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Evaluation of osmotic suction and hydration forces by revised filter paper test

M. K. Khan[1], G. D. Emidio[2], and A. Bezuijen[3]

[1]*Doctoral student, University of Gent, Gent, Belgium, email: muhammadkhizar.khan@ugent.be*

[2]*Professor, University of Gent, Gent, Belgium, email: gemmina.diemidio@ugent.be*

[3]*Ereprofessor, University of Gent, Gent, Belgium, email: .adam.bezuijen@ugent.be*

ABSTRACT

Due to measurement limitations, it is usual practice to substitute total suction for matric suction. However, in the case of even a minor quantity of salt content and the presence of hydration forces, this substitution may make inaccurate evaluation of how the soil reacts to changes in matric suction. The osmotic suction prevails with the increase in the salt content, and for plastic clays, the osmotic suction cannot be calculated by subtracting matric suction from total suction due to the presence of hydration forces. Hence, evaluation of osmotic suction becomes unavoidable. The paper presents an approach to measure the osmotic suction and, subsequently, hydration forces by using the filter paper test, and a few experimental results for its evaluation. The approach allows effective, simple, and cost-effective measurement of osmotic suction and hydration forces as well as matric and total suction.

Keywords: Filter paper test, Suction measurement, Unsaturated soil

1 INTRODUCTION

The vadose zone, where moisture content fluctuates due to human activities and environmental factors, is involved in the construction of nearly every onshore engineering infrastructure. The concept of unsaturated soil mechanics is used to account for moisture content change. The current theory of unsaturated soil mechanics considers two independent stress state variables, i.e., net normal stress and matric suction (Fredlund and Rahardjo 1993). According to the literature, disregarding the matric suction makes it impossible to accurately anticipate how the soil will collapse (Lawton et al. 1991). Leong and Abuel-Naga (2018) concluded that matric suction should be considered when evaluating the shear strength of unsaturated high plastic silty soil because the pore water may create changes in the soil structure.

In general, capillarity, adsorption, and osmosis are the three phenomena that are linked to soil suction. Capillarity and adsorption are captured by matric potential, whereas the ionic effect is described by osmotic suction. The osmotic suction is generally disregarded because of little lasting impact. However, in highly plastic soils, the osmotic suction might be significant due to the clay mineralogy and the presence of dissolved salts (Suwal and Kuwano 2018). Miller and Nelson (2006) demonstrated that a modest amount of salt can have a significant impact on how the soil reacts to stress state variables. Lu et al. (2018) investigated the salinity effect on the water retention curves and concluded that the presence of salt rendered changes in the suction.

The measurement techniques that are being used to measure suction are tensiometer, axis translation, contact filter paper, non-contact filter paper, relative humidity sensor, vapor equilibrium, psychrometer, and chilled mirror dew point potentiometer. The first three methods are used for matric suction measurement whereas the last five methods are common for total suction measurement (Khan et al. 2021). The addition of both matric and osmotic suction is typically termed total suction. However, for highly plastic soils, the overall suction is not simply the sum of the matric and osmotic suctions. Arifin and Schanz (2009) investigated the water retention curves of expansive soils and stated that the difference between total and matric suction represents the osmotic suction and hydration forces. Krahn and Fredlund (1972) deduced that the measured osmotic suction was the difference between total and matric suction for low plastic soils, whereas osmotic suction was lower than the difference in the case of high plastic clay i.e., Regina clay. Thus, for plastic clay, osmotic suction cannot be considered as the simple difference between matric and total suction, hydration forces also play their part, so needs to be considered.

The osmotic suction can be determined by measuring the electric conductivity (EC) or concentration (C) of salts present in pore water (Fredlund and Rahardjo 1993). The pore water is extracted from the soil with the help of squeezing techniques, and electric conductivity is measured. To have enough quantity to measure the EC, high squeezing pressure is applied, which results in lower diffusion of ions and thus unrealistic EC (Arifin and Schanz 2009). Even at high squeezing pressure, an adequate amount of pore water can't be obtained, especially in the case of unsaturated soils. Another method to obtain enough quantity is to make a slurry of the soil. However, in that case, the pore water gets diluted (Abedi-Koupai and Mehdizadeh 2008). Different equations have been proposed in the literature to measure the osmotic suction from EC and salt concentration of the pore fluid as shown in Table 1.

Table 1. *Typical equations for estimating osmotic suction found in the literature*

References	**Equations to estimate osmotic suction**	
(Mitchell and Soga 2005)	$\pi = i\frac{C}{M}RT$	(1)
(Mata et al. 2002)	$\pi = 0.019\left(\frac{EC}{1000}\right)^{1.074}$	(2)
(Richards 1954)	$\pi = 31.92\,(EC)^{1.08}$	(3)
(Leong et al. 2007)	$\pi = 0.31P_{atm}(EC^{1.15})$	(4)
(Arifin and Schanz 2009)	$\pi = 38.54\,(EC)^{1.0489}$	(5)
(Witteveen et al. 2014)	$\pi = 0.407\left(\frac{C}{M}\right)^2 + \frac{3.88C}{M} + 0.61$	(6)
(Mokni et al. 2014)	$\pi = -\frac{RT\rho}{M_w}ln\left[1-\left(\frac{C}{\rho}\right)^2\right]$	(7)

π = Osmotic suction (kPa); i = Van't Hoff's factor; C = Concentration g/L; M = Molar mass of solute (kg/mol); R = Universal gas constant (8.31 J/(mol K)); T = Temperature (kelvin); EC = Electric conductivity (mS/cm); P_{atm}= Atmospheric pressure (kPa); ρ = liquid density (kg/m^3); M$_w$ = Molar mass of water (kg/mol)

Despite, the availability of squeezing techniques and dilution method, the challenges exist to measure the osmotic suction. Therefore, alternate techniques need to be developed in this regard.

The filter paper method has been a viable method for measuring matric and total suction depending upon the full contact (in contact) and without any contact (non-contact) between soil and filter paper, respectively. Besides, it is inexpensive and can measure a wide range of matric suctions (Acikel et al. 2015; Barroso et al. 2006). The filter paper method is based on the equilibrium of the moisture between filter paper and the specimen. Once the equilibrium is established, the water content of the filter paper is measured and related to the specific suction value deduced from the calibration curve (Fredlund and Rahardjo 1993). In the in-contact filter paper method, the mode of transfer of water is capillarity, however, at high suction > 30,000 kPa (Ridley and Wray 1996), the water transfer may take place from the vapor phase, thus providing inconsistent results (Pan et al. 2010). The accurate measurement of filter paper water content is crucial for the accuracy of the results. The equilibrated filter paper needs to be transferred from the testing setup to specimen for weight measurement within 5 seconds (Fredlund and Rahardjo 1993). Thus, the method is highly dependent upon the user.

The study investigates the use of filter paper method to measure osmotic suction along with measurement of hydration forces. In this paper, the theoretical framework and a few experimental results are presented for measuring osmotic suction and subsequently hydration forces from the filter paper method.

2 SUGGESTED APPROACH

The method presented in this approach makes use of contact and non-contact filter paper (ASTM-D5298 2000). For the measurement of osmotic suction, the contact between filter paper and suction is necessary as the capillary transfer of water along with ions is desired, whereas for the measurement of the hydration forces, the in-contact and non-contact filter paper needs to be measured, simultaneously. As mentioned earlier that in the contact filter paper the mode of transfer changes from capillarity to vapor phase above 30,000 kPa, thus the measurement of osmotic suction would be valid up to that suction.

however, it also depends upon the concentration of salts in the soil in the pore fluid. The approach follows the following steps.

1) Firstly, the relationship between EC and C is developed with the help of the salts of known concentrations and by measuring the EC of the salt's solution if the molar concentration is not known. Equation 7 in Table 1 proposed by (Mokni et al. 2014) can be used to predict the osmotic suction without using EC and molar concentration.
2) In the next step, 55 mm filter papers are dried in the oven for 2 hours at 105°C and cooled in a desiccator for 2 minutes and the mass of filter papers (m_{dcf} and m_{dnf}) is measured instantly after the cooling in 0.1 mg balance.
3) Then dried filter paper is inserted in between two 70 mm filter papers, and three stacked filter papers are placed in contact with the soil specimen. Besides, two filter papers are also placed on a mesh/O ring close to the soil mass but without any contact. The setup is sealed in airtight container/plastic bags. Subsequently, the sealed setup is left at 20°C to achieve equilibrium between soil and filter papers.
4) After the equilibrium period, the mass of the 55 mm wet contact (m_{wcf}) and non-contact (m_{wnf}) filter papers is measured and the filter papers are placed in the oven for 2 hours at 105°C, then cooled in the desiccator for 2 minutes and the mass of contact filter paper (m_{dcfe}) and non-contact filter paper (m_{dnfe}) is measured instantly after the cooling.
5) The difference in the mass of contact dry filter papers before and after equilibrium would give the mass of salt content (m_{salt}) present in the pore water i-e. $m_{dcfe} - m_{dcf}$ and the concentration of salt in pore water (C) is calculated as $\frac{m_{dcfe}-m_{dcf}}{m_{wcf}-m_{dcfe}}$.
6) After finding the concentration of salts in pore space, the EC is determined from the relationship between EC and C and subsequently, equations from Table 1 could be used to estimate the osmotic suction.
7) For the matric suction measurement, the water content in filter paper is found out as $\frac{(m_{wcf}-m_{dcfe})}{m_{dcf}}$; In ASTM-D5298 (2000) m_{dcfe} is taken in the denominator, which is correct when the soil contains pure water in the pore space. In the case of an alkaline solution, m_{dcfe} would negatively impact the results because it contains the weight of the salt as well, whereas the calibration curve was established based on pure water. Thus, m_{dcf} is recommended to be used. For the total suction measurement, the water content of non-contact filter papers is calculated as $\frac{(m_{wnf}-m_{dnfe})}{m_{dnfe}}$.
8) After finding the water content of filter papers, matric suction and total suction are calculated by using filter paper calibration curves.
9) Lastly, the hydration forces are calculated by subtracting matric and osmotic potential from total suction.

If only the measurement of osmotic suction is desired, the non-contact approach can be skipped.

3 MATERIAL AND METHODS

Four saturated samples of sodium bentonite (UC) were prepared, and for the hydration, four liquids were used i.e., Deionized water (DW), 5 mM calcium chloride ($CaCl_2$), 10 mM $CaCl_2$, and Seawater (SW). The properties of the bentonite and liquids are shown in Table 2. Besides, Whatman grade 42 filter papers were used. The relationship between EC and C is developed by using a $CaCl_2$ solution of different molarities (Figure 1) and given in equation 8.

$$EC = 1.49C^{0.9418} \qquad (8)$$

Where EC is in mS/cm and C is concentration in g/L

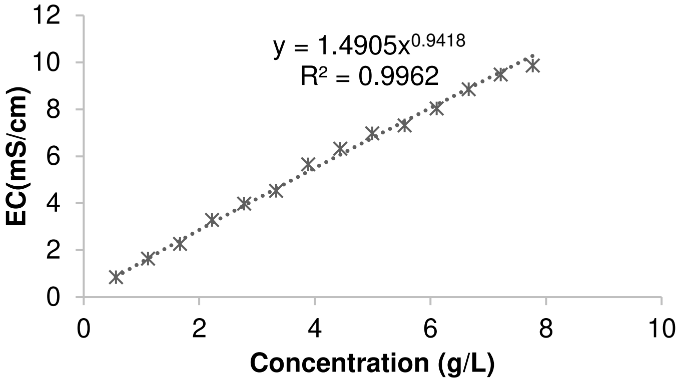

Figure 1. *EC versus concentration relation*

Table 2. *Properties of bentonite and solutions*

Properties	**Bentonite**
Specific Gravity	2.66
Plastic limit (%)	46.9
Liquid limit (%)	625.2
Plasticity Index	578.3
Cation exchange capacity (meq/100g)	85.1
Swell Index in DW (ml/2g)	34
Swell Index in 5 mM CaCl2 (ml/2g)	33
Swell Index in 10 mM CaCl2 (ml/2g)	21
Swell Index in SW (ml/2g)	8
Solutions	**EC (mS/cm)**
DW	0.01
5 mM $CaCl_2$	0.85
10 mM $CaCl_2$	1.64
SW	32.7

The specimen was prepared by hydrating bentonite between filter paper and porous stones in a stainless-steel ring of 7.1 cm diameter by keeping the porosity of 0.718. After hydration, the suggested approach as mentioned in section 2 was carried out by keeping the equilibrium period of 5 weeks. Subsequently, matric was calculated by the equations of the ASTM-D5298 (2000) calibration curve given by Equation 9 and 10, whereas, osmotic suction was estimated by equations presented in Table 1. Figure 1 was used to calculate the EC from the measured salt concentration of the pore fluid for all the liquids used.

The ASTM-D5298 (2000) calibration curve are represented by Equations 9 and 10.

$$w_f \leq 45.3\%, Log_{10}(h) = 5.327 - 0.0779w_f \tag{9}$$

$$w_f > 45.3\%, Log_{10}(h) = 2.412 - 0.0135w_f \tag{10}$$

Where, h = Suction (kPa) and w_f is water content of the filter paper.

4 RESULTS AND DISCUSSIONS

The total suction, matric suction, osmotic suction calculated by Equation 5, and hydration forces are presented in Figure 2. Overall, salt influences both total and matric suction, and total suction is mostly comprised of hydration forces. The trend of Figure 2 is closely related to the results of compacted Indian bentonite used by (Arifin and Schanz 2009). A significant portion of the total suction in the case of Indian bentonite contained hydration forces followed by osmotic and matric suction.

Hydration forces come into play when the water molecules and clay surface approach a few nanometres. The forces are very unusual in nature and can be repulsive, attractive, and oscillatory or combination of all (Park and Seo 2011). The initial hydration of cations and negative charge on the clay acted as the hydrophilic surface of the bentonite leading to a repulsive hydration force (Guancheng 2018).

The amount of salt had an impact on matric suction due to microstructural changes on the surface of clay particles. Miller and Nelson (2006) investigated that matric suction is least impacted by inorganic salts, however, the author used low plastic soils. In the case of plastic soils, matric suction is influenced by the amount of salt (Khan et al. 2022; Lu et al. 2018). In addition, the water content of the SW sample was high compared to other samples leading to lower suction. The 5 mM $CaCl_2$ showed negligible difference compared to DW, as the salt content was too low to be measured with filter paper. Thus, the concentration of salts in pore water and the amount of capillary water are the deciding factors for the measurement of osmotic suction with the filter paper technique. In addition, the sample with 10 mM $CaCl_2$ showed 0.1 and 18% higher matric and total suction.

The osmotic suction depends upon the concentration of ions. With an increase in ionic concentration, osmotic suction increases in the ascending order of salt content i.e., osmotic suction of SW > 10 Mm $CaCl_2$ > 5 Mm $CaCl_2$, and total suction also follow a similar trend.

From the above discussion, it can be concluded that in plastic soils, osmotic suction is not simply the difference between total and matric suction in terms of both thermodynamics and stress state variables. Hydration forces play a big role in saline high plastic soils. Besides, the hydro-mechanical behaviour of plastic soils is affected by dissolved salts.

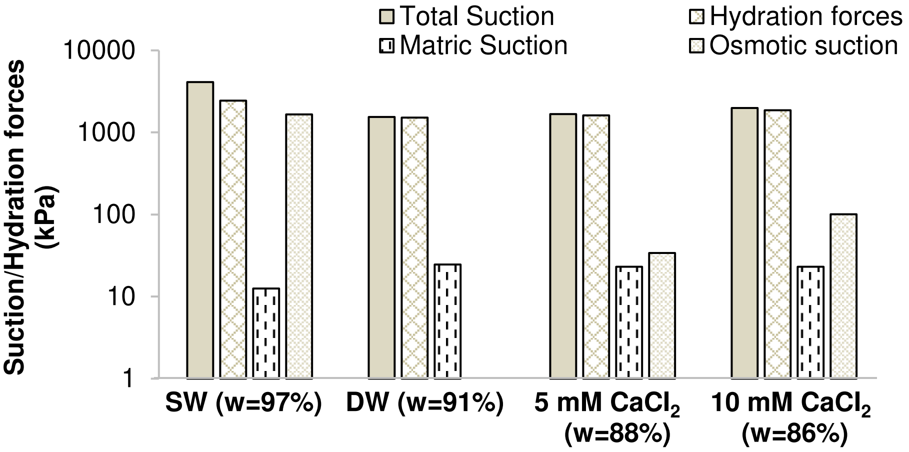

Figure 2. *Suction and hydration forces at different solutions*

The osmotic suction calculated from the equations shown in Table 1 is presented in Figure 3. The Figure highlighted that overall all the methods represent almost the same osmotic suction except the relation proposed by (Mokni et al. 2014). The reason could be the (Mokni et al. 2014) equation is not as based on EC. Also, the results of 10 mM $CaCl_2$ calculated by Van't Hoff's equation (Mitchell and Soga 2005) and (Witteveen et al. 2014) showed higher values of osmotic suction. The respective relations are also independent of EC, their calculations are based on the molar concentration of added liquids. Conclusively, the relations independent of EC showed higher values.

Osmotic suction of bentonite measured with the help of the squeezing pressure technique and measuring electric conductivity measurement of the extracted pore fluid by Arifin and Schanz (2009) was found to be in the range of 44 and 57 kPa at the water content of 60 and 30%, respectively, in distilled water. Similarly, Peroni and Tarantino (2005) showed the osmotic suction of 100 kPa and about 50 kPa at 30% and 45% water content for Kaolin, which depicts that the osmotic suction decreases with an increase in water content. In this study, the osmotic suction values were found to be 34 kPa and 101 kPa for 5 mM and 10 mM $CaCl_2$ at the water content of 88% and 86%. Although the values are closer in range as reported in the literature, but the increase in water content would decrease the osmotic suction while the increase in pore fluid salt would increase it and vice versa. Hence, a detailed and systematic study is under investigation to make a distinct comparison.

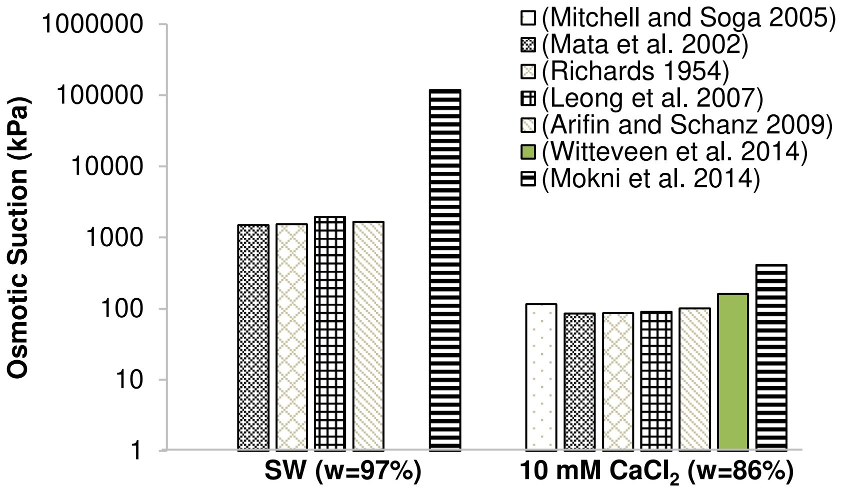

Figure 3. *Osmotic suction estimated by using equations in literature*

5 CONCLUSIONS

Different methods have been used in the past for estimating osmotic suction. In this study, the simplest approach has been identified for measuring osmotic suction and subsequently hydration forces by an already existing widely used method i.e., filter paper. In the past, the filter paper method was used to measure total and matric suction. By using the approach used in this study, the osmotic suction and hydration forces can also be calculated along with matric and total suction. The evaluation of hydration forces would further help in improving constitutive models and exploring in-depth mechanics on meso and micro-level scales.

Although the values are closer in range as reported in the literature but to make a distinct conclusion, further testing and validation are required by keeping the conditions of the testing similar and comparing them with the existing method. Furthermore, the approach is limited to the amount of detectable salt content on the filter paper. At high suction, when the water transfer starts taking place from the vapor phase, osmotic suction and hydration forces cannot be computed but high range is still expected to be covered as compared to other methods. Besides, the osmotic suction of soils containing an insignificant amount of salt is also too low to be measured. In addition, the measurement of the filter paper's weights is quite sensitive, and thus great care needs to be taken during handling and measurement. Thus, the future investigations are recommended regarding the range of the osmotic suction to be measured, relationships between electric conductivity and salt solutions of different molarities, mixture of different salt solutions, and type of ions present on the filter paper to get insight of pore water chemistry. In short, the use of filter paper would provide a handy method for measuring osmotic suction and relieve the cumbersome procedures, the requirement of additional equipment, and the cost.

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