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Wetting Method to Determine Soil-Water Retention Curves in High Plasticity Clays

Ana Sofia DIAS[1], Paul HUGHES[1], David G TOLL[1]

[1]Durham University, Durham, United Kingdom
Corresponding author: Ana Sofia Dias (ana.s.dias@durham.ac.uk)

Abstract

The characterization of soil-water retention curves is a necessity for the modelling of earthworks response to long-term changes in seasonal changes in precipitation, as well as to understand the behaviour of these earthworks under individual rainfall events. Challenges have been faced when experimentally characterizing these curves on active clays due to volume changes occurring during drying-wetting processes, for which the Durham Soil Water Retention Apparatus (DSWRA) was developed. Nonetheless, improvements are still required to allow the continuous measurement of the wetting soil-water retention curve (SWRC). In the present study, a new setup to wet samples on the DSWRA is proposed. The new method of wetting uses mist directed to the soil sample to allow a uniform distribution of water, which improves the quality of the measurements of SWRCs. The wetting of two identical samples of compacted high plasticity London Clay was monitored, one was wetted using mist (new proposed setup), and the other was wetted by water drops added using the setup used in previous studies. The changes in gravimetric water content and void ratio are compared, and the variability in the distribution of the water content in the samples was assessed. The proposed method was observed to produce a wetting of the sample that is more homogenous, providing an improved performance when characterising soils with low hydraulic conductivity. Consequently, the SWRCs obtained using the new proposed method are more realistic than the ones obtained the previous method.

Keywords: Soil-water retention curve, Wetting, Active clays

1. Introduction

The quantification of the Soil-Water Retention Curve (SWRC) is essential for the modelling of soil subjected to moisture changes, such as embankments and dams. The SWRC is the relationship between suction and water content and is hysteretic depending on if the soil is being dried or wetted. The interest in the study of the wetting behaviour of soil comes from the need to simulate the response of soil under rainfall, as this is responsible for loss of strength and swelling and hence a number of geo-hazards including landslides. Stirling et al. (2021) and Toll & Liu (2023) have also shown that environmental cycles lead to a progressive deterioration in strength, so it is important to be able to observe the changes in SWRC with drying and wetting.

The Durham Soil Water Retention Apparatus, initially developed to continuously measure the drying SWRC, has since then been adapted to measure wetting SWRCs. This equipment allows the simultaneous monitoring of water content, suction and volume, which is ideal to study soil that change volume with changes in moisture. Medium plasticity clay (Glacial Till) from the Northeast of England (UK) (Toll et al., 2015); Stirling et al., 2017; Liu et al., 2020), clayey silt from the Northeast of Tanzania (Azizi et al., 2020), and clayey sand from South Africa (Kumar et al., 2022) have been characterised using this method.

Nonetheless, testing soil with very low hydraulic conductivity, either because the soil is a clay or because the soil is at a low degree of saturation, constitutes a challenge when continuous wetting is being monitored. Azizi et al. (2020) observed the importance of using a slow rate of wetting to obtain accurate SWRC measurements. The effect was amplified in soil at low degrees of saturation due to its lowered hydraulic conductivity when compared to soil close to a saturated state. The setup used to wet the soil periodically added water drops on the surface of the tested soil sample. When at a state of low degree of saturation, the water redistribution in the soil is slower which leads to a delayed suction response.

A new method of wetting soil samples on the DSWRA was developed to overcome the challenge of facilitating the distribution of water in a sample with low hydraulic conductivity. Its performance is here discussed according to its adequacy to be used for the hydraulic characterization of a high and very high plasticity clay.

2. Equipment for the measurement of soil-water retention curves

2.1 Durham Soil Water Retention Apparatus

The Durham Soil Water Retention Apparatus was developed to allow continuous measurement of the soil-water retention curve of a soil while monitoring volumetric deformations as a result of changes of moisture content (Toll et al., 2015; Liu et al., 2020). The interpretation of the measurements obtained using this apparatus is based on the assumption that the water content is homogenously distributed within the soil sample so that the measured suction is representative, and that the wetting or drying process does not cause distortion.

This apparatus is composed of a light-weight metallic frame equipped with six displacement transducers and one suction sensor sitting on a balance, which is mounted on a balance bench to isolate surrounding vibrations and ensure accurate measurements. This way, the simultaneous monitoring of volume, weight and suction is possible on the same soil specimen as it is being allowed to dry, or wet. The frame also accommodates a data logger connected to all sensors to minimize the disturbance of weight measurements (accuracy of 0.01g).

The displacement transducers were calibrated to a 0.01mm resolution and are equipped with springs to guarantee that the contact with the sample is permanent. These transducers are installed in pairs: two vertically to measure the height changes in the sample; and two pairs measuring changes in diameter installed along perpendicular directions. The frame was developed to allow the installation of a high capacity tensiometer at the bottom of the sample through a hole on the platform where the sample rests. The connection is sealed using an O-ring and a mix of fine soil with water used to improve the contact between the tensiometer and the testing sample.

The frame can accommodate samples of different dimensions, however a sample of 100mm diameter and 20 to 30 mm height is usually used. Samples of clayey soils should have a smaller height to allow for rapid changes in suction and water content with height. The sample is usually covered by a cowl made up of a ring and a disc (cut in half to allow installation around the sensors) to slowdown the evaporation process and to minimize disparity between the state of the soil at surface and in contact with the tensiometer (Toll et al., 2015; Azizi et al., 2020).

2.2 Wetting setup

Initially wetting was carried out manually (Liu et al. 2020; Toll & Liu, 2023). To automate the process, wetting branches of the SWRC have been measured on the DSWRA using a setup shown in Figure 1a, which periodically adds water drops on the surface of the soil sample. For simplicity, this will be referred as the drops method in the present study.

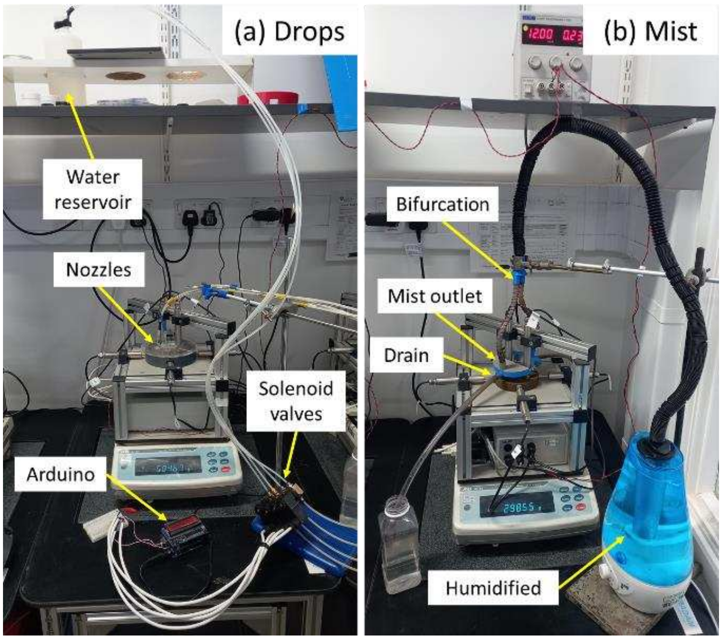

Figure 1: Setups used to wet samples via (a) drops and (b) mist methods.

A water reservoir is kept above the frame and is connected to four nozzles pointing at openings on the sample's cover. The water flows down from the reservoir to the nozzles through a siphon. The rate at which water is dropped on the sample is regulated by a microcontroller that opens and closes solenoid valves. At a regular interval, the valves open and a single drop of water per nozzle is added to the soil sample (Toll et al., 2015).

A new setup to wet soil samples on the DSWRA is here proposed with the objective of producing a more homogeneous distribution of the moisture over the soil samples. The proposed setup is presented in Figure 1b and is here referred to as the mist method. This setup is comprised of a humidifier which produces a fine mist which is channelled along a mouldable tube and diffused over the sample through the mist outlet. As water tends to precipitate on the mist outlet, a drain was included in the design which diverts this excess water into two containers outside the DSWRA. None of the setup touches the DSWRA or the sample because the tube that delivers mist from the humidifier and the mist outlets are fixed to an externally mounted adjustable arm. This way, the sample is enveloped by a cloud of mist which gradually wets the soil over its exposed surface. The rate of wetting can be regulated by the settings of the humidifier but care should be taken not to allow precipitation on the frame.

3. Experimental methods

3.1 Soil and sample preparation

London Clay collected from Clapham in London (UK) was used in the present study. This soil contained 57% clay, 36% silt, and 8% sand. The liquid limit was 60%, while the index of plasticity was of 36%, which led to the soil being identified as a high plasticity clay according to the BS 1377 (1990). The soil samples tested in the present study were statically compacted to a height of 20mm and a diameter of 100mm. The sample subjected to wetting by the drops method was compacted to a void ratio of 0.743 at a water content of 0.200 and sample wetted by the mist was compacted to a void ratio of 0.738 at a water content of 0.201 (specific gravity of 2.77).

3.1 Testing wetting methods

Two different wetting methods were compared in the present study by subjecting two identical samples (previously described) to a similar rate of wetting using different setups (Fig. 1). After approximately 24 hours, the wetting was stopped and the samples were divided into smaller portions to determine the water content distribution. Critical parts of the samples were isolated for each method as illustrated in Figure 2. The sample wetted using the drops method was cut in a way that would isolate the areas directly below each nozzle (portions 1, 2, 7, and 8; Fig. 2a) and the drier areas below the vertical displacement transducers (portions 3 to 6; Fig. 2a). The sample wetted by mist was divided with the objective of isolating the portions below the drain of the mist outlet because some water can leak from the mist outlet drain onto the soil sample (portions 2 and 9; Fig. 2b). The drier portions of the sample wetted by the mist were the areas not covered by the mist outlet (portions 4 to 7; Fig. 2b). In both samples, the central rectangular portion indicated in Figure 2 was cut horizontally into top and bottom (shortened to "bot" in Fig. 2). The top part is exposed to the surface, while the bottom part would be closest to the tensiometer on the base of the sample.

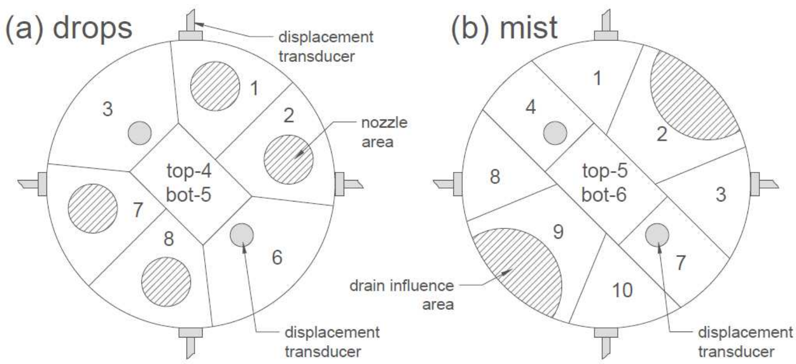

Figure 2: Top view of the portions of the samples used to determine water content variability (top and bot refer to the top and bottom half of the portion divided horizontally).

4. Results

After approximately 24 hours of wetting, the samples were divided as shown in Figure 2 to determine the distribution of gravimetric water content. Figure 3 shows the samples at the end of the wetting process using different wetting setups, reporting the gravimetric water content determined in each portion of the samples.

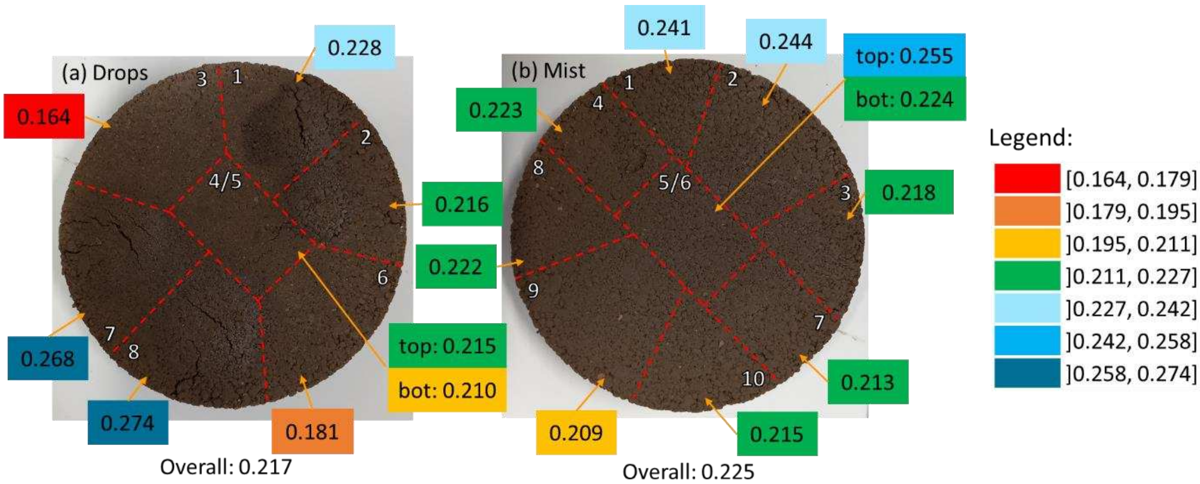

Figure 3: Photographs of the samples after a 24-hour wetting period using the (a) drops and (b) mist method, respectively. The gravimetric water content of each portion is indicated as well as the overall water content of the samples.

The mist method resulted in a distribution of the water content in the sample which shows less variability than the drops method. The standard deviation of the water content associated to the drops method (0.036) is more than twice of that associated to the mist method (0.014). Moreover, the water content in the portions of sample wetted by the mist varied between 0.209 and 0.255, while the same varied between 0.164 and 0.274 in the other sample (Fig. 3).

The drops method presents an additional limitation when compared with the mist method: the sample wetted by drops experienced an overall increase in water content, while some of its parts were experiencing drying. In this sample, portions 3 and 6 dried from the water content at compaction of 0.200 to respectively 0.164 and 0.181, while the areas below the nozzles presented water content values as high as 0.274. As observed in Figure 3a, the areas below the nozzles (portions 1,2,7,8) are darker and presented cracks, while portions 3 and 6 are lighter especially in the sample's extremities indicating a drier state. The low hydraulic conductivity of the tested soil results in a slow water movement through the sample for which the drops wetting method results in irregular water content distribution. If the wetting rate was to be reduced to allow the water to redistribute within the sample, the portions further away from the nozzles would possible dry even further.

An accurate measurement of the SWRC requires a good agreement between the overall water content of the sample and the water content in the vicinity of the tensiometer where suction is measured. In the mist specimen the overall water content and the water content close to the point of installation of the tensiometer were more similar than for the other sample wetted by the drops. The overall water content of the sample wetted by the drops was 0.225 and the water content in portion 6 (location of tensiometer) was 0.224, while the overall water content of sample wetted by the mist was 0.217 and the water content in portion 5 (location of tensiometer) was 0.210 (Fig. 3).

Figure 4a and b shows the evolution of the water content and void ratio during wetting, respectively. The rate of wetting in both methods was very similar as observed in Figure 4a, however, the void ratio change was significantly different (Fig. 4b). The void ratio change in the sample wetted by the mist was approximately linear and quicker than sample wetted by the drops. A linear relationship between water content and void ratio is typical of soil shrink-swell curves before the shrinkage limit is attained (Toll, 1995; Tripathy et al., 2002). The shrinkage limit can be identified at approximately 17% water content for London Clay (Croney, 1977), which is lower than the water content tested in the present study. This linear relationship can be found in Figure 4c in the sample wetted by the mist.

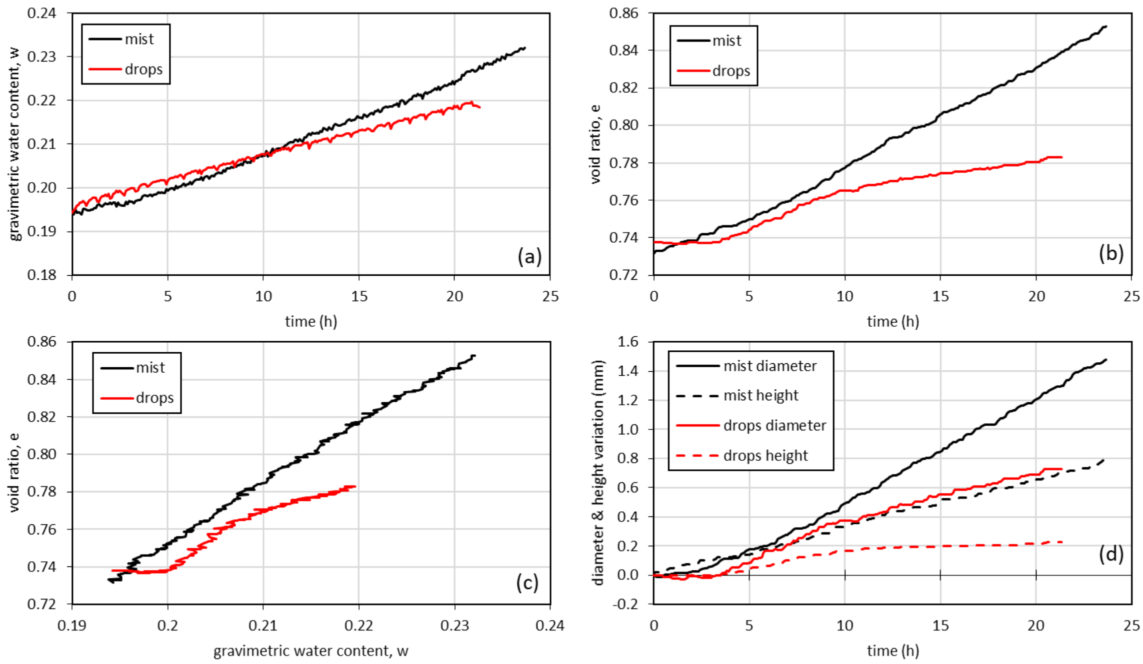

Figure 4: Gravimetric water content (a) and void ratio (b) evolution. Relationship between gravimetric water content and void ratio (c). Evolution of the variation of the samples' diameter and height (d).

The sample wetted by the drops initially presented no change in volume because the wetting was very localized (Fig. 4b). As the wetting progressed, an increase in the rate of the volume change was observed. Figure 4d shows the different evolution of the variation of diameter and height of the samples. The increase in void ratio in this sample mainly resulted from an increase of the sample's diameter as the height stabilized after 10 hours. This increase in diameter may have been amplified by the cracking observed in Figure 3a. Consequently, the soil swelling curve obtained shows an initial increase in water content without change of void ratio and a non-linear evolution, which is not representative of the actual soil behaviour.

Therefore, the drops method results in a distribution of water content in the sample that affects both measured volumetric deformations and possible suction measurements. The mist method was shown to be better to wet soil samples characterized by low hydraulic conductivity. Moreover, the mist method permits the wetting rate to be lower than the one imposed in the present study.

5. Measurement of Soil-Water Retention Curves

Two different London Clay samples were used to determine drying and wetting SWRCs on the DSWRA in which different wetting setups were used. A sample of very high plasticity London clay (71% clay, 26% silt, 3% sand; liquid limit 77%, plasticity index 53%; specific gravity 2.78) was statically compacted at a water content of 0.222 and a void ratio of 1.026 and a second sample of high plasticity London clay (with the same properties of the clay presented earlier) was statically compacted at a water content of 0.187 and a void ratio of 0.772. Both samples were subjected to drying-wetting-drying on the DSWRA after being wetted in a humidity chamber to their initial state. The drops method was used to wet the first sample and the mist method was used to wet the second sample.

The SWRCs and Soil Shrink-Swell Curves for specimens described above are presented in Figure 5. The measured wetting SWRC is above both drying SWRC for the sample wetted by drops (Fig. 5a), which is unrealistic. The initial portion of the wetting SWRC shows an increase of suction with an increase in degree of saturation, which indicates that the soil near the tensiometer is still drying while the sample is already being wetted. This observation results from the non-uniform and slow distribution of water in the soil with low hydraulic conductivity when the drops method is adopted. The SSSCs in Figure 5c also show evidence of localized wetting which amplifies the shift of the SWRC towards higher degrees of saturation as the water content of the sample increases without a detected change in volume.

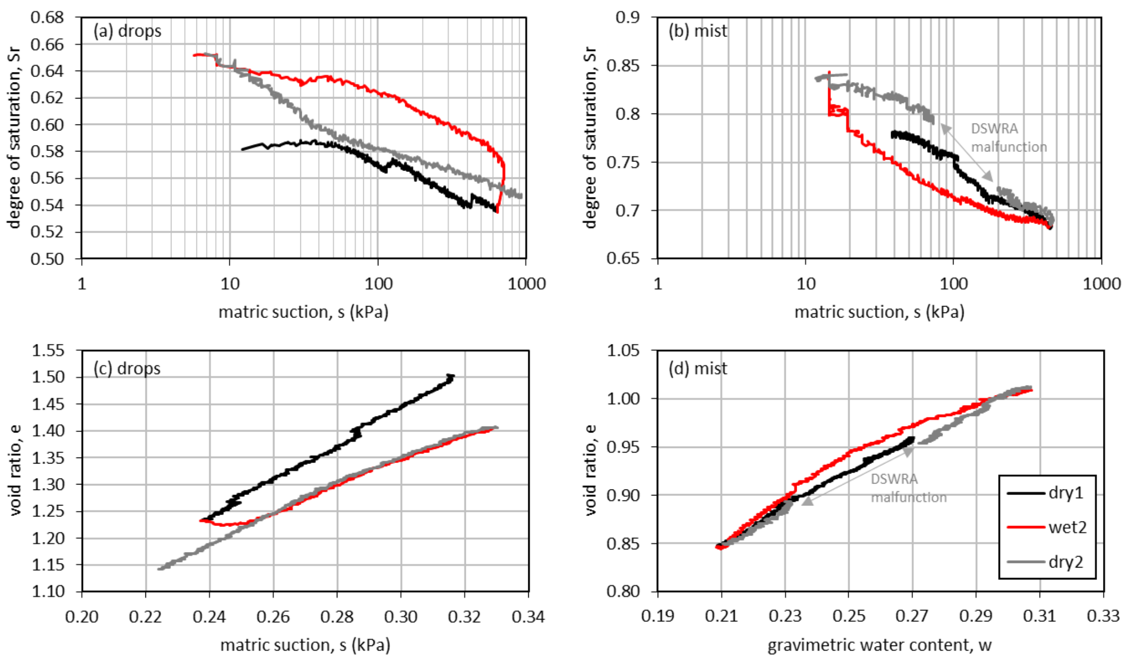

Figure 5: Soil-water retention curves and soil shrink-swell curves of the sequence "dry1-wet2-dry2" of samples subjected to wetting through water drops method and mist method.

The SWRCs of the sample wetted by the mist appear more accurate than those wetted by the drop method (Fig. 5b). The wetting curve is characterized by lower suction values for the same degree of saturation when compared to the drying curves. The initial portion of the wetting curve shows a quicker loss of suction for a small increase in degree of saturation, which is characteristic of wetting SWRCs. In Figure 5d, for the sample wetted by mist, both drying and wetting SSSCs are observed to be linear, which is the typical expected behaviour of this type of clay subjected to this range of changes in moisture (above the shrinkage limit) for which the changes in void ratio is proportional to the changes in water ratio.

6. Conclusions

A new wetting setup to determine the wetting Soil-Water Retention Curve (SWRC) on the Durham Soil Water Retention Apparatus (DSWRA) was tested in comparison with a previous wetting setup. The new system was designed to envelop the tested sample by a mist cloud which results in a uniform distribution of moisture on the surface of the sample.

Two identical samples of compacted high plasticity London Clay were subjected to approximately 24 hours of wetting at a similar rate using two different setups: the original wetting setup that adds water drops to the top of the sample; and the new mist wetting setup. The distribution of gravimetric water content on the samples was measured to assess the performance of each wetting system.

The proposed wetting method by mist performed better than the previous method of adding water drops because:

- Less variability in the distribution of water content in the soil was observed in the sample wetted by the mist then in the sample wetted by the drops;

- Parts of the sample wetted by the drops dried while other parts experienced extreme wetting leading to cracking;
- The water content close to the point of installation of the tensiometer is closer to the overall water content of the sample wetted by the mist than in the sample wetted by the drops method.

The mist wetting setup was therefore shown to be better at imposing wetting on soil with low hydraulic conductivity for continuous measurement of the SWRC.

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