Geotechnical Testing Journal

doi:10.1520/GTJ20190237 / Vol. 43 / No. 6 / 2020 / available online at www.astm.org

TECHNICAL NOTE

E. C. Leong,[1] M. Wijaya,[2] W. Y. Tong,[2] and Y. Lu[3]

Examining the Contact Filter Paper Method in the Low Suction Range

Manuscript received June 19, 2019; accepted for publication March 19, 2020; published online May 29, 2020. Issue published November 1, 2020.

[1] School of Civil & Environmental Engineering, Nanyang Technological University, Blk N1, 50 Nanyang Ave., Singapore 639798 (Corresponding author), e-mail: cecleong@ntu.edu.sg, https://orcid.org/0000-0002-0941-0984

[2] School of Civil & Environmental Engineering, Nanyang Technological University, Blk N1, 50 Nanyang Ave., Singapore 639798

[3] School of Civil Engineering, Guangzhou University, Room 214, Engineering Building (South), Pan Yu District, Guangzhou 510006, China

Reference

E. C. Leong, M. Wijaya, W. Y. Tong, and Y. Lu, "Examining the Contact Filter Paper Method in the Low Suction Range," *Geotechnical Testing Journal* 43, no. 6 (November/December 2020): 1567–1573. https://doi.org/10.1520/GTJ20190237

ABSTRACT

The filter paper method for measuring suction is standardized in ASTM D5298-16, *Standard Test Method for the Measurement of Soil Potential (Suction) Using Filter Paper*. The contact filter paper is usually calibrated using a pressure plate apparatus from 10 to 1,500 kPa. The filter paper calibration curve is commonly plotted on a log-log or semilog graph with water content as the abscissa and suction as the ordinate. To evaluate the accuracy of the filter paper calibration curve in the low suction range (<10 kPa), the Whatman No. 42 filter paper is assessed using the capillary-rise method for suction range from 0.1 to 1.6 kPa and using the Tempe cell for suction range from 3 to 7 kPa. The test results from the capillary-rise method and Tempe cell tests show different trends. The difference in trends is attributed to the limitation of the axis-translation technique used in the Tempe cell test, which is not applicable at a high degree of saturation. The capillary-rise method shows that the Whatman No. 42 filter paper has a maximum water content of about 135 % and minimum measurable suction of about 1 kPa. The water content of the filter paper at 1 kPa suction can be used to supplement the other method for suctions greater than 10 kPa to give the calibration curve of the Whatman No. 42 filter paper.

Keywords

filter paper method, contact, calibration curve, Whatman No. 42, suction, capillary rise, axis-translation

Introduction

The filter paper method has been widely used as an economical method to measure soil suction over a wide suction range and sometimes as a comparison with other suction measurement devices. The contact and noncontact filter paper methods show similar water contents in the high suction range (>3,000 kPa). The filter paper method has been standardized in ASTM D5298-16, *Standard Test Method for the Measurement of Soil Potential (Suction) Using Filter Paper*. For the contact filter paper method, the filter paper is commonly calibrated using the pressure extraction method, which has a suction range from 0 to 1,500 kPa (e.g., Bulut, Lytton, and Wray 2001; Leong, He, and Rahardjo 2002). However, the lowest suction used for such calibration is usually greater than 10 kPa (ASTM D5298-16). The objective of this technical note is to examine the calibration of the Whatman No. 42 filter paper in the very low suction range from 0.1 to 10 kPa and the proposed calibration equations found in the literature for the low suction range.

Background

A number of calibration equations have been proposed for the filter paper method. For the contact filter paper method, the calibration equation of the filter paper is commonly given as a bilinear function on a log-log or semilog plot where the abscissa is water content of the filter paper and the ordinate is suction. **Table 1** shows a list of the calibration equations for the low suction range.

Most contact filter paper calibration curves were obtained using the pressure extraction method where the axis-translation technique introduced by Hilf (1956) was used. The matric suction range applied is usually greater than 10 kPa because of pressure indicators that can measure up to 1,500 kPa not being sensitive enough for below 10 kPa air pressure. In ASTM D5298-16, it is recommended that the filter paper can be calibrated using the pressure membrane from 100 to 1,500 kPa suction and the ceramic plate from 10 to 100 kPa suction as described in ASTM D6836-16, *Standard Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, or Centrifuge*, Methods B and C. There is very limited work done on the calibration of the contact filter paper in the very low suction range (<10 kPa). However, this is important to examine the accuracy of the contact filter paper calibration curve in the low suction range, which usually spans only one log cycle of suction from 10 to 100 kPa.

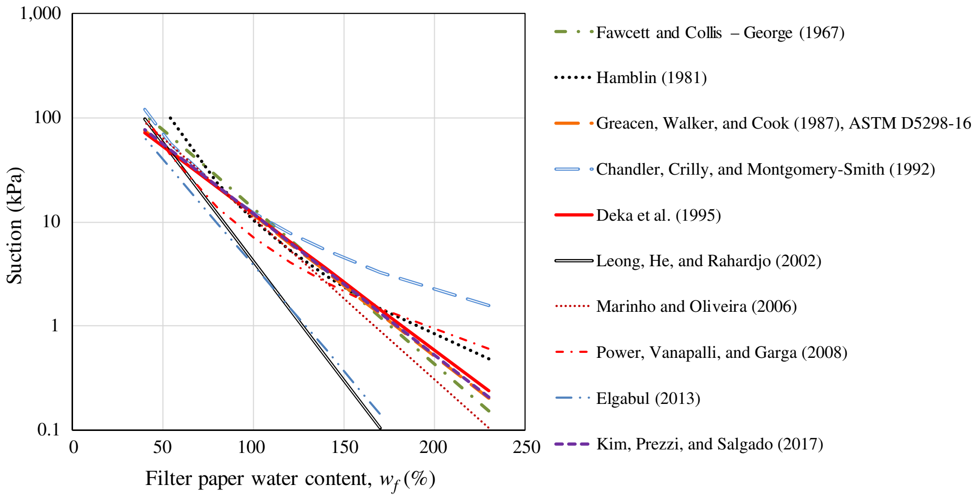
In the literature, only Fawcett and Collis-George (1967), Hamblin (1981), Deka et al. (1995), and Elgabu (2013) showed calibration data for the Whatman No. 42 filter paper between 1 and 10 kPa. All the calibrations were performed using an initially dry filter paper. Fawcett and Collis-George (1967) calibrated Whatman No. 42 filter papers, treated with 0.005 % mercuric chloride ($HgCl_2$), with soil samples from a soil column at equilibrium with a water table but only at suctions of 1 and 10 kPa. Hamblin (1981) calibrated two batches of Whatman No. 42 filter papers, treated with 0.005 % $HgCl_2$ and untreated, two years apart, using a direct suction plate up to 7 kPa suction. Deka et al. (1995) used Whatman No. 42 filter papers from four different batches and calibrated the filter paper using a tension table for suctions from 1 to 65 kPa. The principles of a tension table are similar to that of a suction plate or the hanging column (Method A) described in ASTM D6836-16. It is possible to apply a maximum suction of

TABLE 1
Calibration curves for Whatman No. 42 filter paper in the low suction range

Equation	Reference	Suction Range, kPa	Filter Paper Water Content Range, %	Calibration Curve
1	Fawcett and Collis-George (1967)	1–100	>45.3	$\log \psi = 2.633 - 0.0151 w_f$
2	Hamblin (1981)	1–3,000	N.A.	$\log \psi = 8.384 - 3.683 \log (w_f)$
3	Greacen, Walker, and Cook (1987), ASTM D5298-16	<63	>45.3	$\log \psi = 2.412 - 0.0135 w_f$
4	Chandler, Crilly, and Montgomery-Smith (1992)	≤80	≥47	$\log \psi = 6.05 - 2.48 \log (w_f)$
5	Deka et al. (1995)	<51	>51.6	$\log \psi = 2.383 - 0.01309 w_f$
6	Leong, He, and Rahardjo (2002)	<1,000	>47	$\log \psi = 2.909 - 0.0229 w_f$
7	Marinho and Oliveira (2006)	<115	>33	$\log \Psi = 2.57 - 0.0154 w_f$
8	Power, Vanapalli, and Garga (2008)	20–300	>38	$\log \psi = 6.712 - 2.933 \log (w_f)$
9	Elgabu (2013)	≤32	≥54	$\log \psi = 2.6081 - 0.0203 w_f$
10	Kim, Prezzi, and Salgado (2017)	<65	>45.18	$\log \psi = 2.423 - 0.0135 w_f$

Note: N.A.-Not applicable.

FIG. 1 Calibration curves of Whatman No. 42 filter paper in the low suction range.



up to 80 kPa using a tension table or hanging column with a vacuum pump (Parcevaux 1980). Elgabu (2013) calibrated Whatman No. 42 filter papers in a pressure plate for suctions of 5, 10, 20, 50, 100, and 200 kPa.

The calibration curves of the Whatman No. 42 filter paper as given in **Table 1** are plotted in **figure 1** for suctions from 0.1 to 100 kPa. The calibration curves show greater divergence at suctions less than 10 kPa. The calibration curves can be separated into three groups: (1) below the ASTM calibration curve (Leong, He, and Rahardjo 2002; Elgabu 2013); (2) at the ASTM D5298-16 calibration curve (Fawcett and Collis-George 1967; Greacen, Walker, and Cook 1987; Deka et al. 1995; Marinho and Oliveira 2006; Kim, Prezzi, and Salgado 2017); and (3) above the ASTM D5298-16 calibration curve (Hamblin 1981; Chandler, Crilly, and Montgomery-Smith 1992; Power, Vanapalli, and Garga 2008). A closer examination shows that the calibration curve of Power, Vanapalli, and Garga (2008) agrees with the calibration curves of Leong, He, and Rahardjo (2002) and Elgabu (2013) within the suction range from 10 to 100 kPa, and the calibration curve of Hamblin (1981) agrees with the calibration curves of ASTM D5298-16; Fawcett and Collis-George (1967); Greacen, Walker, and Cook (1987); Deka et al. (1995); Marinho and Oliveira (2006); and Kim, Prezzi, and Salgado (2017) within the suction range from 1 to 10 kPa. The calibration curve of Hamblin (1981) is based on their data and the averaged data from Fawcett and Collis-George (1967). The ASTM D5298-16 calibration curve for Whatman No. 42 filter paper is based on Greacen, Walker, and Cook (1987), who used the averaged data of Fawcett and Collis-George (1967). The Greacen, Walker, and Cook (1987) calibration curve based on their own data was not adopted by ASTM D5298-16. The Kim, Prezzi, and Salgado (2017) calibration curve is based on the reinterpretation of the data from Fawcett and Collis-George (1967) and Graecen et al. (1987).

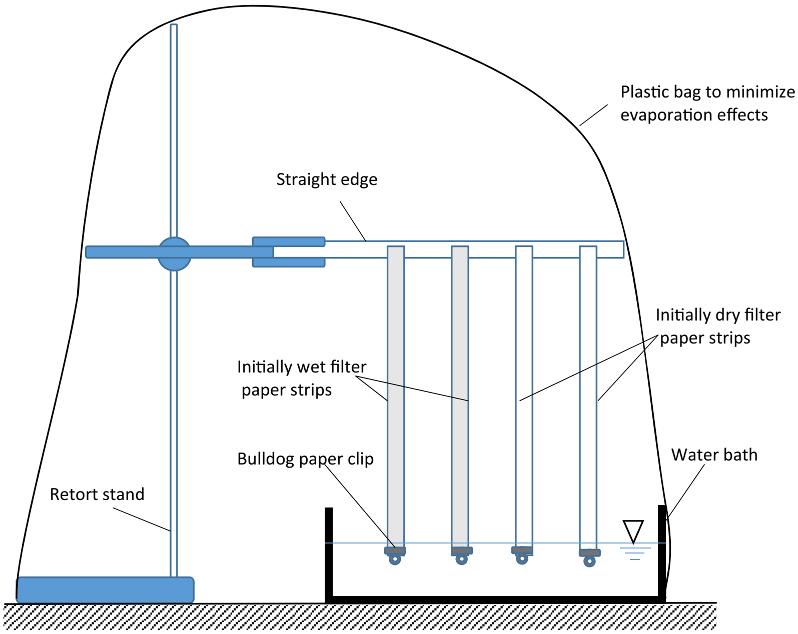
Method

In this technical note, two methods were used to examine the Whatman No. 42 filter paper calibration curve in the very low suction range from 0.1 to 10 kPa. In the first method, a Tempe cell with a 1-bar ceramic disk was used to assess the filter paper in the suction range of 3 to 7 kPa. In the second method, the capillary-rise method was used to assess the filter paper in the suction range of 0.1 to 1.6 kPa. The Tempe cell using the axis-translation technique has the same working principles as the pressure membrane and ceramic plate, which is described in ASTM D6836-16. The capillary-rise method is not used to obtain the water retention curve of soils but has been used to determine the in-plane water retention characteristics of geotextiles (Lafleur et al. 2000; Stormont and Ramos 2004; Nahlawi 2009; Krisdani, Rahardjo, and Leong 2008). The capillary-rise principle has also been used to produce soil samples with a specific matric suction for the calibration of filter papers (e.g., Gardner 1937; Fawcett and Collis-George 1967; McQueen and Miller 1968; Al-Khafaf and Hanks 1974).

For the capillary-rise method, Whatman No. 42 filter paper strips of length 9 cm and width 2.54 cm were used. The filter paper strips were joined by overlapping the filter papers by 1 cm using masking tape on one side to form a 17 cm–long filter paper strip. To investigate the continuity of flow at the overlap, the filter paper strips were joined such that the overlaps were at different locations. The filter papers were suspended vertically by taping the top edge to a straight edge held in place by a retort stand. The bottom edges (1 cm) of the filter papers were immersed in a water bath and weighed down using a small bulldog paper clip. Two initial conditions of the filter papers were tested. One was an initially dry filter paper strip where the filter papers were subjected to wetting and the other was an initially wet condition where the filter paper strip was wetted by a spray bottle and subjected to drying. The setup was enclosed in a plastic bag to minimize evaporation effects as well as maintain a high-humidity environment due to the presence of the water bath. The test was conducted in a laboratory where the temperature is at 26°C ± 4°C. The capillary-rise setup is shown schematically in figure 2. Initial trial tests indicated that the filter paper strips reached the equilibrium condition within three to four days, and hence all tests were left to equilibrate for seven days, the minimum equilibrium period as recommended in ASTM D5298-16. At the end of the equilibrium period, the filter paper strip was cut width-wise into pieces of 1-cm height to determine the water content starting from the end just above the water bath. Aluminum moisture-content cans with lids were pre-dried in an oven, cooled in a desiccator, and weighed before cutting the filter paper strips. The filter paper cutting was collected with the moisture-content can upon cutting and immediately capped to minimize evaporation. The mid-height of each piece of filter paper above the water bath was taken as the average suction for that piece of filter paper. The process of cutting and collecting the filter paper cuttings with the moisture-content can took less than a minute. The moisture-content can with the filter paper cuttings was weighed and then uncapped before placed into the oven for drying. Altogether three sets of capillary-rise tests were performed. In Set 1 (Capillary 1 in fig. 3), three filter paper strips were used for the drying test and three filter paper strips were used for the wetting test. In Sets 2 and 3 (Capillaries 2 and 3 in fig. 3), two filter paper strips were used for the drying test and two filter paper strips were used for the wetting test. The equilibrium water content of the filter

FIG. 2

Setup for capillary-rise method.



paper cuttings was taken as the averaged water contents of the filter paper cuttings from the two or three filter strips at the same elevation above the water bath.

For the Tempe cell, a Whatman No. 42 filter paper was wetted and placed in contact with the ceramic disk in the Tempe cell. No weight was placed on the filter paper to avoid possible alteration to the fiber structure of the filter paper and hence changing its water characteristic curve (Bulut and Wray 2005). Air pressure supply into the Tempe cell was controlled using a differential digital manometer capable of reading a differential pressure of 0.1 kPa. Air pressures were supplied to produce matric suctions of 3, 5, and 7 kPa. After a minimum equilibrium period of seven days, the filter paper was taken out periodically to weigh until the change in weight was less than ±0.0001 g. A weighing balance with a resolution of 0.0001 g was used. When returning the filter paper to the Tempe cell, the surface of the ceramic disk was moistened using a spray bottle to ensure good hydraulic contact of the filter paper with the ceramic disk.

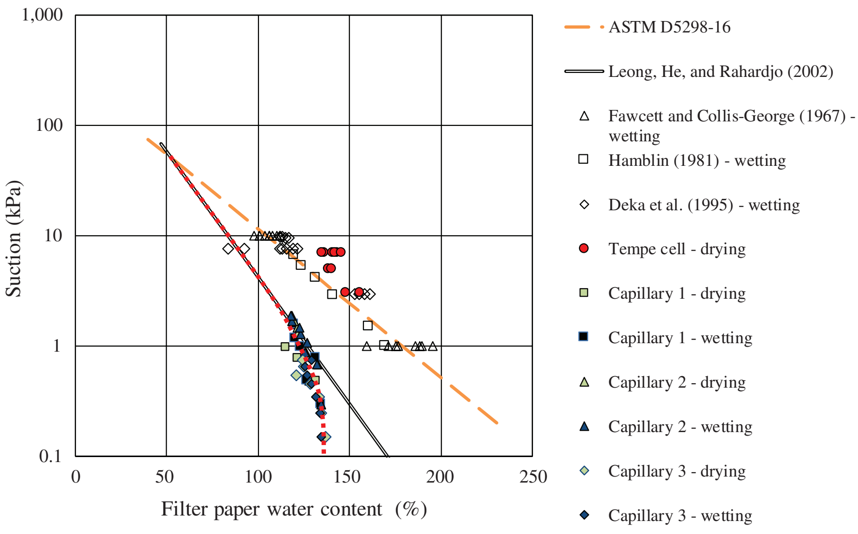
In both methods, the determination of the water content of the filter papers followed the protocol given in Bulut, Lytton, and Wray (2001).

Results and Discussion

The test results of both the initially dry and initially wet Whatman No. 42 filter paper strips from the capillary-rise method are plotted in **figure 3**. For discussion, only the calibration curves of Leong, He, and Rahardjo (2002) and ASTM D5298-16 are shown. There is very little hysteresis observed between the drying and wetting filter paper strips. The filter paper water contents from the capillary-rise method fall serendipitously on the calibration curves of Leong, He, and Rahardjo (2002) and Elgabu (2013) from 1 to 10 kPa with the data for suction less than 1 kPa showing a deviation from the calibration curve, indicating that there is a saturated water content for the filter paper at about 135 %, which may represent the lower limit of suction measurement by the Whatman No. 42 filter paper. The trend is indicated with a dotted line and has a similar shape as the curves shown by Marinho (1994) for the effects of equilibrium time on filter paper calibration curves.

The test results from the Tempe cell test are plotted in **figure 3**. Data from Fawcett and Collis-George (1967), Hamblin (1981), and Deka et al. (1995) for suctions ≤10 kPa are also shown in **figure 3**. The equilibrium water contents of the Whatman No. 42 filter papers from the Tempe cell tests are slightly above those obtained by

FIG. 3 Test results compared with data from literature.



previous researchers as would be expected as only the drying test was performed as compared with the wetting test performed by the previous researchers.

The difference in results between the capillary-rise and Tempe cell tests can be attributed to the test method itself. The Tempe cell test uses the axis-translation technique. The axis-translation technique is not applicable to situations where the air phase is discontinuous (Olson and Langfelder 1965; Bocking and Fredlund 1980). At a high degree of saturation where the air phase may exist as occluded air bubbles, the axis-translation technique may give higher suction. Otter (2011), in determining the soil-water characteristics curve of compacted soils, found that the suction of the soil in the low suction range (<100 kPa) as measured using the tensiometer was lower than that given by the pressure plate for compacted soils at the same water content. Noguchi, Mendes, and Toll (2012) and Tarantino et al. (2011) found the filter paper method underestimated the suction value, whereas the pressure plate overestimated the soil-water content. These findings support the test results obtained in this study. The Tempe cell test gives erroneous results when suction less than 10 kPa is applied. The agreement of the Tempe cell tests with the data of Hamblin (1981) and Deka et al. (1995) shows that the same error was experienced in the suction plate tests.

Conclusion

The calibration curves of Whatman No. 42 filter paper in the very low suction range (<10 kPa) were examined in this paper. The test results from the capillary-rise test showed good agreement with the calibration curves of Leong, He, and Rahardjo (2002) and Elgabu (2013) for the suction range from 1 to 10 kPa. The test results from the Tempe cell tests show good agreement with past researchers using the suction and pressure plates. There is a difference between the results from the capillary-rise and Tempe cell tests. The difference is explained by the fact that the axis-translation technique used in the Tempe cell test is erroneous at a high degree of saturation. The Tempe cell test gives a higher suction than the capillary-rise test for the same water content. The capillary-rise test shows that the Whatman No. 42 filter paper has a maximum water content of about 135 % and minimum measurable suction of about 1 kPa. The water content of the Whatman No. 42 filter paper at 1 kPa can be used to supplement the other method for suctions greater than 10 kPa to obtain the calibration curve of the filter paper.

ACKNOWLEDGMENTS

The third author wishes to acknowledge the support from Nanyang Technological University under the Undergraduate Research Experience on Campus program.

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