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ORIGINAL PAPER

Axis Translation and Negative Water Column Techniques for Suction Control

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Abstract Negative water column and axis translation techniques are conventionally used experimental techniques for obtaining data to interpret the engineering behavior of unsaturated soils. The negative or the hanging water column technique is used as a suction control method in the low suction range (i.e., 0–30 kPa). The axis translation technique is used in the suction range 0 to 500 kPa or higher. This technique is particularly useful for testing specimens with suction values greater than 100 kPa avoiding problems associated with cavitation. While the axis-translation technique has been commonly used, the limitations associated with this technique related to air diffusion, water volume change and evaporation are not discussed in greater detail in the literature. This paper highlights some of the key aspects related to the negative water column and axis translation technique that are of interest both to the researchers and practicing engineers.

Keywords Unsaturated soils · Negative water column technique · Single column technique · Axis translation technique · Suction measuring techniques · Limitations

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1 Introduction

Several disciplines such as soil science, hydrogeology, petroleum, agricultural, ceramics especially geotechnical and geo-environmental engineering have contributed towards our present understanding of the mechanics of unsaturated soils. Significant advancements were made particularly during the last two decades with respect to the development of the theoretical frameworks, experimental methods and numerical techniques related to geotechnical and geo-environmental engineering applications. During this period, four International Conferences on Unsaturated Soils were also held: Paris (France) in 1995, Beijing (China) in 1998, Recife (Brazil) in 2002, and Phoenix (USA) in 2006. As a result, we have a better understanding of the engineering behaviour of unsaturated soils today. Approximately 20% of the publications of recent years in geotechnical and geo-environmental journals are either directly or indirectly related to the research area of unsaturated soils. In spite of the advances of extending the mechanics of unsaturated soils into engineering practice based on experimental methods, there is still a need to better understand the conventionally used negative water column and axis translation techniques that are commonly used in the laboratory testing techniques.

2 Background

The successful implementation of Terzaghi's effective stress principle for saturated soils in the engineering practice has led many researchers to attempt to extend a stress stable variable framework to unsaturated soils. For example Bishop (1959) modified Terzaghi effective stress equation with the introduction of a soil parameter, χ (which is a function of degree of saturation) to interpret the mechanical behaviour of unsaturated soils. Several researchers during the last three decades have proposed frameworks for interpreting the engineering behavior of unsaturated soils in terms of two or more independent stress state variables over a large suction range (Fredlund and Morgenstern 1977; Toll 1990; Wheeler and Sivakumar 1995).

The research direction in recent years has been towards understanding the comprehensive behaviour of unsaturated soils by extending the critical state soil mechanics concepts (Alonso et al. 1990; Wheeler and Sivakumar 1995; Maâtouk et al. 1995; Cui and Delage 1996). More recently, Gallipoli et al. (2003), Wheeler et al. (2003), Tarantino and Tombalato (2005) and Infante Sedano et al. (2007) have proposed coupling of hydro-mechanical behaviour of unsaturated soils. The above research studies were based on experimental studies in which axis translation technique was mainly used as a tool for understanding the comprehensive hydraulic and mechanical behaviour of unsaturated soils.

In recent years several investigators have also proposed indirect methods to predict or estimate the engineering behavior of unsaturated soils. The relationship between water content and suction which, in the literature, is referred to as the soil–water characteristic curve (SWCC) or soil–water retention curve (SWRC) or soil–moisture curve (SMC) has been used as a tool to predict the flow, shear strength and volume change behaviour of unsaturated soils (Fredlund and Rahardjo 1993; Vanapalli et al. 1996; Barbour 1998; Leong and Rahardjo 1997). The negative water column technique which was originally introduced by Haines (1927) and Haines (1930) or axis translation technique proposed by Hilf (1956) are commonly used techniques to study the hydraulic and the mechanical behaviour of unsaturated soils.

In this paper, firstly the negative water column technique and its use in suction control is explained. Secondly, several details related to the axis translation technique and its applications are presented. In addition, the limitations of the axis-translation technique and the methods that can be used to alleviate some of these limitations are highlighted. Various parameters that influence the axis-translation technique such as air diffusion, water volume change, long term testing and evaporation are briefly described.

3 Hanging Water Column

Buckingham (1907) was one of the pioneering scientists who measured the relationship between capillary potential and water content (i.e., SWRC) and expressed it as a continuous function using hanging water column (i.e., negative water column) technique. This relationship has been considered as an important milestone in the history of soil physics and the mechanics of unsaturated soils (Barbour 1998; Narasimhan 2005). Buckingham measured the SWRC of different soils (Fig. 1) using 48-inches-tall soil columns packed into metal cylinders, which were allowed to come to equilibrium with a reservoir of water at a fixed elevation of about 50 mm (2 inches) from the bottom end of the columns. The upper end of the columns was closed to prevent evaporation. The gravitational potential energy within the water at any elevation above the reference reservoir elevation after attaining equilibrium conditions was referred to as the capillary potential. Richards (1928) further simplified and refined this technique and proposed an experimental procedure for determining the SWRC using thin specimens and a water reservoir connected to a vacuum

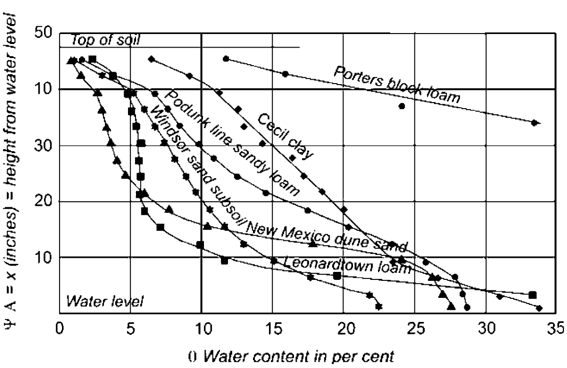


Fig. 1 Soil–water retention curves for six different soils obtained from 48-inch columns (modified after Buckingham 1907)

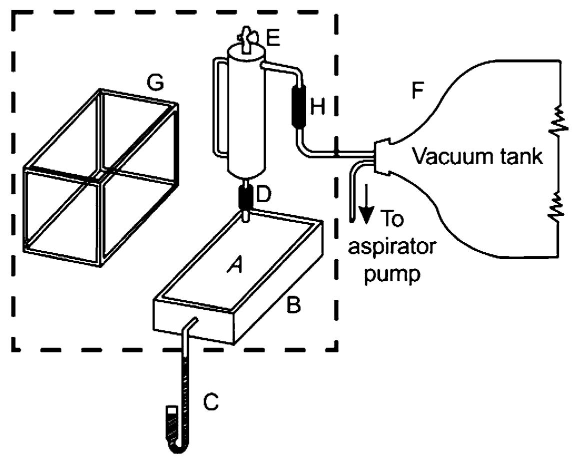


Fig. 2 Richards Apparatus (Richards 1928) (A, Porous plate; B, aluminum case; C, manometer copper tube connection to water reservoir E; F, vacuum tank; G, glass tank; and D, H, rubber connection)

tank (Fig. 2). A constant water level is maintained in this technique; however, it is not possible to monitor water volume changes. In addition, water column height should be checked and adjusted continuously to maintain a constant value of suction.

Figure 3a shows the details of Buchner-Haines funnel apparatus set up. This set up was modified after Haines (1930) who originally introduced the concept of hanging water column technique that can be used for the measurement of the SWRC of coarse-grained soils. The pressure in the water below the porous plate in this apparatus can be reduced to subatmospheric levels by increasing the difference between the elevation of the specimen and the elevation of the reservoir.

More recently, Sharma and Mohamed (2003) used the Buchner funnel apparatus (water column) to investigate contaminants migration in unsaturated/saturated sand for determining the SWRC. The layout of the apparatus is shown in Fig. 3b. Typically, in the Buchner funnel apparatus, specimens are prepared by pouring sand from a fixed height into the water-filled funnel by keeping the water level always above the sand level. The fully saturated specimens are then subjected to increasing capillary tension (i.e., matric suction) by lowering the burette to a given height, to obtain the main drying curve. Similarly, wetting and scanning curves can be obtained by extending this technique. The partial re-wetting of the drying curve by reducing suction and allowing the specimen to imbibe moisture is defined as the scanning curve.

Figure 4 (Dane and Hopmans 2002) can be used to illustrate the Haines' approach in which the matric suction can be regulated varying the level z_1. In Haines apparatus suction is controlled by means of a hanging water column technique that uses both

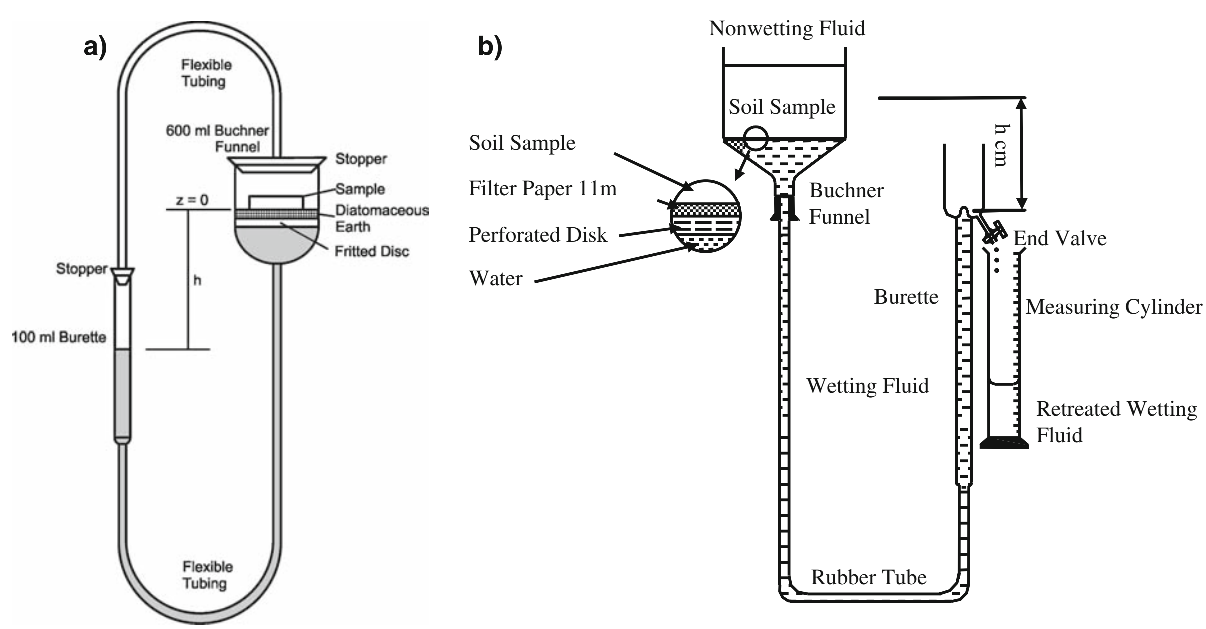


Fig. 3 (**a**) Buchner-Haines funnel apparatus (after Haines 1930); (**b**) Layout of Buchner Funnel for Obtaining SWRC (from Sharma and Mohamed 2003)

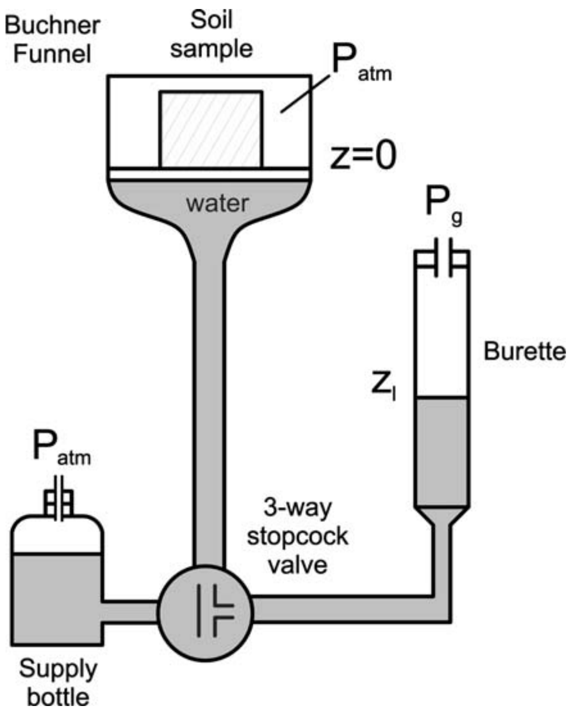


Fig. 4 Diagram of a classical hanging column apparatus (modified after Dane and Hopmans 2002)

vacuum control and hanging column. In the Richards' technique, matric suction can be regulated controlling gas pressure P_g. In the combined apparatus, suction can be regulated either varying the level z_l or by controlling gas pressure P_g.

The maximum suction that can be achieved by the hanging column techniques is typically limited to 20–30 kPa due to practical limitations of achieving higher pressures by adjusting the elevation of the soil specimen and the water level in the column. In the hanging column technique, level z_1 can be adjusted with a resolution of 1 mm and hence suction can be controlled with a resolution of 0.01 kPa. Typically, the hanging column technique is used for investigating water retention features of coarse-grained soils with little fines that drain readily at very low suction values. This technique should be useful to determine SWRCs reliably at low suction values and accurately estimate air entry suction values.

Higher suction values can be attained by "multiple columns" techniques which are described later in the paper. On the contrary, the vacuum control technique permits to directly apply matric suction values in the range from 0 to 80 kPa but requires more sophisticated devices.

One key difference between the hanging column and vacuum control method is associated to the process of air diffusion. Under vacuum control conditions, the gas pressure P_g (see Fig. 4) is maintained at subatmospheric values. However, the air pressure above the porous plate is atmospheric and hence air can diffuse through the drainage system towards the burette. The diffused air can affect the measurements of the water volume flowing in or out of the specimen. However, in the original hanging column technique, the gas pressure P_g above the water reservoir is maintained atmospheric and hence there is no problem associated with air diffusion through the porous plate in the drainage system.

In the vacuum control method, saturated soil specimens are placed in contact with water saturated porous plates or membranes. Matric suction is applied by reducing pore water pressure while maintaining pore gas pressure at atmospheric conditions. The application of matric suction causes water to flow from the specimen until the equilibrium water content corresponding to the applied matric suction is reached.

Different methods can be used to verify the equalization of suction. In the Haines' apparatus (see Fig. 5) equilibrium is established by monitoring the water level; the main shortcoming of this method is related to

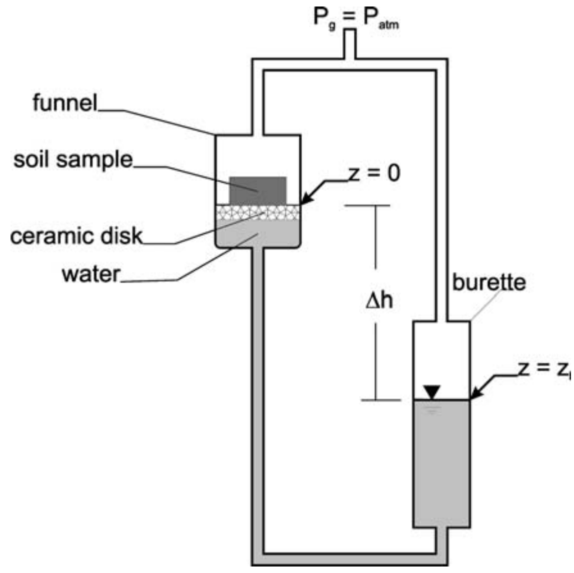


Fig. 5 Haines' apparatus

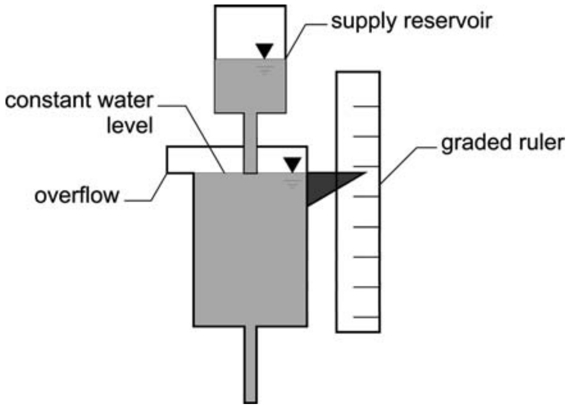


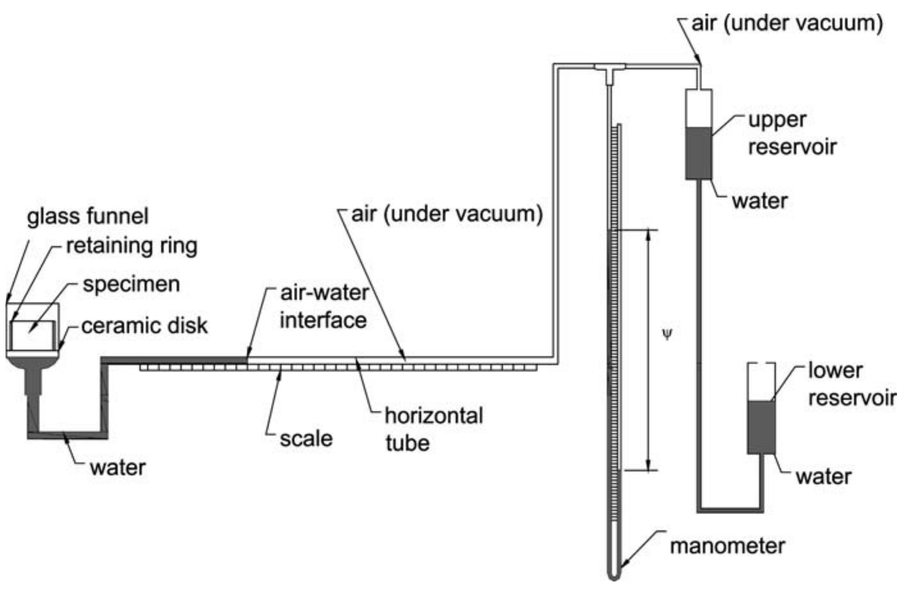
Fig. 6 Levelling device

the burette position which should be continuously adjusted in order to maintain the distance Δh constant. It should be noted that evaporation of water can occur either from the specimen and the porous stone or from the burette. An additional hanging water column should be set up without a soil specimen to measure the evaporation in the system. The information obtained from this additional hanging water column would be useful to apply corrections.

Figure 6 shows a simple levelling device that is useful to keep water flow from the reservoir level constant at the elevation of the overflow. However, equilibrium conditions cannot be assessed by measuring water outflow or inflow from the specimen. To determine suction equilibrium conditions, it is necessary to periodically remove the specimen from the apparatus and measure equilibrium water content. The calculated water content is an average value and corresponds to one matric suction value. This assumption is reasonable for fine textured soil with a gradual change in pore size. However, the same assumption cannot be extended for coarse-grained soils (Dane et al. 1992). The equilibrium matric suction varies linearly with elevation and therefore water content changes along the specimen height. These variations could be significant in the case of coarse-grained soils and hence some corrections should be introduced while measuring the SWRC in the lower suction range (Liu and Dane 1995a; Liu and Dane 1995b).

A recent ASTM standard (ASTM 2003) assumes the configuration of hanging column apparatus represented in Fig. 7. The apparatus consists of a specimen chamber, an outflow measurement tube, and a suction supply system. Water volumes flowing in or out of the specimen during the test are measured using a capillary tube connected to the outflow end of the specimen chamber. The other end of this capillary tube is connected to a vacuum control system consisting of two reservoirs. The relative elevation of these two reservoirs is adjusted to maintain subatmospheric pressures within the water inside the capillary tube. The capillary tube is disposed horizontally at the same elevation of the bottom of the soil specimen; therefore the magnitude of the suction applied can be measured with a manometer. The main advantage of this version

Fig. 7 Hanging column apparatus (ASTM 2003)



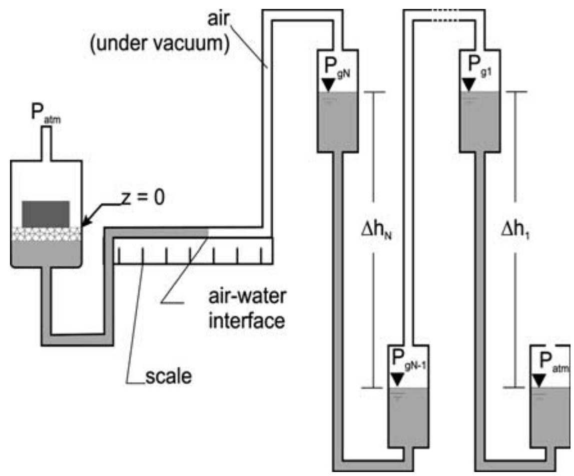


Fig. 8 Multiple hanging water column apparatus

of the hanging column apparatus consists in the fact that equilibrium is established when the water ceases to flow in or out of the specimen without the necessity of continuously adjusting the relative elevation of the reservoirs in order to maintain a constant applied suction. The air diffusion towards the capillary tube however can affect the measurements of the water volume flowing in or out of the specimen.

Multiple hanging water columns with reduced heights can be used to achieve suction values exceeding the limit of 20 to 30 kPa as shown in Fig. 8. As previously stated, higher suction values can be reached using a vacuum control system which consists of a vacuum source and a subatmospheric pressure regulator. An interesting application of the vacuum control system to a suction table is described by Romano et al. (2002). Figure 9 shows an overview of the suction table connected to the devices for controlling the applied suctions in the range from 10 kPa to about 40 kPa. A series of constant-head cylinder (CHC) are used to control the applied suction. Each constant-head cylinder consists of a Mariotte clear plastic or glass cylinders (MAT) forming a bubble tower (BBT). The cylinder has a two-hole rubber stopper at the top. A bubble tube is inserted in one hole of the rubber stopper, whereas the other hole is used to receive a shorter tube for the connection to the adjacent cylinder and, passing through a T-shaped connector, to a valve placed on a panel (PA). The last cylinder in the series is directly connected to the vacuum pump system (VPS). Air bubbles escape out of the bubble tube in the last Mariotte cylinder when the difference between air pressure in the line connected to the vacuum pump system (VPS) and the air pressure in the line of the last bubble tower exceeds the difference between the water pressure at the base of the bubble tube and the air pressure above the water in the column. To keep the release of bubbles to a minimum, it is important to maintain a constant difference between the air pressures in the two lines connected to the bubble tower. Different values of constant suctions can be achieved based on the length of the bubble tube. Applied suction can be adjusted stepwise by sequentially operating the valves on the panel (PA). However fine continuous regulation may be achieved by means of a subatmospheric regulator inserted into the line connecting the bubble towers to the vacuum pump.

More recently, Padilla et al. (2005) provided the design details of a device that can be used for

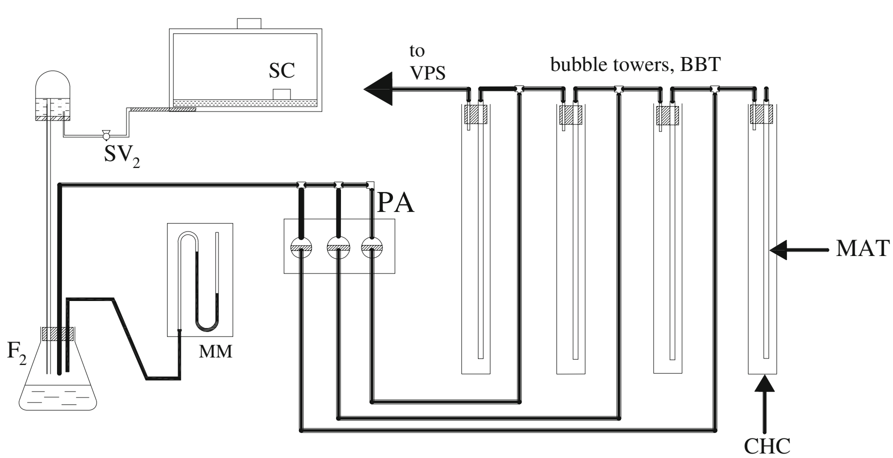


Fig. 9 Schematic diagram of a suction table connected to an high suction system based on vacuum control (after Romano et al. 2002)

measuring SWRCs using relatively thin specimens which facilitate the correction of air diffusion.

4 Axis Translation Technique

Matric suction in an unsaturated soil specimen is defined as the difference between the pore-air pressure, u_a, and the pore-water pressure, u_w. Typically, in an unsaturated soil, pore-air pressure is atmospheric (i.e., $u_a = 0$) and pore water pressure is negative with respect to the atmospheric pressure. The axis-translation technique is conventionally used to determine or apply matric suction to soil specimens (higher than the atmospheric pressure, i.e., greater than 100 kPa) in a laboratory environment without any problems associated with cavitation (Richards 1931; Hilf 1956). This technique translates the origin of reference for the pore-water pressure from standard atmospheric conditions to the final air pressure in the chamber. Figure 10 shows the principle associated with the axis-translation technique (Marinho et al. 2008).

4.1 Equipment Details

The equipment used for measuring the matric suction of an unsaturated soil specimen using the axis translation technique is conventionally called a null pressure plate apparatus. A typical null-type pressure plate assembly is shown in Fig. 11a and the set up of null-type pressure plate device for measuring matric suction is shown in Fig. 11b.

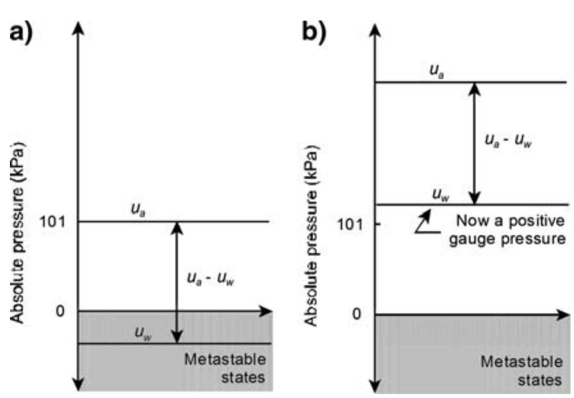


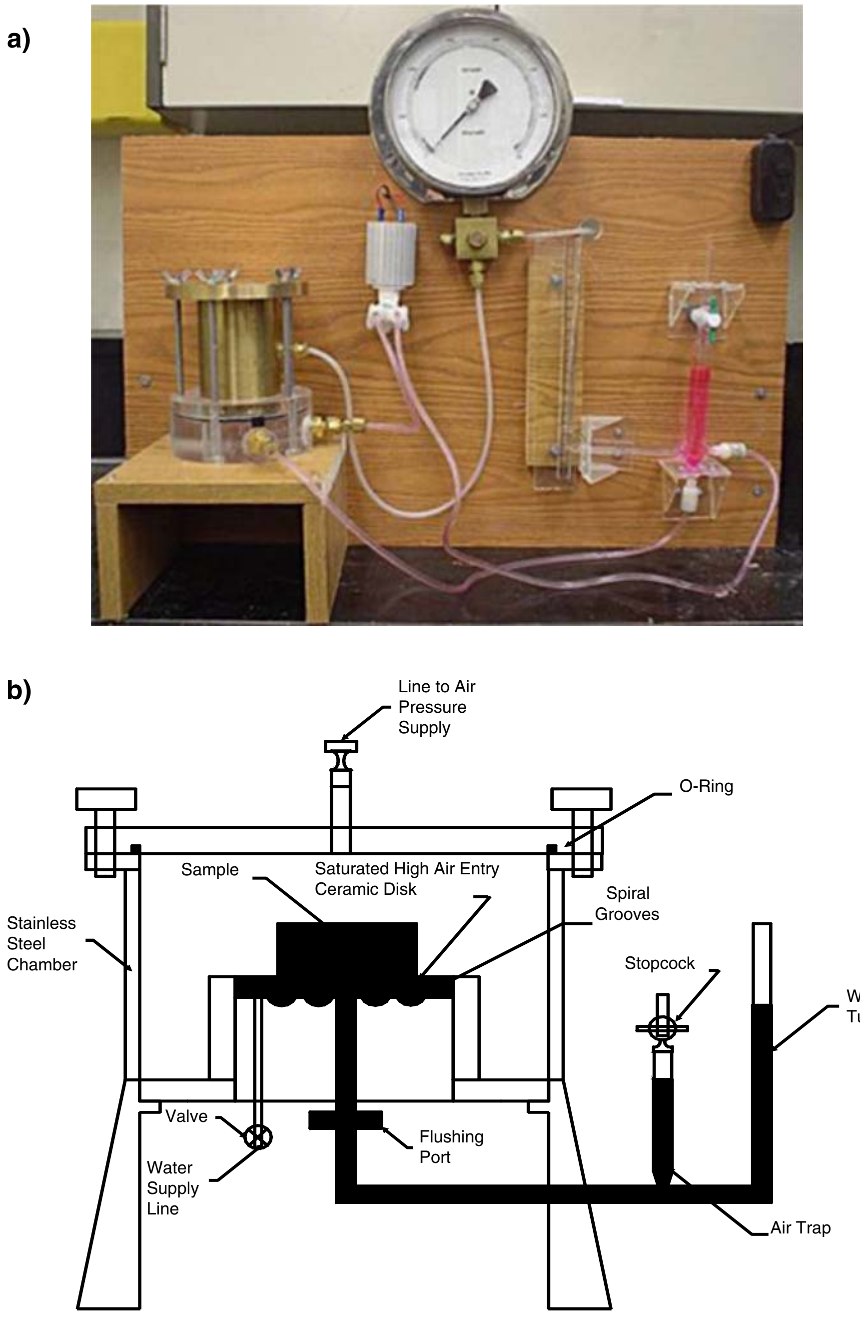
Fig. 10 Use of the axis translation technique to avoid metastable states. (**a**) atmospheric conditions. (**b**) axis-translation (Marinho et al. 2008.)

The axis-translation technique allows the pore-water pressure, u_w, in an unsaturated soil to be measured (or controlled) using a ceramic disk with fine pores (i.e., referred to as the high air-entry disk). These disks are conventionally used in unsaturated soil testing in place of porous disks used in saturated soil testing. The high air-entry disk acts as an interface that separates air and water phases. The separation of water and air phases can be achieved only up to the air-entry value of the disk. The air-entry value refers to the maximum matric suction to which the high air-entry disk can be subjected before free air passes through the disk. The maximum sustainable difference between the air pressure and water pressure is a function of the surface tension and the maximum effective pore size of the ceramic disk material (Fredlund and Rahardjo 1993; Lu and Likos 2004)

The soil specimen is placed in the stainless steel pressure chamber (Fig. 11) on top of the high-air entry disk, which is previously saturated. Several techniques are discussed with respect to the procedures that can be used for saturating the high-air entry disk (Fredlund and Rahardjo 1993; Fredlund and Vanapalli 2002). A good contact should be assured between the soil and the high-air entry disk. As soon as the soil specimen is placed on the high-air entry disk, the water in the tube (see Fig. 11b) goes into tension, which is measured using a pressure gauge (Fig. 11a). The tendency of the water to go into tension is resisted by increasing the air pressure in the chamber. A condition of equilibrium is attained when water in the specimen does not go into tension (i.e., attains "null" condition). The applied pore-air pressure, u_a, is the matric suction when the pore-water pressure, u_w, is set to zero (i.e., open to atmospheric pressure conditions). The equilibration time is dependent of the type of soil, size of specimen and air-entry value of the disk. In many cases, the equilibration occurs in 3 to 6 h in 20 mm thick compacted specimens (Vanapalli et al. 1999; Fredlund and Vanapalli 2002).

In some cases, pore water extraction tests can also be conducted using this apparatus by increasing the air pressure and allowing drainage from the specimen through the ceramic disk pores. The drainage continues until the water content of the specimen reaches equilibrium conditions with the applied matric suction, which is recorded as the difference between the water pressure on one side of the disk, which is

Fig. 11 Axis-translation equipment (from Power 2005)



often atmospheric, and the pore air pressure on the other side of the disk (Lu and Likos 2004).

The pore fluid pressures can be controlled independently from the ports located at the top and the bottom of the chamber (Fig. 11). As the axis-translation chamber should be pressurized with air, the thickness of chamber wall should be sufficiently thick for safety purposes. Also, the time between the unsaturated soil specimen placement and pressurization need be as short as possible. The axis-translation technique is best suited for measuring matric suction of unsaturated soil specimens in which the air phase is continuous. More details related to the limitations of the axis translation equipment are detailed in a later section.

The axis translation technique is routinely extended to different types of equipment for the determination of the mechanical properties of unsaturated soils such as the shear strength, volume change and the coefficient of permeability. Several investigators have successfully used this technique over the last 50 years which paved way for our present understanding of the mechanics of unsaturated soils (Matyas and Radhakrishna 1968; Barden et al. 1969; Fredlund and Morgenstern 1977; and many others during the last thirty years).

4.2 High-air Entry Stone Placement

Several geotechnical laboratories design special equipments that are not commercially available for studying hydraulic and mechanical properties of unsaturated soils extending axis-translation technique. One of the common problems with the design of axis-translation equipment is associated with the air-leakage. The key source of air leakage is through the boundaries of the ceramic stones where it is glued (i.e., epoxied around the edge to form a seal with the pedestal).

Figure 12 shows the recommended procedure for effectively gluing the ceramic stone in stages (i.e., typically two or three) to reduce the formation of air bubbles. Each layer needs to harden before the next layer of glue is placed. A useful guideline is to cure each layer over night under heat lamp before the next layer is placed (Power 2005). Any air bubbles formed in preceding layer should be opened up and filled with epoxy forming the next layer. Air bubbles, if any, will reduce the bonding strength between the ceramic stone and the stainless steel or brass ring leading to leakage with time.

4.3 Flushing System

There will be some air that can diffuse through the high air-entry disk when the axis translation technique is conducted over long periods of time (Fig. 13). It is essential to remove any air bubbles that form under the saturated high air-entry disk

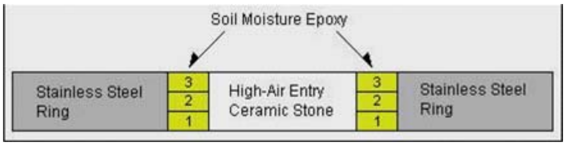


Fig. 12 Gluing high-air entry stone (from Power 2005)

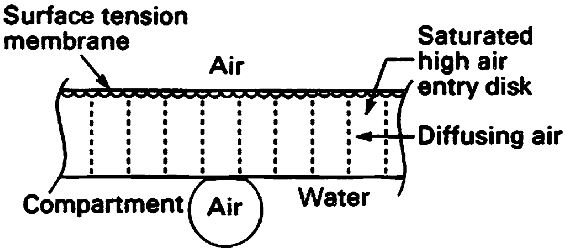


Fig. 13 Diffusion of air into the high-air entry disk (from Villar et al. 2005)

Fig. 14 Flushing diffused air from spiral groove of acrylic chamber

preferably using circular groves below the base of the ceramic stone (Fig. 14). The applied or measured matric suction value is not reliable if diffused air is not accounted for. It is therefore important to incorporate a flushing system to periodically remove any dissolved air that can appear within the null pressure plate system during testing.

The important features of the flushing system are: a pump and dimmer switch, an air trap with stopcock, and a glass tube to indicate the null position during testing (see Fig. 15). The pumps are connected to a common electrical dimmer in order to control the pumping force and eliminate any cavitation that may occur during flushing. In the event that air bubbles do form under the ceramic discs, the pump would be turned on and the air bubbles would flush into the air trap.

Air diffusion through the ceramic disk can be minimised by elevating the water pressure under the saturated air-entry disk, i.e. by applying a back-water pressure (Romero 2001; Marinho et al. 2008)

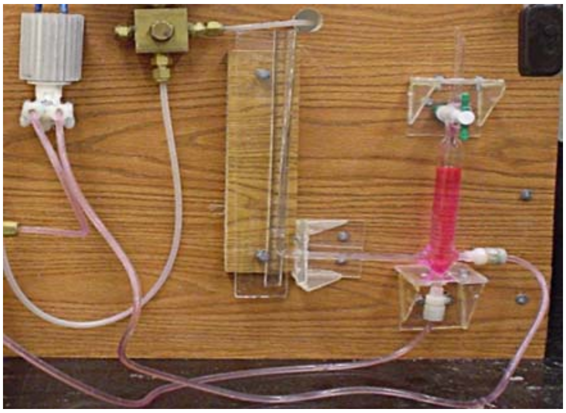


Fig. 15 The important features of the flushing system: the pump and dimmer switch, the air trap with stopcock, and the glass tube to indicate the null position during testing (from Power 2005)

4.3.1 Air-trap for the Flushing System

The air bubbles should be removed from the acrylic base of the equipment and facilitate to flow into the air trap shown in Fig. 15. It is recommended to use acrylic base for the axis translation equipment to facilitate the visualization of air bubbles, if any. Larger air-traps which allow more room for air bubbles are also recommended.

4.4 Axis Translation Technique Limitations

In the axis-translation technique, the air pressure, u_a, is higher than the atmospheric pressure and the pore water pressure, u_w, is positive. Such pressures are not representative of field conditions for unsaturated soils. Due to the applied air pressure in the axis-translation technique, air could seep or diffuse through the ceramic stone as discussed earlier into the drainage system of the apparatuses. The applied air pressure will have a significant effect on the measurements of water exchanges from in and out of the unsaturated soil specimen. For this reason, the rate of air diffusion should be measured for each axis-translation apparatus. To track changes in specimen water content throughout the test in which the axis translation technique is applied, the diffused air volume must be measured and correction to the pore water volume change must be made. This task is generally accomplished by flushing water (and diffused air) out of the ceramic disk into a burette, where the air volume causes change in the water level that can be measured.

In some cases, depending on the rate of application of the chamber air pressure and the compressibility characteristics of the soil specimen, it is possible to temporarily overshoot the actual suction value. In such a case, the peak should not be interpreted as the actual suction, nor should the subsequent down turn of the curve be interpreted as the onset of significant air diffusion. In other words, great care should be applied in the interpretation of the results so that matric suction can be reliably measured using axis translation technique.

The theory associated with the axis translation technique is only valid for soils with totally interconnected pore-air voids and for soil particles that are incompressible and only when air–water interphase is continuous, which is typically observed in specimens with degree of saturation, S, $< 90\%$) (Olson and Langfelder 1965; Bocking and Fredlund 1980). Validity of the axis-translation technique at very high degrees of saturation is discussed by Marinho et al. (2008)

Matric suction in two specimens (say specimens A and B) can be significantly different from one another in spite of having the same dry density, total volume and gravimetric water content. This could be attributed to the arrangement of the soil particles and the amount of air bubbles which may be significantly different from one specimen to the other depending upon the method of compaction. The water phase can be discontinuous due to the presence of occluded air bubbles (for example say, in Specimen A). The trapped water within the air bubbles may not be effective and hence water content of Specimen A can be likely low and hence the suction would be overestimated compared to a specimen without occluded air bubbles (say, in specimen B).

The diffusion of air through porous ceramic disks (i.e., high air-entry disks) also imposes a practical limit on the duration of the test. To alleviate problems associated with diffusion it is necessary to either eliminate diffusion in the drainage system or resort to periodic air washing of the drainage system at the bottom of the high air-entry disk.

There are three key processes that are associated with air diffusion as summarized by Romero (1999) and Farulla and Ferrari (2005):

(i) The first step is to asses the amount of air dissolution into the water in the soil pores.

Henry's law can be used as a tool to understand and calculate the amount of air dissolution.

(ii) The second step is to calculate the dissolved air diffusion through the pore-water in the ceramic disk. Fick's law can be used for calculating the air diffusion.

(iii) The third step is to asses the air coming out from the solution in the water drain lines.

In addition, matric suction in soil specimens is also influenced due to water evaporation originated by the vapour pressure gradient between the pore voids and the soil specimen. Some details on these parameters are presented in later sections on this topic in the paper. However, detailed discussions are beyond the scope of this paper. More information on related topics is available in Romero (1999, 2001) and Oliveira and Fernando (2006). All of the above details related to the null pressure plate equipment is also valid for equipment such as modified direct and triaxial shear equipments and other equipment which use axis translation technique for the determination of the unsaturated soil properties.

5 Special Devices or Equipments

Several investigators developed special devices or equipments to alleviate some of the problems associated with diffusion of air while applying axis translation technique during the measurement of unsaturated soil properties. The suction and volume changes of an unsaturated soil specimen cannot be reliably measured unless diffusion effects are accounted for. The applied or the measured suction values may not be reliable if the ceramic stone in the axis translation equipment is not in a state of fully saturated condition. There can be loss of continuity between the liquid phase in the high-air entry disk (i.e., ceramic stone) with time due to diffusion effects while measuring the unsaturated soil properties extending axis-translation technique for a long period of time (Romero 1999).

The use of bubble pump along with air traps was originally suggested by Bishop and Donald (1961) for alleviating some of the problems associated with diffusion by flushing out the bubbles collected at the bottom the ceramic disk. Fredlund (1975) suggested using Diffused air-volume indicators (DAVI) for

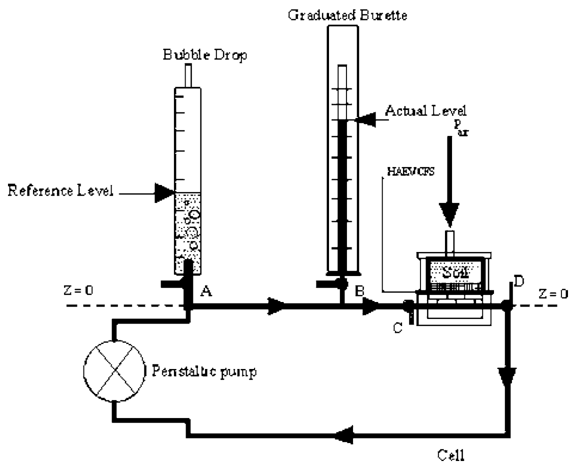


Fig. 16 Double Burette System for Measuring Diffused Air (De Gennaro et al. 2002)

measuring the diffused air volume when axis translation technique is employed. More details related to the DAVI are available in Fredlund and Rahardjo (1993). Comprehensive details related to the measurement of volume changes associated with diffusion using different types of equipment are available in Romero (1999) and Vilar et al. (2005).

In recent years several investigators used different techniques to measure both total volume and air volume changes associated with unsaturated soil testing and discussed the merits of methods they investigated (Adams et al. 1996; Macari et al. 1997; Romero et al. 1997, Ng et al. 2002; Aversa and Nicotera 2002). Also, more sophisticated equipments are available now to measure the diffused air volumes in unsaturated soil specimens when axis translation techniques are employed. For example, De Gennaro et al. (2002) suggested a technique for measuring the quantity of air diffused and then removing it using a double burette system (Fig. 16).

Lawrence et al. (2005) suggested power pulse technique for the measurement of air volume diffused from the specimen through a high air-entry disk into the measuring system. In this technique, the diffused air doesn't necessarily have to be flushed; its volume simply needs to be measured. By comparing the changes in water volume reading to the initial readings for a given pressure (through the determination of correction factor) it is possible to calculate the volume of air from Boyle's law. This is a promising technique.

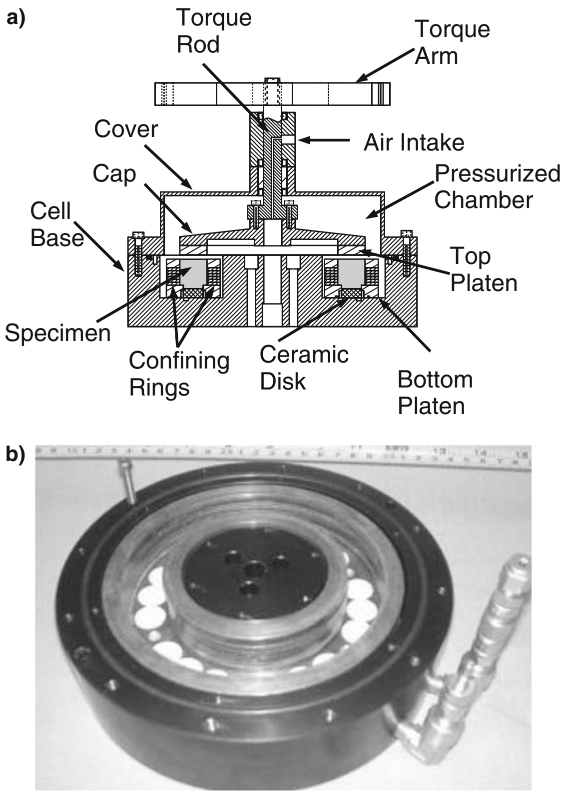


Fig. 17 (**a**) Schematic of modified ring shear cell assembly (**b**) Base of unsaturated ring shear cell with ceramic disks and inner confining ring stacks in place (from Infante Sedano 2006)

5.1 Implementing Axis-translation Technique in Mechanical Testing

A modified ring shear test equipment has been designed and reliable test data have been obtained related to the hydraulic and mechanical behavior of unsaturated soils (Vanapalli et al. 2005; Infante Sedano et al. 2007). A schematic view of this equipment is shown in Fig. 17. For the purpose of the determination of the hydraulic and mechanical behavior of an unsaturated soil specimen, the cell should be enclosed in a sealed chamber so that the specimen can be subjected to a high air pressure for the application of the axis translation technique. The key components are the ring shear cell, an air trap, and an electronic scale for the measurement of water overflow from the soil specimen (Fig. 18). A pump forces the water to circulate below the ceramic disks in the modified ring shear apparatus to flush the air bubbles that are collected below the base of ceramic disks. The flushed out air accumulates in the air trap, where a small bore syringe is used to reset the water level to a fixed reference mark after flushing. Any overflow water is collected in a small plastic container placed on an electronic balance for measuring the mass of water. This technique of flushing out the air bubbles can be used with the double burette or any other method using an air trap in conjunction. More details about the correction for air diffusion are detailed in the next section.

5.1.1 Correcting for Air Diffusion

Figure 19a illustrates a typical water mass measurement readings versus time curve obtained during a suction increase stage. Breaks in the curve are apparent at the time of flushing the air bubbles. With time, as more air bubbles form, any subsequent flushing will show other breaks in the curve. There will be drop in the water mass reading after flushing which is equal to the actual volume of air removed. The rate of air infiltration (which includes combined diffusion and air leakage) is the reduction in the water mass reading divided over the time interval between flushing operations (Fig. 19b). If the curve after each flushing break point is moved upward, as shown in Fig. 19c, a continuous curve is generated. This continuous curve corresponds to the condition where no flushing would have been performed. The curve tends towards a constant slope, which indicates that the rate of air infiltration is also constant (Fig. 19c). This constant rate of air infiltration is now plotted in Fig. 19d, and is shown as line i). By subtracting the ordinate of line i) from curve ii), and adding the magnitude of the initial reading as a constant, the corrected curve iii) is generated. Curve iii) represents the best estimate of the readings that would have been generated had there been no infiltration.

5.1.2 Correcting for Evaporation and Condensation

Even after having applied the corrections for air infiltration, it is possible that the resulting curve showing water mass readings over time will not converge to a horizontal asymptote as would be expected in an ideal system. This may be due to evaporation if humidity is lost to a relatively dry air phase in the pressurized chamber or due to condensation if a saturated air phase transmits humidity to the soil.

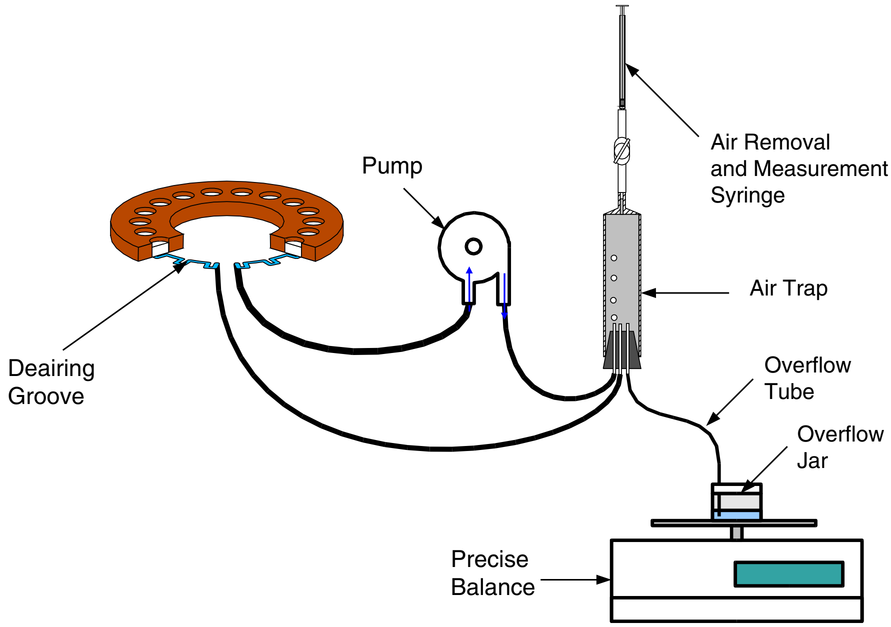


Fig. 18 Idealized schematic of the de-airing system for the modified ring shear apparatus (modified after Infante Sedano et al. 2007)

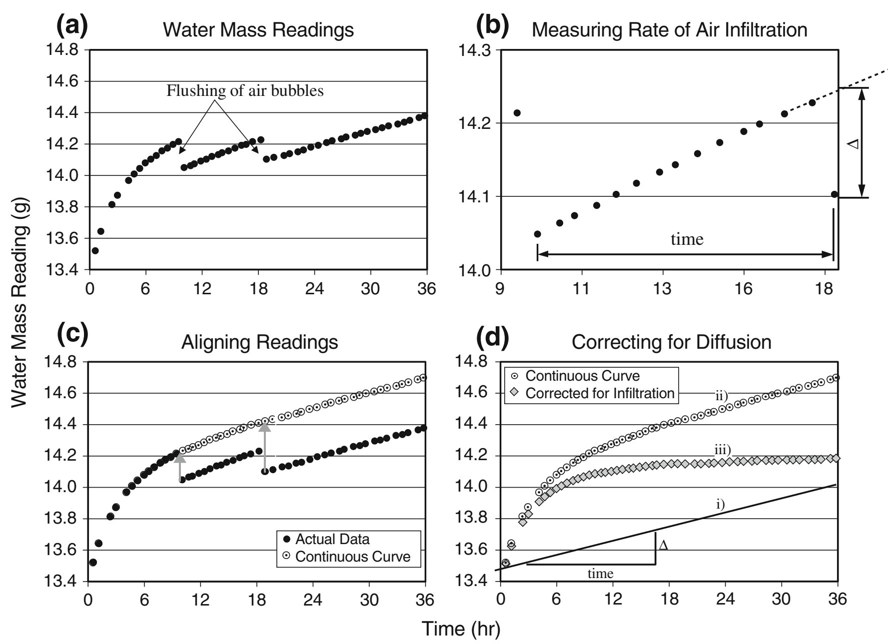


Fig. 19 Measurement of air infiltration, and its correction to the water content measurement (after Infante Sedano et al. 2007)

Although the air used to pressurize the ring shear chamber is bubbled through water, it is still possible for it to be relatively dry for a number of reasons including leakage in the cell. The dry air could cause the corrected water mass reading curve to show a downward trend, suggesting evaporation from the specimen (see curve a in Fig. 20a) Alternatively, if there is no leakage and the water phase can become saturated through contact with the bubbling chamber, then there will be a tendency to transfer moisture to the specimen, unless the degree of saturation of the air phase is in equilibrium with the matric suction of the specimen (Fig. 20b). More details related to this equipment design are discussed in Infante Sedano (2006).

In addition, details along similar lines related to soil water evaporation along a wetting path have been

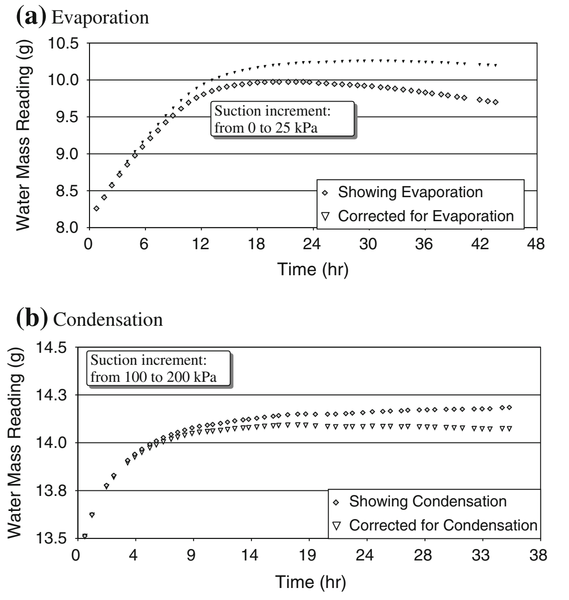


Fig. 20 Measurement of air infiltration, and its correction to the water content measurement (after Infante Sedano et al. 2007)

suggested by Romero (1999) and Vilar et al. (2005) for tests undertaken using triaxial shear apparatus. Several new equipments are now available that can be used to address challenges associated with unsaturated soils testing (Padilla et al. 2006; Hoyos et al. 2006). In years to come it is likely that we will have more reliable experimental data that can be useful for developing rigorous constitutive models for unsaturated materials.

6 Summary

Significant advancements were made during the last two decades related to our present understanding of the mechanics of unsaturated soils using experimental methods. This paper provides a summary of the two techniques which are commonly employed in the testing of the hydraulic and mechanical behavior of unsaturated soils (i.e., negative water column and axis translation techniques). All aspects related to the testing procedures and other details could not be summarized in greater detail due to space limitations. However, an attempt was made to provide several of the key references that would be useful in providing the remainder of the details.

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