Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1713

A Proposed Method for Determining the Plastic Limit of Undisturbed Soil Samples at Zero Suction

Paul Vosloo, Philip Rob Stott, Elizabeth Theron
Central University of Technology Free State, South Africa, pvosloo@cut.ac.za

ABSTRACT: The plastic limit (PL) is a key index property in soil mechanics, but conventional rolling-thread methods disturb the soil structure and rely on subjective operator judgement, leading to high variability. This preliminary study presents an alternative approach for determining the PL of undisturbed specimens equilibrated to a total suction of 0 kPa, defined according to Kelvin's equation at 100 % relative humidity. A single cohesive soil type was tested using both the proposed zero suction equilibration method and the standard SANS 3001 rolling-thread method, with multiple replicates for each method. Probability density functions (PDFs) were used to characterize intrinsic soil variability. The equilibration method yielded a narrower PDF and slightly lower mean moisture content than the conventional method, suggesting that it captures primarily intrinsic soil variability while reducing operator-induced effects. The results also indicate a potential correspondence between the PL and the air-entry value (AEV) when defined from a Kelvin law zero suction baseline. These findings are based on a single soil type and therefore require validation across a broader range of soils to assess their general applicability.

KEYWORDS: plastic limit, soil variability, undisturbed soil, thread rolling method, zero suction.

1 INTRODUCTION

The plastic limit (PL) represents a fundamental threshold in the behaviour of fine-grained soils, marking the transition from a plastic to a semi-brittle state under deformation. It is widely used in geotechnical engineering for classification, design, and prediction of soil performance. Despite its importance, the PL is typically determined through the rolling-thread method, as codified in standards such as SANS 3001-GR10, which involves remoulding soil and rolling it into threads until crumbling occurs. This procedure is known to be highly operator-dependent, introducing significant variability between laboratories and even within repeated tests by the same technician (Liu, 1964; Moreno-Maroto and Alonso-Azcárate, 2016).

Recent developments in unsaturated soil mechanics emphasize the use of suction and related thermodynamic potentials as fundamental state variables for describing soil behaviour (Fredlund & Rahardjo, 1993; Lu & Likos, 2004; Lu, 2020). Within this suction-centered framework, classical index tests such as the plastic limit (PL) have been reinterpreted in terms of these state variables, rather than a fixed undrained strength threshold (Haigh et al., 2013; O'Kelly, 2024). The air-entry value (AEV), which marks the onset of desaturation, is conventionally identified on a soil water characteristic curve (SWCC) as the suction at which air first invades the largest pores. However, in typical SWCC plots, suction is presented on a logarithmic axis, compressing the fully saturated zone into a nearly vertical segment and obscuring the true zero-suction condition.

In this study, zero suction is defined according to Kelvin's equation, in which 100 % RH corresponds to a total suction of 0 kPa. From this perspective, the AEV is the first departure from zero suction, occurring when RH falls below unity and menisci form in the largest pores. By equilibrating undisturbed soil specimens to zero suction and then determining the PL, this study explores the hypothesis that, for certain soils, the PL coincides with the AEV in a Kelvin-law sense.

2 BACKGROUND

2.1 *Limitations of Conventional SWCC Representation and Interpretation*

Questions have been raised about whether the soil–water characteristic curve (SWCC) as commonly determined and plotted provides a reliable basis for identifying features such as air-entry and residual suction. Stott and Theron (2022) note that retention curves are often constructed from slurried or otherwise strongly disturbed samples using axis-translation, with little standardization of starting and ending water contents, so that the resulting curves may not reflect field-relevant hydraulic states.

Comparing data extracted from Fredlund's (2019) example SWCCs, they show that a curve which appears sigmoidal on a log–linear plot and is used to infer an air-entry value of 10 kPa and a "residual suction" of 120 kPa becomes a smooth, featureless curve when replotted on linear–linear axes, with no indication of distinct break points near those suctions. On this basis they conclude, following Blight, that the familiar sigmoidal form of the log–linear SWCC and the associated identification of air-entry and residual suction values can be artefacts of the logarithmic suction scale, particularly near low suctions where plotting suctions below about 1 kPa is "somewhat dubious" yet occupies a disproportionately large region of the graph. They further argue that if the retention curve is to represent field conditions, it should be plotted on linear–linear axes and expressed in terms of gravimetric water content, which is the quantity actually measured, since the log–linear representation is "deceptive" and deductions from its sigmoid form "appear to be artifacts of the log scale".

In addition to representation issues, Stott and Theron (2022) emphasize that the usefulness of a single SWCC is limited by the intrinsic spatial variability of soils. Drawing on soil science work, they recall that soil properties often display fractal-type variability over scales "from micrometers to the landscape" (Pachepsky et al., 2000), a feature that has generally received little attention in geotechnical practice. They highlight examples from Stott and Theron (2017) where engineering failures could be largely attributed to small-scale spatial variability in suction potential within apparently uniform clay layers and discuss the heave pattern observed under a simulated foundation, arguing that strong variability in swelling potential provides a more plausible explanation than simple stratigraphic irregularity. On this basis, they warn that current sampling and testing practices, which typically rely on one or two specimens to define a "characteristic" retention curve, may give a poor indication of behaviour for soils with large intrinsic variability, and that the time and cost of producing such SWCCs may not yield meaningful predictions regardless of the sophistication of the subsequent numerical modelling.

2.2 *Current AEV estimation practice*

In routine practice, the air-entry value (AEV) is commonly estimated graphically from the soil–water characteristic curve (SWCC) as the "knee" or break point between the low-suction saturated plateau and the main desaturation branch. Typical procedures involve visual identification of this transition, drawing straight lines through the near-horizontal saturated segment and the steeply descending portion of the curve and taking their intersection, or locating the point of maximum curvature on the drying SWCC (e.g. Leong & Rahardjo, 1997; Fredlund, 2019; Soltani et al., 2021). More formally, widely used parametric SWCC models such as those of Brooks and Corey (1964), van Genuchten (1980) and Fredlund and Xing (1994) include a parameter that governs the position of this transition denoted, for example, as the bubbling pressure $\psi_b$in the Brooks–Corey equation and this parameter is routinely interpreted as an approximate air-entry suction for the soil.

2.3 *Zero suction and Kelvin's law*

In thermodynamic terms, total suction (ψ_t) can be related to RH through the Kelvin equation (Likos and Lu, 2003):

$$\psi_t = -\frac{R.T}{v_{w0}.w_v}.\ln RH \qquad (1)$$

where R is the universal gas constant (8.314 J/mol.K), T is absolute temperature (K), v_{wo} is the specific volume of water or inverse of the density of water (m^3/kg), w_v is the molecular mass of water vapor (18.016 kg/kmol), and RH is the relative humidity. At RH=1.00, ln (1) = 0 and thus total suction will be equal to 0 kPa. This zero-suction state represents water at the same free energy as pure liquid water under atmospheric pressure, with all pores fully saturated. Vapour equilibrium techniques achieve this by sealing specimens over free water in a closed chamber (Greenspan, 1977; Tang & Cui, 2007).

In SWCC practice, the initial saturated state is typically compressed into an unresolved section of the curve, and "zero suction" is often represented as a small positive value on the logarithmic axis. This is a scaling artefact rather than a true reflection of the thermodynamic condition.

2.4 *Air-entry value in the Kelvin framework*

From the Kelvin equation, total suction $\psi_t$is related to the relative humidity (RH) of the pore air; at $RH = 100\%$the Kelvin relation gives $\psi_t = 0$, and any reduction in RH below unity produces a positive total suction. In unsaturated soil mechanics, the air-entry value (AEV, or bubbling pressure) is defined as the matric suction at which air first starts to enter the largest pores and desaturation begins, corresponding physically to the formation of stable air–water menisci in those pores. From a Kelvin-law standpoint, the AEV can therefore be seen as the first significant departure from the zero-suction state, in the sense that meniscus curvature (and hence capillary suction) becomes non-zero as RH falls slightly below 100%.

Haigh et al. (2013), re-analyzing desaturation curves for three saturated soils prepared from slurry, FoCa clay, Jossigny silt and La Verne dam material, showed that for the relatively coarser Jossigny silt and La Verne material the suction at the plastic limit "corresponds reasonably well with air entry", whereas for the finer FoCa clay the plastic-limit suction is about two orders of magnitude lower than the air-entry suction. They interpreted the former case as brittle failure triggered by air entry and desaturation, and the latter as brittle failure governed by heterogeneous cavitation of the pore water within a still-saturated fabric. These observations indicate that any equivalence between PL and AEV is soil-type dependent: for some silts and low-air-entry materials the PL may coincide with, or lie close to, the AEV, whereas for high-air-entry clays the PL can occur at much lower suctions associated with cavitation rather than air entry. Plastic limit mechanisms and operator effects.

The PL is traditionally defined as the water content at which a soil thread crumbles when rolled to a 3 mm diameter, but the failure mechanism is not purely mechanical. Haigh et al. (2013) demonstrated that PL behaviour is governed by either air entry or cavitation, depending on particle size and pore structure. Coarser silts and sandy clays tend to reach PL at suctions close to their AEV, whereas finer clays reach PL at suctions one to two orders of magnitude lower than AEV, due to cavitation within pore water.

2.5 *Limitations of conventional PL determination*

The operator-dependent rolling method (Moreno-Maroto & Alonso-Azcárate, 2016) suffers from high inter-laboratory variability (Liu, 1964), in part because it relies on remoulded material prepared at a subjective moisture content (CT-204; Caltrans, 2010). Moreover, by ignoring the suction state, traditional methods cannot distinguish whether failure at PL arises from desaturation (air entry) or from cavitation. This lack of suction control obscures the physical meaning of PL and reduces the reproducibility of results across different soil types and operators.

2.6 *Variability in soil mechanics*

Soil variability has long been recognized by soil scientists, with fractal-type patterns evident across scales ranging from microscopic pore structures to field-scale stratigraphy (Pachepsky et al., 2000). In the context of index testing, such variability can influence measured values as much as, if not more than, procedural or operator differences. The conventional practice of reporting a single "representative" value for a given stratum risks obscuring this inherent variability, leading to misleading expectations of reproducibility across laboratories.

In the case of plastic limit (PL) testing, differences between laboratories have often been attributed to operator bias, procedural variations, or lack of diligence (Liu, 1964). However, direct observation of commercial laboratory practice shows that technicians generally work to high procedural standards, and managers prioritize accuracy to maintain reputations. This suggests that observed differences are frequently a reflection of the natural, scale-dependent variability of soils rather than poor practice.

Recognizing this, it becomes important to employ test methods that reveal, rather than mask, soil variability. The proposed zero-suction equilibration method offers an advantage in this respect, as it controls suction while preserving undisturbed soil structure, allowing the PL to be measured at a consistent thermodynamic starting point. By contrast, the conventional rolling-thread method involves remoulding, which can reduce or obscure natural variability through disturbance and operator adjustments.

2.6.1 *Assessing variability*

Quantifying soil variability for engineering design increasingly relies on statistical descriptors such as the probability density function (PDF) of measured values. For a normal distribution, a large number of replicates on the order of hundreds would be required to achieve the confidence levels used in reliability-based design frameworks (Stott & Theron, 2019). While such sample sizes are impractical for most geotechnical projects, even moderate replication can provide valuable insight into the spread and shape of the underlying distribution.

Importantly, South African studies have shown that PDFs for certain soil properties do not always follow standard forms such as the normal, lognormal, or Gumbel distributions (Stott & Theron, 2019). This means that assumptions about variability made without empirical verification can lead to unsafe underestimation or overly conservative overestimation of design parameters.

In this study, PDFs were constructed for two independent datasets of PL measurements: one from conventional SANS 3001 rolling-thread tests and one from the zero-suction equilibration method. Comparing these distributions allows for the assessment of both central tendency and spread, providing a more complete picture of soil behaviour. By capturing the shape of the distribution rather than relying solely on a single mean value, the analysis acknowledges the role of natural variability in PL determination and highlights the potential of suction-controlled testing to produce more consistent results without disregarding that variability.

3 METHODS AND MATERIALS

3.1 *Soil type and sampling*

Undisturbed soil samples from a layer of dark brown clay from a test pit at a housing development in the central Free State were prepared using a procedure described in Stott & Theron (2017), which leads to little disturbance of soil structure and no remoulding. Small soil fragments were broken along lines of weakness or selected from fragments which had separated spontaneously. The clay soil has a liquid limit of 74%, a plasticity index of 52%, a hydrometer clay fraction of 38% and a USCS classification of "CH", Figure 1, 2 and 3 shows the grading curve, SWCC on a linear scale and SWCC on a log scale respectively. Lines of weakness like slickensides occur at the boundaries between regions having different properties. Such samples appear to be useful for estimating intrinsic variability of a soil. Soil scientists have found that soil properties vary on fractal scales which may vary "from micrometers to the land scape" (Pachepsky et al. 2000). The size of fragments surrounded by planes of weakness appears to be one of these fractal scales. Engineers have largely paid little attention to fractal aspects of variability, but Yang et al. (2023) used a fractal soil–water characteristic curve model based on particle size distribution to evaluate SWCCs for twelve soil textures, demonstrating how fractal metrics can link soil structure and hydraulic behaviour.

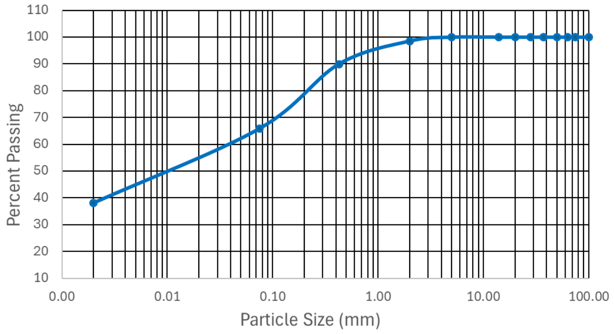

Figure 1. Soil particle size distribution.

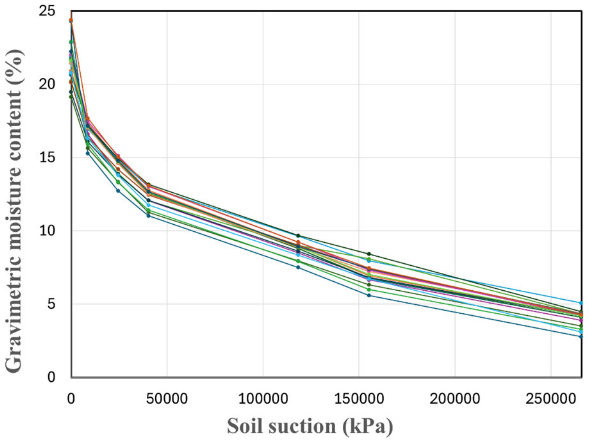

Figure 2. SWCC of soil on a linear-linear scale.

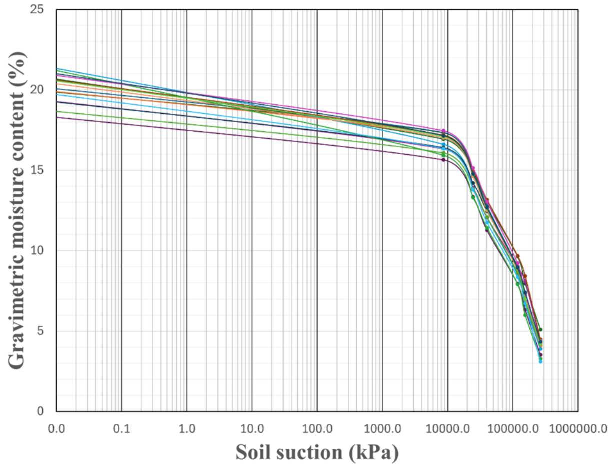

Figure 3. SWCC of soil on a linear-log scale.

3.2 *Conventional plastic limit testing*

The baseline PL was determined following the rolling-thread method specified in SANS 3001-GR10, in which a 3 mm diameter thread is rolled until crumbling occurs. This method uses remoulded specimens prepared from the bulk soil at moisture contents near the expected PL and is inherently operator-dependent (Moreno-Maroto & Alonso-Azcárate, 2016; Liu, 1964). A large number of replicate tests were performed to capture natural variability in both material behaviour and operator execution, Figure 1 shows the "crumbled" clay threads from the study.

Figure 4. Soil thread after rolled to crumbling state.

3.3 *Zero-suction equilibration method*

For the proposed method, undisturbed soil fragments as described in the previous section were equilibrated to zero suction following the general approach outlined by Stott (2017), adapted for this study.

Each specimen fragment was first brought to full saturation under positive pore-water pressure by applying distilled water dropwise to the exposed surface, while taking care to avoid mechanical disturbance of the soil structure. The saturated specimens were then placed in a sealed chamber containing a distilled-water reservoir to maintain the internal atmosphere at 100% relative humidity as shown in Figure 2. At a constant temperature of 20 °C, this condition corresponds, according to the Kelvin equation, to a total suction of approximately 0 kPa (Likos & Lu, 2003; Greenspan, 1977).

Figure 5. Small soil fragments in glass weighing bottles.

Equilibration was monitored gravimetrically by periodically weighing the specimens on a high precision balance (0.0001g) until daily successive measurements showed no further change in mass within the sensitivity of the balance, indicating hydraulic equilibrium throughout each fragment. The controlled chamber ensured stable temperature and relative humidity for the duration of the test, thereby imposing a well-defined and reproducible zero-suction state prior to plastic limit determination.

In this study, the plastic limit is operationally defined as the equilibrium water content of the undisturbed specimens at 100% RH (0 kPa total suction). It is determined directly from these equilibrated specimens and is not inferred from a measured soil–water characteristic curve.

3.4 *Probability density function analysis*

PL results from both methods were compiled and used to generate separate PDFs. This statistical approach accounts for soil spatial variability, which can skew results if based on limited data (Phoon & Kulhawy, 1999). Each PDF was constructed from multiple replicates to provide robust estimates of central tendency and spread.

3.5 *Comparative analysis*

The two PDFs were overlaid to assess alignment in mean values and variability. The degree of overlap was taken as an indicator of correspondence between the methods.

4 RESULTS

4.1 *Conventional PL results*

The SANS 3001 tests yielded PL values in the range 17.7–28.8 %, with a mean of 23.1 % and standard deviation of 1.7 %. The PDF shown in Figure 3 showed a moderate spread, with a slightly skewed tail toward higher moisture contents.

Table 1. Descriptive statistics for the thread rolling PL data.

	Value	Unit
Count	295	no.
Max	28.8	%
Min	17.7	%
Mean	23.1	%
Median	23.2	%
std dev	1.7	%
COV	7.5	%
5th percentile	19.60	%
95th percentile	25.68	%
Variability. range	6.08	%

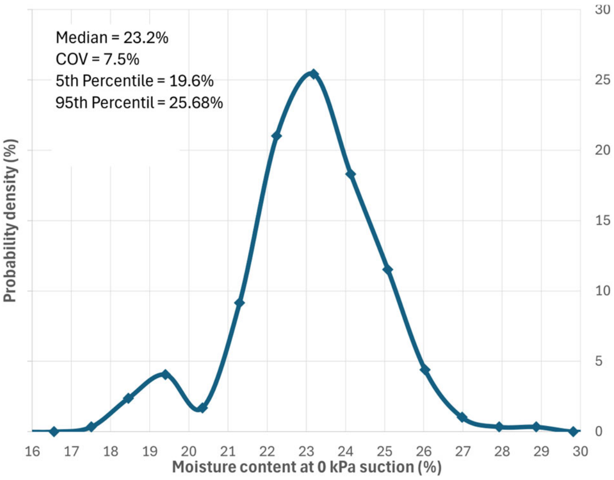

Figure 6. Thread rolling PL Probability density function.

4.2 *Zero-suction PL results*

The equilibration method produced PL values between 17.5–27.7 %, with a mean of 22.0 % and a narrower spread. The PDF shown in Figure 4 is more peaked, indicating greater consistency between replicates.

Table 2. Descriptive statistics for the zero suction PL data.

	Value	Unit
Count	351	no.
Max	27.7	%
Min	17.5	%
Mean	22.0	%

Median	22.0	%
std dev	1.4	%
COV	6.3	%
5th percentile	19.87	%
95th percentile	24.31	%
Variability. range	4.44	%

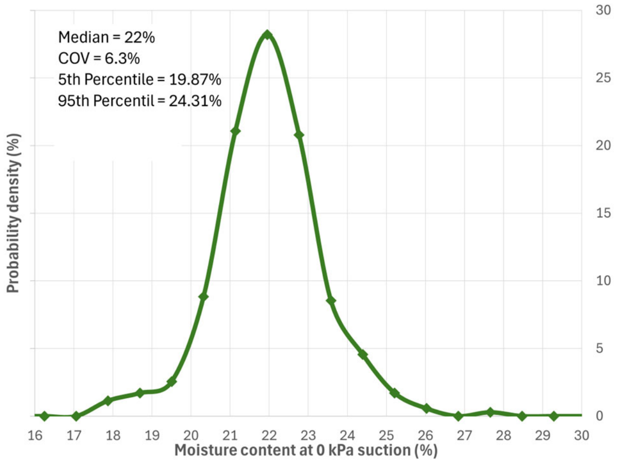

Figure 7. Zero suction PL Probability density function.

4.3 *Comparative PDFs*

The green PDF (zero suction) is centered slightly to the left of the blue dotted PDF (thread rolling), suggesting a marginally lower mean moisture content. The narrower profile of the equilibration PDF reflects reduced variability. Overlap between the curves indicates that both methods yield broadly similar PL values for this soil, consistent with the hypothesis that the PL approximates the AEV when defined from a zero-suction baseline.

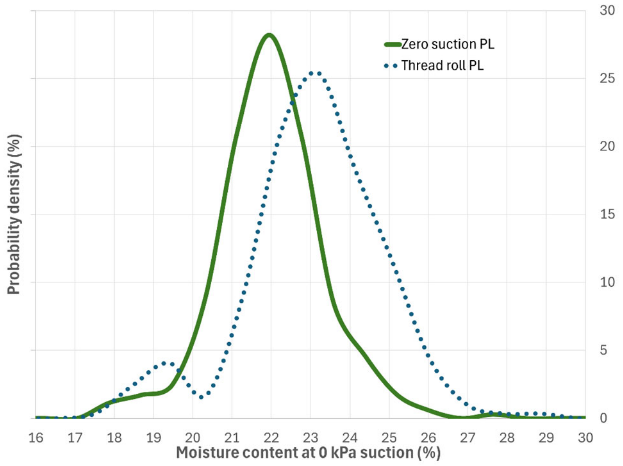

Figure 8. Comparison of the probability density functions.

5 DISCUSSION

5.1 *Reduced variability from suction control*

The equilibration method's reduced spread is attributable to controlling initial suction and preserving natural soil structure. This minimizes the disturbance effects and operator judgement variability inherent in the conventional method.

5.2 *Intrinsic vs. Operator-Induced Variability*

Interestingly, the undisturbed method expected to preserve natural variability produced less spread than the remoulded method, which in theory should homogenize the sample. This suggests that the higher variability in the rolling-thread results stem from operator effects such as differences in rolling pressure, speed, and crumbling point judgement, rather than soil fabric.

5.3 *Linking PL to AEV*

Under Kelvin's definition, zero suction corresponds to full saturation, and the AEV is the first suction increment as RH drops below 100 %. For the tested soil, the close alignment of PL values from both methods suggests that PL coincides with the AEV. This finding mirrors Haigh et al. (2013) for coarse soils and supports the theoretical equivalence for soils of similar pore size distribution.

5.4 *Broader implications*

Adopting a suction-controlled PL method could tie the gap between traditional classification tests and unsaturated soil mechanics. For soils where PL ≈ AEV, the index property gains a direct physical interpretation and becomes more reproducible. This could be particularly valuable in design contexts where suction-related behaviour is critical.

6 CONCLUSION

This preliminary study evaluated a zero suction equilibration method for determining the plastic limit of undisturbed soil specimens, using Kelvin's equation to define a thermodynamically consistent baseline condition. Compared with the standard SANS 3001 rolling-thread method, the proposed approach yielded a narrower probability density function and slightly lower mean moisture content for the tested soil. The reduced variability likely reflects measurement of the soil's intrinsic variability rather than operator-induced variability, which appears to be a significant factor in the conventional remoulded method despite its theoretical homogenizing effect.

For the soil examined, the results suggest that the plastic limit approximates the air-entry value when measured from a Kelvin law zero suction baseline. This interpretation could enhance the physical significance and reproducibility of the PL in geotechnical engineering practice. However, because the present work was limited to a single cohesive soil type, the findings should be considered indicative rather than definitive. Broader validation across a spectrum of soils is required before the method could be proposed for standardization or routine use.

7 REFERENCES

Blight, G.E. 1997. Interactions between the atmosphere and the earth, *Géotechnique*, 47(4), 715–767.

Brooks, R.H. and Corey, A.T. 1964. Hydraulic properties of porous media, *Hydrology Paper 3*, Colorado State University, Fort Collins, CO.

Caltrans, 2010. *CT 204: Method of Tests for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.* Sacramento: California Department of Transportation.

Fredlund, D.G. 2019. State of practice for use of the soil-water characteristic curve (SWCC) in geotechnical engineering. *Canadian Geotechnical Journal*. 56(8): 1059-1069

Fredlund, D.G. and Rahardjo, H. 1993. Soil Mechanics for Unsaturated Soils, John Wiley & Sons, New York.

Fredlund, D.G. and Xing, A. 1994. Equations for the soil–water characteristic curve, *Canadian Geotechnical Journal*, 31(4), 521–532.

Greenspan, L. 1977. Humidity fixed points of binary saturated aqueous solutions, *Journal of Research of the National Bureau of Standards – A*, 81A(1), 89–96.

Haigh, S.K., Vardanega, P.J. and Bolton, M.D., 2013. The plastic limit of clays, *Géotechnique*, 63(6), 435–440.

Leong, E.C. and Rahardjo, H. 1997. Review of soil–water characteristic curve equations, *Journal of Geotechnical and Geoenvironmental Engineering*, 123(12), 1106–1117.

Likos, W.J. and Lu, N. 2003. Automated humidity system for measuring total suction characteristics of clay, *Geotechnical Testing Journal*, 26(2), 179–190.

Liu, T.K. 1964. Study of the reproducibility of Atterberg limits, *Highway Research Record*, 63, 1–11.

Lu, N. and Likos, W.J. 2004. Unsaturated Soil Mechanics, John Wiley & Sons, Hoboken, NJ.

Moreno-Maroto, J.M. and Alonso-Azcárate, J. 2016. A bending test for determining the Atterberg plastic limit in soils, *Journal of Visualized Experiments*, 112.

O'Kelly, B.C. 2024. Theory of liquid and plastic limits for fine soils, methods of determination and outlook, *Geotechnical Research*, 11(1), 43–61.

Pachepsky, Y.A., Timlin, D.J. and Rawls, W.J. 2000. Soil water retention as related to topographic variables, *Soil Science Society of America Journal*, 64(5), 1627–1635.

Phoon, K.K. and Kulhawy, F.H. 1999. Characterization of geotechnical variability, *Canadian Geotechnical Journal*, 36(4), 612–624.

SANS 3001-GR10. 2011. Civil Engineering Test Methods. Part GR10: Determination of the one-point liquid limit, plastic limit, plasticity index and linear shrinkage (1.1 ed.). Pretoria: SABS Standards Division.

Soltani, A., Azimi, M., Boroomandnia, A. and O'Kelly, B.C. 2021. An objective framework for determination of the air-entry value from the soil–water characteristic curve, *Results in Engineering*, 12, 100298.

Stott, P.R., Theron, E. 2017. Estimating shrink/swell potential and variability of clays using small-scale suction tests. *Geotechnical Engineering Journal of the SEAGS & AGSSEA, 48(2), 115–125.*

Stott P.R. and Theron E. 2019. Investigation of the probability density functions of suction potential of soils. *Proceedings of the 17th African regional conference on Soil Mechanics and Geotechnical Engineering, Cape Town, South Africa, 17, 125-130*

Stott, P.R. and Theron, E. 2022. Questions concerning the usefulness and validity of the soil–water characteristic curve in unsaturated soil mechanics, *Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering (ICSMGE 2022)*, Sydney, Australia, 1533-1537.

Tang, A.-M. and Cui, Y.-J. 2007. Controlling suction by vapour equilibrium technique at different temperatures, *Canadian Geotechnical Journal*, 44(2), 267–271.

Yang, C., Wu, J., Li, P., Wang, Y. and Yang, N. 2023. Evaluation of soil–water characteristic curves for different textural soils using fractal analysis, *Water*, 15(4), 772.