Unsaturated Soils – Alonso & Gens (eds)
© 2011 Taylor & Francis Group, London, ISBN 978-0-415-60428-4

Evaluation of filter paper calibrations for indirect determination of soil suctions of unsaturated soils

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ABSTRACT: This paper evaluates the use of several published calibration curves (Fawcett & Collis-George 1967; Hamblin 1981; Chandler & Gutierrez 1986; Chandler et al. 1992; ASTM Standard D 5298; Leong et al. 2002, and Oliveira & Marinho 2006) for the Whatman 42 filter paper for indirect laboratory estimation of soil suctions. Evaluation of the filter paper calibrations was carried out using the experimental results given by Fleureau et al. (2002) obtained with other techniques used to measure or control the soil suctions in a compacted silty sand. Significant discrepancy exists among the calibrations that are commonly used for determining suction using the gravimetric water content of the filter paper data. The FPM offers a simple technique for the determination of soil suction, provided that an adequate calibration curve is used for the investigated suction range.

1 INTRODUCTION

The experimental techniques commonly used for measuring or controlling soil suctions vary widely in terms of cost, complexity, and measurement range. The soil suctions can be determined from previous calibration or can be measured directly. Because of the various difficulties involved in the direct suction measurements, a simple and economical laboratory method for measuring suctions, even if a degree of approximation is involved, is of considerable value.

In this paper, the contact filter paper method is used as an indirect method of estimating matric suctions of an unsaturated compacted silty sand. The matric suction values inferred from filter paper measurements depend on a calibration between the water content of the filter paper and suction. Therefore, various calibration curves proposed at the literature (Fawcett & Collis-George 1967; Hamblin 1981; Chandler & Gutierrez 1986; Chandler et al. 1992; ASTM D 5298; Leong et al. 2002; and Marinho & Oliveira 2006) for the Whatman 42 filter paper are used to estimate the suctions of an unsaturated compacted silty sand of known suctions. A modified calibration function, which gives better estimation of the measured suctions, is suggested.

2 FILTER PAPER METHOD (FPM)

Gardner (1937) was the first to introduce calibrated filter paper as an indirect means of determining the suction in soils. Since then, many researchers have been involved in the use of filter paper for estimating soil suctions (Fawcett & Collis-George 1967; Al-Khafaf & Hanks 1974; Hamblin 1981; Chandler & Gutierez 1986; Greacen et al. 1989; Chandler et al. 1992; Ridley 1993; Marinho 1994; Houston et al. 1994; Leong et al. 2002; Marinho & Oliveira 2006; Bulut & Leong 2008). The filter paper method calculates the soil suction indirectly from predetermined calibration. Basically, the filter paper comes to equilibrium with the soil either through vapor (total suction measurement) or liquid (matric suction measurement) flow. At equilibrium, the filter paper and the soil will have the same suction value. After equilibrium is established between the filter paper and the soil, the gravimetric water content of the filter paper disc is measured. The gravimetric water content of filter paper is converted to suction using a predetermined calibration curve for the type of paper used. This is the basic approach suggested by the American Society for Testing and Materials (ASTM) standard D5298 for the measurement of either matric suction using the contact filter paper technique or total suction using the non-contact filter paper technique. The ASTM D 5298 employs a single calibration curve that has been used to infer both total and matric suction measurements and recommends the filter papers to be initially oven-dried (16 h or overnight) and then allowed to cool to room temperature in a desiccator. The ASTM D 5298 calibration curve is a combination of both wetting and drying curves. However, because of the marked hysteresis on wetting and drying of the filter paper, the calibration curve for initially dry filter paper is different from that of the initially wet filter paper. Some publications presents calibration for the wetting path, with the paper initially air dry (Chandler & Gutierrez 1986; Chandler et al. 1992; Ridley 1993; and Marinho 1994).

The contact filter paper technique is used for measuring matric suction of soils. In this technique, water content of an initially dry filter paper increases due to a flow of water in liquid form from the soil to the filter paper until both come into equilibrium. Therefore, a good contact between the filter paper and the soil has to be established. The contact filter paper method becomes inaccurate in high matric suction range since water transport is dominated by vapour transport (Marinho & Chandler, 1993; Fredlund et al., 1995).

2.1 *FPM calibration curves*

The calibration curve for the filter paper matric suction measurement is commonly established using a pressure plate apparatus (e.g., Al-Khafaf and Hanks 1974; Hamblin 1981; Greacen et al. 1989). It is important to note that only ash-less filter papers should be used in the filter paper technique. Although there are several ash-less filter papers available, only Whatman 42 and Sleicher and Schuell 59 (or SS 59) are commonly used.

A number of calibration functions for Whatman. 42 filter papers have been published in the literature. The functions share a number of similarities, allowing them to be written in a general form as:

$$\mathrm{Log}_{10}\,(\text{suction})\ (\text{kPa}) = A - B\,w\,(\%) \qquad (1)$$

where w is the gravimetric water content of the filter paper at equilibrium. Chandler and Gutierrez (1986) presented a calibration curve for Whatman No. 42 filter paper for suctions in the range of 80 kPa to 6000 kPa that included their own results and also those from Fawcett and Collis-George (1967) (i.e., A = 5.777 and B = 0.06) and Hamblin (1981) (i.e., A = 6.281 and B = 0.0822), therefore, the obtained calibration curves are similar with obtained A = 5.85 and B = 0.0622.

Table 1 lists some calibrations presented in the literature for the filter paper Whatman. 42 with an inflection point occurring at a filter paper gravimetric water content value somewhere between 33 and 47% (corresponding 115 kPa > suction > 60 kPa). The calibration curves proposed by Chandler et al. (1992), ASTM Standard D 5298 and Leong et al. (2002)—Matric suctions are similar with A in Eq. (1) ranging from 4.842 (Chandler et al 2002) to 5.327 (ASTM D5298) and B ranging from 0.0622 (Chandler et al. 1992) to 0.0779 (ASTM D5298).

Figure 1 shows calibrations curves for proposed by Fawcett & Collis-George (1967), Hamblin (1981), Chandler & Gutierrez (1986), Chandler et al. (1992), ASTM D 5298, Leong et al. (2002) and Marinho & Oliveira (2006) for w values < 50%. A similar agreement can be seen in the suctions derived using the curves proposed by Chandler et al. (1992), ASTM D 5298 and Leong et al. (2002)—Matric suctions.

Table 1. Calibrations curves for Whatman 42 filter paper.

References	Suction type	w (%) range (suction) (KPa)	Log_{10} (suction) (kPa)
ASTM D5298	Total and Matric	w < 45.3 (suction > 62.8)	5.327–0.0779 w
		w > 45.3 (suction < 63.2)	2.412–0.0135 w
Chandler et al. (1992)	Matric	w < 47 (suction > 82.9)	4.842–0.0622 w
		w > 47 (suction < 80)	6.05–2.48 Logw
Leong et al. (2002)	Matric	w < 47 (suction > 60.5)	4.945–0.0673 w
		w > 47 (suction < 68)	2.909–0.0229 w
	Total	w > 26 (suction < 1058)	8.778–0.0222 w
		w < 26 (suction > 1014)	5.31–0.0879 w
Marinho & Oliveira (2006)	Total and Matric	w < 33 (suction > 115)	4.83–0.0839 w
		w > 33 (suction <115)	2.57–0.0154 w
Bicalho et al. (2009)	Matric	36 < w <50 (220 < suction < 1000)	4.75–0.048 w
		55 < w <50 (80 < suction < 220)	3.365–0.027 w

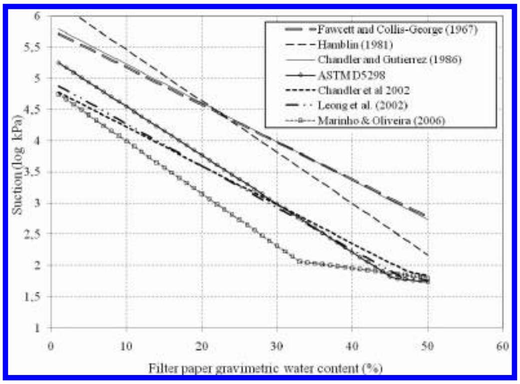

Figure 1. Published calibration curves for Whatman 42 paper.

Considerable variability is observed between their results and those of Fawcett and Collis-George (1967), Hamblin (1981) and Chandler & Gutierrez (1986) (which seem to overestimate the values of suction). The calibration proposed by Marinho & Oliveira (2006) is for a specific batch and cannot be directly compared. Although Leong et al. (2002) suggested the use of different calibration curves for matric and total suction, caution is recommended when using published total suction calibration curves since such curves are expected to be valid only for the equalization time used during the corresponding calibration. If the equilibrium between the filter paper and the soil has not yet been achieved, the total suction calibration curve might give total suction estimations smaller than corresponding matric suction estimations, yielding an unrealistic negative value of osmotic suctions. Walker et al. (2005) and Marinho & Oliveira (2006) suggest that the filter paper calibration is unique in relation to the type of suction (i.e., total or matric). Bulut & Wray (2005) recommend a single calibration curve based on water vapor measurements for both total and matric suction determinations.

Even though, Hamblin (1981) did not observed significant difference between batches of filter paper produced at different times, Likos & Lu (2002) and Marinho & Oliveira (2006) have shown that the filter paper calibration curves can significantly vary among the same type of filter paper from one "batch" or "lot" to another. They recommend batch-specific calibrations.

The non-contact filter paper technique for estimating total suctions must be performed with extra cares to avoid suction errors induced by temperature gradient, relative humidity error, and equilibrium time. It is recommended to allow the filter papers to equilibrate for a sufficient time period. Liquid phase equilibration is fairly rapid in the wet range (high potential) and generally requires only a few days. In contrast, vapor equilibration is slow in the wet range because a large amount of water needs to be transferred. Thermal equilibration is also important. Temperature gradients in the sample can result in liquid flow. In addition, temperature gradients can result in large errors when vapor exchange is used for equilibration.

3 TYPE MATERIAL AND METHODS

3.1 *Material*

The tested material is a residual silty sand, hereafter called Perafita sand, formed by the weathering of granite, which has been used as a building material for a road in the north of Portugal. It contains about 20% of grains smaller than 80 µm, with a layered structure similar to that of clay particles. The liquid limit of the Perafita sand is 32.6%, the plastic limit is 25%, clay fraction is 2.5%, specific gravity is 2.66, standard Proctor optimum water content is 17.6% and the corresponding dry density is 16.8 kN/m^3, modified Proctor optimum water content is 13.2% and the corresponding dry density is 18.6 kN/m^3.

3.2 *Test program*

The preparation procedure of samples is the same for all the tests: the soil is sieved to avoid the presence of coarse grains (maximum size 4.75 mm), then it is mixed up with the right quantity of water; after that, it is placed in a sealed plastic bag for 24 hours to allow the hydric equilibrium to establish at a zero vertical stress condition (Chandler & Gutierrez 1986; Chandler et al. 1992). The contact filter paper tests were carried out on soil specimens compacted to the Modified Proctor Optimum water content (13.2%) and nearly maximum density (18.6 kN/m^3) following the drying path (degree of saturation <85%). The compacted soil specimen sizes were 102 mm in diameter and 23.35 mm high.

The test procedure involves placing a piece of initially air dry filter paper against the compacted soil specimen whose matric suction is required and sealing the whole to prevent evaporation. The filter paper then wets up to a water content in equilibrium with the magnitude of the soil matric suction, and careful measurement of the water content of the filter-paper enables the soil matric suction to be obtained from a previously established correlation. This provides a measure of the matric suction, which is assumed to be the same numerically as the capillary pressure (the reference being the atmospheric pressure). The Whatman 42 filter paper was used in all tests. The other techniques used to measure or control the negative pore water pressure in the compacted soil specimens are not discussed in this paper since the purpose herein is to discuss the filter paper technique only. Details of the experimental techniques are given in Fleureau et al. (2002).

4 TESTS RESULTS AND ANALYSIS

The measured suctions of compacted Perafita sand specimens resulting from several methods used by Fleureau et al. (2002) and contact filter paper tests investigated in this paper are plotted versus degree of saturation in Figure 2. The term matric suction is used to indicate the negative pressure of water relative to atmospheric air pressure, i.e.—($u_w - u_{atm}$). In order to verify the effect of the filter paper calibration curves on the contact filter paper method for matric suction measurement, the calibration curves proposed by Chandler et al. (1992), and ASTM D5298 are used to interpret the measured contact filter paper gravimetric water contents (w). Although it was observed a general agreement between the FPM test results using the calibration curves ASTM D 5298 and Chandler et al. (1992) and other techniques used to measure or control suctions in the compacted soil specimens for 100 kPa < suction < 300 KPa, the calibration curves overestimated the suctions for suction >300 kPa.

The very wide interval presented in Figure 2 may indicate that more data should be collected before anything very definite can be said about the calibration function. Assuming a linear relationship between suctions (logarithmic scale) and degree of saturation, S, (suction = 1537 exp (−0.03 S)) based on the correlation coefficient criterion ($R^2 = 0.92$) using the measured soil suctions (Fleureau et al. 2002) a modified calibration function for the Whatman 42 filter paper is determined by curve fitting to the experimental results (Bicalho et al. 2009). The suggested calibration curve for estimating of soil suctions in the range of 80 kPa to 1000 KPa for the experimental data presented by Fleureau et al. (2002) is:

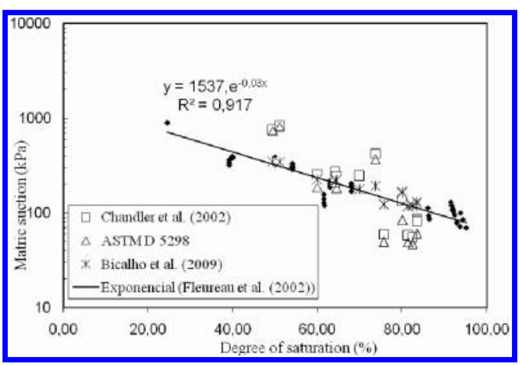

Figure 2. Effect of the filter paper (FPM) calibrations on the derived soil suctions for Perafita sand.

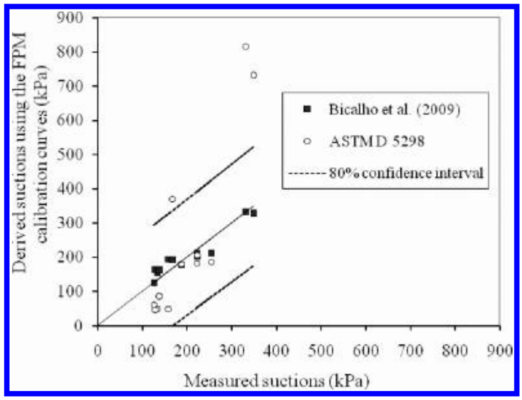

Figure 3. A pair of 80% confidence intervals (upper and lower limits) calculated from two calibration functions.

For 36% < w < 50%

$$\text{Log}_{10}\,(\text{suction})\ (\text{kPa}) = 4.75 - 0.048\ w \quad (2a)$$

For 55% > w > 50%

$$\text{Log}_{10}\,(\text{suction})\ (\text{kPa}) = 3.365 - 0.027\ w \quad (2b)$$

Equation 2 is specific to the tested filter paper, soil and suction ranges and has not been tested in other configurations of measurement system.

A confidence interval gives an estimated range of values which is likely to include an unknown population parameter, the estimated range being calculated from a given set of sample data. The level of a confidence interval gives the probability that the interval produced by the method employed includes the true value of the parameter. Figure 3 shows a pair of 80% confidence intervals (upper and lower limits) calculated from each calibration line, but varies from calibration line to calibration line, although obtained under the same experimental conditions. The results presented in Figure 3 are obtained for the calibration functions proposed by Bicalho et al. (2009) and ASTM D 5298 and the measured data (Fleureau et al. 2002). The data suggest that the predicted suctions using calibration curve proposed by ASTM D 5298 increase significantly when measured suctions are greater than 300 kPa. Therefore, the calibration curve used for determining suction using the gravimetric water content of the filter paper data needs to be verified before applying the filter paper method.

5 CONCLUSIONS

Many empirical calibration equations have been proposed to calculates soil suction indirectly by measuring the gravimetric water content of the filter paper at equilibrium, but none of them perform well in a wide range of circumstances and for all soil types. Significant discrepancy exists among the published calibrations that are commonly used for determining suction using the gravimetric water content of the filter paper data.

The deviation among the calibration curves proposed by Chandler et al. (1992), ASTM D 5298, Leong et al. (2002)—Matric suctions and Marinho & Oliveira (2006) decreased at suctions less than about 60 kPa. Although it was observed a general agreement between the FPM test results using the calibration curves ASTM D 5298 and Chandler et al. (1992) and other techniques used to measure or control suctions in the compacted soil specimens for 100 kPa < suction < 300 KPa, the calibration curves overestimated the suctions for suction > 300 KPa. Calibration curves proposed by Fawcett & Collis-George (1967), Hamblin (1981) and Chandler & Gutierrez (1986) overestimated the values of suction. The FPM offers a simple technique for the determination of soil suction, provided that an adequate calibration curve is used.

ACKNOWLEDGMENTS

The first author is grateful for sponsorship by the Brazilian government agencies CAPES and CNPq.

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