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An Improved Volume Measurement for Determining Soil Water Retention Curves

ABSTRACT: The complete determination of soil water retention curves requires the sample volume to be measured in order to calculate its void ratio and degree of saturation. During drying in the pressure plate apparatus, cracks often appear in the sample altering its deformation and evaporation patterns. Consequently, this causes a significant scatter in the volume measurement when using the volume displacement method. This paper proposes a simple method to avoid cracking, by limiting friction and adhesion boundary effects, to allow for unrestrained shrinkage of the sample. Such modification of the technique decreases the measurement error by a factor of three.

KEYWORDS: soil water retention curve, friction, shrinkage, cracks, volume measurement accuracy

Background

The soil water retention curve defines the relationship between gravimetric or volumetric water content, w , (or degree of saturation, S_r , or void ratio, e) and soil suction, s (Barbour 1998). The reliability in the determination of the soil-water retention curve is of great interest in unsaturated soil engineering practice, as suction changes are generally related to significant changes in volumetric strain, effective stress, strength, and flow properties.

The relationship between water content and suction is commonly determined by the pressure plate apparatus test (see, e.g., Richards 1941). This test relies on the axis translation technique to impose suction on soil samples (see, e.g., Hilf 1956). Assuming that both air and water are incompressible, it is possible to control suction by applying air overpressure to the sample, and independently controlling its pore water pressure. In the pressure plate apparatus, samples are placed in containers and put in contact with a water-saturated, high air entry value porous ceramic plate (or a cellulose membrane), that allows the water pressure to be controlled in the sample (Fig. 1).

The determination of the soil water retention curve requires the sample volume to be measured as it evolves in order to calculate the value of soil void ratio or degree of saturation, or both. It is relatively easy to determine the volume of a sample responding to an external mechanical load while maintaining its original shape. Indeed, soil water retention curves are often determined in K_0 conditions. A vertical load applied to the sample should guarantee the contact between the sample and oedometer wall and, hence, volume change due to suction change could be determined simply by monitoring the axial displacement of the top plate (Padilla et al. 2005). These conditions can easily be achieved for compacted stiff soils (Romero et al. 1999), but it is doubtful that they are achieved for an initially saturated slurry subjected to suction changes. In addition,

sample deformation induced by suction is sensitive to the displacement boundary conditions (Sibley and Williams, 1989).

The volume measurement in the pressure plate apparatus is performed on an unconfined sample under zero mechanical stress and is achieved not without some difficulties as indicated by Geiser (1999), who compared various volume measurement methods on unconfined samples. She concluded that measurement of the sample dimensions using displacement sensors is inaccurate, as the regularity of the sample is often lost during drying, and is particularly unsuitable for samples of low consistency soils. An alternative method discussed by Geiser consists of measuring the displaced volume of a fluid when the sample is dipped in it. The use of Kerdane as the displaced fluid was found to give the best results. The principle of the method is described by Head (1980), and the use of Kerdane has been described among others by Zerhouni (1991) and Abou-Bekr et al. (2005).

Cracking is one of the major causes of inaccuracy in measuring volume change of the samples. Cracking has often been reported to develop in samples in the pressure plate apparatus, as shown in Fig. 2 (see, e.g., Geiser 1999; Dyer 2005). As their response to dehydration consists in shrinkage, it is critical that this shrinkage be unrestrained. If unintended kinematic constraints to the sample deformation arise, the sample is likely to respond by building up a stress pattern. As the stress is likely to be tensile, and soils are generally

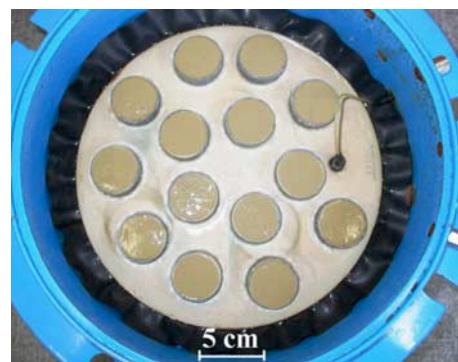


FIG. 1—Photograph of the slurry samples placed in the pressure plate apparatus.

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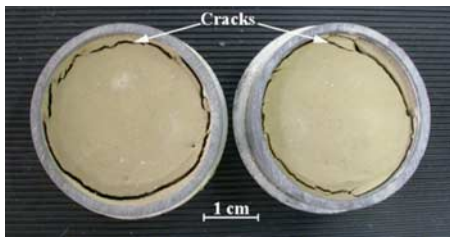


FIG. 2—Photograph of cracked slurry samples dried in the pressure plate apparatus.

weak in tension, cracks are expected to occur at relatively low tensile stresses (Péron et al. 2005).

Typical constraints arise due to adhesion of the sample to the container walls or formation of a thin film layer of water between the soil and the substrate material, or both. The latter case has been investigated by Corte and Higashi (1960), who observed the development of such a layer during drying. They measured a shear stress of 25 kPa stress between a sample of till at $w=20\%$ and a glass substrate at the layer's failure. Tensile stress arising in samples due to the development of moisture gradients is often cited as a potential source of cracking (Kowalski 2003; Itaya et al. 1997). When moisture transfer in and out of the soil sample is extremely slow (conditioned by the hydraulic conductivity of the ceramic, i.e., $2.59 \times 10^{-11} \text{ m} \cdot \text{s}^{-1}$ for a 1500 kPa air entry value), the water content gradient within the sample is negligible and so are the potential self-stresses. Nevertheless, it does not seem that the constraints on shrinkage arising during drying are significant for compacted soils with a relatively low water content, see Kodikara et al. (2002).

This paper proposes a simple way to avoid cracking during the application of suction in the pressure plate apparatus in order to improve the accuracy of volume change measurements. The aim of the improvement is to increase the reliability of the water retention curve, especially for soils dried from slurry conditions.

Material, Equipment and Test Procedure

The main series of tests were performed on a clayey silt from Bioley (Switzerland). The grain size distribution curve of that material is given in Fig. 3. The clay fraction of the soil is 27 %, the liquid limit is $w_L=31.8\%$, the plastic limit is $w_P=16.9\%$, and the unit weight of the solid particles is $\gamma_s=27.1 \text{ kN/m}^3$. The soil contains

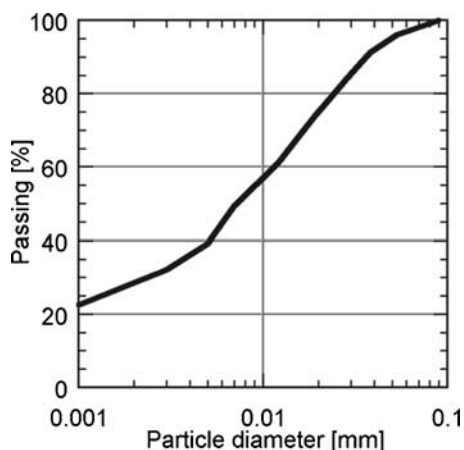


FIG. 3—Grain size distribution curve of the Bioley silt.

quartz, calcite, potassium feldspar, and clay minerals, i.e., illite (10 % of the total amount of mineral species), smectite (10 %), and chlorite (5 %). The dry loose soil was mixed with deaired and demineralized water at a gravimetric water content of 1.5 times the liquid limit. The resulting slurry was then vigorously mixed and vibrated for two minutes to remove air bubbles. It appears that following this technique an initial nearly 100 % saturation is achieved. Before use, the soil was left to settle for at least one day to ensure homogenization of the water content. The initial water content of the slurry in the tested series was 48.5 %, on the average.

The slurry was poured in small cylindrical containers 50 mm in diameter and 10 mm in height, and placed on a saturated ceramic stone inside the pressure plate apparatus (see Fig. 1). The contact between the ceramic stone and the soil was ensured by filter paper, which also prevents soil from penetrating into the ceramic stone pores.

Air pressure was imposed on the pressure plate apparatus, and water pressure was kept at the atmospheric pressure value. Regular weighing of the samples allowed the operator to determine when equilibrium was reached.

At that time, seven samples were removed from the pressure plate apparatus: five were set aside for volume measurements, and two were weighed and oven dried for water content determination. The total test duration for the entire determination of the water retention curve was about three months. Each measurement on Bioley silt was repeated five times; however, average data points only are reported. Additional data also have been obtained for Sion silt to broaden the database.

The adopted procedure for volume measurement was based on the general method using fluid displacement described, for instance, by Head (1980), with some modifications developed by Zerhouni (1991) and Geiser (1999). The fluid used for volume measurement was Kerdane. The volume measurement method implies that the specimen must be destroyed. This is a destructive technique, not appropriate for testing natural soils, where variability among specimens may become a major issue.

Kerdane is a trade name of an oil from which aromatics are extracted. It can most likely be substituted with any relatively clean paraffin oil, like kerosine, available on the open market. It mainly contains aliphatic hydrocarbon chains. Kerdane (and similar substances) are listed as a hazardous compound by INRS (1998). Several health and safety rules should be followed when using it. Contact with skin and eyes should be avoided: latex gloves and safety glasses should be used. Vapors should not be inhaled, and it is recommended to carry out the entire test under a hood. Kerdane's flash point is about 65°C . As soil samples containing small quantities of Kerdane must be oven-dried during the procedure, it is highly recommended to use an oven with an aspiration system, not to bring a flame near to it, to avoid any accumulation of static electricity, and to work in a laboratory with an effective ventilation system.

All tests were performed at a temperature of 22°C , for which Kerdane's specific gravity is 0.802. First, prior to each use, a clean, dry pycnometer was filled with Kerdane. The mass of the pycnometer is 215.02 g, its volume is approximately 200 mL, and its diameter 50 mm. Subsequent pycnometer filling and weighing were performed until a prescribed mass value was obtained, constituting the mass m_{p1} (mass of the pycnometer filled with Kerdane only), paying attention to use an identical filling technique each time. Afterwards, each sample set aside for volume measurement was very

carefully removed from the retaining ring (when it was possible), and weighed to determine its wet mass, m_1 (mass of the wet sample). The sample was then lowered into a bath of Kerdane. Kerdane is nonmiscible in water and invades the pore spaces filled with air without affecting the soil structure. After three hours, the sample was removed from the Kerdane bath. Kerdane only invades air-filled pore spaces connected to the surface. The estimated duration of the process (three hours) is based on our observations: at the beginning of the bath, air bubbles are released from the samples; after three hours this phenomenon stops. The sample was then very carefully wiped with absorbent paper, and weighed again to obtain m_2 (mass of the Kerdane/water saturated sample). Then the sample prepared in this way was placed into an empty pycnometer. The remaining volume of the pycnometer containing the saturated wet sample was then entirely filled with Kerdane, adopting the same filling technique as that used for the determination of m_{p1} , and taking special care to avoid any air bubble entrapment. At this stage, it was assumed that the total volume of the sample was measured: the preliminary Kerdane bath actually prevents Kerdane from penetrating into the sample pore space during pycnometer filling. The pycnometer filled in this way, was weighed, yielding the mass m_{p2} (mass of the pycnometer containing Kerdane and Kerdane/water saturated sample). Finally, the mass m_s (solid mass of the sample) was determined by oven drying. The sample volume V can be calculated using the following relationship:

$$V = \frac{(m_{p1} + m_2 - m_{p2})}{\rho_K} \quad (1)$$

with ρ_K being the specific mass of Kerdane.

The corresponding void ratio equals to:

$$e = \frac{V_v}{V_s} = \rho_s \frac{m_{p1} + m_2 - m_{p2}}{m_s \rho_K} - 1 \quad (2)$$

and the degree of saturation is:

$$S_r = \frac{V_w}{V_v} = \frac{\frac{(m_1 - m_s)}{\rho_w}}{\frac{m_{p1} + m_2 - m_{p2}}{\rho_K} - \frac{m_s}{\rho_s}} \quad (3)$$

where V_v and V_s and V_w are, respectively, the volumes of void, solid particles, and water, respectively, ρ_s is the specific mass of the solid particles, and ρ_w the density of water.

Sibley and Williams (1989) used the same principle, but reported a different technique: they measured the displaced volume of fluid immediately after immersion of the sample in the pycnometer, without letting the fluid to fill the air porosity. Consequently, the volume measurement must be performed very quickly. They found that ten seconds of delay in the immersion in the measuring fluid yielded a 3 % drop in volumetric air content V_a/V_s . Hence, the difficulty to control delay times obviously produced nonnegligible uncertainty in the volume determination. It is therefore concluded that for unsaturated samples, the preliminary immersion in Kerdane (prior to the total volume measurement) is of significance, as it prevents the pore air space from an uncontrolled Kerdane invasion during pycnometer measurement, thus avoiding a potential source of measurement inaccuracy.

The Proposed Technique

There is no standard test method for determining the volume changes during dehydration of soil in the pressure plate apparatus. The current ASTM Standard (ASTM D 2325, Test Method for Capillary-Moisture Relationships for Coarse- and Medium-Textured Soils by Porous-Plate Apparatus) allows the determination of an experimental relationship only between gravimetric water content and suction. The proposed technique aims at removing a source of a systematic bias in volume measurements when using ASTM D 2325 test conditions, and, hence, at improving the quality of the evaluation of volume change during dehydration of soil.

Motivation

Following the current ASTM D 2325 technique, dehydration of soil is conducted in containers that do not allow for the control of displacement boundary conditions. The theoretical conditions at the walls of the container imply a free (inward) displacement and free (tangential) displacement along the bottom. Use of the recommended rigid plastic rings causes an uncontrolled sticking of the sides of the sample to the wall during sample shrinking. This eventually leads to mainly circumferential cracking. At the bottom, the contact with the substrate occurs via a sheet of filter paper. The filter paper may be the source of possible friction at the sample bottom.

Cracks constitute a substantial deviation from the assumed experimental conditions for three major reasons. First, cracks alter (increase) the rate of dehydration by creating additional and usually random interfaces through which surface evaporation proceeds. Second, after a crack develops, the subsequent shrinkage causes an independent deformation (and volume change) of highly irregular, separate sample fragments, whose geometry depends on the crack pattern and their individual constraints (e.g., sticking to the container wall). Finally, cracks may lead to large and uncontrollable errors in the volume measurement. This paper focuses on the latter issue, as the first two types of drawbacks resulting from cracking are eliminated when cracking is suppressed.

The role of cracks in volume measurement is addressed first. During the first immersion in Kerdane, prior to volume measurement in the pycnometer, Kerdane fills the cracks directly connected to the sample surface. When the sample is removed from the bath, a varying amount of Kerdane is trapped in the cracks (forming menisci). This unknown amount of Kerdane is erroneously considered as a part of the soil volume when volume is subsequently measured in the pycnometer. Consequently, a substantial scatter in the measurement arises. By the same token, the total volume and void ratio tend to be overestimated, and water degree of saturation tends to be underestimated.

The objective of the proposed technique is to eliminate the crack formation during dehydration. This would eliminate the first two shortcomings from the ASTM D 2325 procedure, and would render the volume measurement much more reliable.

Proposed Modifications

The constraints on free shrinkage during dehydration appear at the sides or at the bottom of the sample, or both. At the sample sides, water film between the rigid plastic ring and the sample body is invariably formed, inducing capillary or adhesive forces, or both.

TABLE 1—Water content (w), sample total volume (V) and solid volume (V_s), degree of saturation (S_r) and void ratio (e) at various suction levels (s), using original PVC rings.

Suction Level [kPa]	w [%]	V_s [cm ³]	V [cm ³]	S_r [%]	Exp. Std Deviation [%]	Relative Error [%]	e [-]	Exp. Std Deviation [-]	Relative Error [%]
20	30.01	5.92	10.81	98.25	0.6	0.6	0.825	0.005	6
40	27.45	5.90	10.50	95.00	3	3	0.781	0.02	25
60	26.44	5.95	10.85	85.93	9	11	0.822	0.08	10
80	24.24	6.06	10.33	99.18	3	3	0.651	0.03	5
90	21.70	5.84	9.62	99.00	7	7	0.639	0.04	6
120	21.32	6.01	10.45	72.31	14	20	0.737	0.06	8
150	20.05	5.97	10.06	80.54	4	5	0.686	0.02	3

To minimize the effects of adhesion, a strip of a low wetting angle material such as Teflon is proposed to be inserted inside the rigid plastic ring and glued to it. Additionally, the Teflon surface is to be coated with a hydrophobic substance (which contains silicon). The soil is then poured into these containers and the samples are placed on the pressure plate following the classical procedure described above.

At the bottom a Teflon porous sheet was tested instead of the filter paper. Such a Teflon sheet was subsequently abandoned as the material appeared to be too hydrophobic permitting practically no water drainage from the sample. However, it appeared that the filter paper after its wetting would probably not eventually restrain the sample significantly and would shrink with it. Hence, the filter paper use may be continued as before.

Validation of the Proposed Procedure

To validate the procedure, a number of tests were performed in which water content, w , void ratio, e , and degree of saturation, S_r , were determined for different values of suction imposed in the pressure plate apparatus, with and without the modifications.

ASTM Ring—Method Assessment

The first series of results was obtained using the ASTM D 2325 recommended apparatus, with rigid plastic (PVC) rings as containers and with the filter paper at the bottom. The results of the volume measurements are compiled in Table 1, with the resulting mean values of void ratio and the degree of saturation. In addition, experimental standard deviation (see Appendix A for the definition adopted) and an experimental relative error, obtained by dividing the experimental standard deviation by the measured value, are given. The obtained values of water content versus imposed suction are plotted in Fig. 4.

The corresponding s - e and s - S_r curves are given in Fig. 5(a) and 5(b). A substantial scatter is observed in the results, especially for suction values above 40 kPa. At the same time cracks appeared in about 75 % of soil samples. Generally, the cracks were very thin. They were most often circular but not necessarily continuous over the whole diameter, and located at 1 or 2 mm from the actual sample circumference (see Fig. 2). For most of the cases it was not possible to remove fragments of the cracked sample attached to the wall for the volume measurement without disturbing the sample. In such a case the sample must be immersed with the ring, and the results need to be appropriately calibrated.

Proposed Method—Evaluation

The results obtained using Teflon-lined rings and filter paper at the bottom are compiled in Table 2. For various suction steps, total volume of the sample, volume of the solid, water content, void ratio, and degree of saturation were determined and compared to those in Table 1. The resulting s - e and s - S_r curves are given in Fig. 5(c) and 5(d). With Teflon-lined rings, after the equilibration time, cracks almost never have developed within the sample; for suctions above 20 kPa, the shrunken soil samples were no longer in contact with the ring (see Fig. 6(a)) and could easily be removed from the ring without any disturbance. Most importantly, the scatter of the results for almost all variables decreased noticeably. The mean values of the degree of saturation, void ratio, and relative errors at all the suction stages were calculated for the ASTM ring method and for the proposed method, respectively (see Table 3). Experimental relative error was on the average reduced three times when the proposed method was used. Finally, void ratio values are in general lower with the proposed method than with the ASTM method, whereas degree of saturation is higher.

A photograph of the final shape of a sample dried using the Teflon-coated ring is presented in Fig. 6(b): usually the shape is much more regular and the bottom of the sample is not significantly larger than the top (as it is without Teflon) indicating homogeneous deformation.

Using the Teflon-coated rings for suction lower than 100 kPa, the slope of the suction-void ratio curve was found to be close to the saturated isotropic compressibility C_c of the Bioley Silt, which is 0.195 according to our measurement in triaxial conditions. Conse-

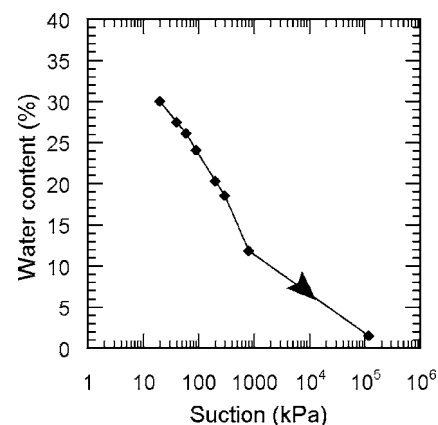


FIG. 4—Water content—suction curve for Bioley silt.

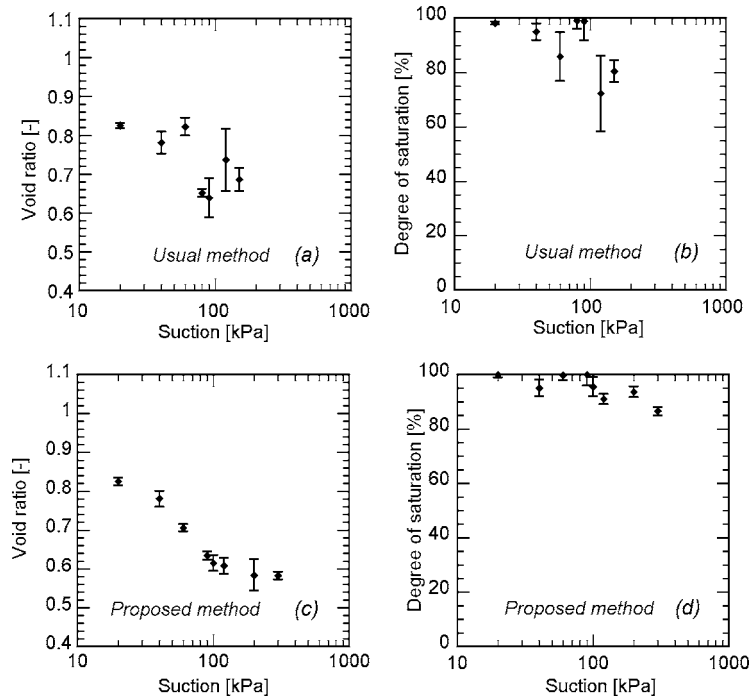


FIG. 5—Comparison of suction/void ratio and suction/degree of saturation curves obtained with the usual method, (a) and (b), and the proposed method, (c) and (d); results for Bioley silt.

quently, it was possible to extrapolate the void ratio versus suction to the value of suction equal to 1 kPa using isotropic compressibility. Degree of saturation and void ratio were also determined after air-drying samples in the laboratory at a temperature of 24 °C and a relative humidity of 40 % (which theoretically corresponds to a suction of about 120 MPa). The resulting s - e and s - S_r curves with these additional points are shown in Fig. 7(a) and 7(b).

Tests on Sion Silt

To demonstrate the applicability of the proposed technique for different soils, the technique was used to determine the water retention curve of a different soil, which is Sion silt. The clay fraction of Sion silt is 8 %, the liquid limit is $w_L=25.4$ %, the plastic limit $w_P=16.7$ %, the initial water content is 1.5 times the liquid limit,

TABLE 2—Water content (w), sample total volume (V), and solid volume (V_s), degree of saturation (S_r) and void ratio (e) at various suction levels (s), using Teflon lined rings.

Suction Level [kPa]	w [%]	V_s [cm ³]	V [cm ³]	S_r [%]	Exp. Std Deviation [%]	Relative Error [%]	e [-]	Exp. Std Deviation [-]	Relative Error [%]
20	29.75	6.03	10.89	99.94	1	1	0.823	0.01	1.2
40	28.48	5.87	9.92	95.01	3	3	0.781	0.02	2.5
60	26.10	5.62	9.60	99.88	2	2	0.706	0.01	1.5
90	22.85	5.84	9.62	100.0	4	4	0.634	0.01	1
100	22.79	5.57	9.00	95.63	3.5	3.5	0.615	0.02	3.2
120	22.51	5.51	8.86	91.05	2	2	0.608	0.02	3.2
200	20.51	5.50	8.69	93.69	2	2	0.584	0.04	6
300	19.27	5.69	9.00	86.58	1.5	2	0.583	0.01	1.7

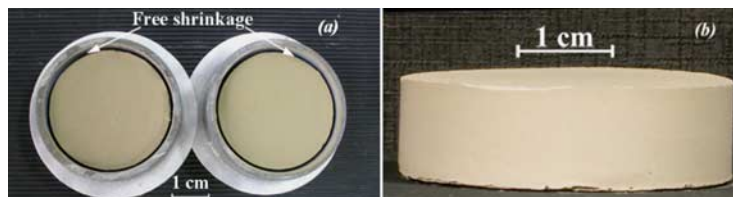


FIG. 6—Proposed method: samples inside the rings (suction level = 100 kPa) (a), and close-up view of a sample (b).

TABLE 3—Mean value of error measurements using the ASTM and proposed method.

Measurement Method	Relative Error Mean Value [%]	
	Degree of Saturation, S_r	Void Ratio, e
ASTM Ring Method	7.1	9
Proposed Method	2.4	2.5

while the unit weight of the solid particles is $\gamma_s = 27.4 \text{ kN/m}^3$. The resulting s - e and s - S_r curves are compared with those obtained by Geiser (1999), using the ASTM ring method (see Fig. 8). The mean values of relative error for void ratio and saturation ratio are of 4.3 and 1.7 %, respectively, hence, comparable to those obtained for Bioley silt (Table 3). As for Bioley silt only circumferential detachment cracks developed at the ring. These results indicate that the proposed technique is also suitable for soil with low clay content, and for a relatively low degree of saturation.

Comparison of Experimental Results to Calculated Uncertainty

The uncertainty of a measurement can be quantified by the experimental standard deviation of its mean value. The experimental standard deviation of the mean, called standard uncertainty (ISO 1993), is directly deduced from the experimental standard deviation (an exact definition is given in the Appendix). Void ratio and degree of saturation standard uncertainties, calculated from the standard deviations listed in Tables 1 and 2, are presented in Table 4.

Besides experimental standard uncertainties of void ratio and degree of saturation, directly deduced from experimental results, a “theoretical” standard uncertainty of these two quantities can also be calculated, only considering the accuracy of the measurement devices (for instance, the balances) and of constant parameters entering in the calculation. The details of the calculation are given in the Appendix. These “theoretical” values of uncertainty can be considered as the best expected values, given the precision of the mea-

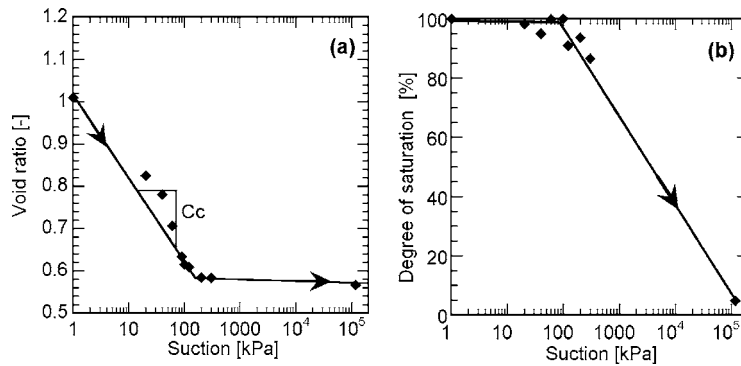


FIG. 7—Suction—void ratio and degree of saturation curves obtained with the proposed method for Bioley silt.

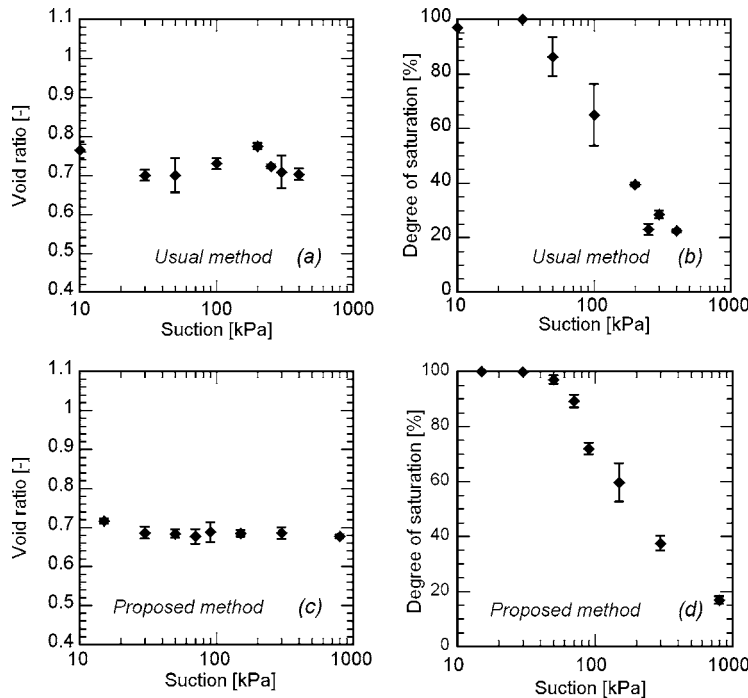


FIG. 8—Comparison of suction/void ratio and suction/degree of saturation curves obtained with the usual method, (a) and (b) from Geiser (1999), and the proposed method (c) and (d); results for Sion silt.

TABLE 4—Comparison of experimental uncertainties calculated for void ratio and degree of saturation.

Measurement Method	Experimental Standard Uncertainty ^a		Best Expected Standard Uncertainty	
	Void Ratio [-]	Degree of Saturation [%]	Void Ratio [-]	Degree of Saturation [%]
ASTM Ring Method	0.0163	2.6	0.004	0.2
Proposed Method	0.008	1.1	0.004	0.2

^aMean values of the totality of suction stages.

surement instruments and our knowledge of the material properties. Moreover, we can reasonably assume that any higher values of uncertainty are due to errors related to the quality of the experiment itself (in addition to a possible bias). These are listed in Table 4 and can be compared with experimental standard uncertainties obtained with the ASTM and proposed methods.

Possible sources of additional uncertainty include: (i) a possible loss of soil during handling of the sample (after its removal from the pressure plate and when placing soil into the first Kerdane bath and during wiping); (ii) mass loss during the sample removal from the Kerdane bath and inaccurate Kerdane wiping, possibly also leaving the liquid residues on the sample surface; (iii) imprecision in pycnometer filling when measuring m_{p2} .

From the values of uncertainties given in Table 4, it appears that the ASTM ring method measurements give standard uncertainties much higher than the best expected values. Void ratio and degree of saturation standard uncertainties in the proposed method measurements are slightly above the theoretical uncertainty. Indeed, this residual error is thought to be largely acceptable, given the relatively large explored range of void ratio (e varies between 1 and 0.5).

Conclusions

In this paper a straightforward remedy is proposed to minimize the shrinkage cracking occurring within the sample body during the determination of soil water retention curves. Lining the container side ring with a Teflon strip substantially regularizes the shape of the sample, allowing for its smooth detachment from the wall. Consequently, as cracks are deemed to be the cause of significant errors in volume measurement, such a method noticeably increases the reliability of water retention curve measurements. In addition, a regularized sample shape improves repeatability of the rate of dehydration. Based on the tests conducted on two types of silts, a substantial decrease in experimental scatter has been shown.

Acknowledgments

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Appendix

(A) Standard Uncertainty (ISO 1993)

The standard uncertainty $u(x_i)$ of the experimental observations x_i is defined as the experimental standard deviation of the mean value of n independent observations, and is given by:

$$u(x_i) = s(\bar{x}) = \frac{s(x_i)}{\sqrt{n}} \quad (\text{A1})$$

where n is the number of experimental observation, \bar{x} is the arithmetic mean of the n observations, and $s(x_i)$ is the experimental standard deviation of the experimental observations x_i . $s(x_i)$ is given by:

$$s(x_i) = \sqrt{\left(\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2 \right)} \quad (\text{A2})$$

(B) Evaluation of the Standard Uncertainty of an Input Quantity and Law of Propagation of Uncertainties (ISO 1993)

Void ratio and degree of saturation are not directly measured but calculated from experimental data considered as input quantities. In the present experiments, standard uncertainties of the input quantities such as m_1 , m_2 , m_s , m_{p1} , m_{p2} , ρ_w , ρ_s , and ρ_K are of two types: (i) those depending on accuracy specifications (m_1 , m_2 , m_s , m_{p1} , m_{p2}) and (ii) those depending on existing knowledge of constant parameters (ρ_w , ρ_s , and ρ_K).

(i) In this case, mass measurements are dealt with, and only the manufacturer's accuracy specification is available ($\pm a$). If there is no specific knowledge about the possible values of an input quantity within an interval, one can only assume that it is equally probable for this quantity to lie anywhere within it (corresponding to a uniform or rectangular distribution of possible values). The standard uncertainty $u(x)$ of an estimate x lying in the interval of accuracy a is then given by:

$$u(x) = \frac{|a|}{\sqrt{3}} \quad (\text{B1})$$

where a is the interval of accuracy.

m_1 , m_2 and m_s are measured with a precision balance (Metler PR203) accurate to $a = \pm 0.001$ g according to the manufacturer. m_{p1} and m_{p2} are measured with a precision balance (Metler PM6100) accurate to $a = \pm 0.01$ g according to the manufacturer. Corresponding standard uncertainties are calculated using (B1).

(ii) In the considered case, the three input quantities, ρ_w , ρ_s , and ρ_K , are known from experimental data. ρ_w was deduced from ambient temperature measurement at the time of the test $\pm 0.5^\circ\text{C}$, leading to a standard uncertainty of $0.001 \text{ g}\cdot\text{cm}^{-3}$. The experimental standard uncertainty is $0.004 \text{ g}\cdot\text{cm}^{-3}$ for ρ_s and $0.001 \text{ g}\cdot\text{cm}^{-3}$ for ρ_K .

Once the standard uncertainties of the input quantities are known, void ratio and degree of saturation "theoretical" standard uncertainties are determined. The calculation relies on the law of propagation of uncertainties (ISO 1993):

- the combined standard uncertainty $u_c^2(y)$, of the quantity y to be determined from noncorrelated input quantities, is given by:

$$u_c^2(y) = \sum_{k=1}^N \left(\frac{\partial f}{\partial x_k} \right)^2 u^2(x_k) \quad (\text{B2})$$

where x_k are the input quantities, f is the dependence law of y on x_k , and $u^2(x_k)$ is the input quantity standard uncertainty.

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