost often limits laboratory testing performed on site specific soils. Estimations of the SWCC is commonly made for projects with relatively low risk (Fredlund et al. 2012).

Typically, soil water content is measured in geotechnical engineering as a gravimetric water content. If no volume change occurs when drying, the degree of saturation can be calculated if the specific gravity of the soil solids is known. However, plastic soils often undergo volumetric strain as the matric suction increases the effective stress. If one also considers the Shrinkage Curve in their analysis, the unsaturated soil properties can be more accurately defined for soils experiencing volume change (see Fredlund et al. 2018). The shrinkage curve considers changes in volumetric strain (or void ratio) with changes in gravimetric water content. Combining the

shrinkage curve with the gravimetric SWCC (w -SWCC), the following relationships are established:

- 1) Gravimetric Water Content versus Soil Suction
- 2) Void Ratio, e , versus Soil Suction
- 3) Volumetric Water Content versus Soil Suction
- 4) Degree of Saturation versus Soil Suction

For soils which are not subject to volume change with increasing suction (i.e., non-plastic soils) assuming a constant void ratio with suction will yield similar curves for relationships 1,3 and 4. However, many soils encountered in geotechnical applications will experience volume change through drying (plastic soils). As a result, the SWCC should also include instantaneous measurements of the soil void ratio with changing water content (Fredlund et al, 2013). Consideration of volume change will produce a more reliable and realistic estimate of the air-entry value (Ψ_{AEV}) and unsaturated hydraulic conductivity. The degree of saturation SWCC (S-SWCC) should be used when estimating the unsaturated hydraulic conductivity (Zhang et al. 2016, 2017).

Soils exhibit hysteresis dependent on whether they are drying or wetting, and the SWCC can be represented as a wetting or drying curve, or an infinite number of scanning curves in between. However, the most common approach is to study the main drying curve for unsaturated soil behaviour (Fredlund et al, 2018). For more complex

models, hysteresis of the SWCC can be incorporated to fully quantify the soil behaviour.

The high nonlinearity when considering unsaturated soil behaviour of plastic soils makes accurate testing and prediction of unsaturated functions challenging. However, it is the objective of this paper to demonstrate a simple, interactive system to minimize user effort and maximize the accuracy of the results. Using a low cost single-board computer, an automated program was developed in Python to approximate the SWCC and the unsaturated hydraulic conductivity function. This program effectively performs multiple outflow measurement steps and measures the outflow with respect to time. Air pressure is applied to simulate the application of matric suction via axis translation (Hilf, 1948).

2 COMPUTER SYSTEM

The Raspberry Pi (RPI) was initially released in 2012 to promote computer science in schools and in developing countries. However, the RPi has expanded to numerous other markets such as robotics, home automation, and research purposes due to its low cost and ability to add on numerous inputs and outputs. The RPi typically runs a Linux based operating system (Raspbian) and uses Python as the main programming language. Python is an open source coding language which contains a large number of available libraries that expedite the coding process during the creation of specialized testing equipment; it is often taught to engineering undergraduate students during computer science.

The automated system contains 5 main components, as shown in Figure 1:

- Tempe cell - isolate soil sample in pressurized environment above a high air entry porous ceramic
- Scale - track volume outflow from Tempe Cell
- Electronic regulator - control pressure in cell
- Electronic solenoid - facilitate flushing of ceramic base
- RPi - control regulator and solenoid and track scale

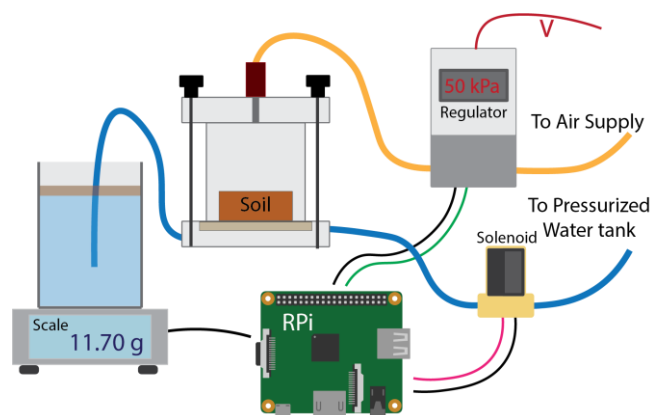


Figure 1. Current Auto-SWCC device

The RPi has a number of pin outputs targeted to a variety of processes and controls. A “breadboard” is used to configure the circuitry during prototype stages. The circuitry of the current version of the Auto-SWCC device is shown in Figure 2.

An electronic pressure regulator is electronically connected to the RPi using a digital-to-analog converter (DAC) (MCP4725). A DAC is a device that outputs a voltage signal proportional to a digital number range. For this device, a range of 0-5 V was output to a pressure regulator capable of 5-900 kPa (full scale). The regulator output was 450 kPa at a maximum DAC output of 5V, which was sufficient for the pressure cell and soil used. Alternative regulator options, such as current control (4-20 mA), can also be used in a similar matter, and would depend on the electronic regulator used.

To track volume outflow of the soil, a common laboratory scale (Mettler Toledo) was connected using a USB AB cable and readings were taken via serial communication protocol. The scale was capable of reading to the nearest 0.01g. Other scales could be used, as long the scale was capable of outputting the current mass to the RPi. The Python code was written to track the serial output by “listening” for inputs and subsequently recorded measurements depending on the logging interval.

The pressure plate cell was connected to the scale using plastic hose. The hose was inserted from above into a beaker such that it was only in the water and did not touch the sides or the bottom of the beaker. To prevent evaporation, a small film of oil was added above the water. The beaker was found to remain at a constant mass over a period of 48 hours; thus, verifying that the oil method was sufficient and evaporation considerations were not necessary. Others have used a separate scale on with a beaker of water to log evaporation losses and correct the scale mass (Shao et al. 2017).

A major limitation of testing with fine-grained soils is the need to use higher air entry ceramic disks. Higher air entry ceramics are subject to the diffusion of air through the disk, which requires frequent flushing if the measurements are to be accurate. The rate of air diffusion is a function of both the air entry value of the ceramic and the applied pressure (Padilla et al. 2006). Stones with an air entry value of 100 to 300 kPa may only require flushing once every couple days as opposed to the daily flushing of a 500 kPa stone (Padilla et al. 2006).

Pressure plate cells often contain two outlets along the bottom to facilitate flushing of air bubbles through the stone. In this set up, the second outlet was connected to the downstream side of a solenoid valve (normally closed). The upstream side of the solenoid valve was connected to a tank filled with distilled de-aired water under approximately 50 kPa of pressure. When subject to 12V, the solenoid opened and flushed water into the beaker on the scale (through the connected lines). It is important to ensure the beaker is large enough to accommodate multiple flushing's without overtopping. An image of the circuitry is given in Figure 3.

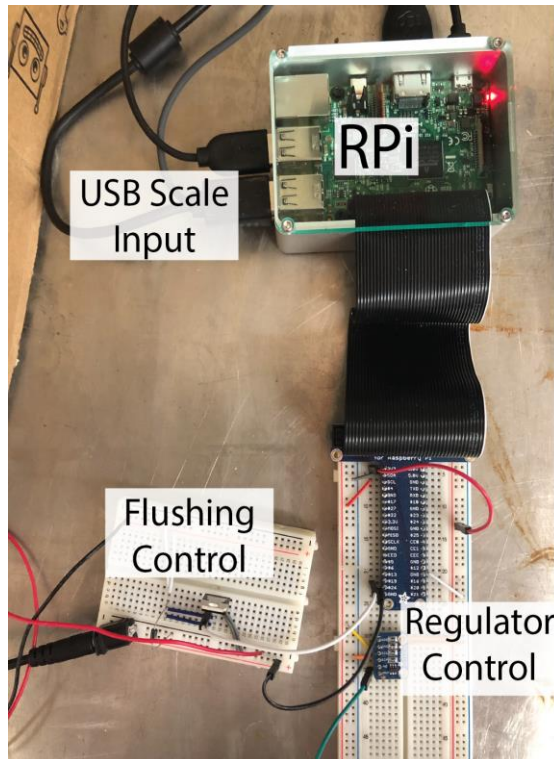


Figure 3: Circuit layout for automation of SWCC device

To control the solenoid, one of the RPi's general purpose input/output pins (i.e., GPIO pins) was used to control an electrical switch (transistor). When the GPIO pin is set to HIGH, the transistor is activated with 5V and the valve opens. When set to LOW (0V), the valve closes. Through trial and error, it was found that approximately 2-5 seconds was adequate to facilitate bubble removal; though, this estimate is dependent on the length of hosing and pressure of tank.

A script was developed in Python on the RPi to accomplish the following goals:

- Log and track the scale mass over time,
- Flush the system at user defined intervals,
- Account for increased mass on the scale due to flushing,
- Track and determine whether relative equilibrium has been achieved, and automatically increase the pressure to the next stage (as required), and
- Cycle through wetting and drying curves, or manually enter pressure increments to evaluate any number of scanning curves.

To facilitate user interaction, a user interface (as shown in Figure 3) was created using the PyQt library and QtDesigner. The user interface plots the outflow data in real time using the PyQtGraph library. The user can also override the automation to begin the next stage, or to flush the stone an additional time through buttons.

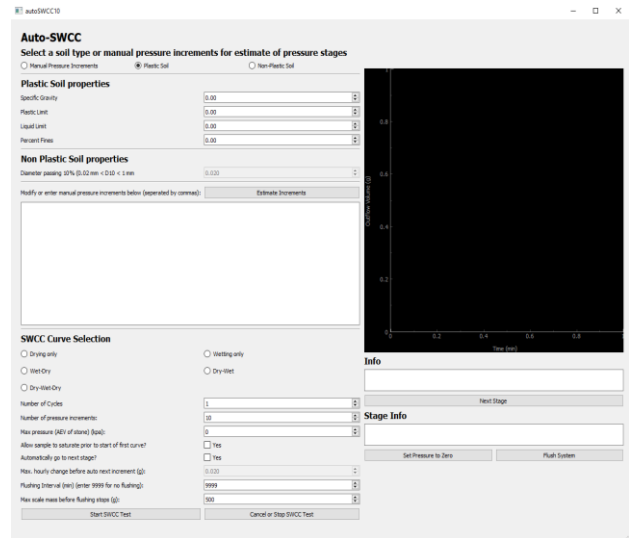


Figure 3: Auto-SWCC interface

To assist users in selecting pressure increments, a SWCC can be estimated based on common soil parameters. The user can first specify if the soil is plastic or non-plastic. If the soil is plastic, the user can input the following soil properties to estimate the SWCC based on the method proposed by Zapata (1999): Specific Gravity, Plastic Limit, Liquid Limit, and Percent Fines. If the soil is non-plastic, the user must input the diameter at which ten percent of the soil is passing during a sieve analysis to estimate the SWCC based on the method proposed by Torres (2011).

With the soil properties entered, the user then specifies the type of SWCC curve they wish to obtain from the experiment: Drying Only, Wetting Only, Wet-Dry, Dry-Wet, or Dry-Wet-Dry. The program then estimates the approximate Ψ_{AEV} and divides the specified increments logarithmically between the 1/3 of the Ψ_{AEV} and the maximum pressure of the plate being used. Alternatively, manual pressure increments can be entered, and soil parameters can be bypassed to allow for any scanning curve to be analyzed.

The essential computer components were purchased for less than \$100 CAD. The more expensive components of the system consist of the laboratory scale, Tempe Cell, and electronic regulator.

3 RESULTS AND DISCUSSION

3.1 Materials

As the objective of this paper is the unsaturated response of plastic soils, a clayey-silt sample has been used for preliminary testing. The characteristics of this soil are given below in Table 1.

Table 1: Clayey-Silt Properties

Characteristic	Clayey-Silt
USCS Classification	ML
Specific Gravity	2.71
Liquid limit	38
Plastic limit	31
% Fine Sand	31
% Silt	59
% Clay	10

The soil was uniformly molded into two samples, which were placed in oedometer rings and consolidated lightly to 14 kPa. Each sample was initially measured using calipers, and carefully placed within pressure plate cells (containing 5-bar stones). An air line was split and connected to each of the cells to ensure that they were subject to identical pressures. One cell was connected to an early-version of the Auto-SWCC device as described above.

Pressure was increased to pre-defined manual increments based on past knowledge and testing of this soil. The volume outflow was measured over time and manually interpreted to determine when equilibrium was reached. Equilibrium had not been reached for the final stage of testing (i.e., 350 kPa) at the time of writing this paper; thus, highlighting the extensive testing time required.

3.2 Shrinkage Curve

Currently, shrinkage curves are measured using laser scanners (Wong et al. 2018) or photogrammetry (Li et al. 2018). To measure the shrinkage curve, the cell not connected to the RPi was disassembled and the soil sample was weighed once equilibrium was reached for each increment. A photogrammetry procedure was then used to measure the volume of the soil specimen. Photogrammetry involves taking numerous photos using a high-resolution camera and triangulating common points between pictures (see Luhmann et al. 2014). A typical mesh and the original image are given in Figure 4.

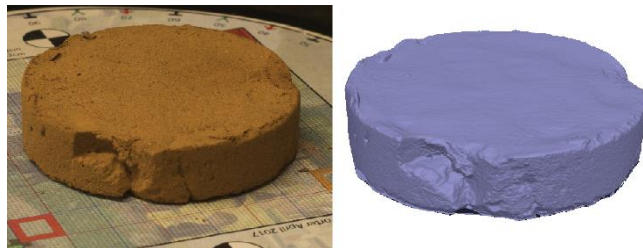


Figure 4: Mesh created (right) from photogrammetry on soil specimens to determine void ratio during testing

Calipers were also used as an alternative to measure the soil specimen. Due to irregularities (as seen in Figure 4), the calipers tended to overestimate the void ratio. However, recent work by Wong et al. (2018) has

demonstrated that the shrinkage curve can be estimated by the plasticity ratio. The parameters for the shrinkage curve were estimated using the Wong et al. (2018) procedure and confirmed with a photogrammetry and caliper points as shown in Figure 5.

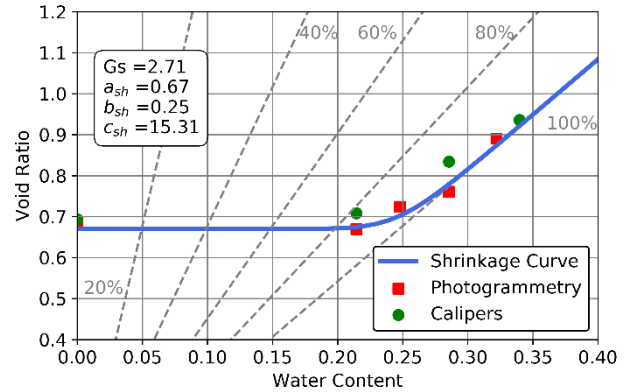


Figure 5: Shrinkage curve and fitting parameters as estimated by Wong et al. (2018) along with points measured during testing

3.3 Soil water characteristic curves

Based on the net outflow from increments as recorded by the device, the gravimetric SWCC (w-SWCC) could be estimated and is shown in Figure 6. Points above 500 kPa were estimated using a dewpoint potentiometer. This was compared to the curve as predicted by Zapata (1999).

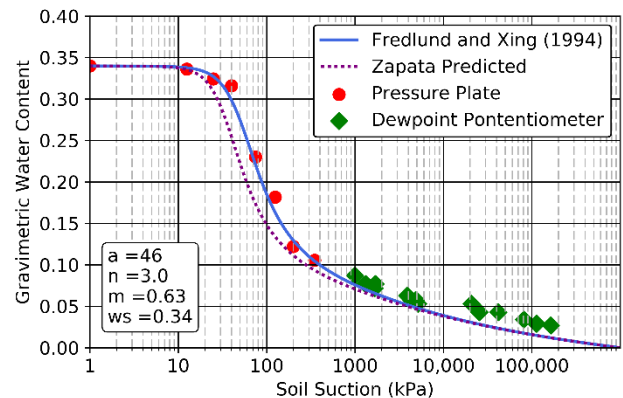


Figure 6: w-SWCC and fitting parameters for Clayey Silt

The measured SWCC falls to the right of the curve as predicted by Zapata, indicating a higher air entry value. The shape is relatively similar, as could be expected. Prediction of the SWCC prior to measuring gives a good indication of pressure increments for the device, and increases the efficiency by reducing the number of points that provide little data to the user (ex: suction values much less than the air entry value). It is also advantageous as many times

users may not have extensive knowledge in unsaturated soil mechanics.

Using the relationship between void ratio, specific gravity, and the w-SWCC, the degree of saturation S-SWCC could be approximated (see Zhang et al. 2017) and is shown in Figure 7. It is the S-SWCC that should be used in determining the unsaturated hydraulic conductivity function for soils that change volume during changes in matric suction (Zhang et al. 2017; Fredlund et al. 2018).

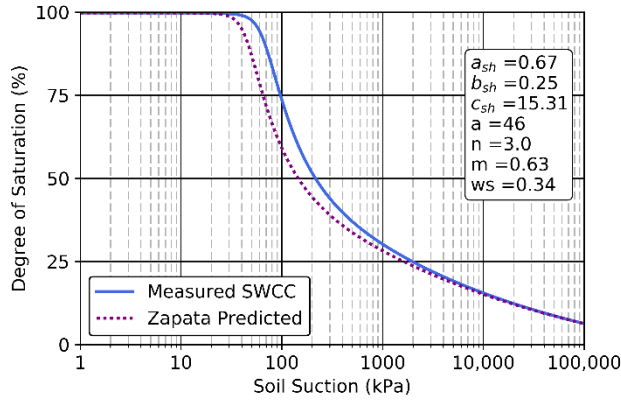


Figure 7: S-SWCC and fitting parameters for Clayey Silt

The curve estimated using the method by Zapata (1999) and the predicted shrinkage curve tends to under predict the “true” air entry value. This in turn would affect the prediction of unsaturated permeability, as well as other geotechnical parameters (Fredlund, 2012).

3.4 Unsaturated conductivity function

The hydraulic conductivity function is both influenced by the degree of saturation and the void ratio of the soil specimen. The estimated unsaturated conductivity is a function of the reference saturated permeability, but the reference saturated permeability decreases as the void ratio decreases (Zhang et al. 2017, 2016). To account for this change, falling head tests were conducted at different void ratios. The following relationship was determined between saturated conductivity and void ratio:

$$k_{sat} = 1.5 \times 10^{-8} e^{4.03}$$

Where e = void ratio. The unsaturated hydraulic conductivity function could then be estimated using the following equation considering changes in saturated conductivity with void ration and changes in unsaturated conductivity with changes in degree of saturation (Zhang et al. 2017, 2016):

$$k(\psi) = \frac{A[e(\psi)]^B \int_{\ln(\psi)}^b \frac{S(e^y) - S(\psi)}{e^y} S'(e^y) dy}{\int_{\ln(\psi_{aev})}^b \frac{S(e^y) - S(\psi_{aev})}{e^y} S'(e^y) dy}$$

Where $A = 1.5 \times 10^{-8}$ m/s, $B=4.03$, e =void ratio, ψ = soil suction. The resulting hydraulic conductivity function is shown below in Figure 8 considering both a constant k_{sat} assumption ($A = k_{sat}$, $B=0$) and a variable k_{sat} function as described above.

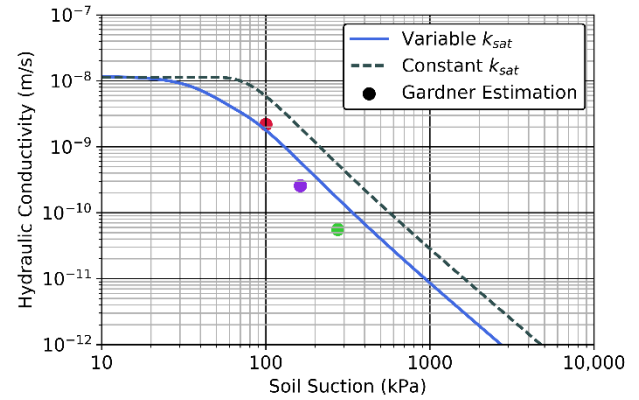


Figure 8: Estimated hydraulic conductivity function and estimated outflow measured points for Clayey Silt

An advantage of the developed system is the ability to collect numerous data points and analyze the outflow data. Numerous attempts to back calculate the SWCC and unsaturated functions have been made based on the transient outflow response for primarily non-plastic soils (van Dam 1994; Eching et al. 1994; Chen et al. 2016). A simple model, as described by Gardner (1956) was used in this study to approximate the diffusivity, which can be used to calculate the hydraulic conductivity. The major assumption is that the coefficient of permeability is constant and volumetric water content is linear for a small increase in matric suction. Both of these assumptions are nevertheless wrong, especially for a soil exhibiting volume change. The diffusivity does, however, give some indication of the time required until equilibrium is reached for an increment as well as the approximate hydraulic conductivity. A normalized outflow with time and estimated diffusivity is given in Figure 9 where Q_o is the total outflow for the given increment.

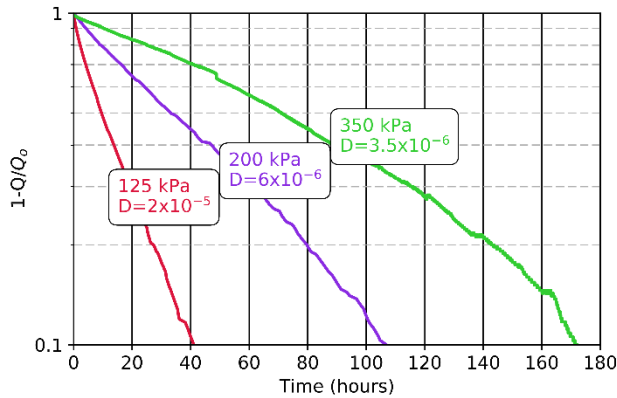


Figure 9: Normalized semi-log plot of outflow as a function of time

The time to reach a $1-Q/Q_0$ value of 0.1 ranged from 40, 104 to 170 hours for the 125, 200 and 350 kPa pressure increments respectively. The plot should be linear, if the assumptions are correct. Non-linearity likely occurred because of large suction increments. The hydraulic conductivities were estimated from the diffusivities and are shown on Figure 8 as Gardner Estimation points. The resulting diffusivity is the average diffusivity over the entire increment, similar to the assumptions during a classical Terzaghi consolidation analysis (Rahardjo 1990). More accurate estimations of unsaturated conductivity could be performed if smaller increments of pressure were used, although this would increase the time of testing.

4 FUTURE WORK

A major hurdle of the automated system is the determination of equilibrium for a given stage. The time to equilibrium increases as the diffusivity (and hydraulic conductivity) of the soil decreases. This may likely be more problematic for coarser soils on pressure plates, such as silty sands, as the hydraulic conductivity and diffusivity decrease to the point that equilibrium takes weeks (Gee et al. 2002). Improper assessment of equilibrium could result in errors in the SWCC. Through user input of select parameters, an algorithm could feasibly be designed to predict the various SWCC's, the unsaturated function (and corresponding diffusivities), and the time to equilibrium for each step. The program could then estimate the time to completion for the multiple stages as well as the sequence. Work is in progress to optimize the numerous components.

Further components could also be added. Linear voltage displacement transducers to measure vertical volume change with time could be incorporated through use of an analog to digital converter add on to the RPi.

An attempt will be made to better calculate the unsaturated hydraulic conductivity from the transient outflow measurements. To date, there has been numerous multi and single step outflow measurements, but these have primarily been performed on non-plastic soils or soils exhibiting little volume change.

An option for implementation of a null pressure plate type system (Olson and Langfelder 1965; Power and Vanapalli 2010) could also be done using a controlled feedback loop. This would allow for estimation of in situ suction values of relatively undisturbed soil samples prior to testing the SWCC. A more accurate scale may be required to improve the response time required for the null technique.

5 CONCLUSION

The improvement and availability of low cost computers, such as the Raspberry Pi, coupled with numerous open-source consumer hardware add-ons, has made it possible to develop and program specialized laboratory tests without extensive computer science knowledge. In this study, a RPi was used to control and monitor the results of a pressure plate device to measure the soil water characteristic curve of a clayey silt soil exhibiting volume change during drying.

The device was set up using the RPi, an electronic regulator and solenoid valve, and scale capable of outputting serial readings. A script and user interface was written in the language Python to control and measure the pressure plate over a number of predefined pressure increments. The device was used to measure and interpret data from a clayey silt soil.

The results show that the SWCC for a soil exhibiting volume change can be reasonably estimated using the device with limited user interaction. By prompting a user for a few initial soil parameters, the S-SWCC and shrinkage curve can be predicted and then subsequently measured. The measurement of the S-SWCC is important as it is used to more accurately predict the unsaturated hydraulic conductivity function (Zhang et al. 2017, 2016).

The continuous recording of outflow data may be used to estimate points along the unsaturated conductivity function. In the current study, the method described by Gardner (1956) was used to estimate points and fit reasonably well with the estimate conductivity function. However, the fit was improved by considering changes in reference saturated conductivity with volume change. Future versions of the automated system could be improved to refine and iterate estimated SWCC values from the unsaturated conductivity function and the SWCC functions.

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