Experimental Set-up for Determining Soil Water Retention Curves for Granular Soils During Drying

LI Qingtian\textsuperscript{1} and Jamie STANDING\textsuperscript{2}

\textsuperscript{1} China Zhonghua Geotechnical Engineering Co., Ltd. Beijing 102600, China
\textsuperscript{2} Imperial College London, South Kensington. SW7 2AZ, UK

Abstract: Soil water retention curves (SWRCs) provide an important means of describing the response of unsaturated soils during drying / wetting processes in terms of variations of degree of saturation, water content or void ratio with suction. A key consideration in generating these curves is how to measure the suction. Frequently the filter paper technique is adopted, especially when high suctions are developed, e.g. with plastic clays. As each measurement takes at least a week with this technique, it can take months or years to generate a full SWRC in drying and wetting. Developments in laboratory tensiometers now allow matrix suctions up to about 1.5 MPa to be measured. With such a device it is possible to develop SWRCs for granular soils such as silts and clays in hours or days by continuous measurement. This paper describes an experimental set-up that was developed to measure changes in volume, water content and matrix suction during drying of three granular soils. Limitations of the apparatus and usefulness of the curves are discussed.

Key words: unsaturated soils, suction, SWRC, tensiometers

1 Introduction

The importance and relevance of the mechanics of unsaturated soils has been appreciated for several decades. It has wide application to areas such as the construction of earth dams and embankments, slope stability analysis, foundations on swelling and shrinking soils, unmetalled roads and more recently groundwater and pollutant flow and the containment of nuclear waste.

The subject of unsaturated soil mechanics is more complex than that of saturated soil mechanics because of the additional gas (air) phase that has to be taken into account. Volume measurements are more difficult because of the compressibility of the air (and so volume changes cannot be determined simply by water flow in / out of the sample) and more significantly the pore water pressure is usually negative. With standard soil testing apparatus, measuring negative pore water pressures lower than −100 kPa is difficult because cavitation tends to occur at this point in conventional pore pressure transducers. Cavitation is the process where air becomes present within a previously saturated system, either by coming out of solution or expanding with reducing pressure and escaping from within microcrannies in the surfaces of components of the transducer (Knapp et al., 1970; Marinho, 1994). Once cavitation has occurred the pore water pressure measuring system no longer works reliably and needs to be carefully de-aired before using again. In the two past decades considerable advances have been made in the measurement of negative pore water pressures, which are usually expressed in terms of matrix suction, $s = u_a - u_w$, where $u_a$ and $u_w$ are the pore air and water pressures respectively (thus suction is a positive quantity). Most notable of these developments is the suction probe developed at Imperial College London by Ridley and Burland (1993). This device is able to measure suctions well in excess of 1 MPa. A number of similar devices based on the same principles have been developed but they do not operate to the same range (e.g. Tarantino and Mongiovi, 2003; Take and Bolton, 2003).

A key means of expressing the behaviour of unsaturated soils during drying and wetting is the Soil Water Retention Curve (SWRC). This curve can be expressed as changing degree of saturation, $S_v$, water content, $\omega$ (gravimetric) or $\theta_w$ (volumetric), or void ratio, $e$, plotted against the logarithm of suction (often matrix suction). When generating these curves, the suction is often measured using the filter paper technique (Chandler and Guitierrez, 1986; Marinho, 1994; Melgarejo Corredor, 2004) or

\* Corresponding author. E-mail: 18612218239@163.com

© 2014 Geological Society of China
pressure plate apparatus (Fredlund and Rahardjo, 1993). Samples are gradually dried and wetted over extensive periods that can extend to years.

In this paper an experimental set-up developed to determine SWRCs for granular soils by continuous measurement is described. It is similar to the set-up described by Toker et al. (2004) but has a number of differences, as described and discussed.

2 Soil Water Retention Curves

As a soil is dried, suction within it increases while degree of saturation, void ratio and water content reduce. When dried from a slurry, the resulting path is referred to as the principal drying curve (PDC). Key points on the curve are the air-entry value (AEV), when air starts to enter into the body of the soil, and the residual point beyond which there are negligible changes in $S_r$, $w$, $\theta_r$, or $e$. For granular soils, the AEV will correspond to low suction values (typically in a range of 1 to 40 kPa for sands) while for very plastic clays it can be of the order of MPa. In the latter case $S_r$ will not reduce to zero (as it will with sands for example) because of the presence of adsorbed and chemically bonded water, therefore the residual point often lies at an $S_r$ value considerably greater than zero. As a soil is wetted from its residual point it does not follow the same path as drying but is hysteretic and $S_r$ does not usually return to 100%. A series of typical drying SWRCs representing soil types ranging from sands to clays and a hysteretic SWRC are shown in Figs. 1a and b.

3 Measurement of Suction

Total suction is defined as the sum of matrix suction and osmotic suction. Both of these components influence the relative humidity (RH) of the air above the surface of water within a soil independently with RH reducing as suction increases. Matrix suction is derived from capillary effects and meniscus water and is linked to the mechanical strength of the soil. Osmotic suction is controlled by the presence of salts within the soil water.

There are numerous instruments and techniques for determining suction, some of them measure suction directly and others indirectly (Ridley and Wray, 1996). Devices such as tensiometers measure suction directly, i.e. an instrumented diaphragm is deflected by the pull from the tension acting within the water at a negative pressure. Indirect suction determinations are made by measuring other quantities such as relative humidity (e.g. psychrometer devices) or water content (e.g. filter paper technique). Suction is then determined from these quantities through known relationships. An important factor of the measuring technique is whether or not the measurement is made with the device in contact with the soil. Tensiometers are placed directly in contact with the soil. In this situation water can flow freely (albeit in minute quantities) and so if any salt is present it affects both the measuring system and soil equally. In this situation it is matrix suction that is measured. Total suction is determined with devices that measure relative humidity, i.e. the device is not in contact with the soil water and so is referred to as a non-contact measurement.

3.1 Filter paper technique

Suction measurements required to generate SRWCs are often achieved using the filter paper technique. This method is briefly described as it sets the scene and allows comparisons to be made with the set-up described in this paper. Usually a disc of soil is allowed to dry / wet in small increments (sufficiently small to define the SWRC). After drying / wetting, one filter paper is placed directly in contact on one side of the disc and on the other the paper is placed on a perforated perspex disk so that it is close but not in contact with the soil. In this way, both matrix and total suction can be measured (and so the osmotic component can be determined from the difference between them). The sample is then wrapped and sealed and stored for one to two weeks to allow equilibration of suctions within the sample and between the sample and the filter paper. After equilibration, the water content of the filter papers is measured and suction determined from calibration curves (e.g. Chandler and Gutierrez, 1986;
Dineen, 1997; Ridley et al., 2003). At the same time, the
mass and dimensions of the sample are carefully measured
to determine $S_w$, $w$, $\theta_a$, and $e$. The next incremental
drying / wetting stage is then started and the process
repeated. Establishing a full SWRC from incremental
drying followed by wetting can therefore take months and
even years if multiple steps are involved to define the
curves clearly (Malgarejo Corredor, 2004). A detailed
procedure has been developed at Imperial College over
several years, details are provided by Ridley et al. (2003).

3.2 Tensiometers

Tensiometer devices measure soil suction directly. Typically
there is a porous stone, a very small water
reservoir behind the stone and a pressure measuring
system connected to the water reservoir. The porous tip
links the soil to the pressure measuring system and
transfers the soil water pressure to the water in the
reservoir. Modern laboratory tensiometers usually operate
with an electrical pressure transducer, involving strain-
gauged diaphragm. Key elements for successful
measurements of suction with tensiometers are the air-
entry value of the stone, effectively sealing the stone into
the body of the device and fully de-airing the reservoir.
The Imperial College suction probe (tensiometer)
incorporates a porous ceramic stone with an air-entry
value of 1500 kPa (Ridley and Burland, 1993). This
suction probe can measure soil suction up to 1500 kPa for
short periods if it is (i) effectively de-aired and (ii) in
perfect contact with the soil sample. The mechanism of the
Imperial College suction probe is shown in Fig. 2a and a
photograph of the device in Fig. 2b.

Satisfying as fully as possible the two essential criteria
for measuring suction accurately is paramount. As the
tensiometer is a closed system, specific techniques are
required to remove as much air as possible prior to using
the probe. Initially, the probe is placed under a vacuum
within a chamber that also contains a water reservoir. A
vacuum of about -100 kPa is applied and left for a period
of several hours. The chamber is then slowly rotated so
that the water comes into contact with the porous stone
and eventually completely covers the face of the probe.
The system is left in this condition for several hours. The
probe is then transferred to and sealed into another small-
bore chamber containing de-aired water with the facility to
apply positive pressure to the probe. The probe is then
cycled from zero to a pressure of about 4 MPa numerous
times for about one week (when not being cycled it is kept
under the 4 MPa pressure). In this process any remaining
air in the system is dissolved or driven deep into the far
recesses of any microcrevices. The face of the probe is
orientated upwards so that any air bubbles that appear
during the unloading cycles rise to the top of the chamber.
The cycling induces very small amounts of flow in and out
of the stone and after multiple cycles the probe should
have negligible amounts of air present. The second
criterion is that the suction probe should have good
contact with the sample so that the soil water pressure can
be fully transmitted to it. It has been observed by
Colmenares Montanez (2002) that with granular samples
sometimes it is difficult to achieve good contact and
equilibration times can be much longer than with clay
soils. In order to get a good contact, sometimes excess
moisture is added to the surface of the suction probe or
kaolin paste is smeared over the face of the suction probe
to help seat it into the soil sample. Neither of these
methods was necessary in the set-up described here as the
sample was formed on top of the upturned face of the
probe. Once the probe is fully saturated it is important to
try to avoid de-saturating it because of the prolonged re-
saturation process.

Ridley et al. (2003) compared measurements taken
using the suction probe and filter paper method and found
excellent agreement between them over the full range of a
suction probe (exceptions are when testing samples with
appreciable salt concentrations which are not covered in
this paper). In principle it should therefore be possible to
generate SWRCs from suction measurements made using

![Fig. 2. Imperial College suction probe (a) schematic showing main components (after Ridley and Burland, 1993), (b) photograph of device.](image)
a suction probe (tensiometer).

4 Experimental Set-up for Determining SWRC for Granular Soils

Toker et al. (2004) describe the details of an experimental set-up they developed for determining SWRCs using a tensiometer device (suction probe). In their set-up the sample mass is measured and so the SWRCs presented are in terms of matrix suction versus gravimetric water content. In these SWRCs the maximum suctions are about 10 to 20 kPa. The set-up now described was used to generate SWRCs for three soils, one of which was subject to significantly greater suctions as it dried. There are a number of other differences compared with the Tokar et al. set-up: these are discussed along with assumptions made and limitations encountered when trying to determine accurately changes in sample volume as well as mass.

4.1 Experimental set-up

The apparatus set-up for determining SWRCs of granular soils is shown in Fig 3. The ambient conditions around the test set-up should be kept as stable as possible during the process of developing SWRCs and so it is contained within an insulated chamber (with wooden walls). The assembly was set up in a laboratory where generally temperature was controlled to 20 ± 1°C. This is also important as suction is strongly controlled by temperature and humidity (total suction is directly related to temperature and the natural log of relative humidity according to the psychometric law).

The principal components of the set-up are as follows.
- Container within which the sample is placed and subsequently dried.
- Weighing balance to measure changes in the mass of the sample (to 0.01g).
- Suction probe / tensiometer for measuring matrix suction of the sample.
- LVDT (linear variable differential transformer) to measure changes in sample height.
- Thermistor to monitor temperature within the insulated chamber.
- Hygrometer to monitor humidity within the chamber.
- Computer for data logging.
- System for preventing cavitation of the probe (incorporating an electrical valve and small water reservoir).

Initially three container sizes of varying diameter and thickness were manufactured so that they could be filled with granular samples. The intention was to investigate the effect of sample dimension on the suction measured to find an optimum size where suctions should be reasonably uniform throughout the sample height and so that the sample size would be sufficient to measure suction and volume change reliably during drying and so that drying did not take place too quickly. Following some initial trials a container size of 40 mm internal diameter and depth 12.5 mm was adopted. Each container was machined from solid sections of PVC, with three brass legs for support and to provide space for the suction probe. The face of the suction probe, with incorporated porous stone, was connected and sealed into the base of the container so that it was just flush with the lower internal surface.

Overall sample volume changes (ΔV) were determined from the LVDT measurements made on its upper surface (Fig. 3). In doing so it was assumed that volume changes were one-dimensional. Although it is realized that in practice this is strictly not the case, no radial contraction could be observed by eye during drying – overall volume changes were very small for the three grain sizes tested. Sands contained in such a way would not be expected to have significant volume changes as they are under zero total stress and would quickly reach the shrinkage limit during drying (at which point voids do not change volume but water is replaced by air). Samples were assumed to be fully saturated at the start of each test (this is discussed further in the section of sample preparation) and the volume of water lost from the sample during drying (ΔVw) was determined from the changes in overall mass registered by the electronic weighing balance. The change
in volume of air at any time \( \Delta V_a \) can then be determined from the corresponding change in water volume less any overall sample volume change at that time. Knowing the initial volumes of water and solids present, calculating the degree of saturation is straightforward.

The purpose of the insulated chamber is to minimize changes in temperature and humidity. Humidity was not controlled and in practice changes did occur, although in most tests the average chamber humidity was usually within a range of 10 %. Humidity might be expected to increase during drying of the samples. Occasionally temperature exceeded the 20 \( \pm 1 ^\circ \text{C} \) control value but only for very short periods. Monitoring such quantities helps with the interpretation of data, e.g. drying rates reduce with reducing temperature and increasing humidity.

The procedure for saturating the suction probes was described earlier. On each occasion when the suction probe was removed from the pressurizing chamber, it was observed that water on the surface of the suction probe very quickly started to evaporate. Within a few minutes of exposing the probe, suctions of about 1 MPa could be registered. In order to avoid cavitation of the probe during the final stages of drying the samples, a system was developed, comprising an electronically-controlled valve connected to a water reservoir and positioned above the surface of the sample (see Fig. 3). When the suction probe reached a limiting value of 600 kPa, as logged by computer, the valve was activated by a logic-switch and would open for a short period to release a small amount of water onto the surface of the sample. As a consequence suctions would reduce and in this way accidental cavitation of the suction probe was avoided. This system saved a great deal of time – it was necessary as with the coarser granular soils, suctions sometimes increased very quickly after the soil had essentially fully dried (in the same way as when the probe was removed from the duty chamber). It also meant that the tests could be left overnight to dry gradually without concerns about cavitation of the probe.

During the course of the period over which testing was performed, all the channels were logged at low frequency but continuously to check the stability of the ambient conditions within the insulated chamber and the stability of the transducers. Clearly when testing, much higher frequencies of logging were used, typically with readings taken at 1 to 2 minute intervals.

4.2 Preparation of samples

In generating drying SWRCs it is essential that the samples are initially fully saturated. Preparation and saturation procedures for the sands were slightly different from the silt used. When mixed with water the silt became 'lumpy' and needed thorough mixing to remove air, while the sands immediately settled with minimal air around them.

The exact amount of sand required to fill the container in a dense state was determined by trial and error using dry sand. The test container, with suction probe fitted into its base, was then partially filled with pure water and the required sand quantity mixed with de-aired water in a separate small beaker. Both container and beaker were then placed in a vacuum chamber for de-airing. Numerous small air bubbles would come to the water surfaces initially but the process was usually complete after about 10 minutes. After removing from the vacuum, the sand-water mixture was gradually poured into the water within the test container, stirring and lightly tampering until all of the prepared sand was added and its surface flush with the top of the container. The container with sand and probe was then placed in the vacuum again and left for another period of about 10 minutes until no bubbles could be seen exiting from the saturated sand surface. On removal from the vacuum, any surplus water was removed and the container weighed. The mass of the sample could then be calculated by subtracting the mass of the dry container and attached probe. Precautions were taken when weighing the dry container, to not allow any force from the cable to influence the results – the cable was supported during the test – additionally the mass of the LVDT plunger was also taken into account.

Preparation of the silt sample needed more care and it took longer. It was necessary to place the silt-water mixture in the water-filled container in several layers as there were greater quantities of air within the silt. When the air exited from the silt-water mixture, sometimes large bubbles formed which could cause small overflows which could lead to errors. Generally about 15 minutes was needed each time the sample was placed in the vacuum chamber. Good sample preparation is essential for achieving accurate results.

Once the sample was prepared it was placed on the weighing balance within the environmental chamber, the LVDT plunger positioned on its upper surface and then the chamber sealed. Evaporation of the water was allowed under these conditions without any further facilitation.

4.3 Soils tested

Three soils were tested: medium sand, fine sand and silt. These soils were supplied commercially. The silt is derived from crushed silica and known as HPF4 (more details are given by Zdravković, 1996). The sands were also of silica and for all three soils a value of 2.65 was assumed for the specific gravity. The two sands were both of quite uniform grading, as shown in Fig. 4, while the silt
grading covers a much wider range (mostly within the silt faction). As mentioned earlier, the materials were prepared in a dense state.

5 Experimental Results

The development of suction with time, as the three soils gradually dried out, is shown in Fig. 5. Initially suctions develop quite quickly for all the soils, during this phase the meniscus at the upper surface of the samples will start to form as the water recedes into the soil. Up to this point the soils are still essentially saturated. Air will then start entering the sample from the surface in the form of ‘fingers’ of air and occluded bubbles will form within the water-filled soil voids. There is little increase in suction values for the two sands as they dry out, until the very end of the drying process when continuous air phases reach the face of the probe at the base of the samples.

There was considerable scatter in suction measurements for the medium sand. As the average values are quite low, being less than 10 kPa, this scatter made it difficult to observe the overall trend of the data (as it was ±10 to 20 kPa) and so much of it has been removed from the data for the medium sand profile. The scatter is thought to originate from cavities forming within the sand and becoming interconnected. As individual cavities coalesce, there are small temporary reductions in suction, which then starts building up again until there is another joining of several isolated voids. Scatter has not been removed from the fine sand data. As the average suction in this case is higher, being in a range from about 20 to 50 kPa, the scatter does not obfuscate the overall trend of the data. The silt data exhibited much smaller degrees of scatter.

5.1 Experimentally determined SWRCs

SWRCs for the three soils tested are shown in Fig. 6.

5.1.1 Medium sand

The SWRC for this soil is very steep after the air entry value (AEV) has been exceeded (judged to be about 6 kPa). As mentioned above, the data presented have been selected to remove considerable scatter that occurred with this medium soil. The soil fully dried with degree of saturation reaching essentially zero at a suction value of about 20 kPa. Most of the suction values are within a range of 6 to 12 kPa.

5.1.2 Fine sand

The AEV of this material is estimated to be about 35 kPa and again the path followed by the SWRC is quite steep beyond this point (although it is slightly less steep than for the medium sand). As with the medium sand

there was quite a lot of scatter, especially in the later stages of the test when the water was becoming discontinuous throughout the sample. Maximum suction towards the end of the test was registered to be about 200 kPa which occurred at a degree of saturation of about 15% both values seem high for sand. For this finer material it is likely that small quantities of water remained within the container, particularly at the junction between the walls and the base, leading to S values greater than in the vicinity of the probe. The suction measurements increased rapidly at the end of the test, reaching the 600 kPa point when the wetting system was activated, preventing
cavitation of the suction probe.

5.1.3 Silt

The soil water retention curve developed for the silt was much smoother than those for the sands. There are two instances where there appears to be a reduction in $S_r$ followed shortly afterwards by an increase. The reason for this is not clear, basically the recorded mass reduced and then increased again afterwards. The overall trend in the data is still very clear. It was not necessary to filter out scatter in this case as the probe was in contact with continuous phases of water for most of the test as the pore spaces within the silt are much smaller. A drawback of this is that, because of the low permeability of the silt there is more likely to be a potential gradient in suction over the height of the sample, but as the sample thickness is very small (12.5 mm) this effect has been ignored. The AEV is not much greater than for the fine sand, being estimated to be about 40 kPa. However, the curve is much less steep than those for the sands. This is almost certainly a reflection of the wider grading for the silt (Fig. 4). At a degree of saturation of about 20 %, suctions increased without changing $S_r$. This marks the point when the residual condition is being approached and suctions increase as the probe starts to dry as water is no longer continuous. Again the cavitation prevention system activated at a suction value of 600 kPa.

5.2 Summary

In all cases the suctions measured are lower than those representing the whole sample (i.e. average values) because the measurements were made at the base while the samples were dried from the upper surface. However, because of the granular nature of the samples, particularly the sands, this effect is not thought to be significant as the suction ranges were only small. In the case of the silt, the smaller pore size would have led to greater continuity in the water phase and so suctions would have been more uniformly distributed over the height of the sample (12.5 mm). In all cases, consideration might be given to correcting the SWRC by shifting it very slightly to the right of the curves shown. The SWRC for the fine sand should probably be extended to a lower $S_r$ value.

6 Discussions and Application of the Results

The data are discussed in a more general sense here and applications for the developed SWRCs put forward.

6.1 Limitations of the data

The soil water retention curves developed from the laboratory set-up described here exhibit some imperfections, especially for medium sand. However, the overall trend of the SWRCs is well defined, especially for the silt tested, and it is possible to identify AEV and residual points.

The main potential drawback of the apparatus is that there is a gradient of suction and degree of saturation within the sample. At the base of the sample where suction is measured, $S_r$ is higher than the average value, which is calculated from the overall volume-mass measurements on the sample. Thus, the suction measurement and the degree of saturation do not correspond for much of the drying process. At the start, when the soil is fully saturated, $S_r = 1$ for the entire sample and there is no gradient over its height. Equally when the soil has completely dried, $S_r = 0$ throughout (assuming they do dry out completely, as is usually the case for granular soils) and again there is no gradient. Between these conditions, a gradient of both $S_r$ and suction exists over the sample height. To make the measured suction value compatible with the measured $S_r$ value, a correction would have to be implemented. The sense of the difference in measurements and the correction required are expressed figuratively in a qualitative sense in Fig. 7. No adjustments have been made to the data presented. It is assumed that the differences in suction and degree of saturation across the samples are negligible. One way of overcoming this problem might be to incorporate another suction probe at the upper surface of the sample (and perhaps within the wall of the container).

Other potential sources of error within the experimental set-up come from the loss of small amounts of the solid

![Fig. 7. Schematic illustrating differences in suction and $S_r$ (a) over height of sample, (b) during drying process.](image-url)
material during the de-airing procedure and saturation itself. The cable leading from the suction probe should ideally be fully supported. In reality it is connected to the container and sample and so might influence mass measurements to small degrees.

6.2 Mathematical modelling of the SWRCs

Soil Water Retention Curves are often modelled mathematically using the van Genuchten formulation (van Genuchten, 1980). In this relation usually suction is related to volumetric water content: it can also be expressed in terms of degree of saturation. There are three experimental variables $\alpha$, $m$ and $n$ which control the position and shape of the curves. This exercise has been performed to model the experimental data as closely as possible and the modelled curves are shown in Fig. 8.

6.3 Application of the SWRCs

Soil water retention curves constitute an important set of relationships for unsaturated soils. Although historically SWRCs have been developed for clays, it is also appropriate to understand the response of granular soils such as silts and sands. Once the experimental data have been generated they can be modelled using formulations such as that of van Genuchten and used as part of numerical analyses to simulate boundary value problems involving unsaturated soils. The curves used in this study were used to help understand the processes of desaturation of granular strata during water table drawdown in the London Basin and the processes that took place during recharge of the water table (Standing et al., 2013). The curves were used (along with other SWRC data for London Clay, determined using the filter paper technique in the conventional way) both qualitatively and quantitatively. Another potential application could be in the advanced analysis and modelling of oil and gas extraction from granular strata where the soils have three phases: solids, liquids and gas (i.e. they are unsaturated). Enormous reservoirs have been discovered in recent years (e.g. Hao et al., 2011) and the efficient extraction of resources should always be optimized.

7 Conclusions

Soil Water Retention Curves are used extensively in unsaturated soil mechanics to express how quantities such as degree of saturation, water content and void ratio change with suction during drying and wetting processes. The experimental set-up described in this paper concentrates on the generation of SWRCs during the drying of granular soils. Difficulties in measuring volume changes of the granular soils during drying have been overcome by preparing and drying the soils in a container which also incorporates a suction probe. The suction probe is a key component of the apparatus and was able to measure suctions to at least 1MPa. A system was incorporated into the set-up to avoid cavitation within the probe during drying of the soil samples. Changes in the mass and volume of the sample were recorded during the drying process.

SWRCs have been generated experimentally for a medium sand, fine sand and silt. Although there was considerable scatter in the suction measurements for the medium sand, the overall SWRC could still be formulated. The scatter is ascribed to the process of drying causing small perturbations of suction as isolated air voids (occluded bubbles) coalesce, leading to small temporary releases in suction. The experimental data have been modelled mathematically using the van Genuchten formulation. The data were used to help understand the processes of cavitation during water table drawdown in a granular soil.

The main limitation of the set-up is that during drying, small gradients in suction will exist over the height of the sample. In the current study of granular soils these have been assumed to be negligible. This issue could be overcome by incorporating one or more additional suction probes within the sample container (e.g. at the top or within the side walls).

Acknowledgements

Special thanks are given to the technical staff of the Geotechnics Section at Imperial College London: Steve Ackerley, Graham Keeffe and Alan Bolsher for their guidance of the operation of the tests included in this project. The apparatus would not have been created without Steve’s great creativity and ingenuity.

Glossary

e = void ratio = volume of voids / volume of solids
RH = relative humidity = \( \frac{u_v}{u_{vo}} \)

\( u_v = \) absolute vapour pressure / absolute saturated vapour pressure

\( s = \) matrix suction = \( u_s - u_w \)

\( s_v = \) degree of saturation = volume of water / volume of voids

\( u_s = \) pore air pressure

\( u_w = \) pore water pressure

\( w = \) gravimetric water content = mass of water / mass of solids

\( \theta_v = \) volumetric water content = volume of voids / total volume

\( \pi = \) osmotic suction

\( \psi = \) total suction = \( s + \pi \)

References


About the first author

Li Qingtian: Male; born in 1988 in Dalian City, Liaoning Province, master; Engineer of the China ZhongHua Geotechnical Engineering Co., Ltd, responsible for the Soil Mechanics Laboratory. Studied Soil Mechanics in Imperial College London from 2010-2011, specializing unsaturated soil and SWCC, firstly developed SWCC using Imperial College Tensiometer.

Email: 18612218239@163.com

phone: 010-60212296, 18612218239.