# Evaluation of filter paper calibrations for indirect determination of soil suctions of an unsaturated compacted silty sand

## Évaluation del'étalonnage du papier filtre pour la détermination indirecte de la succion d'un sable silteux compacté non saturé

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ABSTRACT
The soil suction is a key variable in the analysis of the hydro-mechanical behavior of unsaturated soils. The filter paper method (FPM) calculates soil suction indirectly by measuring the gravimetric water content of the filter paper at equilibrium that is related to soil suction through a predetermined calibration curve between the water content of the filter paper and suction. This paper evaluates the use of six published calibration functions for the Whatman 42 filter paper for indirect determination of soil suctions of an unsaturated compacted silty sand. 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 the compacted silty sand. The results show that the matric suctions inferred from FPM depend on the used calibration function. A modified calibration function is suggested, which gives better estimation of the soil water retention curve for the investigated soil. The FPM offers a promising simple technique for the determination of soil suction, provided that an adequate calibration function is used for the investigated soil saturation range.

RÉSUMÉ
La succion du sol est une variable importante dans l'analyse du comportement hydromécanique des sols non saturés. La méthode du papier filtre (FPM) permet d'évaluer la succion du sol indirectement en mesurant la teneur en eau massique du papier filtre à l'équilibre, qui est liée à la succion de sol par une courbe d'étalonnage prédéterminée entre la teneur en eau du papier filtre et la succion. Cet article évalue l'utilisation de six fonctions de calibrage pour le papier filtre Whatman 42 pour la détermination indirecte de la succion d'un sable silteux compacté non saturé. L'évaluation de l'étalonnage du papier filtre a été effectuée en utilisant les résultats expérimentaux donnés par Fleureau et al. (2002), obtenus avec d'autres techniques employées pour mesurer ou contrôler la succion du sable vaseux compact. Les résultats prouvent que les succions déduites de la FPM dépendent de la fonction de calibrage utilisée. Une fonction de calibrage modifiée est proposée, qui donne une meilleure évaluation de la courbe de succion de sol. La FPM est une technique simple prometteuse pour la détermination de la succion du sol, à condition que d'utiliser une fonction d'étalonnage adaptée à la gamme de saturation du sol étudiée.

Keywords : soil suctions, unsaturated soil, filter paper calibration

## 1 INTRODUCTION

Many geo-environmental engineering problems involve unsaturated soils (i.e., the construction of embankments or earth dams, roads and railways, excavations around construction sites, slope stability, and clay liners in waste containment). It is accepted that the matric suction, which is commonly associated with the capillary pressure (i.e., the pressure difference between air and water components in soil voids, $u_a$ - $u_w$), is a key variable in the analysis of the hydro-mechanical behavior of unsaturated soils. The relation between the soil suction and the amount of water within the soil is a key relationship of the soil. This relation is called soil water retention curve (SWRC). For this reason, the development of theoretical and experimental methods for defining the SWRC has become one of the most important and active topics of research.

A comprehensive description of the experimental techniques commonly used for measuring or controlling soil suctions can be found in many references (Fredlund & Rahardjo 1993; Lee & Wray 1995; Ridley & Wray 1996; Lu & Likos 2004). The techniques 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 (formed by the weathering of granite) which has been used as a building material for a road in the north of Portugal. The matric suction values inferred from filter paper measurements depend on a calibration between the water content of the filter paper and suction. Therefore, some 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 et al. 2008) 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 is suggested, which gives better estimation of the soil water retention curve for the investigated soil.

## 2 FILTER PAPER METHOD

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

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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 and Leong 2008). The filter paper method calculates the soil suction indirectly from previous 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 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 the contact filter paper 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 and Chandler, 1993; Fredlund et al., 1995). 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 a number of ash-less filter papers available, only Whatman 42 and Sleicher and Schuell 59 (or SS 59) filter papers are commonly used.

## 3 FPM CALIBRATION CURVES

A number of calibration functions for Whatman. 42 filter papers have been published in the literature. The usual calibration function (suction-water content relationship) is:

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

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 bilinear 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 30 and 50% (corresponding 120 kPa > suction > 60 kPa). The calibration curves proposed by Chandler et al. (1992), ASTM 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 Whatman 42 proposed by Fawcett & Collis-George (1967), Hamblin (1981), Chandler & Gutierez (1986), Chandler et al. (1992), ASTM D 5298, Leong et al. (2002) and Marinho & Oliveira (2006) for filter paper gravimetric water content (w) values ranging from 20 to 60 %. A similar agreement can be seen in the suctions derived using the calibration curves proposed by Chandler et al. (1992), ASTM D 5298 and Leong et al. (2002)-Matric suctions. Considerable variability is observed between their results and those of Fawcett and Collis-George (1967), Hamblin (1981) and Chandler & Gutierrez (1986). 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. Marinho & Oliveira (2006) show that the filter paper calibration is unique in relation to the type of suction (i.e., total or matric).

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. Therefore, they recommend batch-specific calibrations. It is important to mention that the non-contact filter paper technique must be performed with extra cares to avoid suction errors induced by temperature gradient, relative humidity error, and equilibrium time.

Table 1. Calibrations curves for Whatman 42 filter paper

| Reference | Suction | W(%) range | $\text{Log}_{10}$(suction) (kPa) |
|---|---|---|---|
| ASTM D5298 | Total and Matric | w < 45.3 | 5.327 -0.0779 w |
| | Total and Matric | w > 45.3 | 2.412 -0.0135 w |
| Chandler et al. (1992) | Matric | w < 47 | 4.842-0.0622 w |
| | Matric | w > 47 | 6.050-2.48 Log w |
| Leong et al. (2002) | Matric | w < 47 | 4.945-0.0673 w |
| | Matric | w > 47 | 2.909-0.0229 w |
| | Total | w > 26 | 8.778-0.0222 w |
| | Total | w < 26 | 5.31-0.0879 w |
| Marinho and Oliveira (2006) | Matric and Total | w <33 | 4.83 – 0.0839w |
| | Matric and Total | w > 33 | 2.57 – 0.0154w |

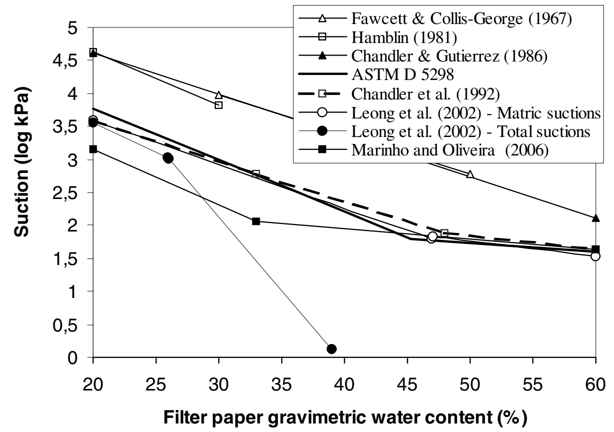


Figure 1. Calibration curves for Whatman 42 filter paper

## 4 MATERIAL AND METHODS

### *4.1 Test material*

Tests were performed on a residual silty sand, hereafter called Perafita sand, resulting from weathered granite. 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 $kN/m^3$.

### *4.2 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. 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).

## 5 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).

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 C 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 Chandler et al. (1992) and ASTM D5298 and the measured data (Fleureau et al. 2002). The very wide interval presented in Figure 3 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 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 (see Figure 2). The suggested calibration curves for estimating of soil suctions in the range of 80 kPa to 1000 KPa for the experimental data presented by Fleureau et al. (2002) are given by:

$$\text{Log}_{10}(\text{suction})\ (\text{kPa}) = 4.75 - 0.048\,w, \quad \text{for } w < 50\% \qquad (2a)$$

$$\text{Log}_{10}(\text{suction})\ (\text{kPa}) = 3.365 - 0.027\,w, \quad \text{for } w > 50\% \qquad (2b)$$

The suggested calibration functions (Equation 2) are used for estimating the soil suctions in the range of 80 kPa to 1000 kPa from the measured gravimetric water content of the filter paper at equilibrium (Figure 2).

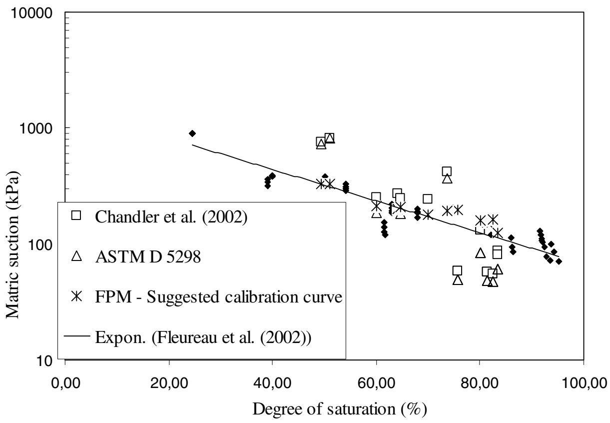


Figure 2. Effect of the filter paper (FPM) calibrations on the derived soil suctions for compacted Perafita sand specimens.

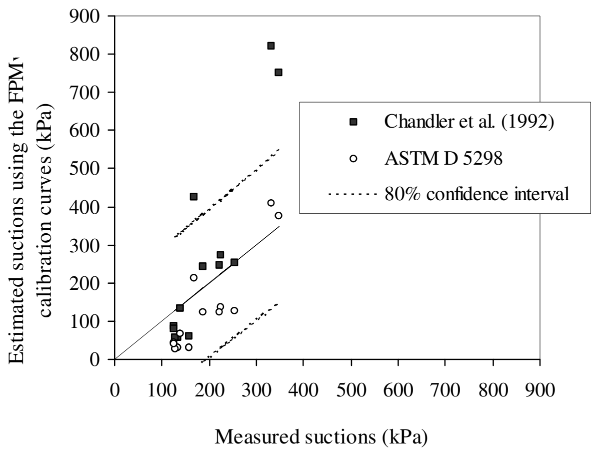


Figure 3. A pair of 80% confidence intervals (upper and lower limits) calculated from two calibration functions

## 6 CONCLUSIONS

We conclude from our results that, for the range of water content investigated, the matric suctions inferred from filter paper measurements depend on the used calibration function and the deviation among the calibration curves proposed by Chandler et al. (1992), ASTM D 5298, and Marinho & Oliveira (2006) decreased at suctions less than about 80 kPa and corresponding degrees of saturation high than 80%. 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 60% < degree of saturation < 80 %, the calibration curves overestimated the suctions for degree of saturation equal to 50%. Calibration curves proposed by Chandler & Gutierez (1986) overestimated the values of suction. The offers a simple technique for the determination of soil suction, provided that an adequate calibration curve is used. It is always recommended to verify if the calibration can be used without causing significant errors in the suction values to be determined.

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