A Simple Approach to Monitor Soil Moisture Dynamic in a Vapour Equilibrium Cell

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ABSTRACT: Vapour equilibrium technique (VET) is usually used to determine the water retention curve of soils. It is a suction-controlled technique where the soil specimen is allowed to reach the suction equilibrium in a desiccator where the relative humidity is controlled by a chemical solution. The suction equilibrium condition is deemed to have been reached when its soil moisture content does not change with time. Therefore, VET requires continuous monitoring for moisture content of the testing soil without disturbing the water vapour exchange process. The aim of this study is to present the electrical resistivity (ER) method that can be used to measure the moisture content of the specimen in VET without disturbance. The ER method is able to monitor the changes of soil moisture with time, and to successfully determine the time at which the soil moisture reaches the equilibrium state. The total suction equilibrium condition was validated independently with the suction measurements using a WP4C water potential meter. The results show good agreement between the total suction equilibrium condition determined by the proposed ER method and the WP4C measurements.

KEYWORDS: Vapour equilibrium technique, Unsaturated soil, Electrical resistivity, Water retention

1. INTRODUCTION

The water retention curve expresses the constitutive relationship between water content and suction. Therefore, it represents the fundamental characteristic of the unsaturated soil (Likos and Lu, 2002; Ridley and Wray, 1996; Romero, 1999). According to Abuel-Naga and Bouazza (2010) there are two ways to evaluate the water retention curve, one is to control suction and measure water content and other is to control water content and measure suction. The first method includes axis translation, vapour equilibrium and osmotic technique. The latter one includes filter paper, psychrometer and tensiometer. However, each method has its intrinsic limitations. The axis translation and osmotic technique may have a capillary barrier; the filter paper may suffer from the possible evaporation at measurement stage; the tensiometer needs a good contact between sensor tip and the soil; and the psychrometer needs a stable temperature condition (Southen and Rowe, 2007; Zur, 1966; Delage et al., 1998; Monroy et al., 2006; Agus and Schanz 2005; Fredlund and Rahardjo, 1993; Blatz et al., 2008; Pintado et al., 2009; Fu et al., 1990; Vasko et al., 2001; Lu et al., 2017).

Despite the limitations of vapour equilibrium technique (VET) in terms of the possible water condensation and the long time required for reaching the equilibrium condition, it has been widely used to create constant suction (Bernier et al., 1997; Blatz et al., 2008; O'Brien, 1948; Tang and Cui, 2005). Salager et al. (2011) recommended an innovated vapour equilibrium method to measure the specimen mass without exposing the specimen to an environmental condition different than the desiccator condition. This method involved measuring the specimen weight while hanging it in the desiccator. However, the possible effect of water condensation was not resolved in this method. Likos and Lu (2002) and Houston et al. (1994) highlighted the consequence of the condensed water in the desiccator and suggested to smear oil on the lid and tilt the desiccator by an angle (e.g. 10 to 20 degrees). The aim of this paper is to introduce an innovative method to determine the vapour equilibrium condition and special setup to overcome the condensation problem. The proposed method could also have the potential of reducing the required equilibrium time as samples are no longer taken out for weight measurements during the vapour equilibrium process.

2. PROPOSED METHOD & SETUP

The use of electrical resistivity (ER) in geotechnical engineering has been carried out extensively in recent years (Rashid et al., 2018; Kibria and Hossain, 2012; Beck et al., 2011; Seladji et al., 2010) and shows good application in soil physics (Corwin and Lesch, 2003; Samouëlian et al., 2005; Campanella and Weemees, 1990). The ER of a soil is strongly influenced by moisture content and several other parameters such as soil structure, texture, mineralogy, temperature and salt content in water (Seladji et al., 2010; Beck et al., 2011; Kibria and Hossain, 2012). Therefore, monitoring soil ER can be used to measure soil moisture and even replace the mass measurement to determine the moisture equilibrium condition of soils.

The proposed method measures the ER of soil specimen inside a PVC tube placed horizontally in a desiccator where the soil specimen fills the middle part of the tube (Figures 1 and 2). When the ER measured over a period of time reaches a constant value, the soil specimen is deemed to have reached equilibrium suction condition. Another advantage of this setup is that the condensed water vapour forming under the desiccator lid will not fall directly onto the soil specimen, since the tube acts as a barrier and shields the soil specimen from water droplets.

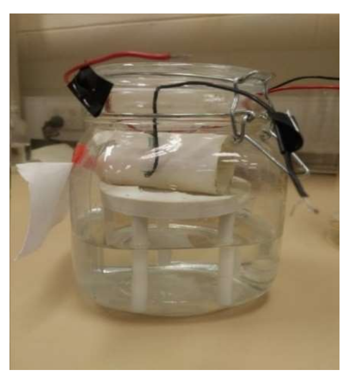

Figure 1 Test setup in the desiccator with different concentrations of NaCl solutions

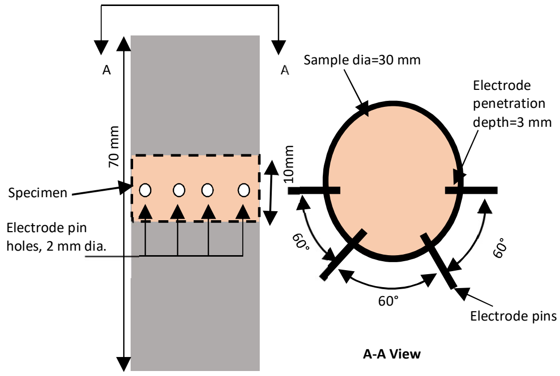

Figure 2 Details of test specimen inside PVC tube

The PVC tube is 30 mm in diameter and 70 mm long and includes four predrilled holes (2 mm in diameter) for inserting the pin electrodes into the soil specimen (Figure 2). To ensure a good contact condition between the stainless steel pins and soil sample, the pins had a penetration depth of 3 mm into the soil sample. The pins are connected to a resistivity meter (Figure 3) to measure the soil resistivity. The desiccator controls the total suction through using different concentrations of NaCl solution (i.e. 0.2M, 0.5M, 1M, 1.5M and 2M).When the measurement of soil ER is required, the alligator clips are connected to the four wires that are fixed to the desiccator lid (Figure 1). This connection will be able to measure soil ER without opening the lid. This is an important feature of the setup ensuring experimental errors are eliminated during the measurement.

Figure 3 Resistivity meter

3. LABORATORY TESTING

3.1 Specimen preparation

Kaolin clay was used in this study. The basic properties of the kaolin clay are shown in Figure 4 and Table 1. The specific gravity, plastic and liquid limit obtained for the kaolin material are 2.58, 32%, and 74%, respectively. These values are close to those reported by Tripathy et al. (2014) that were 2.61, 32% and 51%. During static compaction in a cell, the soil density is likely to be non-uniform along the height (Figure 5). However, Whitman et al. (1960) and Booth (1976) showed that the density variation along the height would be minimal if the diameter is more than double its height. In the current study the diameter to height ratio was 3 which is well above the requirement. A conventional food mixer, equipped with rotary blades was used to mix clay and water to minimize the possibility of having nonuniform moisture distribution. Water was added by spraying to reach the target water content of 30%. After mixing, the mixture was stored in a sealed plastic bag for one day to achieve good uniformity. Finally, a small amount of sample (e.g. about 15g) was taken and transferred to the cell (Figure 5) to be compacted statically at 200 kPa vertical stress. Once no more vertical deformation was observed, the specimen was left under 200 kPa for one hour to ensure good homogeneity, stress relaxation and to reduce the elastic rebound of the sample during unloading. The final dry density, height and degree of saturation achieved for the specimen were 1.7 g/cm^3, 10mm and 100%, respectively.

Finally, the soil specimen (Figure 5) was carefully extruded from the cell and then transferred into to the tube before placing the assembly in the desiccator to be equilibrated at different relatively humidities (RH) provided by different molarities of NaCl solution at 25^{o}C.

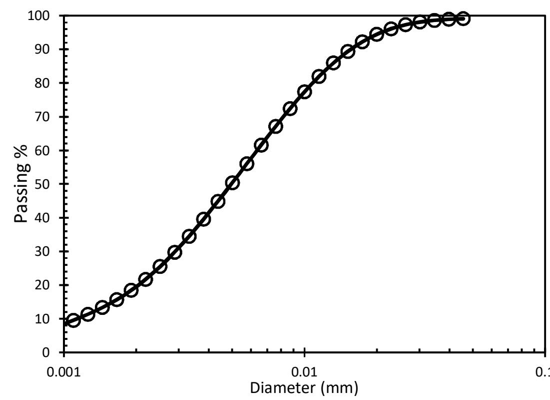

Figure 4 Particle size distribution curve of kaolin material

Table 1 Properties of kaolin in this study and its comparison

	Kaolin	Tripathy et al. (2014)
Liquid limit (%)	74	51
Plastic limit (%)	32	32
G_s	2.58	2.61

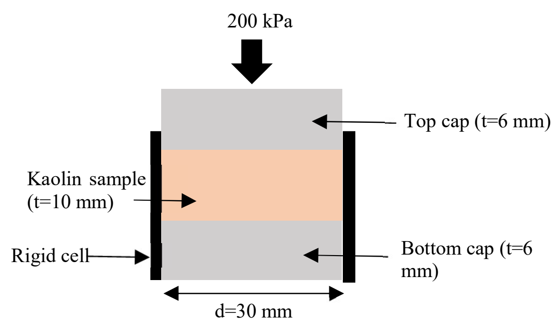

Figure 5 Static consolidation of the kaolin sample

3.2 Testing procedures

The ER readings were measured with time until they became constant. At the completion of the test, the soil specimen in the tube was taken out of the desiccator and the final weight was taken to determine the water content. Two consecutive weight readings four-day apart were also taken to confirm the moisture equilibrium of the tested soil samples. Finally, the total suction of the soil specimen and the NaCl solution in the desiccator were measured by WP4C (Figure 6) to check the equilibrium condition.

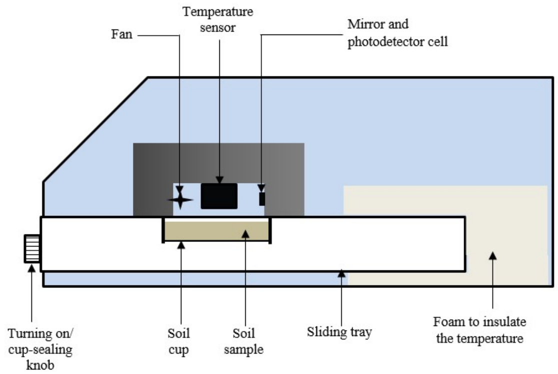

Figure 6 WP4C apparatus used to measure the suction of the specimen and the salt solutions

Figure 6 shows the schematic diagram of WP4C. This device has a temperature sensor, mirror and photodetector cell. When the cup is about half-filled with soil specimen and sealed in the chamber, it will be equilibrated with the vapour in the air above the soil. Once the dew-point temperature is detected by the mirror and reflected into the photodetector cell, the suction is computed using Eq.1 below. A fan is used to accelerate the condensation and hence reduce the equilibrium time. Many studies have used WP4C to examine the water retention behaviour (Bulut and Leong, 2008; Leong et al., 2003; Lu et al., 2017; Seiphoori et al., 2016, 2014; Ferrari et al., 2014).

$$\psi = -\frac{RT}{v_{w0}\omega_V}\ln\left(\frac{u_V}{u_{V0}}\right) \quad (1)$$

where ψ is the total suction (kPa); R is the gas constant (8.31432 J/(mol K)); T is the absolute temperature (T= (273.16+t°C) K), t is the temperature (t°C); v_{w0} is the specific volume of water ($1/\rho_W$ m^3/kg); ω_V is the molecular mass of water vapour (18.016 kg/kmol); u_V is the partial pressure of pore water vapour (kPa); and u_{V0} is the saturation pressure of water vapour over a flat surface of pure water at the same temperature (kPa). The term ratio of u_V/u_{V0} is also called the relative humidity.

4. RESULTS AND DISCUSSIONS

The initial condition of the specimen made the water retention curve to be along the drying path of the curve and the ER readings of all the samples increased with time (Figure 7). Similar to the conventional VET where the equilibrium is defined when a constant mass is achieved. The definition of the equilibrium condition in this study was that at least three similar ER readings were taken continuously prior to terminating the test. The results of the ER reading with time in Figure 7 show that the equilibrium condition was generally achieved after 80 days. In general, increasing the molality of NaCl solution resulted in an increase in the ER readings. It needs to be highlighted that the ER readings obtained could only be used to estimate the equilibrium time. This is because the initial conditions such as the penetration depth of the pins and the spacing between adjacent pins could be slightly different, although the design should be identical. This small difference could have an effect on ER, so the readings obtained could not be used for other purpose. In fact, an important requirement for using ER for soils is they must have equal spacing and penetration depth. Additionally, the shrinkage of soil samples at different RH at the equilibrium condition would be different as well, resulting in different penetration depth compared with 3mm at beginning. These factors could cause the ER results to be unreliable, especially when comparing the data with different samples. For instance, two samples at 1.5M NaCl were used to check repeatability. Both samples approached equilibrium after approximately 60 days with similar pattern, but the ER readings were 7×10^{-4} and 4×10^{-4}, respectively (Figure 7). This difference could be due to the reasons mentioned above.

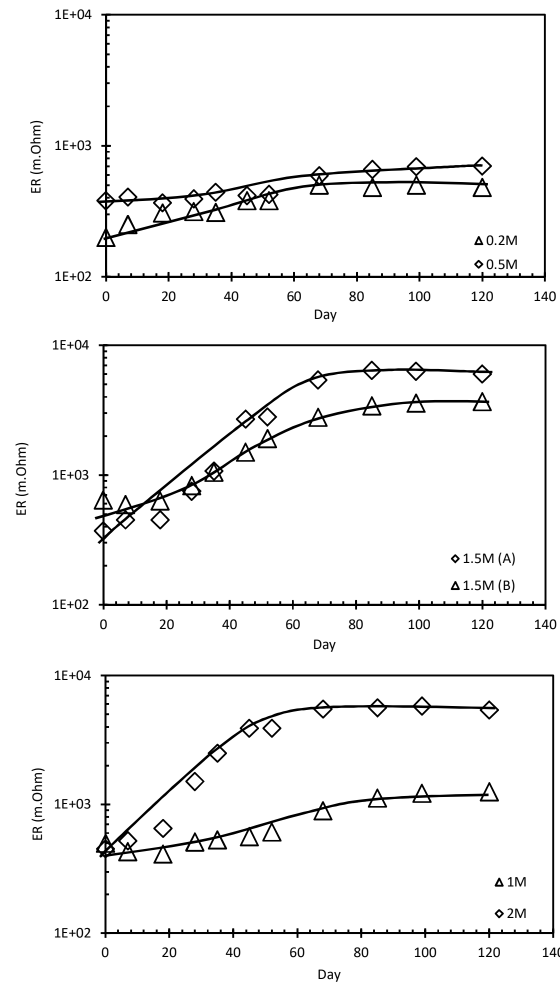

Figure 7 ER reading against time in different molarities of NaCl solution (0.2M, 0.5M, 1M, 1.5M and 2M)

Immediately after the termination of the experiment, the mass of each specimen was measured directly with a 0.0001g resolution balance based on the traditional VET method and the water content variation within 8 days was found to be constant (Figure 8). The two groups (i.e. 1.5M) used for repeatability validation both reached around 6% in water content showing good consistency (Figure 9). Although the concentration difference between 0.2M and 0.5M was small, the difference in equilibrium water content dropped from 22% to 18%. On the other hand, the equilibrium water content difference between 1.5M and 2M was less than 2%. Overall, this direct verification indicated that the technique to measure soil ER was good to estimate the soil equilibrium time and had a good consistency with the VET method.

Furthermore, both osmotic suction of NaCl solution in the desiccator and the total suction of the corresponding soil specimen were measured by WP4C. The results obtained by WP4C showed the total suction of NaCl solution and soil specimen are almost similar. Therefore, vapour equilibrium condition is already achieved. Comparison with the water retention result (Tripathy et al., 2014) conducted on a different type of pure kaolin, the two water retention curves were found to be very similar (Figure 10). Romero et al. (1999) did an experiment on a clay whose main component was kaolin and showed that the dry density had no effect when suction was beyond 1MPa. Although there would be an argument in terms of the effect of dry density to water retention curve for Figure 10, the effect should be negligible for the range of testing in this study.

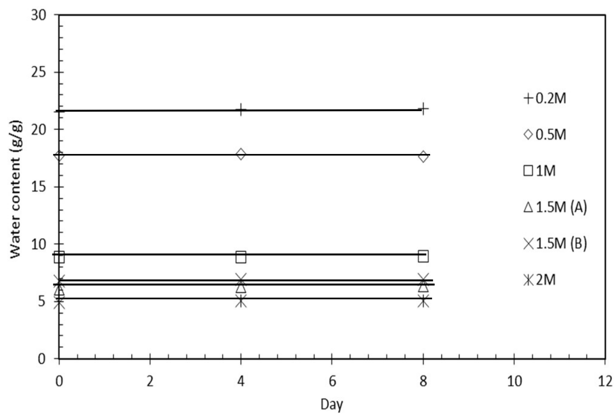

Figure 8 Confirmation of specimen equilibrium measured by the water content change

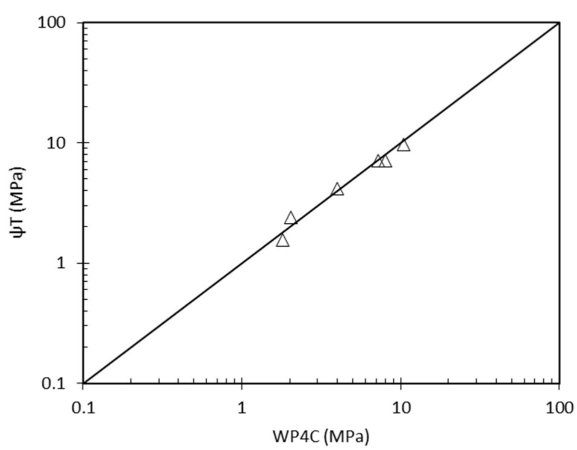

Figure 9 Relationship between total suction of soil specimen measured by WP4C (i.e. WP4C) and NaCl solution (i.e. ψ_T)

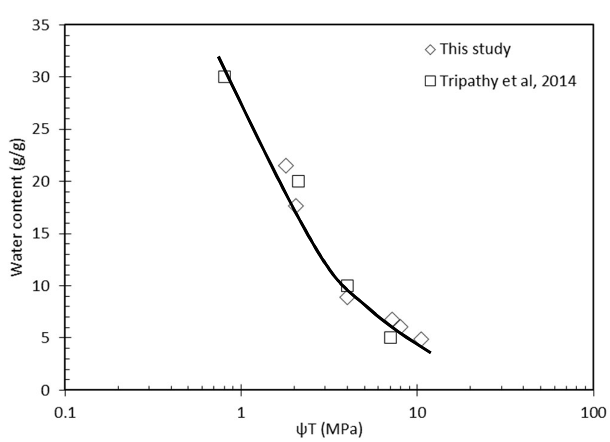

Figure 10 Water retention curve of kaolin based on this study and Tripathy et al. (2014)

5. CONCLUSION

A simple innovative method is introduced to monitor soil moisture dynamic behaviour based on the existing VET method. This method allows the moisture content of the soil sample to be monitored without sample disturbance by measuring the ER of soil sample placed in the desiccator. The ER method is able to monitor the changes of soil moisture with time, and to successfully determine the time at which the soil moisture reaches the equilibrium state.

Compared with the traditional method, this method only needs the final mass to obtain water content and the measurement is not affected by possible condensed vapour drop that may change the moisture content of the specimen during testing. The preliminary results indicate good agreement of the soil equilibrium time and the water retention curve for kaolin clay.

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