 https://doi.org/10.1051/e3sconf/202338225004

Reliability of HCT-based Soil Water Retention Curves

Meghdad Bagheri[1*], *Vasileios* Matziaris[2], and *Damilola* Akinniyi[1]

[1]School of Energy, Construction and Environment, Coventry University, Coventry, UK
[2]VJ Tech Ltd, Reading, UK

Abstract. The measurement of SWRCs using HCTs has been the subject of several recent studies. Consequently, there have been several design and experimental procedures developed. However, despite these developments, the accuracy, range and duration of HCT-based measurement is still largely characterized by uncertainties and inconsistencies, thereby, reducing the reliability of the obtained SWRCs. In this work, an experimental program is designed to address these uncertainties. SWRCs of reconstituted London clay were measured using the continuous drying method with evaporation rate control. The obtained SWRCs were analysed based on the maximum suction value recorded by HCTs (s_{max}), the obtained air-entry value (s_{aev}), the suction at inflection point (s_i), the water content at inflection point (w_i), and the slope of tangent to inflection point (m_i). A percentage uncertainty of ±4% was obtained for the s_{aev} and s_i values. Similarly, percentage uncertainties of ±6% and ±0.5% were obtained respectively for the m_i and w_i values. These results were further compared with parametric analysis of the reported SWRCs of the same soil in the literature. Given the observed tolerance ranges, cautions must be taken in selecting values for these parameters e.g. as input values in mathematical curve fitting equations for prediction of the entire SWRC, or in unsaturated constitutive modelling, to enhance reliability of the outputs.

1 Introduction

Experimental investigation of unsaturated soils' hydro-mechanical behaviour and determination of unsaturated soil parameters typically involves complex, costly, and time-consuming procedures. Indirect determination of unsaturated soil parameters, such as permeability and shear strength, from the soil water retention curve (SWRC) has proven to be a pragmatic and viable alternative [1]. However, the precision and reliability of the obtained unsaturated parameters is directly influenced by the accuracy and reliability of the SWRC that is in turn dependent to the accuracy and consistency of suction measurement.

The tensiometer method is the only direct soil suction measurement method among the various techniques proposed in the literature. Since the development of high-capacity tensiometers (HCT) in early 1990s, the use of this technique in SWRC measurement has been the subject of numerous studies and resulted in development of several experimental procedures. However, despite these developments, the accuracy, range and duration of HCT-based measurement is still largely characterized by uncertainties and inconsistencies. Several factors including early cavitation of the tensiometer below its nominal capacity, lack of ultimate contact between the sensor and the soil, temperature variations during the test, non-uniform distribution of pore-water throughout the specimen, and possible ceramic filter's pore clog associated with successive use of the sensor and long-term contact with fine soils can influence the HCT measurements.

This paper aims at investigating the uncertainties associated with HCT-based SWRCs through statistical analysis of the derived SWRC parameters.

2 Test Material

The material used in this study was London clay (LC), which was collected from an engineering site in the Isle of Sheppey, UK [2]. The specimens were prepared following the procedure outlined in [3, 4]. The natural samples were initially oven-dried at 105°C, then crushed into powder and sieved through a 1.18 mm sieve. The dry soil was mixed with distilled deaired water at 1.5 times the liquid limit. The obtained soil slurry was then consolidated in a 100 mm diameter consolidometer for 7 days. The consolidated sample was then extracted and cut into three equally sized subsamples of 100 mm diameter and 35 mm height. Finally, the test specimens were cored from the subsamples using a standard 75 mm diameter and 20 mm height oedometer ring. The specimens had initial void ratio of $e_0 = 1.0 \pm 1\%$ and initial water content of $w_0 = 39.5 \pm 0.5\%$. It must be noted here that the presence of coarse-grained peds in the soil samples resulted in an air-entry value (AEV) of around 260 kPa that is significantly lower than that of natural LC reported in the literature [5,6]. This allowed for detection of unsaturated states on SWRC within the capacity of HCTs [7].

* Corresponding author: ac6031@coventry.ac.uk

3 Experimental Program

3.1 HCT

The HCTs used in this study were fabricated at the University of Warwick. This sensor, named Warwick tensiometer (WT) hereafter, has a nominal capacity of 1500 kPa and a measurement resolution of 0.23 kPa. It has been successfully used in several experimental studies of the unsaturated soils' behaviour for monitoring long-term soil suction evolutions [8, 9]. In this work, four WTs of the same design characteristics were used for measurement of SWRCs. These sensors are denoted WT-A, WT-B, WT-C, and WT-D. Fig. 1 presents a schematic diagram of the WT. Prior to each test, the tensiometers were preconditioned following the procedure described in [10, 11].

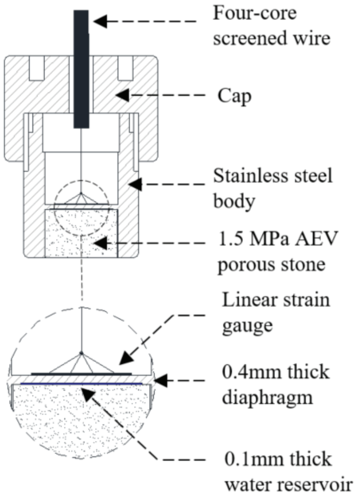

Fig. 1. Schematic diagram of the Warwick tensiometer

3.2 Experimental Procedure

Generally, two methods namely, static and dynamic, are available for HCT-based SWRC measurement. In the static method, the soil specimen is air-dried to known water contents and then stored in sealed containers for at least two days to attain moisture equilibrium prior to suction measurement. In the dynamic method, the soil specimen is placed on a digital balance and exposed to continuous air-drying. Changes of water content are simultaneously monitored by the electronic balance, while the evolution of suction in the continuously drying specimen is recorded by the HCT. The latter method is considered in this study.

Initially, the soil specimen, enclosed in the oedometer ring, was placed on a digital balance with a 0.01 g resolution. A porous disk was considered as the interface between the soil and the balance plate to expose the specimen's base to the atmosphere and hence facilitate the process of continuous air drying. The porous disk being dry and having a large pore size has a negligible effect on the soil specimen and only provide a passage for air circulation at the base of the specimen. Using a mini augur, four holes of 10 mm diameter and 6 mm depth were created on the specimen's surface to accommodate the WTs. The probes were then gently pushed into the holes so that their tips, covered with a thin layer of paste made of the test material, were in ultimate contact with the specimen. Installation of the probes following this procedure deemed to be effective and minimize the local consolidation of the specimen at the soil-sensor interface, non-uniform evaporation at the exposed surface, and accelerated drying in localized areas due to surface cracking [4]. Finally, a perforated chamber was placed around the specimen to control the evaporation rate, allowing more time for equilibrium establishment between the soil and the HCTs. The rate of gravimetric water content change was around 0.15%/h for all tests. The change in soil mass due to the pore water evaporation was continuously measured by the digital balance and recorded on a computer using an RS232 interface. All tests were carried out under the constant temperature and humidity conditions. Fig. 2 presents a schematic diagram of the experimental setup.

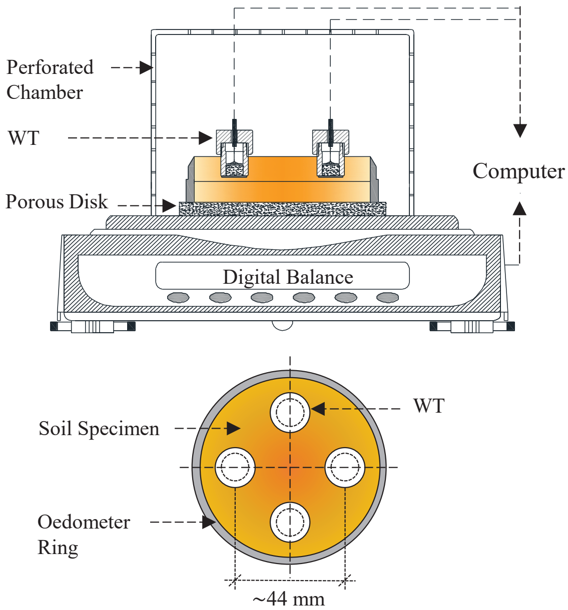

Fig. 2. Schematic diagram of the experimental setup

3.3 Parameter Derivation

In this study, six tests were carried out for direct measurement of the SWRCs of the reconstituted LC. In these tests, only the main drying branch of the SWRC was produced in the gravimetric water content versus suction ($w - s$) domain. The true air-entry values were derived based on the method suggested by [12] whereby the water retention data are plotted on both semi-log and log-log scales on the same graph and the AEV is obtained as the boundary between saturated (linear or bilinear behaviour in semi-log plot) and unsaturated (straight line in log-log plot) zones. This method was later validated by [13] using a machine learning method for estimation of the true AEV of 790 samples in the unsaturated soil hydraulic database, UNSODA [14]. Other parameters including suction at inflection point (s_i), the water content at inflection point (w_i), and the slope of tangent to inflection point (m_i) were obtained from graphical interpretation of the SWRCs as shown in Fig. 3.

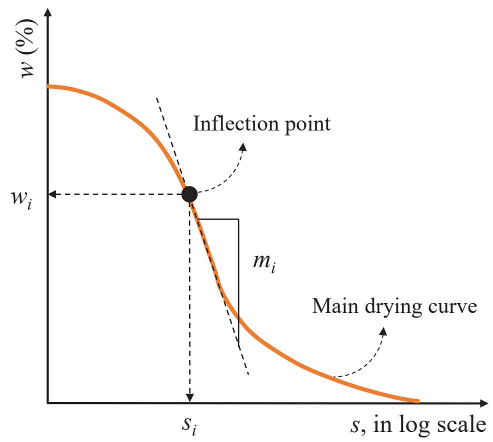

Fig. 3. Graphical derivation of SWRC parameters

4 Results and Discussion

4.1 Maximum Attainable Suction

Fig. 4 presents an example of the obtained SWRCs in a $w - s$ plot. A comparison of the maximum attainable suction, s_{max}, recorded by each WT during the six performed tests is shown in Fig. 5. The WT-A with a mean s_{max} = 1550 kPa and standard deviation (SD) = 57 kPa appears to have a relatively consistent performance. The WT-B with a mean s_{max} = 1372 kPa exhibited the poorest performance in terms of maximum attainable suction and generally cavitated at suctions well below its nominal capacity. However, excluding the results of Test 5, where a s_{max} of above the nominal capacity was recorded, the WT-B's performance may be considered as reasonably consistent. The WT-C and WT-D sensors with SD of respectively 91 and 109 kPa recorded the highest measurement variations.

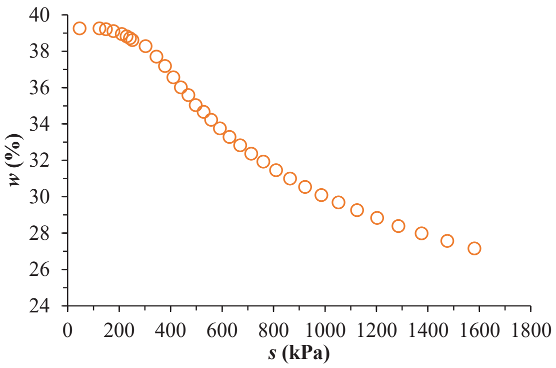

Fig. 4. An example of the obtained SWRC

The absolute uncertainty (measured as the range of the measurements divided by two) in s_{max} values obtained in each test falls within a range of 98 – 160 kPa. This corresponds to a range of 4.9 – 13.0% relative uncertainty. Such a tolerance range necessitates the use of more than one HCT on a single specimen for measurement of SWRC, especially in fine-grained soils where the transition from saturated to unsaturated state may take place at very high suctions.

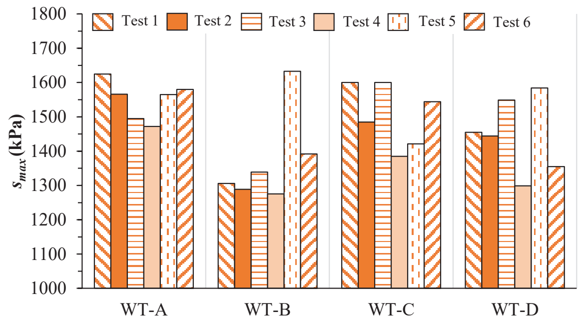

Fig. 5. s_{max} values recorded by each HCT

4.2 Suction at Air-entry Value

Fig. 6 presents the mean true s_{aev} values of the four SWRCs measured in each test. The s_{aev} values fall within a range of 242 – 272 kPa. However, the mean s_{aev} values obtained in each test falls within a range of 254 – 263 kPa. Similar range was obtained for mean s_{aev} values recorded by each WT. The maximum and minimum absolute uncertainties of 12.5 and 8.8 kPa were obtained respectively in Test 1 and Test 5. The corresponding relative uncertainty values are shown in Fig. 6. Conducting a similar analysis for each WT, the maximum and minimum absolute uncertainties of 15.3 and 4.1 kPa were obtained respectively for WT-D and WT-A. The mean s_{aev} values recorded by each WT along with their corresponding relative uncertainty values are shown in Fig. 7. It was also observed that two WTs placed on the same specimen (e.g. WT-A and WT-D in Test 1) may record varied suction at air-entry values with differences being as high as 25 kPa. As it will be explained later in this paper, such differences may result in estimation of significantly different suctions corresponding to a given water content when mathematical curve fitting methods are used for prediction of the entire SWRC beyond the HCTs' measurement capacity.

Despite every attempts made to ensure consistency in specimen preparation, HCT preconditioning, and test setup, minor differences may result in such moderately large variations in the obtained s_{aev} values from different WTs. Moreover, slight differences in the sensor manufacturing process may also cause measurement inconsistencies. For instance, the surface roughness of the inner wall of the diaphragm on the water reservoir side may be slightly different for WT-A and WT-D. This may result in more numbers of crevices and hence, higher number of entrapped gas nuclei that could potentially disrupt the suction measurements [11]. Overall, a percentage uncertainty of ~4% seems reasonable for reporting the s_{aev} values. Such a small tolerance range and the relatively narrow range of mean s_{aev} values obtained are promising and confirm the reliability of the air-entry values obtained from the HCT-based SWRCs.

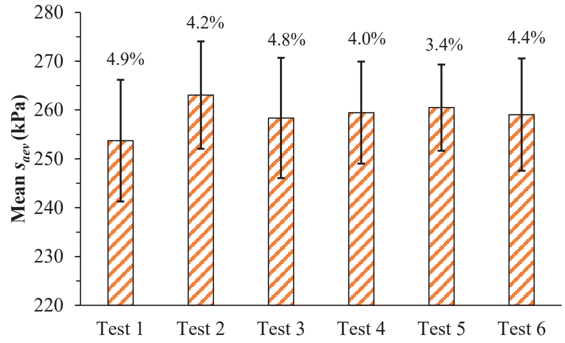

Fig. 6. Mean s_{aev} obtained in each test

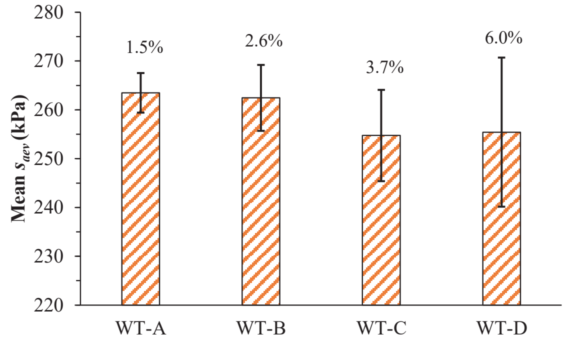

Fig. 7. Mean s_{aev} recorded by each HCT in all performed tests

4.3 Inflection Point

Fig. 8 presents the mean values of the gradient of the tangent line to the inflection point, m_i, obtained in each test. The m_i values fall within a range of 14.5 – 18.6. The maximum and minimum absolute uncertainties of 1.3 and 0.7 were obtained respectively in Test 3 and Test 4. The corresponding relative uncertainty values are shown in Fig. 8. Overall, a percentage uncertainty of ~6% seems reasonable for reporting the m_i values.

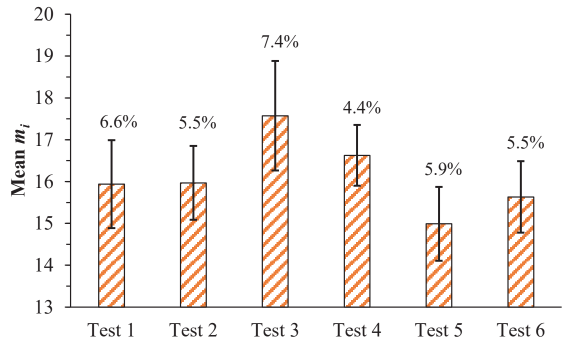

Fig. 8. Mean m_i values obtained in each test

Fig. 9 presents the mean values of the suction at inflection point, s_i, obtained in each test. The s_i values fall within a range of 344 – 414 kPa. The maximum and minimum absolute uncertainties of 22.9 and 8.6 were obtained respectively in Test 6 and Test 2. The corresponding relative uncertainty values are shown in Fig. 9. Overall, a percentage uncertainty of ~4% seems reasonable for reporting the s_i values.

The m_i and s_i parameters govern the shape of the SWRC and are two input parameters in mathematical curve fitting equations [15]. Despite their relatively small percentage uncertainty, it is believed that small variation of these parameters could potentially result in significant suction changes corresponding to a given water content on the main drying branch of the SWRC.

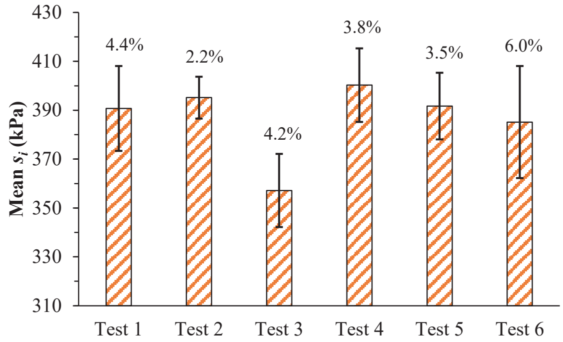

Fig. 9. Mean s_i values obtained in each test

Fig. 10 presents the mean values of water content at inflection point, w_i, obtained in each test. The w_i values fall within a range of 37.1 – 38.0%. The maximum and minimum absolute uncertainties of 0.33 and 0.09 were obtained respectively in Test 5 and Test 1. The corresponding relative uncertainty values are shown in Fig. 10. Overall, a percentage uncertainty of ~0.5% seems reasonable for reporting the w_i values.

In the performed tests, the water evaporation process was facilitated through both the top and bottom of the specimen. However, the distribution of pore-water at the mid-height of the specimen (approximately where suction was measured) might be different to the global change in water content measured by the digital balance. This may explain the slight differences observed in the SWRCs and the estimated w_i values.

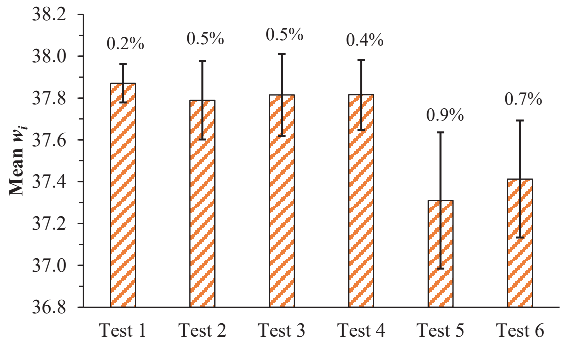

Fig. 10. Mean w_i values obtained in each test

4.4 Additional Parametric Study

To further investigate the accuracy of the extracted parameters from HCT-based SWRCs and their potential impacts, a simple analysis was carried out employing the sigmoidal curve fitting equation proposed by [15]. The m_i, w_i and s_i values obtained in Test 1, along with the saturated water content w_{sat} = 39.5% and residual soil suction s_r = 7.0 MPa were used to develop a mathematical extrapolation of the variation of water content with soil suction where the data points for high suctions (>s_{max}) were not available. Two additional analyses were carried out with s_i + 4% and s_i – 4% as input values. The obtained results revealed that variation of s_i by 4% shifts the best-fit curves resulting in ±5% change in the s_{aev} (Fig. 11). For better visual clarity of the obtained results only the experimental data and

 https://doi.org/10.1051/e3sconf/202338225004

mathematical predictions up to s = 550 kPa are shown in Fig. 11.

The obtained data in this study, in terms of s_{max}, s_{aev}, s_i, and w_i, are in close agreement with those reported in [4] where modified performance-improved WTs were used for SWRC measurement of reconstituted Sheppey LC.

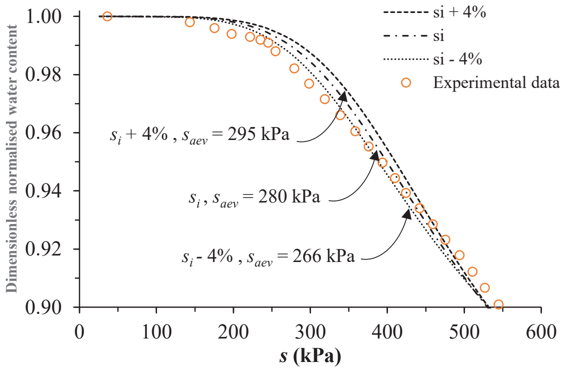

Fig. 11. Impact of change in s_i values on the s_{aev} values obtained from mathematical curve-fitting

5 Conclusions

A statistical analysis of the data obtained from a series of SWRC measurements using HCTs was presented. Despite their occasional measurement inconsistencies, HCTs can be reliably used for development of SWRCs in laboratory. The parameters obtained from HCT-based SWRCs should be reported with an appropriate tolerance range. Analysis based on SWRCs obtained using only one HCT should consider a tolerance of $\pm$4% for the suction at air-entry value, s_{aev} , and suction at inflection point, s_i, a tolerance of $\pm$6% for the slope of the tangent line to the inflection point, m_i, and a tolerance of $\pm$0.5% for the water content at inflection point, w_i. Given the sporadic inconsistencies in HCTs' performance, it is recommended, where possible, to use two or more sensors on a specimen to record soil suction changes during SWRC measurement. Cautions must be considered in use of the extracted parameters from HCT-based SWRCs in mathematical curve fitting or numerical modelling. The recommended tolerance ranges are based on the limited data of this study. Further investigations on different soil types and using different HCT prototypes are required for validation of the obtained results. Finally, although this research is focused on the performance of a specific HCT, the procedure described could potentially be used to establish the reliability of any other commercially available or custom-made instrument used to develop water retention curves.

References

1. S.K. Vanapalli, D.G. Fredlund, D.E. Pufahl, A.W. Clifton, Model for prediction of shear strength with respect to soil suction, Can. Geotech. J. **33**, 379-392 (1996)
2. M. Bagheri, M. Rezania, Geological and geotechnical characteristics of London clay from the Isle of Sheppey, Geotech. Geolog. Eng. **39**, 2, 1701-1713 (2021)
3. M. Bagheri, Experimental investigation of the time and rate-dependent behaviour of unsaturated clays, PhD Thesis, University of Nottingham (2018)
4. M. Bagheri, M. Rezania, Effect of soil moisture evaporation rate on dynamic measurement of water retention curve with high-capacity tensiometer, Int. J. Geomech. **22**, 3, 04021301 (2022)
5. R. Monroy, L. Zdravkovic, A.M. Ridley *Volumetric behaviour of compacted London clay during wetting and loading*, in Proceedings of the 1st European Conference on Unsaturated Soils, E-UNSAT2008, 2-4 July 2008, Durham, UK (2008)
6. M. Mavroulidou, Z. Xiwei, M.J. Gunn, Z. Cabarkapa, Water retention and compressibility of a lime-treated high plasticity clay, Geotech. Geolog. Eng. **31**, 1171-1185 (2013)
7. M. Bagheri, M. Mousavi Nezhad, M. Rezania, A CRS oedometer cell for unsaturated and non-isothermal tests, Geotech. Test. J. **43**, 1, 20-37 (2019)
8. M. Bagheri, M. Rezania, M. Mousavi Nezhad, Rate-dependency and stress relaxation of unsaturated clays, Int. J. Geomech. **19**, 12, 04019128 (2019)
9. M. Rezania, M. Bagheri, M. Mousavi Nezhad, Creep and consolidation of a stiff clay under saturated and unsaturated conditions, Can. Geotech. J. **57**, 5, 728-741 (2020)
10. A. Tarantino, L. Mongiovi, *Design and construction of a tensiometer for direct measurement of matric suction*, in Proceedings of the 3rd International Conference on Unsaturated Soils, UNSAT2002, 10-13 March 2002, Recife, Brazil (2002)
11. M. Bagheri, M. Rezania, M. Mousavi Nezhad, Cavitation in high-capacity tensiometers: effect of water reservoir surface roughness, Geotech. Res. **5**, 2, 81-95 (2018)
12. A.Y. Pasha, A. Khoshghalb, N. Khalili, Pitfalls in interpretation of gravimetric water content–based soil-water characteristic curve for deformable porous media, Int. J. Geomech. **16**, 6, D4015004 (2016).
13. M.S. Es-haghi, M. Rezania, M. Bagheri, Machine learning-based estimation of soils' true air-entry value from GSD curves, Gondwana Res. In Press, (2022)
14. F.J. Leij, W.J. Alves, m.Th. van Genuchten, J.R. Williams, The UNSODA unsaturated hydraulic database, USEPA, Cincinnati, Ohio. EPA/600/R-96/095 (1996)
15. D.G. Fredlund, A. Xing, Equations for the soil-water characteristic curve, Can. Geotech. J. **31**, 521-532 (1994)