# Soil water retention curve: usage considerations and variability assessment

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ABSTRACT: The Soil Water Retention Curve, also known as the Soil Water Characteristic Curve plays a leading role in almost the whole field of unsaturated Soil mechanics. There are, however reasons for questioning whether some widely adopted practices are sound. One such practice is relying on very few measured values to decide on a definitive retention curve. In this investigation we examine the variability implicit in the first twenty experimental drying curves of an ongoing experiment to assess full probability density functions for multiple cycles of drying and wetting and generating a soil water characteristic curve without conventional curve fitting.

## 1 INTRODUCTION

The value of the Soil Water Retention Curve (SWRC) or Soil Water Characteristic Curve (SWCC) was first realised by Soil Scientists concerned with Agricultural production. It was found to be very useful for assessing water mobility and water storage. They developed techniques based on the principle, often called "Axis Translation", in which water is forced from a sample standing on a porous plate. When engineers realised the usefulness of the SWRC they adopted Soil Science practices. Some of these practices may not be ideal for engineering purposes. For example, since the porous plate contains pore water expelled from the sample, the measured pressure is not a measure of the suction in the soil, but is the difference of the total suction and the osmotic pressure within the soil. This is called matric suction. Unsaturated soil mechanics developed taking this as the suction to be used in calculations.

However, more recently, several techniques were developed for measuring soil suctions, particularly suctions greater than those possible with available porous plates. Measurement of total suction became common, and now the SWRC is often constructed with two different suctions, matric and total for different parts of the same curve. Another practice apparently brought in from Soil Science is the use of a logarithmic scale for suction and a linear scale for water content. Blight (2013) pointed out the inadvisability of this because although a log scale is convenient for putting a large range of suctions on a conveniently sized diagram, if the plot is not linear it gives little useful information and invites unwarranted speculation about the observed shape of the graph. Stott & Theron (2022) gave a typical example of this in accepted practice as shown in Figure 1 (Fredlund 2019).

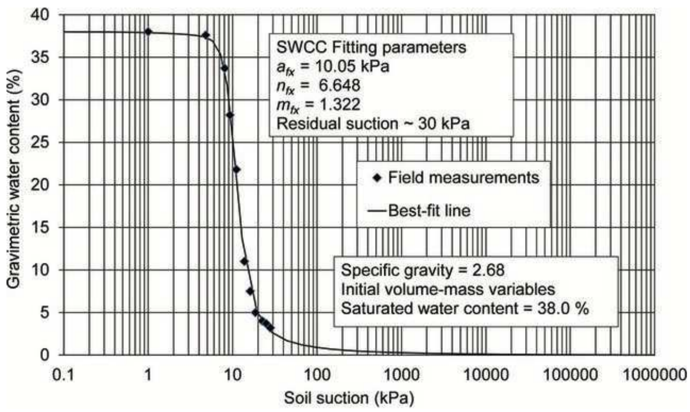


Figure 1. The typical SWCC in log scale (Fredlund 2019)

Another questionable aspect of the traditional SWRC was also pointed out; high water content values are usually allocated small positive suction values in the graphical representation. In many cases the relevant water contents correspond to small positive pore pressures. In many cases the initial soil is a slurry – often at the Liquid limit in order to ensure good contact with a porous plate. However, it is increasingly being recognised that the use of the SWRC is most valuable for "undisturbed" conditions.

It appears that for the SWRC to achieve its full usefulness, agreement should be reached on procedures which give meaningful and consistent results. The SWRC is widely taken as providing a fundamental unifying feature in the field of unsaturated soils, enabling properties of soils to be assessed over a wide range of water contents. But in addition to the above questions there is also the problem of variability which is ignored in the standard texts on unsaturated soils. A preliminary investigation reported in Stott and Theron (2018) suggested that neglect of variability may lead to misleading results.

## 2 VARIABILITY IN SOIL MECHANICS

Soil variability, particularly its fractal distribution patterns, was acknowledged by soil scientists long before engineers recognized its significance. As noted by Pachepsky et al (2000), soil properties exhibit fractal-based variability across multiple scales, from microscopic structures to entire landscapes. Given this characteristic, it is beneficial to adopt testing methods that reveal, rather than obscure, soil variability. The conventional assumption that a single representative value can define a soil stratum has led to concerns regarding inconsistent test results across different laboratories. Minty et al. (1979) proposed that such discrepancies could arise from operator bias or variations in testing procedures, while others have attributed them to negligence or procedural shortcuts. However, direct observations of commercial laboratories suggest that technicians are highly skilled and dedicated to maintaining rigorous standards. Laboratory managers also prioritise accuracy and uphold their reputations, indicating that variations in test results likely reflect the natural fractal-scale variability of soil samples rather than errors in testing.

There has been a general realisation that the long-established practice in soil mechanics and geotechnical engineering known as “Working Load Design” is unsatisfactory and should be replaced with procedures conforming to best practice in other branches of Civil Engineering. To this end, the code of practice widely considered to be the best available at this time, Eurocode 7, has been, or is being adopted, in many countries including South Africa. This code is a simplified approach to Reliability Based Design, which attempts to assess uncertainties in each aspect of design and carry those uncertainties through the entire design process. Eurocode’s simplified approach specifies that for soil properties one should determine a value for a property, the *Characteristic Value*, which will give no more than a 5% chance of failure due to inadequacy of that property. A factor of safety is applied to the Characteristic value which should lead to a design value for the property with a very small probability of failure.

Unless Unsaturated Soil Mechanics is to be excluded from engineering design in South Africa, then it also needs to make realistic estimates of the Characteristic values to be used in design. Since the SWRC is a key element in estimating those soil property values, it should be considered a relevant part of the determination of Characteristic values.

### 2.1 *Assessing variability*

There appears to be only one way to reliably assess the 5 percent chance of failure required by the code of practice and that is to assess the probability density function (PDF) associated with a sufficient number of tests. Such tests need to be suitable for *revealing* variability. Many of the standard tests performed in commercial laboratories were designed for giving the average, or “representative” values called for in working load design and are not fit for purpose in regard to revealing variability. The number of tests required for the desired confidence level for a normal distribution is 636 (Eaton et al. 2019) For soil *actions* the code assumes a Gumbel maximum distribution for assessing the 95$^{th}$ percentile. For soil *resistances* a log normal distribution is assumed for assessing the 5$^{th}$ percentile. However, Stott and Theron (2019) demonstrated that many South African soils do not have PDFs resembling either Lognormal or Gumbel distributions, and these assumptions could lead to unsafe values for soil resistance estimation in some instances, and uneconomical, over-conservative values in others.

The SWRC tracks the relationship between soil water content and consequent suction induced in the soil. It is therefore necessary to know how the PDF changes as water-content/suction changes. A testing program is in progress at the Central University of Technology, Freestate (CUT) to examine this question. It is intended to examine drying and wetting curve PDFs for specimens of several different soil types. This paper presents results for the initial drying curves for twenty samples of one soil layer in one test-pit and illustrates aspects of variability worthy of further investigation.

## 3 METHODS AND MATERIALS

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 and Theron (2017), which leads to little disturbance of soil structure and no remoulding. Small samples were broken along lines of weakness or selected from fragments which had separated spontaneously. 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 micrometres to the landscape” (Pachepski et al. 2000). The size of peds 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) have proposed using fractal soil properties for estimating SWCCs.

Samples were individually saturated to satiation with distilled water using a dropper bottle. They were then brought to equilibrium over distilled water. The soil suction at equilibrium at 25$^0$C is taken to be 0 kPa. Progress to equilibrium was monitored by weighing until no further weight change was observed, all samples were kept in a process control chamber at 25$^0$C. The samples were transferred to platforms in containers with a saturated solution of $KNO_3$ below the platform. The glass containers were opened and the soil samples were thus exposed to suction 8660 kPa. After reaching equilibrium they were transferred to a saturated solution of KCl (24400 kPa). This procedure was repeated with NaCl (40300 kPa), $K_2CO_3$ (118200 kPa), $MgCl_2$(155200 kPa) and LiCl (265600 kPa). The samples were then oven dried to determine moisture content. All other samples will complete the full series of drying/wetting cycles before oven drying, Figure 2 and 3 shows the containers with saturated solutions and the opened glass containers with the exposed soil samples.


Figure 2. Airtight container with satiated $K_2CO_3$ solution


Figure 3. Batch of soil samples equalising to $K_2CO_3$ solution

Table 1. Sample data analysis

| Salt | $H_2O$ | $KNO_3$ | KCl | NaCl | $K_2CO_3$ | $MgCl_2$ | LiCl |
|---|---|---|---|---|---|---|---|
| Suction (MPa) | 0 | 8.66 | 24.4 | 40.3 | 118.2 | 155.2 | 265.6 |
| Count | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| Max | 24.4 | 17.7 | 15.1 | 13.2 | 9.7 | 8.4 | 5.1 |
| Min | 17.9 | 13.9 | 11.4 | 9.2 | 6.1 | 5.6 | 2.6 |
| Mean | 21.2 | 16.5 | 14.0 | 12.1 | 8.6 | 7.0 | 4.0 |
| Std. dev | 1.7 | 1.0 | 1.0 | 1.1 | 0.9 | 0.7 | 0.6 |
| COV | 8.2 | 6.1 | 7.3 | 8.8 | 10.3 | 9.6 | 15.8 |
| 5th percentile | 18.37 | 14.54 | 12.04 | 9.87 | 6.95 | 5.97 | 2.77 |
| 95th percentile | 24.32 | 17.47 | 15.06 | 13.10 | 9.65 | 8.11 | 4.54 |
| skewness | 0.022 | -1.122 | -1.136 | -1.363 | -1.271 | 0.064 | -0.905 |

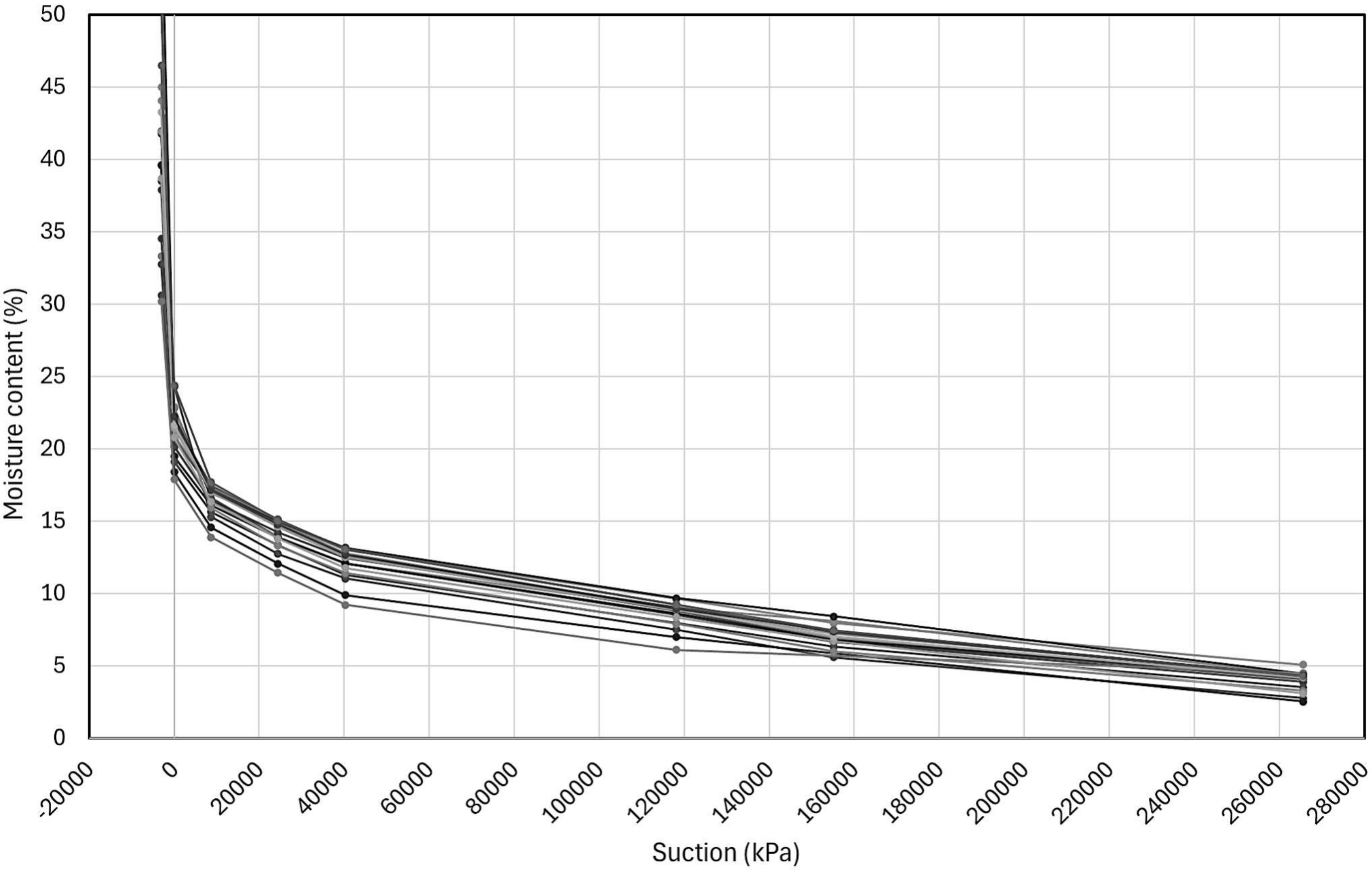


Figure 4. SWCC linear scale graph depicting moisture content versus suction.

## 4 RESULTS

Table 1 shows the statistical analysis of the 20 samples at each fixed suction level. The 5th, 95th percentile and skewness refer to the quantiles and skewness calculated from the probability density functions discussed in section 4.2.

### 4.1 *Soil Water Characteristic Curve Analysis*

The Soil Water Characteristic Curve (SWCC) for the dark brown clay layer from the test pit in the central Free State with an average liquid limit, plastic limit and linear shrinkage of 71%, 23% and 15.2mm respectively, shows the relationship between suction and moisture content across a range of suctions. Figure 4 illustrates the drying curves developed from twenty samples, reflecting the progressive decrease in moisture content with increasing suction.

The moisture content ranged from approximately 21% at 0 kPa to near 3% at the highest suction (265600 kPa).

The curve reveals a diminishing gradient trend with distinct flattening from about 40000 kPa as shown in Figure 4.

This SWCC was developed from experimental data collected during systematic testing. No curve-fitting factors or pre-defined mathematical models were used, ensuring the results reflect the real behaviour of the soil samples.

### 4.2 *Probability Density Function (PDF) Analysis*

The PDF analysis of moisture content at different suctions, presented in Figure 5, highlights the variability in the soil properties.

It should be noted that each PDF was produced from only 20 samples, therefore these PDFs are only indicative and should be interpreted with caution and viewed as a foundation for further analysis. Nevertheless, certain possibilities are indicated. Additional data from ongoing experiments will provide more complete and certain PDFs.

The zero suction distribution was quite broad with median probability 35%.

Suction levels up to 40300 kPa showed tighter distributions, with median probabilities from 50% to 55%, indicating reduced variability as water was probably released predominantly from micropores.

At the suction levels up to 265600 kPa moisture content distributions narrowed with median probabilities rising to 75%.

In this case, it appears that the variability at higher suctions, is significantly less than the variability for the initial case of little or no suction.

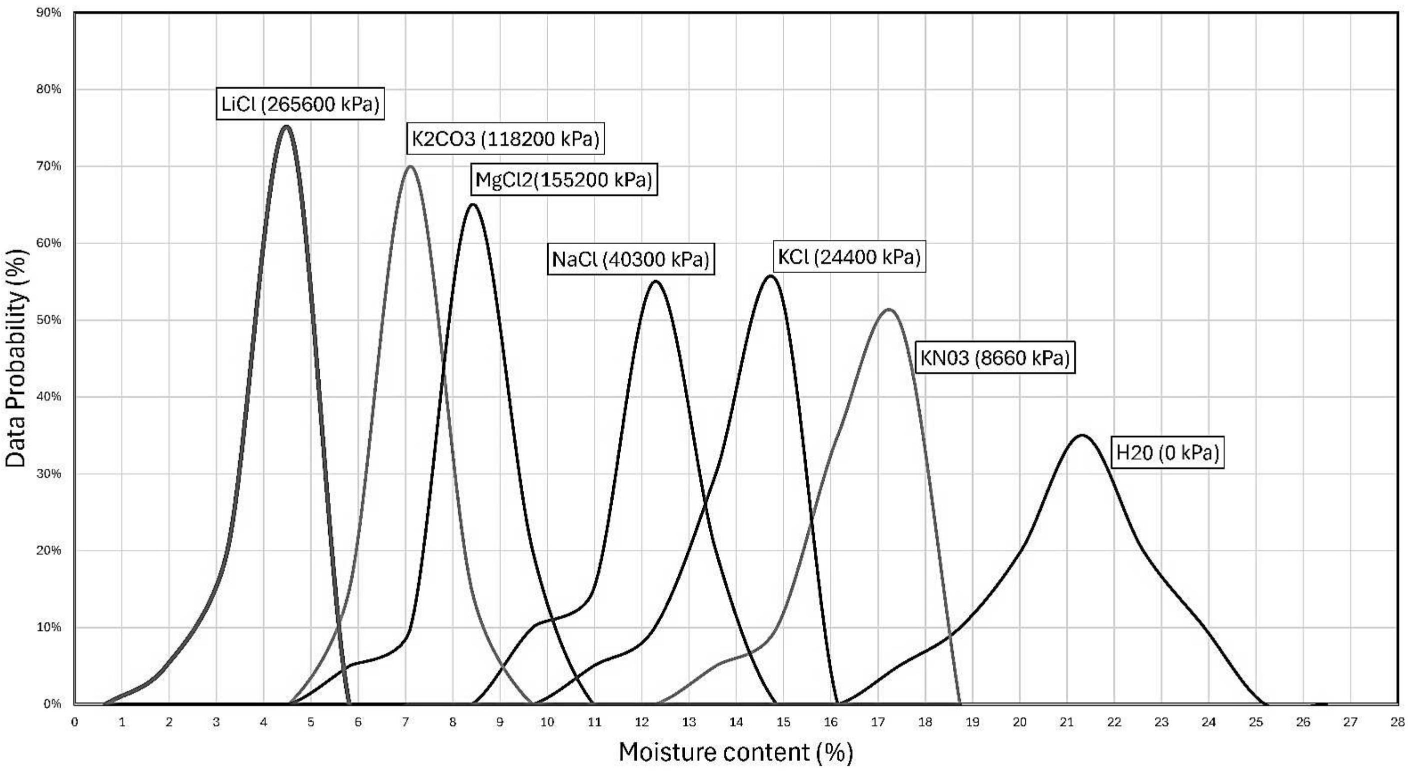


Figure 5. PDF graphs of moisture content variability across a range of fixed suctions.

## 5 CONCLUSIONS

The SWCC revealed a continuously diminishing gradient trend with distinct flattening from the saturated condition. No changing gradient or other features seem to correspond with common features of the usual logarithmic representation.

The PDFs show a reduction in soil variability from low to high suctions.

The lower variability at higher suctions would give confidence that an initial assessment of the variability of this soil will be conservative for characteristic value predictions using the SWCC.

The SWCC is usually done with only one sample/test, since it is time consuming and expensive. By looking at SWCCs and PDFs together, we can get a better idea of the true representative SWCC for a soil.

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