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► **To cite this version:**

Zi Ying, Nadia Benahmed, Yu-Jun Cui, Myriam Duc. Determining osmotic suction through electrical conductivity for unsaturated low-plasticity soils. *Journal of Rock Mechanics and Geotechnical Engineering*, 2022, 14 (6), pp.1946-1955. <10.1016/j.jrmge.2021.12.020>. <hal-04011788>

HAL Id: hal-04011788

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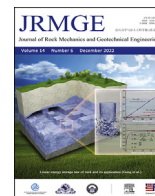


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Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.jrmge.cn

Full Length Article

Determining osmotic suction through electrical conductivity for unsaturated low-plasticity soils

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ARTICLE INFO

Article history:

Received 9 August 2021

Received in revised form

2 November 2021

Accepted 2 December 2021

Available online 31 January 2022

Keywords:

Unsaturated soils

Mixed salt solutions

Osmotic suction

Electrical conductivity (EC)

ABSTRACT

Determining osmotic suction from the electrical conductivity (EC) of soil pore water was widely reported in the literature. However, while dealing with unsaturated soils, they do not have enough soil pore water to be extracted for a reliable measurement of EC. In this paper, the chilled-mirror dew-point hygrometer and contact filter paper method were used to determine the total and matric suctions for low-plasticity soils with different salinities (0.05‰, 2.1‰ and 6.76‰). A new piecewise function was proposed to calculate the osmotic suction, with the piecewise point corresponding to the first occurrence of precipitated salt in mixed salt solutions (synthetic seawater). EC, ion and salt concentrations used for osmotic suction calculation were transformed from the established relationships of mixed salt solution instead of experimental measurement. The calculated osmotic suction by the proposed equation and the equations in the literature was compared with the indirectly measured one (the difference between the measured total and matric suctions). Results showed that the calculated osmotic suction, especially the one calculated using the proposed function, was in fair agreement with the indirectly measured data (especially for specimens with higher salinity of 6.76‰), suggesting that the transformation of EC and concentrations from the established relationship is a good alternative to direct measurement for low-plasticity soil. In particular, the proposed method could be applied to unsaturated low-plasticity soils which do not have enough soil pore water for a proper EC measurement.

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1. Introduction

Osmotic suction, which is correlated to the salinity of soil pore water, is one of the major factors influencing the hydro-mechanical behaviour of soil with salinity. Rao and Shivananda (2005) investigated the swelling potential of salt-amended expansive soils using deionised water and observed that it was independent of initial osmotic suction. However, they found that the rate of swelling decreased with increasing osmotic suction. By contrast, Rao et al. (2006) reported that, for compacted specimens with low initial salinity, the swelling magnitude was decreased by the osmotic gradient between reservoir salt solution and soil pore water. Witteveen et al. (2013) performed chemical loading on a

compacted non-swelling illite by replacing soil pore water with sodium chloride (NaCl) solution, and found that the initial stiffness and yield stress decreased as osmotic suction increased. Mokni et al. (2014) reported that the osmotic suction caused a decrease of compressibility and an increase of pre-consolidation stress for compacted Boom Clay. Therefore, it appears that the determining soil osmotic suction is indispensable and crucial for better understanding the hydro-mechanical behaviour of saline soils.

Miller and Nelson (1993) and Tang et al. (2002) indicated that the total suction was not simple addition of matric and osmotic suctions. Krahn and Fredlund (1972) stated that the difference between the total and matric suctions was the measured osmotic suction for Till (low-plasticity soil), whereas it was higher than that for Regina clay (high-plasticity soil). Arifin and Schanz (2009) reported that the difference between the total and matric suctions corresponded to the osmotic suction and hydration force for expansive soils. In general, it has been admitted that considering the osmotic suction as the difference between total and matric suctions was problematic for high-plasticity soils due to the effect

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

of hydration force, but plausible for low-plasticity soils (Edil and Motan, 1984; Wan et al., 1995; Sreedeeep and Singh, 2006; Dao et al., 2008).

The osmotic suction of salted soils can be deduced from the relationship between electrical conductivity (EC), salt and ion concentrations of soil pore water. Several equations for its determination were reported in the literature, as listed in Table 1. Van't Hoff equation (i.e. Eq. (1)) was widely used in determining the osmotic suction of salt solution (Mitchell and Soga, 2005; Rao and Thyagaraj, 2007a, b; Witteveen et al., 2013). As shown in Fig. 1, the United States Salinity Laboratory Staff (1954) gave the variations of osmotic suction with the EC for a single salt solution and saturation extract of soil pore water in saline soils. Based on such variations, Mata et al. (2002) derived the relationship between the osmotic suction and EC of soil pore water (Eq. (2)). Rao and Shivananda (2005) established the calibration curve as expressed in Eq. (3), relating the EC of soil pore water to osmotic suction. Leong et al. (2007) estimated the osmotic suction for NaCl solution using Eq. (4). Arifin and Schanz (2009) calculated the osmotic suction from the measured EC of soil pore water using Eq. (5). Witteveen et al. (2013) described the relationship between the measured osmotic suction and the corresponding concentration of NaCl solution by Eq. (6), as shown in Fig. 1. The United States Salinity Laboratory Staff (1954) also gave a relationship between the osmotic suction of saturated soil water extract and its EC, represented by Eq. (7). Abedi-Koupai and Mehdizadeh (2008) indicated that the soil osmotic suction, at a particular water content, can be transformed from the osmotic suction of saturated soil water extract by assuming a linear dilution for salt concentration (Eq. (8)). Mokni et al. (2014) proposed a relationship between osmotic suction and sodium nitrate (NaNO₃) solution, expressed by Eq. (9).

To determine the soil osmotic suction by the aforementioned equations, it is essential to obtain soil pore water which can be squeezed out with the aid of pore fluid squeezer (ASTM D4542-95, 2001; Rao and Shivananda, 2005; Rao et al., 2006; Leong et al., 2007; Thyagaraj and Rao, 2010; Thyagaraj and Salini, 2015). Arifin and Schanz (2009) indicated that the osmotic suction of soil pore water decreased with increasing squeezing pressure due to the restrictive membrane effect, resulting in lower diffusion of ions at higher squeezing pressure. For unsaturated soils, even with the squeezing technique, they still do not have enough pore water to be obtained. Thus, a soil-water slurry was usually prepared to obtain soil pore water (Krahn and Fredlund, 1972; Abedi-Koupai and

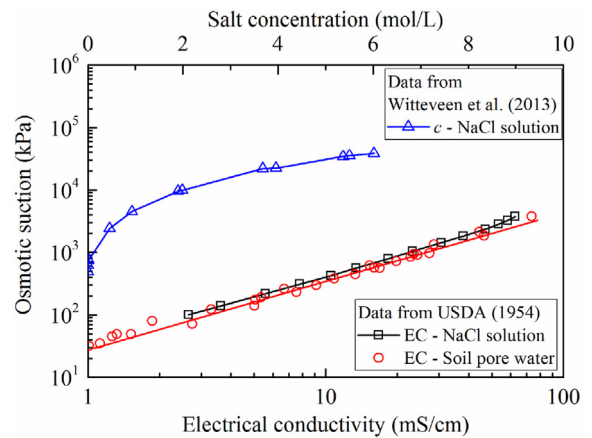


Fig. 1. Relationships between osmotic suction and EC/salt concentration.

Table 2
Geotechnical characteristics of the tested soil.

Property	Unit	Value
Specific gravity		2.71
Liquid limit	%	29
Plastic limit	%	19
Plasticity index	%	10
Specific surface area	m ² /g	24
Optimum water content	%	17.1
Maximum dry density	Mg/m ³	1.68

Mehdizadeh, 2008). In practice, the deionised water adding to soil slurry would also induce the dilution of salt concentration in soil, thus distorting the initial osmotic suction (Boso et al., 2005).

In this study, to calculate the osmotic suction of compacted specimens, EC, ion and salt concentrations of soil pore water were derived from the established relationships of mixed salt solutions (EC versus water salinity, EC versus ion and salt concentrations) instead of the direct measurement. This is of paramount importance for unsaturated soils which do not have enough soil pore water for chemical analysis. The water salinity (the mass ratio of salt to salty water) of compacted specimens was derived from the soil water content and soil salinity (the mass ratio of salt to dry soil). Then, the EC was transformed from the water salinity. Once the EC was obtained, the ion and salt concentrations were determined, allowing hence the calculation of osmotic suction by the equations in Table 1. Besides, a new equation to calculate soil osmotic suction from EC was proposed, taking into account the dissolved and the precipitated salts. In order to verify the relevance of the proposed equation, the calculated osmotic suction using the latter was compared with the value calculated from several equations in Table 1, as well as with the indirectly measured osmotic suction (the difference between the total and matric suctions). The measurement of the total suction was carried out by the chilled-mirror dew-point hygrometer (WP4C), and that of the matric suction by the contact filter paper method.

2. Material and methods

2.1. Materials

The tested material is a natural soil collected from Salin-de-Giraud, in south of France. This soil consists of 30% fine sand (0.075–2 mm), 53% silt (0.002–0.075 mm), and 17% clay fraction (<0.002 mm). Table 2 illustrates the geotechnical properties of tested soil. According to the ASTM D2487-00 (2000), this soil

Table 1
Equations for determining soil osmotic suction.

Equation No.	Equation	Source
1	$\pi = iRT$	Mitchell and Soga (2005)
2	$\pi = 0.019 \left(\frac{EC}{1 \mu S/cm} \right)^{1.074}$	Mata et al. (2002)
3	$\pi = 31.92EC^{1.08}$	Rao and Shivananda (2005)
4	$\pi = P_a(0.31EC^{1.15})$	Leong et al. (2007)
5	$\pi = 38.54EC^{1.0489}$	Arifin and Schanz (2009)
6	$\pi = 0.407c^2 + 3.88c + 0.61$	Witteveen et al. (2013)
7	$\pi_e = -360EC_e$	United States Salinity Laboratory Staff (1954)
8	$\pi = \pi_e(w_s/w)$	Abedi-Koupai and Mehdizadeh (2008)
9	$\pi = -\frac{RT\rho_1}{M_w} \ln \left[1 - \left(\frac{cM_s}{\rho_1} \right)^2 \right]$	Mokni et al. (2014)

Note: c: salt concentration; i: ion concentration; EC_e: electrical conductivity of saturated soil water extract; M_w: molar mass of water; M_s: molar mass of salt; P_a: atmospheric pressure; R: universal gas constant (8.31 J/(mol K)); T: absolute temperature; w: actual water content of soil; w_s: water content of soil at saturated state; ρ₁: liquid density; π: osmotic suction; π_e: osmotic suction of saturated soil water extract.

belongs to low-plasticity sandy lean clay (CL). Thus, its osmotic suction can be considered as the difference between total and osmotic suctions, as indicated previously. This soil is saline, with a soil salinity of 2.1‰ (g of salt/kg of dry soil). The salt composition and concentration of soil pore water are listed in Table 3.

The mineral composition of tested soil was detected by X-ray diffraction (XRD) analysis. The D8 Advance diffractometer was used to collect the XRD pattern. Minerals were quantified with EVA and TOPAS software coupled with ICDDPd2 database. The XRD pattern of the tested soil is presented in Fig. 2. It indicates that this soil is composed of 15.7% clay minerals and 84.3% non-clay minerals. The clay minerals are identified as illite, chlorite and kaolinite. The non-clay minerals are quartz, calcite, feldspars and halite NaCl. This soil is highly crystallized without organic minerals (De Baecque, 2019).

2.2. Soil salinity adjustment

Five different salts of synthetic seawater (Table 4, French standard AFNOR NF P 18-837, 1993) were used to reconstitute mixed salt solutions needed for preparing the salted soils. The target soil salinity was fixed at $r' = 6.76‰$ (g of salt/kg of dry soil), corresponding to the water salinity of soil pore water of $r = 35‰$ (g of salt/kg of salty water) for salted soils at water content of 20%. This water salinity was exactly the salinity of synthetic seawater. To avoid destroying soil aggregates, the mixed salt solution was gently sprayed over natural soils layer by layer to reach the required salinity level. The salinity precision of prepared salted soils was verified and the relative error between the target salinity and measured salinity was found less than 4.75%. More details about the calculation of additive salts and preparation for salted soils can be found in Ying et al. (2021a).

To prepare the salted soils with a salinity lower than the initial one, leaching equipment was used and deionised water was flowed through natural soil from bottom to top (Ying et al., 2021b), as shown in Fig. 3. The water head and water flow rate were controlled to be lower than 1 m and 0.3 mL/s, respectively, to avoid destroying soil aggregates and migration of fine particles. Leached water (or effluent) at the top of the specimen was collected for the EC control. Once the EC was close to that of deionised water, the leaching process was stopped. The final measured soil salinity of leached soil was down to 0.05‰ (g of salt/kg of dry soil), which was sufficiently low and could be ignored in further analysis.

2.3. Specimen preparation

The natural saline soil, salted soil, and leached soil were air-dried, ground and passed through 0.4 mm sieve. The dry soil powders with different soil salinities of 0.05‰, 2.1‰ and 6.76‰ were then humidified by spraying a certain quantity of deionised water to reach the target water content (17%). Then, they were thoroughly mixed and statically compacted to the target dry density (1.63 Mg/m³). The compacted specimens had the same respective soil salinities as dry soil powders.

2.4. Matric suction measurement

The matric suction was measured by the contact filter paper method (Sun et al., 2010; ASTM D5298-16, 2016) which has high

Table 3
Salt composition and concentration of natural soil pore water.

Chemical composition (mg/L)					Salt concentration, c (g/L)
Cl	Na	Ca	K	Mg	
7521	5096	215	225	176	13

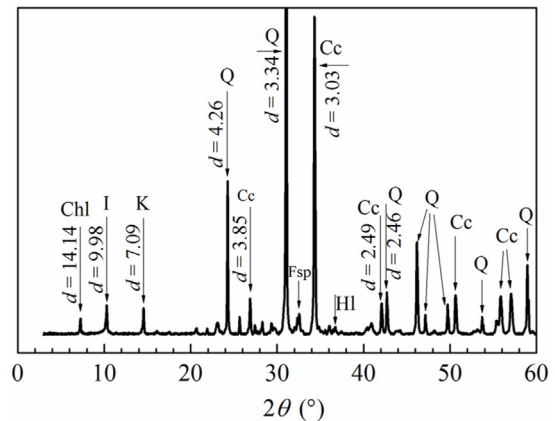


Fig. 2. X-ray diffraction (XRD) pattern of tested soil (Chl: chlorite; I: illite; K: kaolinite; Q: quartz; Cc: calcite; Fsp: feldspar; HI: halite).

Table 4
Salt composition of synthetic seawater.

Composition	Salt mass (g) in 1000 g deionised water	Percentage (%)
NaCl	30	70.26
MgCl ₂ ·6H ₂ O	6	14.05
MgSO ₄ ·7H ₂ O	5	11.71
CaSO ₄ ·2H ₂ O	1.5	3.51
KHCO ₃	0.2	0.47

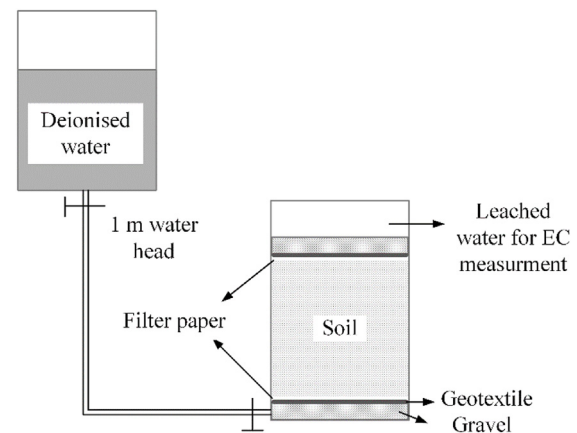


Fig. 3. Equipment for salt leaching test (after Ying et al., 2021b).

accuracy for matric suction measurement in the range of 10 kPa to 100,000 kPa. The used filter paper was Whatman No. 42, which was oven-dried before usage. The compacted specimens with 20 mm in height (h) and 50 mm in diameter (d) were air-dried to reach different target water contents that were 14%, 11%, 8.5%, 6%, 4%, 3%, and 1.5%. The water content of air-dried specimens (w) was preliminarily controlled by monitoring the mass of soil specimen during drying (Tang et al., 2011):

$$w = \frac{(1 + w'_0)m_a}{m_0} - 1 \quad (10)$$

where w'_0 is the compacted water content of specimen (17%); m_0 is the mass of as-compacted specimen; and m_a is the mass of air-dried specimen.

After air-drying, two replicated specimens with the same water content were used for one matric suction measurement. A filter paper used for matric suction analysis was sandwiched between two other filter papers whose diameter was slightly larger to prevent the central one from the direct contact with soil. To measure the matric suction, the stacked filter papers were put in the middle of two specimens (Fig. 4). The specimens with filter papers were carefully wrapped and covered to avoid water evaporation. Then, they were stored for two weeks to allow the fluid transfer between specimens and filter papers. Afterwards, the water contents of specimen and filter paper were measured by oven-drying at 105 °C. Then, the water content of salted specimen (w') was calculated by (Ying et al., 2021a):

$$w' = \frac{m_{sw}}{m_s} = \frac{m - m_d}{m_d - rm} \quad (11)$$

where r is the water salinity, m_d is the oven-dried mass (dry soil and salt), m is the mass of wet soil, m_{sw} is the salty water mass, and m_s is the dry soil mass.

To convert the soil salinity ($r' = m_{sa}/m_s$, where m_{sa} is the dissolved salt mass) to water salinity ($r = m_{sa}/m_{sw}$), the following equation was used (Ying et al., 2021a):

$$r = \frac{r'}{w'} \quad (12)$$

The soil matric suction (ψ_m) was determined from the water content of filter paper (w_f) using Eq. (13) (calibration equation for Whatman No. 42, ASTM D5298-16, 2016):

$$\log_{10}\psi_m = \begin{cases} 5.327 - 0.0779w_f & (w_f \leq 45.3\%) \\ 2.412 - 0.0135w_f & (w_f > 45.3\%) \end{cases} \quad (13)$$

The accuracy and reliability of Eq. (13) were also confirmed by Leong et al. (2002).

2.5. Total suction measurement

Chilled-mirror dew-point hygrometer (WP4C) was used to determine the total suction of soil specimens (Fig. 5a). It has higher precision for total suction measurement in comparison to that of non-contact filter paper method (Bulut et al., 2002; Leong et al., 2003, 2007). This technique is based on the relative humidity measurement (Leong et al., 2003, 2007; Sun et al., 2014; Sun and Cui, 2020). The total suction was determined through Kelvin's equation:

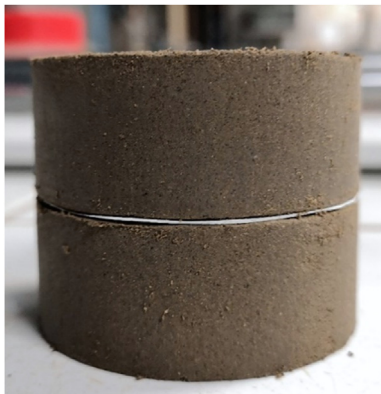


Fig. 4. Matric suction measurement by contact filter paper method.



(a)



(b)

Fig. 5. Setup of total suction measurement: (a) Chilled-mirror dew-point hygrometer device, and (b) Specimens.

$$\psi = \frac{RT}{M_w} \ln RH \quad (14)$$

where ψ is the total suction.

After compaction, each specimen ($d = 38$ mm, $h = 100$ mm) was cut into small slices (Fig. 5b). Then, they were air-dried to different water contents. It appears from Fig. 5b that the drying process did not induce macro-cracks on the surface of specimens. After air-drying, they were sealed for 24 h for water equilibrium. Then, the total suction of these soil slices were measured by WP4C.

2.6. Osmotic suction measurement

Soil osmotic suction can be measured by several techniques, or computed from the EC of soil pore water extract. In this study, first, the osmotic suction of mixed salt solutions prepared by five different salts (Table 4) was measured by WP4C. Afterwards, the ECs of these mixed salt solutions were systematically measured by a conductivity meter. The conductivity meter was calibrated by the standard solution prior to the measurement. The measured EC is the value at 25 °C. Then, the relationship between the measured osmotic suction and EC is plotted in Fig. 6 and the following equation is established:

$$\pi = \begin{cases} 23.15EC^{1.17} & (EC \leq 100 \text{ mS/cm}) \\ 0.28EC^{2.12} & (EC > 100 \text{ mS/cm}) \end{cases} \quad (15)$$

where π is the osmotic suction (kPa) and EC is the electrical conductivity of mixed salt solutions (mS/cm). This equation is a piecewise function, with a piecewise point at EC of 100 mS/cm. Ying et al. (2021a) prepared the same mixed salt solutions and filtered them by 0.45- μ m filter paper. They found that some salts started to precipitate at EC of 100 mS/cm. It indicates that the piecewise point of the proposed equation (Eq. (15)) is the critical point where the precipitated salts occurred. The relationship between the total

water salinity and EC is also shown in Fig. 6. Note that the total water salinity consisted of dissolved and precipitated salts when the EC was higher than 100 mS/cm.

Since the mixed salt solutions (Table 4) had the same chemical composition of the soil pore water (Table 3), the osmotic suction of soil specimens could be estimated by Eq. (15) once the EC was determined. To this end, the relationship between the EC and dissolved/total water salinities of mixed salt solutions established by Ying et al. (2021a) was used, as shown in Fig. 7. The relationship between the EC and the total water salinity (r) is expressed as

$$EC = -0.0027r^2 + 1.5228r + 0.4093 \quad (16)$$

The total water salinity was the mass ratio of total salt to additive deionised water. The dissolved water salinity was the mass ratio of dissolved salt to additive deionised water, with dissolved salt mass obtained by oven-drying the filtered clear salt solution (without precipitated salt) at 180 °C. None-, partial-, and full-precipitation zones of the mixed salt solutions were identified according to the critical point ($r_d = 76\%$ or g dissolved salt/kg of salty water, $EC = 100$ mS/cm) and the maximum value of EC (219 mS/cm). When adding salts in water, some salts having high solubility were dissolved, while some with low solubility started to precipitate when the water salinity was higher than the value at the critical point. When the salts quantity reached a certain level, the water could not dissolve salts anymore leading to the maximum values of dissolved water salinity and EC. In the none-precipitation zone, the total and dissolved water salinities were the same, whereas in the partial- and full-precipitation zones, the total water salinity consisted of dissolved and precipitated salts. It is worth pointing out that the total and dissolved water salinities are related to the same EC value, because there is no contribution of precipitated salts to the value of EC.

As mentioned previously, unsaturated soils usually do not have enough soil pore water for the EC measurement. Thus, the following calculation was used to obtain the EC of soil pore water as an alternative to direct measurement. Firstly, the total water salinity of soil specimen after total suction measurement was obtained by combining Eqs. (11) and (12). Secondly, the corresponding EC of soil pore water was calculated using Eq. (16). Substituting the EC into Eq. (15), the osmotic suction of the soil specimen at given water content was obtained. It should be pointed out that if the calculated total water salinity was higher than the maximum dissolved water salinity, the corresponding EC was regarded as the maximum value.

In this study, Eqs. (1)–(6) were also used to calculate the osmotic suction for a comparison with the newly proposed equation

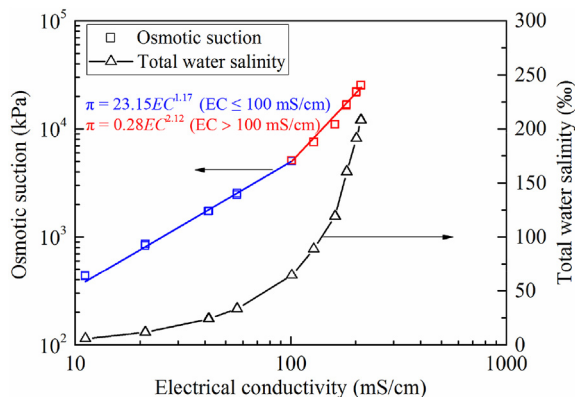


Fig. 6. Relationships between osmotic suction/total water salinity and EC for mixed salt solutions.

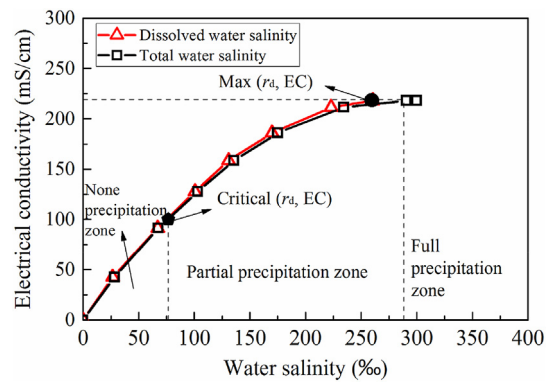


Fig. 7. EC variations with water salinity for mixed salt solutions (after Ying et al., 2021a).

(Eq. (15)). To this end, the ion concentration (i , mol/L) and salt concentration (c , mol/L) of soil pore water needed to be determined. Concerning the mixed salt solutions, the relationship between the EC and the dissolved water salinity in Fig. 7 can be transformed to the relationships between the EC and the dissolved ion concentration (i) as well as dissolved salt concentration (c). Firstly, each salt quantity (mol) was obtained by the salt mass divided by molar mass. Ion quantity (mol) was determined according to the molecular formula of salt (Table 4). Afterwards, the total ion and salt concentrations (mol/L) were determined as the ratio of the quantity of total ion (mol) or salt (mol) to the volume of additive deionised water (L). The dissolved ion and salt concentrations were determined by the total concentration multiplying the percentage of dissolved salt which was the mass ratio of dissolved salt to total salt. The EC variations with dissolved ion concentration (i) and dissolved salt concentration (c) of mixed salt solutions are presented in Fig. 8. The corresponding relationships were expressed in Eqs. (17) and (18), respectively:

$$EC = -2.0426i^2 + 42.241i \quad (17)$$

$$EC = -8.5963c^2 + 86.655c \quad (18)$$

With the EC obtained from Eq. (16), the dissolved ion and salt concentrations can be obtained from Eqs. (17) and (18), respectively. Then, substituting the EC, the dissolved ion and salt concentrations into Eqs. (1)–(6), the osmotic suction was obtained from different equations. Note that the determining ion and salt concentrations as well as EC at different water contents did not take into account the cation exchange and adsorption, because of the low-quantity and low-activity clay minerals (illite, chlorite, and kaolinite) in the tested soil, as well as its small specific surface area ($24 \text{ m}^2/\text{g}$) leading to low cation exchange and adsorption.

3. Results and discussion

3.1. Total and matric suctions

The water retention curves with the matric suction obtained from contact filter paper method and the total suction determined by WP4C are presented and discussed in this section. Fig. 9a represents the global void ratio of air-dried specimens versus water content. It appears clearly that the void ratio was almost constant during the drying process. This was confirmed by mercury intrusion porosimetry tests conducted by Ying et al. (2021c) on the same soil that the total mercury intruded void ratio was close to the global one without volume shrinkage during drying. They also pointed out that for the tested soil with a clay-size particle fraction

as low as 17%, upon drying, the clay shrinkage led to the change of pore size distribution without the development of shrinkage cracks (see Fig. 9b, i.e. specimens with 2.1‰ soil salinity). Therefore, the effect of shrinkage cracks on the suction variation was not considered in this study.

The suction measurements of soil specimen with soil salinity of 2.1‰ were duplicated to check the test reproducibility. As shown in Figs. 10 and 11, the two water retention curves of soil specimens with 2.1‰ soil salinity were fairly similar, implying a good repeatability of the matric and total suction measurements. The average values of the duplicated measurements of specimens with 2.1‰ were used in this study.

It can be seen from Fig. 10 that there was no significant distinction between water retention curves of matric suction for specimens with different soil salinities: at the same water content, the values of matric suction for specimens with negligible soil salinity (0.05‰) and with soil salinities of 2.1‰ and 6.76‰ were close to each other. This result suggested that the matric suction was not significantly affected by soil salinity.

From Fig. 11, it appears that the total suction were different when varying the salinity, indicating clearly that the total suction was significantly affected by soil salinity. Besides, the curves of specimens at higher salinity lied above those of specimens at lower soil salinity. It appears also that the curves converged gradually with decreasing water content.

The variations of the total and matric suctions with water content are depicted in Fig. 12a and b for specimens with soil salinities of 2.1‰ and 6.76‰, respectively. It is observed that the total suction was quite high compared to matric suction. The difference between the total and matric suctions can be attributed to the contribution of the osmotic suction, which is generated from the dissolved salt in soil pore water. As shown in Fig. 12a, for specimens with 2.1‰ soil salinity, the matric suction curve converged towards the total suction curve with decreasing water content. When the water content was lower than 4.3%, the two curves are similar within the accuracy of the measurement leading to an osmotic suction close to zero. This overlapping phenomenon of total and matric suctions at lower water content was in agreement with the results obtained by Arifin and Schanz (2009) and Sreedeeep and Singh (2006). It might be attributed to the dominant vapour transfer among specimens and contact filter papers at low water content (Arifin and Schanz, 2009). Thus, the suction measured by contact filter paper method consisting of capillary and osmotic components was close to the total suction. In the case of specimens with 6.76‰ soil salinity, at low water content, the matric suction curve also converged towards the total suction curve but remained relatively lower than the latter

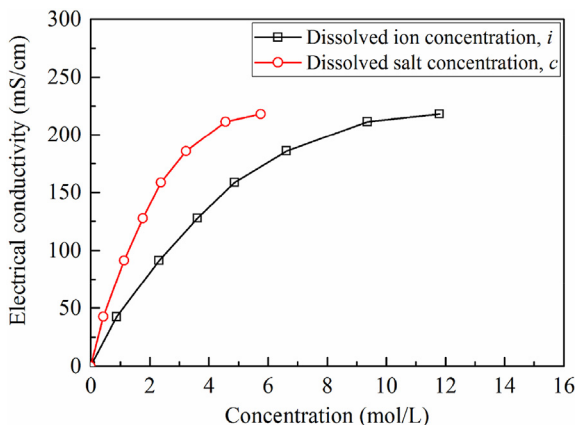


Fig. 8. EC variations with dissolved ion and salt concentrations.

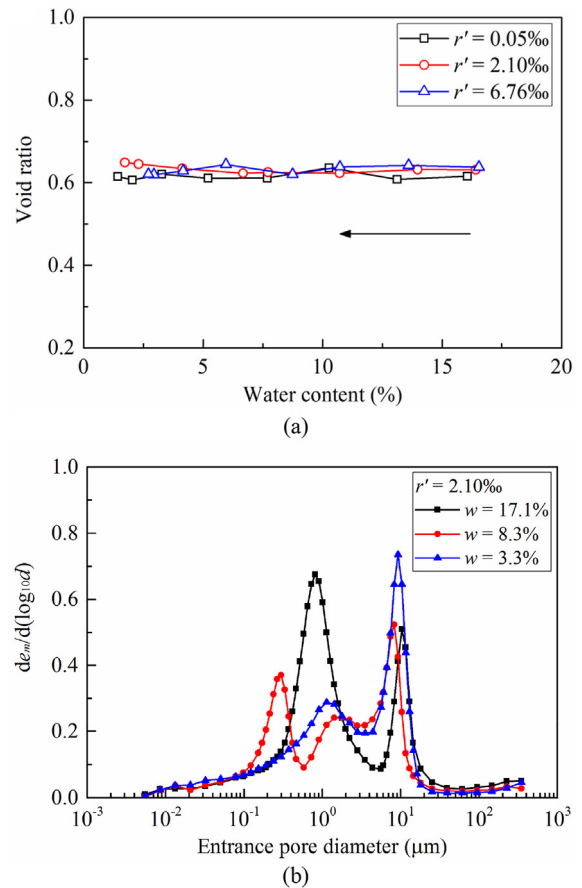


Fig. 9. The variations of (a) void ratio and (b) pore size distribution during drying (after Ying et al., 2021c).

(Fig. 12b). It can be inferred that the fluid transfer was still predominant at low water content due to the expanded channels for fluid transfer resulting from the shrinkage of diffuse double layer, giving rise to a more precise measurement of matric suction.

The water retention curves in terms of osmotic suction defined by the difference between the total suction (ψ) and the matric suction (ψ_m) are shown in Fig. 13. It is worth noting that the osmotic suction of soil specimen with soil salinity below 0.05‰, which is a negligible level, was not considered here due to (i) the low accuracy of total suction measurement below 1000 kPa and (ii) the non-reliable osmotic suction determination at such low salinity. For specimens with 2.1‰ soil salinity, the osmotic suction increased slightly as the water content decreased to 10%, then stayed in the range between 1200 kPa and 1450 kPa when the water content was in the range of 5%–10%. Below the water content of 5%, the osmotic suction tended towards zero which corresponded to the section of the curves where the matric and total suctions overlapped as shown in Fig. 12a. In the case of the specimens with soil salinity of 6.76‰, the osmotic suction increased as the water content decreased, and the rate of increase was higher when the water content was lower than 8%. The osmotic suction was highly correlated to the dissolved water salinity in soil pore water. Ying et al. (2021a) stated that, for this salted soils (the same soil as in this study) with salinity of 6.32‰ close to the one used in this study (6.76‰), the dissolved water salinity increased slightly from 35‰ to 70‰ when the water content decreased from 17% to 8.5%, then it increased drastically to 260‰ as the water content decreased to 2.5%, and stayed constant at the maximum value with further

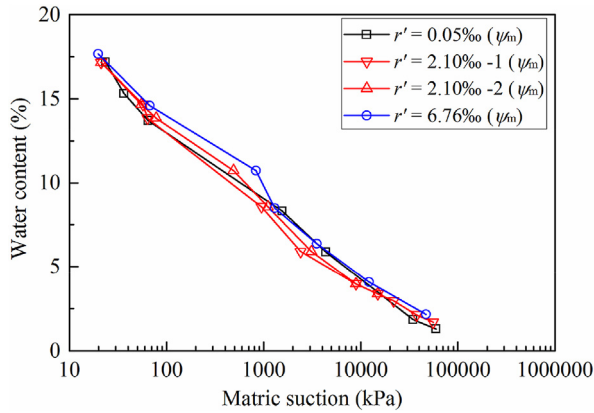


Fig. 10. Water retention curves in terms of matric suction.

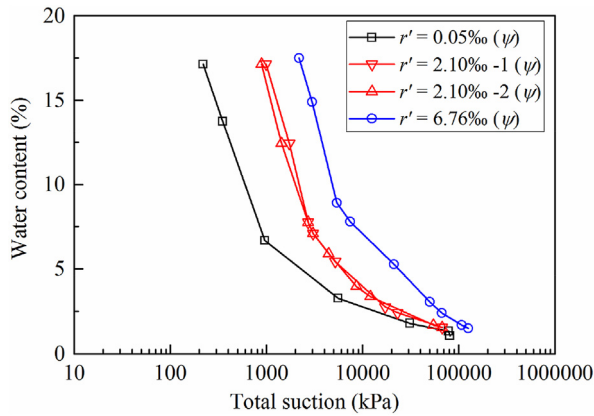


Fig. 11. Water retention curves in terms of total suction.

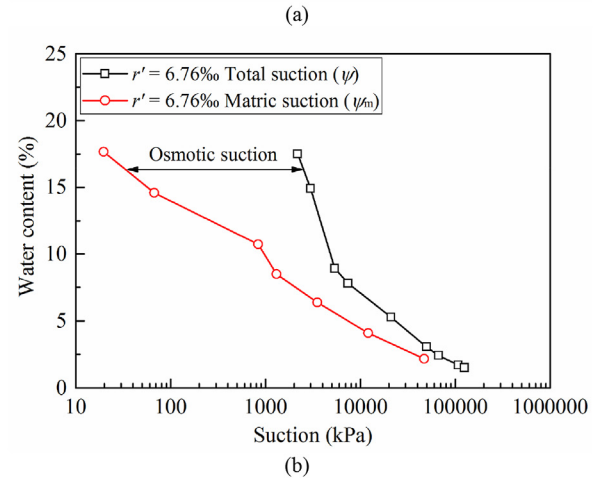
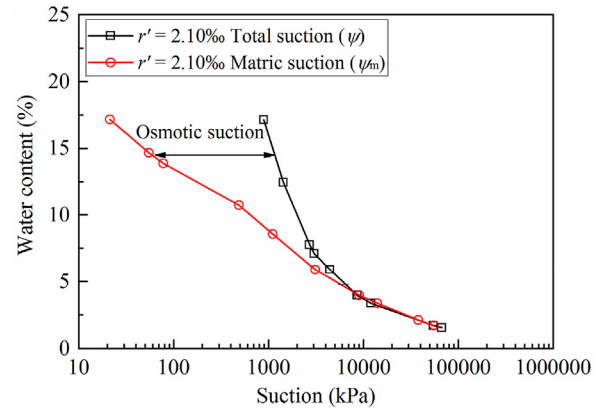


Fig. 12. Water content versus total and matric suctions at (a) $r' = 2.1‰$ and (b) $r' = 6.76‰$.

drying. Consequently, for specimens with 6.76‰ soil salinity, the dissolved water salinity increased slightly when the water content decreased down to 8%, and then increased significantly with further decrease of the water content. Therefore, the osmotic suction has a generic trend with two slopes increase with the water content: a low increase followed by a higher one as highlighted in Fig. 13. Concerning the specimens with soil salinity of 2.1‰, the dissolved water salinity increased slightly as the water content decreased to 5%. As a result, the osmotic suction varied slightly during drying.

3.2. Osmotic suction evaluation

The values of osmotic suction determined from indirect measurement ($\psi - \psi_m$) and calculated from the piecewise function (Eq. (15)) proposed in this study for specimens with soil salinities of 2.1‰ and 6.76‰ are shown in Figs. 14 and 15, respectively. For comparison, the values of osmotic suction calculated by Eqs. (1)–(6) from the literature are also presented. It appears that the osmotic suctions calculated from the relationships for single salt solution, such as those of Eqs. (1), (4) and (6), exhibited higher values, whereas the calculated osmotic suction obtained from the relationships of soil pore water was lower (Eqs. (2), (3) and (5)). This can be attributed to the different bases of these equations. Indeed, as shown in Fig. 1, at the same EC, the NaCl solution gave higher

osmotic suction in comparison to the soil pore water (United States Salinity Laboratory Staff, 1954).

Fig. 14 shows that for specimens with 2.1‰ soil salinity, the osmotic suction calculated using Eq. (15) proposed in this study on the basis of mixed salt solutions matched quite well with the ones calculated using Eqs. (2), (3) and (5) when the water content was higher than 2.5%, while they were consistent with those calculated using Eqs. (1), (4) and (6) as the water content was lower than 2.5%. The same observation was made on soil specimens with 6.76‰ soil

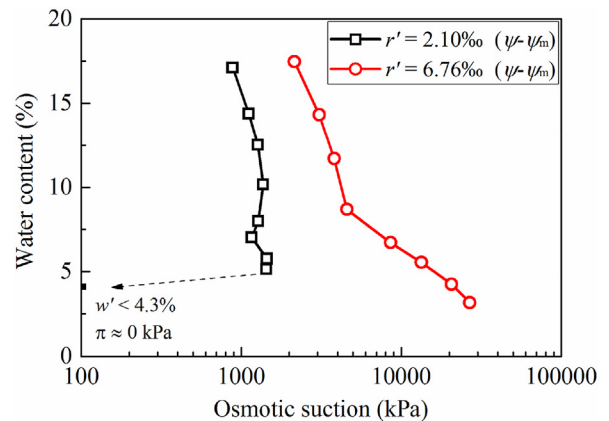


Fig. 13. Water retention curves in terms of osmotic suction.

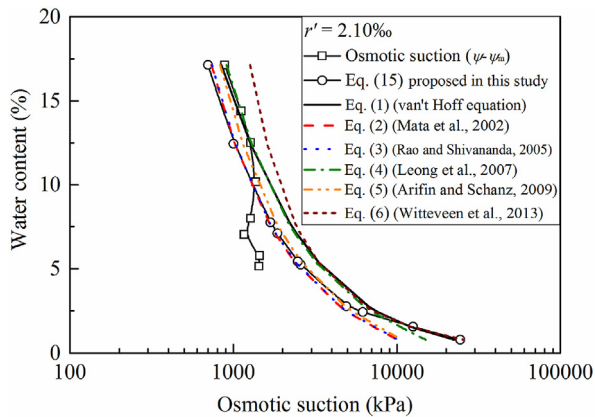


Fig. 14. Comparison of osmotic suctions for specimens at 2.1‰ soil salinity.

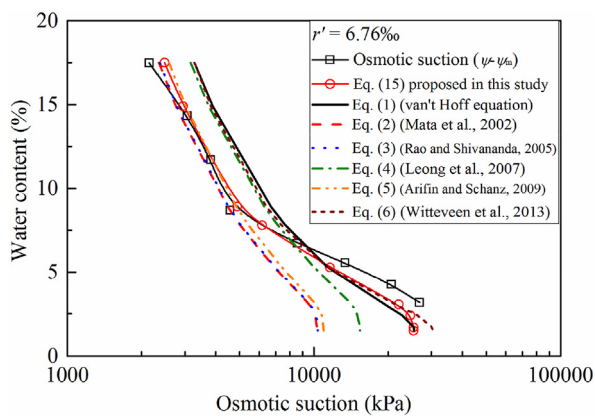


Fig. 15. Comparison of osmotic suctions for specimens at 6.76‰ soil salinity.

salinity, as shown in Fig. 15. The osmotic suction calculated from Eq. (15) proposed in this study coincided with the values calculated from Eqs. (2), (3) and (5) when the water content was higher than 8%, whereas they became gradually consistent with the values calculated from Eqs. (1), (4) and (6). Interestingly, the osmotic suction for specimens with 2.1‰ soil salinity at water content of 2.5% and for the specimens with 6.76‰ soil salinity at 8% water content was around 5000 kPa. This value corresponded to the piecewise point ($EC = 100$ mS/cm, $\pi = 5110$ kPa) of Eq. (15). In the first section ($EC < 100$ mS/cm, $\pi < 5110$ kPa), the calculated osmotic suction coincided with the value calculated from the equations based on soil pore water, due to the similar bases used to derive Eq. (15) and these equations with respect to soil pore water. With an increase of water salinity or subsequent EC, some mixed salts with low solubility started to precipitate as indicated in Fig. 7 (partial-precipitation zone). In this range, the value calculated from Eq. (15) was consistent with that obtained by the equations on the basis of single salt solution. It was also observed that, for specimens with 6.76‰ soil salinity, the calculated osmotic suction varied slightly when the water content was lower than 2.5%, which might be attributed to the constant values of maximum EC or dissolved ion and salt concentrations in soil pore water at such low water content. This was consistent with the observation made by Mata et al. (2002), stating that the osmotic suction was constant at water content lower than the micro-structural water content.

The calculated osmotic suction was also compared with the indirectly determined osmotic suction from the difference between the measured total and matric suctions ($\psi - \psi_m$). In the case of the specimens with 2.1‰ soil salinity, the indirectly measured osmotic suction ($\psi - \psi_m$) was in the range of the calculated osmotic suction when the water content was higher than 10%, whereas the indirectly measured value was lower than the calculated one when the water content was in the range of 5%–10%. This is because the measured matric suction by the contact filter paper method at low water content gave a higher value which partially included osmotic component (Arifin and Schanz, 2009), thus leading to a lower osmotic suction which was taken as the difference between measured total and matric suctions. The indirectly measured osmotic suction ($\psi - \psi_m$) for the soil specimens with soil salinity of 6.76‰ was in good agreement with the calculated one, especially for the value calculated by Eq. (15) proposed in this study. It indicated that Eq. (15), a piecewise function for osmotic suction calculation, described both dissolved and precipitated salts, providing thereby precise determination of the osmotic suction for highly salted soils. The coincidence of experimental osmotic suction ($\psi - \psi_m$) and calculated one also suggested that determining EC, ion and salt concentrations of soil pore water from the relationships shown in Figs. 7 and 8 and expressed by Eqs. (16)–(18), was an appropriate approach. Using this determination method, the osmotic suction of soil specimens (especially at higher salinity of 6.76‰) at any considered water contents can be determined satisfactorily instead of using an elaborate experimental measurement, avoiding the difficulties of extracting soil pore water for unsaturated soils.

However, it should be mentioned that the proposed piecewise function for osmotic suction determination is only appropriate for the low-plasticity soils with limited cation exchange capacity and its soil pore water has similar salt composition to that of synthetic seawater. Further exploration on the extension of the proposed method to high-plasticity soils will be conducted, with considering the cation exchange and adsorption between soil particles and soil pore water.

4. Conclusions

The matric and total suctions of compacted specimens were determined by the contact filter paper method and chilled-mirror dew-point hygrometer (WP4C), respectively. Then, the osmotic suction was determined as the difference between the total and matric suctions. Furthermore, a relationship between EC and osmotic suction was established for the mixed salt solution, and a new piecewise function was proposed. This mixed salt solution had the same salt composition as that of soil pore water. Similarly, a series of equations in the literature was used to calculate the osmotic suction for comparison. Based on the obtained results, the following conclusions can be drawn:

- (1) The osmotic suction calculated by different equations in the literature presented different values: the osmotic suction calculated by the equations considering the main salt (NaCl) was higher than that derived from the relationship based on the soil pore water.
- (2) The proposed equation taking dissolved and precipitated salts into account was a piecewise function whose piecewise point ($EC = 100$ mS/cm, $\pi = 5110$ kPa) was related to the first appearance of precipitated salt in the mixed salt solution. When the osmotic suction was lower than 5000 kPa (close to piecewise point), the osmotic suction calculated by the

piecewise function coincided with that calculated from the equations on the basis of soil pore water. When the osmotic suction was beyond 5000 kPa, the osmotic suction obtained by the piecewise function converged with the higher value obtained from the equations for single salt solution.

- (3) The indirectly determined osmotic suction (ψ - ψ_m) and calculated osmotic suction were in good agreement for soil specimens with 2.1‰ soil salinity when water content was higher than 10%, and for soil specimens with 6.76‰ soil salinity in the whole considered range of water contents. This highlighted that the osmotic suction can be accurately determined from EC, ion and salt concentrations for low-plasticity soils. It is worth noting that this method is more precise for highly salted soils. By this method, the osmotic suction can be determined more easily for saturated low-plasticity soils. Most importantly, this method can be applied to unsaturated low-plasticity soils, which do not have enough pore water for EC measurement.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank the China Scholarship Council (CSC). The support provided by Ecole des Ponts ParisTech and INRAE is also greatly acknowledged.

List of symbols

c	Salt concentration
EC_e	Electrical conductivity of saturated soil water extract
i	Ion concentration
m	Wet soil mass
m_d	Oven-dried mass including dry soil and salt
m_{sw}	Salty water mass (water and salt)
m_s	Dry soil mass
M_w	Molar mass of water
M_s	Molar mass of salt
P_a	Atmospheric pressure
r	Water salinity (the mass ratio of salt to salty water)
r'	Soil salinity (the mass ratio of salt to dry soil)
R	Universal gas constant
T	Absolute temperature
w	Water content of soil
w'	Water content of salted soil (the mass ratio of salty water to dry soil)
w_s	Water content of soil at saturated state
w_f	Water content of filter paper
ρ_1	Liquid density
π	Osmotic suction
π_e	Osmotic suction of saturated soil water extract
ψ	Total suction
ψ_m	Matric suction

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