Calibration of filter paper for measuring total soil suction

P. B. Pande¹ · S. R. Khandeshwar¹ · S. P. Bajad² · S. P. Raut¹

© Springer Nature Switzerland AG 2019

Abstract

Calibration curve plays an important role in filter paper method because it affects accuracy in soil suction values. Osmotic coefficient and relative humidity govern the osmotic suction required to develop calibration curve and equation. Most of the researchers used the readily available total (osmotic) suction values from various studies to develop the calibration curve. Very few researchers used the osmotic coefficient in calibration and studied its effect on calibration and measuring suction. In this paper, the effect of the osmotic suction proposed by various researchers on calibration of Whatman 42 Filter paper was studied. Logarithmic and exponential calibration equations were developed and compared. The NaCl solution used in the present study provides limited total suction range of 0–30,000 kPa. The total suction of clayey soil was measured to validate the calibration curves proposed in this study. The feasibility of proposed osmotic coefficients is verified by measuring total suction of soil. The total suction estimated from calibration curve using osmotic coefficients was found to be more accurate.

Keywords Filter paper calibration · Suction · Osmotic coefficient

List of symbols

ψ_t	is the total suction
ψ_π	is the osmotic suction
R	is the universal gas constant (8.314 Nm/Kmol)
T	is the absolute temperature ($T = 269.261$ K, for 25 °C)
v_{wo}	is the specific volume of water
w_v	is the molecular mass of water vapour (18.016 kg/kmol)
RH	is the relative humidity
P	is the partial pressure of pore water vapour with soil water
P_o	is the partial pressure of the water vapour in equilibrium with an identical solution at atmospheric pressure
$\emptyset$	is the osmotic coefficient
v	is the number of ions from one molecule of salt ($v = 2$ for NaCl)
m	is the molality

w	is the molecular mass of water
ρ_w	is the density of water
a	is the slope of calibration curve
b	is the y intercept of the calibration curve
w_f	is the gravimetric filter paper water content
γ_{dmax}	is the maximum dry density
w_L	is the liquid limit
w_p	is the plastic limit
G	is the specific gravity
S_r	is the degree of saturation

1 Introduction

Due to unavailability of economical and easily available resources, measuring suction is hard to use in engineering practice which is the part of geotechnical engineering. The filter paper as a soil suction measuring resource is available in soil science which is simple, reliable and economical

✉ S. P. Raut, sprce22@gmail.com; sprce@rediffmail.com; spraut@ycce.edu; P. B. Pande, prashantbpande21@gmail.com; pbpande@ycce.edu; S. R. Khandeshwar, khandeshwar333@yahoo.com; hod_ce@ycce.edu; S. P. Bajad, s.p.bajad@gmail.com |

¹Department of Civil Engineering, Yeshwantrao Chavan College of Engineering, Nagpur, India. ²Department of Civil Engineering, Government Polytechnic, Amravati, India.

[1–3]. ASTM D 5298-94 [4] recommended filter paper method as a standard test for measuring soil suction. The trial operation is simple and sparing and does not need any extra equipment.

The dependability of the filter paper method is founded on understanding the principles and laboratory procedure followed. Essentially, the filter paper and soil reach equilibrium through vapour (total suction measurement) or liquid (matric suction measurement) flow. After reaching equilibrium, the soil suction is indirectly measured from the prior established calibration curve. Precise measurement of suction is governed by the accuracy of the filter paper water content versus the suction calibration curve [5–7]. The calibration curves are usually obtained from the processes of wetting the filter papers through vapour transfer (salt solutions) and drying the filter papers through fluid transfer (porous plates). For measuring total suction, the calibration curves are obtained from the wetting and drying process of the filter papers through vapour transfer (salt solutions). For measuring matric suction, the calibration curves are obtained from the wetting and drying of the filter papers through fluid transfer (porous plates). Total suction and pore fluid osmotic suction can be confidently determined using non-contact filter papers difference of which will give matric suction [8].

This paper is focusing on the total (osmotic) suction values used for calibration of filter paper by wetting process through NaCl salt solution. The calibration curves were developed by using water content of filter papers with total suction values.

Most of the researchers used the readily available total suction values from various studies to develop the calibration curve. Bulut et al. [5] used the total suction values prepared by Lang [9] to construct the calibration curve. ASTM D 5298 suggested to calculate the total suction value from the relative humidity by using Kelvin's equation (Eq. 1) also provides a standard critical table giving relationship between salt concentration and relative humidity. Lu and Likos [10] used total suction calculated from relative humidity proposed by Bulut [11] for an unsaturated NaCl salt solution.

As osmotic coefficient and relative humidity govern the total suction required to produce a calibration curve and its equation, it is essential to study the performance of calibration curve. Most of the researchers have been applied the total suction values prepared by either Lang or combination of relative humidity and Kelvin's equation (Eq. 1). Bulut [11] suggested that the combination of Kelvin's equation (Eq. 1) and Lang's equation (Eq. 2) can be used to calculate the osmotic suction for various salt solutions. Hamer and Wu [12] proposed the osmotic coefficients which is necessary to calculate osmotic suction values. For the calibration of

Whatman 42 filter paper, the osmotic coefficient (Eq. 3) was not used by any of the researchers.

This paper studied the rarely discussed issues related to the calibration of Whatman 42 filter paper for total suction testing. In this study, the calculated osmotic suctions have been used as total suction values to develop calibration curve. The total suction values obtained [9, 12] were taken into consideration to study the effect on the calibration curve. The osmotic coefficients and the total suction values proposed [9, 12] were used to develop the calibration curve for Whatman 42 filter paper to investigate variations in measured soil suction. Additionally, curve recommended in ASTM D 5298 was considered to compare the measured soil suction values. The logarithmic and exponential equations (Eqs. 7, 9) of developed calibration curves were obtained, and the measured soil suction from (Eqs. 6, 8) was compared.

Suction was measured in clayey soil to validate the curves proposed in this study. The trial was led on 30 numbers of identical soil samples for measuring total suction from proposed curve. The measured soil suction values obtained from the developed calibration curves were compared. In this study, the filter paper gravimetric water content (w_f) is in between 17 and 36%, and hence, the work is restricted to the curves within this range. Numerous researchers investigated the suction from the curve within this range. Also, equation from ASTM D 5298 and various studies available within this range were compared with the proposed equations.

2 Filter paper technique

By attaining the equilibrium between the soil and calibrated filter paper, suction can be determined from calibration curve of filter paper. Water content of filter paper at equilibrium stage and calibration equation gives the suction of soil. Both the non-contact and contact filter paper methods were used to quantify the total and matric suctions, respectively.

In this study, filter papers were initially dried at room temperature which was in between 34 and 40 °C. A clean tweezers were used to handle filter papers by wearing hand gloves to ensure no contamination of filter papers.

In terms of thermodynamic relationship, total suction (ψ_t , kPa) and relative humidity of pore water vapour are given by Kelvin's equation (Eq. 1).

$$\psi_t = \frac{RT}{V} \ln \left(\frac{P}{P_0} \right) \quad (1)$$

Osmotic coefficient (Eq. 2) is proposed by Lang [9].

$$\phi = \frac{\rho_w}{vmw} \ln \left(\frac{P}{P_0} \right) \quad (2)$$

The combination of Eqs. (1) and (2) gives a useful relationship which is adopted in the present study to calculate

osmotic suctions (Eq. 3) for different salt solutions which is represented in Table 1.

$$\pi = -vRTm\phi \quad (3)$$

Osmotic coefficients [12] for different salt solutions are readily available. Table 1 gives the osmotic coefficients for NaCl salt solutions.

The osmotic coefficient of sodium chloride (NaCl) solution is typically used to establish the calibration curve. Typical NaCl solution concentrations (ranges in between 0.05 and 2.0) and the respective osmotic suction value calculated from their osmotic coefficient are given in Table 1.

Figure 1a, b shows the plots between the total suction with osmotic coefficient and relative humidity, respectively [13] for temperature 25 °C which covers the range used in this study. In both cases, the total suction is plotted in logarithmic scale. Total suction decreases with the decrease in osmotic coefficient up to value 0.92; however, the total suction decreases as osmotic coefficient starts increasing again from 0.92 (Fig. 1a). Figure 1b shows the relative humidity ranging from 94.7 to 99.8%, and the total suction decreases with high rate and becomes zero when relative humidity approached to 100%. Occurrence of soil suction is always at the values less than 100% relative humidity; the same phenomenon is observed in the present study. Also, it is observed that at high concentration salt solution with constant temperature in a closed container has low relative humidity above its surface [11].

Different concentrations of sodium chloride solutions used in this study (Table 1) were plotted against corresponding osmotic (total) suction values proposed by Hamer and Wu [12] and Lang [9] in log kPa units at 25 °C (Fig. 2). The relation between osmotic suction and molality (Fig. 2) shows that as molality increases the total suction

Fig. 1 **a** Relationship between osmotic suction with osmotic coefficient. **b** Relationship between osmotic suction with relative humidity

Table 1 Molality, NaCl concentration, osmotic coefficients for NaCl salt solutions [12] and osmotic suction (ψ_π) for 25 °C Eq. 3

Molality	NaCl in (g) in 1000 ml of water	NaCl in (g) in 150 ml of water	Osmotic coefficients at 25 °C for NaCl (Hamer and Wu [12])	Total suction (ψ_π)	
				Hamer and Wu [12]	Lang [9]
0.05	2.9221	0.4383	0.94357	211	234
0.1	5.8443	0.8766	0.93250	418	462
0.2	11.6886	1.7533	0.92387	827	915
0.3	17.5328	2.6299	0.92123	1237	1368
0.4	23.3771	3.5066	0.92000	1648	1823
0.5	29.2214	4.3832	0.92224	2062	2281
0.6	35.0657	5.2599	0.92300	2480	2744
0.8	46.7542	7.0131	0.92900	3328	3682
0.9	52.5985	7.8898	0.93350	3762	4158
1	58.4428	8.7664	0.93600	4191	4640
1.4	81.8199	12.2730	0.95300	5974	6623
1.6	93.5085	14.0263	0.96487	6892	7652
2	116.8856	17.5328	0.98400	8812	9780

Fig. 2 Molality of NaCl solution versus osmotic suction

increases. The trend of the curves for water potential versus molality is similar for 25 °C.

3 Filter paper calibration

The precision of the filter paper water content versus the suction calibration curve governs the accuracy of the filter paper technique. It is necessary to develop the calibration equation for the particular filter paper being used during the experimental work. The filter paper was calibrated by using the relationship between equilibrium filter paper water content (w_f) and total suction ψ_t (or osmotic suction). Filter paper calibration curves are usually found in two segments named as wetting and drying calibration curves. Wetting calibration curves are prepared by hanging dry filter paper over salt solution of known water potential. Drying calibration curves are produced by placing wet filter paper between the soil specimens in pressure plate or pressure membrane apparatus. The calibration for the suction wetting curve for filter paper using salt solutions is based upon the thermodynamic relationship between total suction, ψ_t (or osmotic suction) and the relative humidity resulting from a specific concentration of a salt in distilled water.

In this study, the filter paper was calibrated by the following combination of procedures suggested by the ASTM D 5298 and Bulut [11]. The ash-free and quantitative type II filter paper Whatman No. 42 having a diameter 5.5 cm weighing on the order of 0.2 g has been used as per ASTM D 5298 guidelines. For developing the wetting filter paper calibration curve initially, dry filter papers were suspended over salt solutions with known water potential. An equilibration period suggested in various studies for wetting

Fig. 3 Total suction calibration test configuration

curve was 2 weeks. In this study, NaCl salt solution was used as the osmotic suction source. Salt concentrations ranging from 0.05 to 2.0 molality were prepared, and filter papers were simply placed above salt solutions (in a non-contact manner) with the help of plastic support in sealed containers. The calibration test configuration adopted for this research is presented in Fig. 3. The filter paper and salt solution setup in the sealed containers were set in a constant thermal environment for equilibrium of 14 days [1, 5, 14]. Filter paper suction measurement gives misleading results if the influence of temperature is not counted in the calibration equation [14, 15]. Hence, during the calibration constant temperature (25 °C) was considered [4]. To avoid the condensations and evaporations, temperature variation was maintained as the temperature fluctuations were negligible (less than ± 0.1 °C) [1].

4 Filter paper calibration curve

The most commonly adopted filter papers, in practice, are Schleicher and Schuell No. 589-WH and Whatman No. 42. ASTM D 5298 reports two different calibration curves for each of these filter papers. The calibration curves are unique for each type of filter paper and should be used to obtain soil suction and measurement of total and matric suction measurements [16, 17]. The calibration curve recommended in ASTM D 5298 is a combination of both wetting and drying curves. By allowing enough time for thermodynamic equilibrium, the amount of water absorbed by initially dry filter paper would be the same for both the non-contact (total suction) and contact (matric suction) measurements [18]. In the present study, single curve was developed by using wetting calibration method from NaCl salt solutions for total suction measurements of soil.

Mostly the filter paper calibration curves for the Whatman No. 42 are bilinear in the logarithm of suction versus

filter paper water content [19]. The nature of the filter paper calibration curve was expressed by trend line. The slope of curve changes at the point of discontinuity in the line, and it is generally observed between 38 and 47% filter paper water contents. The trend line is found to be linear with a coefficient of determination, i.e. R^2 value not less than 0.9479. Both segments of a line are represented by the standard expression (Eq. 4).

$$\log_{10} \psi = -bw_f + a \quad (4)$$

$$\log_{10} (\psi) = ae^{-bw_f} \quad (5)$$

Thus, the exponential (Eq. 5) can be used to evaluate the suction as it is intrinsically linear and can be converted into a straight line through the logarithmic transformation [20]. These equations (Eqs. 4, 5) are taken into consideration in the present study to compare the suction values. Table 2 reviews the equations for the Whatman No. 42 filter paper calibration curves ($w_f < 47\%$) proposed by various researchers.

The a and b parameters (slope of the calibration curve and y intercept of the calibration curve) obtained from calibration curves developed by several researchers as well as the author (Eqs. 6, 8) are exemplified in Table 2. These parameters (Table 2) have been suggested based on filter paper water content and suction measurements in the range of $w_f < 47\%$.

5 Results and discussion

From the curves obtained (Figs. 4, 5) filter paper water content (w_f) reaches to 36% and the total suction decreases significantly, this can be linked to the nature of Kelvin's equation [25]. Filter paper does not assimilate the water

beyond this point; hence, the maximum water content absorbed by the filter paper is 36%. These results conclude that the filter paper method can give reliable suction values below this range. In other words, it is not possible to measure the suction lower than 2 log kPa by using filter paper method. The suction lower than this range is measured as matric suction and can be measured by means of the methods like pressure plate, pressure membrane and suction plate recommended by various researchers. Therefore, the curves obtained in this study can only be applicable to assess the total suction of soil.

Figures 4 and 5 show the results of calibration performed for filter paper Batch no. 9850766 (CAT No. 1442-125) used in this study. Two curves were established from same filter paper with different suction values. Curve 1 was developed with the osmotic suction values calculated from osmotic coefficient given by Hamer and Wu [12], and curve 2 was

Fig. 4 Calibration curves in linear logarithmic form (i) curve 1 using osmotic coefficient [12] and (ii) curve 2 using water potential [9]

Table 2 Equations for calibration curves for Whatman 42 filter paper [19, 20]

References	Water content (%)	a and b parameters
Fawcett et al. [21]	$W_f < 45.3$	$a = 5.777$ and $b = 0.06$
ASTM-5298	$W_f < 45.3$	$a = 5.327$ and $b = 0.0779$
Hamblin [22]	–	$a = 6.281$ and $b = 0.0822$
Greacen et al. [23]	$W_f < 45.3$	$a = 5.327$ and $b = 0.0779$
Chandler and Gutierrez [3]	$W_f < 47$	$a = 4.842$ and $b = 0.0622$
Oliveira and Marinho [6]	$W_f < 33$	$a = 4.83$ and $b = 0.0839$
Bulut et al. [5]	$W_f < 47$	$a = 5.4246$ and $b = 8.247$
Leong et al. [15]	$W_f < 47$	$a = 4.945$ and $b = 0.0673$
Leong et al. [15]	$W_f < 26$	$a = 5.31$ and $b = 0.0879$
ASTM-5298	$W_f < 45.3$	$a = 5.327$ and $b = 0.0779$
Bicalho et al. [20]	$W_f \leq 47$	$a = 5.201$ and $b = 0.062$
Purwana [24]	$W_f < 26$	$a = 5.0304$ and $b = 0.0938$
Author (using Lang water potential)	$W_f < 36$	$a = 5.4816$ and $b = 0.0813$
Author (using Hamer osmotic coefficient)	$W_f < 36$	$a = 5.4297$ and $b = 0.0813$

Fig. 5 Calibration curves in exponential form (i) curve 1 using osmotic coefficient [12] and (ii) curve 2 using water potential [9]

developed from osmotic suction values directly given by Lang [9] (Table 1). The curve suggested in ASTM D 5298 has also been included in this study as shown in Fig. 4 to compare proposed curves. Figure 4 shows the linear logarithmic curve, and Fig. 5 shows the exponential nature of the linear logarithmic curve developed in this study. It is observed that the osmotic coefficients [12] give lower osmotic suction values as compared to Lang [9] and ASTM D 5298 [4].

Calibration curves and their equations developed by the author are similar to the curves cited (Table 2) in this study. The proposed curve 1 and curve 2 follow the linear logarithmic trend whose coefficient of determination (R^2) were obtained as 0.9495 and 0.9501 which was not less than 0.9479 [10]. The linear trend line obtained by using osmotic coefficient has a slope of -0.0813 and zero intercept of $5.4304 \log \text{ kPa}$, nearly similar to the trend line obtained by use of osmotic suction suggested by Lang [9]. Also, the calibration equations from proposed curves are similar to the equations referred in Table 2. The curve 1 and curve 2 are much closer to each other; however, the total suction values result in large difference. The series of tests was conducted on twenty-one soil samples to confirm the divergence between these two curves. Total suction values were evaluated at the average water content of 31.44% which is almost equal to optimum moisture content. These suction values are obtained utilizing the filter paper technique on locally available clayey soil near the study location at Nagpur, Maharashtra, India (Table 3).

$$\log_{10} \psi_t = -0.0813w_f + 5.4297 \quad (6)$$

$$\psi_t = 268,964e^{-0.187w_f} \quad (7)$$

$$\log_{10} \psi_t = -0.0816w_f + 5.4816 \quad (8)$$

$$\psi_t = 298895e^{-0.187w_f} \quad (9)$$

Table 4 shows the soil suction values in filter paper water contents ranges (w_f) $\leq 47\%$ calculated by using proposed equations (Eqs. 6–9).

Figure 4 gives a linear logarithmic calibration curve for Whatman 42 filter paper used in the experimental work which is expressed by Eqs. 6 and 8. At 31.44% average soil water content, total suction was found to be 16,998 kPa from linear logarithmic curve 2 and 15,267 kPa from the linear logarithmic curve 1. The percentage decrease in total suction value was 10.18%. The total suction was also calculated with the help of calibration equation recommended by ASTM D 5298 and was found to be 13,549 kPa, and the percentage decrease in total suction value was 20.29%. The percentage decrease in total suction values from curve 1 with respect to ASTM D 5298 is 11.25%. The percentage change of suction values from curve 1 and curve 2 is less as compared to ASTM D5298. This shows that suction evaluated from curve 1 is closest to the curve 2. The curve 1 gives lower total suction values as compared to curve 2 and higher as compared to ASTM D 5298. Thus, the suction values obtained from Hamer's osmotic coefficient lies between the values obtained from Lang and ASTM D5298. It means osmotic coefficient gives the realistic calibration which results well agreed total suction values of soil.

Table 3 Properties of soil

Properties	Values
Liquid limit (w_L)	61%
Plastic limit (w_p)	37%
specific gravity (G)	2.6
Degree of saturation (S_r)	96%
Maximum dry unit weight (γ_{dmax})	13.2 kN/m ³
Optimum moisture content	32%

Table 4 Total and matric suction values obtained using logarithmic and exponential equation

Soil water content (%)	From logarithmic equation			From exponential equation	
	Curve 1 (Hamer's osmotic coefficient)	Curve 2 (Lang's suction values)	ASTM	Curve 1 (Hamer)	Curve 2 (Lang)
	Total suction (kpa)	Total suction (kpa)	Total suction (kpa)	Total suction (kpa)	Total suction (kpa)
38	18,449	20,758	16,158	18,668	20,745

The exponential calibration curves developed for Whatman 42 filter paper are illustrated in Fig. 5 and expressed by Eqs. 7 and 9. The suction values obtained from linear logarithmic equations, i.e. Eqs. 6 and 8, are much closer to the suction calculated from the exponential equations. The total suction value obtained from exponential curve 2 is 16,900 kPa, and similarly, it is 15,288 kPa obtained from the exponential curve 1. The percentage decrease in the suction values obtained from curve 1 and curve 2 was 9.54% which is less as compared to the percentage decrease observed in the values obtained from linear logarithmic curves. The exponential equation is more feasible and accurate for calculating the total suction since it reflects less difference in percentage increase in suction values.

6 Conclusions

The effect and variation in developed calibration curve of Whatman 42 filter paper was studied. The difference in calibration curves developed from various osmotic suction values was estimated. The total suction values obtained were also compared with values computed from curve recommended in ASTM D 5298. The total suction calculated from calibration curve using osmotic coefficients was more realistic as the difference was very low when it compared to ASTM D 5298. The feasibility of proposed osmotic coefficients is verified by measuring total suction of soil.

Acknowledgements The authors would like to acknowledge the In-house minor scheme, Yeshwantrao Chavan College of Engineering, Nagpur, and Nagar Yuvak Shikshan Sanstha, Nagpur, which collectively funded this project.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

- Al-Khafaf S, Hanks RJ (1974) Evaluation of the filter paper method for estimating soil water potential. *Soil Sci* 117:194–199
- Fredlund DG, Rahardjo H, Fredlund MD (2012) *Unsaturated soil mechanics in engineering practice*. Wiley, Hoboken
- Chandler RJ, Gutierrez CI (1986) The filter-paper method of suction measurement. *Geotechnique* 36(2):265–268
- ASTM (2007) D 5298: test method for measurement of soil potential (suction) using filter paper. ASTM International, West Conshohocken
- Bulut R, Lytton RL, Wray WK (2001) Soil suction measurements by filter paper. ASCE Geotechnical Special Publication No. 115, pp 243–261
- Oliveira OM, Marinho FAM (2006) Evaluation of filter paper calibration. In: *Proceedings of a conference on UNSAT 2006*
- Navaneethan T, Sivakumar V, Wheeler SJ et al (2015) Assessment of suction measurements in saturated clays. *Proc Geotech—ICE Virtual Libr* 158(1):15–24
- Thyagaraj T, Salini U (2015) Effect of pore fluid osmotic suction on matric and total suctions of compacted clay. *Geotech, ICE Virtual Libr* 65(11):952–960. <https://doi.org/10.1680/jgeot.14.P.210>
- Lang ARG (1967) Osmotic coefficients and water potentials of sodium chloride solutions from 0 to 40 °C. *Aust J Chem* 20:2017–2023
- Likos WJ, Lu N (2004) *Unsaturated soil mechanics*. Wiley, New York
- Bulut R (1996) A re-evaluation of the filter paper method of measuring soil suction. Ph.D. thesis, Civil Engineering
- Hamer WJ, Wu YC (1972) Osmotic coefficients and mean activity coefficients of univalent electrolytes in water at 25 °C. *J Phys Chem Ref Data* 1(4):1047–1099
- Likos WJ, Lu N (2002) Filter paper technique for measuring total soil suction. *Transportation Research Record* 1786, 02-2140, pp 120–128. <http://trrjournalonline.trb.org/doi/10.3141/1786-14>
- Haghighi A, Medero GM, Marinho FAM et al (2012) Temperature effects on suction measurement using the filter paper technique. *Geotech Test J* 35(1):83–90
- Leong EC, He L, Rahardjo H (2002) Factors affecting the filter paper method for total and matric suction measurements. *Geotech Test J* 25(3):322–333
- Houston SL, Houston WN, Wagner AM (1994) Laboratory filter paper suction measurements. *Geotech Test J* 17(2):185–194
- Leong EC, Kizza R, Rahardjo H (2016) Measurement of soil suction using moist filter paper. In: *Proceedings of E3S web of conferences on E-UNSAT 2016*
- Bulut R, Wray WK (2005) Free energy of water-suction-in filter papers. *Geotech Test J* 28(4):355–364
- Power KC, Vanapalli SK, Garga VK (2008) A revised contact filter paper method. *Geotech Test J* 31(6):461–469
- Bicalho KV, Cupertino KF, Bertolde AI (2007) Filter paper method of soil suction measurement. In: Caicedo et al (eds) *Proceedings of conference on advances in unsaturated soils*. Taylor & Francis Group, London, pp 225–230
- Fawcett RG, Collis-George N (1967) A filter-paper method for determining the moisture characteristics of soil. *Aust J Exp Agric Anim Husb* 7:162–167
- Hamblin AP (1984) Filter paper method for routine measurement of field water potential. *J Hydrol* 53(3/4):355–360
- Greacen EL, Walker GR, Cook PG (1987) Evaluation of the filter paper method for measuring soil water suction. In: *International Conference on Measurement of Soil and Plant Water Status*, pp 137–143
- Purwana YN (2017) Laboratory work on total suction calibration curve. *J Ris Rekayasa Sipil Univ Seblas Mark*. <https://doi.org/10.20961/jrrs.v1i1.14708>
- Bulut R, Leong EC (2008) Indirect measurement of suction. *J Geotech Geol Eng* 26(6):633–644

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.