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Full-range water retention properties of a collapsible soil with focus on osmotic potential

Propriétés de rétention d'eau sur toute la gamme d'un sol pliable en mettant l'accent sur le potentiel osmotique

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ABSTRACT: Water retention curve of fine-grained soils is a consequence of interaction between immiscible pore fluids and soil constituents under different water potential. The presence of clay minerals highlights the role of adsorption mechanism in high suction range where the practical controlling range of the Axis-Translation technique is a serious barrier. In order to cope with this limitation, a combination of the Axis-Translation and filter paper methods is adopted in this study to provide insight into water retention behavior of a collapsible soil for the full suction range. Importantly, the influence of osmotic potential and its possible interaction with matric potential through modification of soil microstructure is explored by considering two extreme levels of osmotic suction. Distilled water and saturated sodium chloride are used as the wetting pore fluid to produce the two distinct osmotic suctions. Measurements are conducted in terms of both total and matric suction with known and measured electrical conductivity of pore fluid to re-evaluate the osmotic suction as the third component. According to the experimental results, new insight is provided into the water retention behavior of collapsible soils with and without osmotic potential.

RÉSUMÉ : La courbe de rétention d'eau des sols à grains fins est une conséquence de l'interaction entre les fluides interstitiels non miscibles et les constituants du sol sous un potentiel hydrique différent. La présence de minéraux argileux met en évidence le rôle du mécanisme d'adsorption dans une plage d'aspiration élevée où la plage de contrôle pratique de la technique Axis-Translation est un obstacle sérieux. Afin de faire face à cette limitation, une combinaison des méthodes Axis-Translation et papier filtre est adoptée dans cette étude pour fournir un aperçu du comportement de rétention d'eau d'un sol pliable pour la plage d'aspiration complète. Important encore, l'influence du potentiel osmotique et son interaction possible avec le potentiel matriciel par la modification de la microstructure du sol est explorée en considérant deux niveaux extrêmes d'aspiration osmotique. De l'eau distillée et du chlorure de sodium saturé sont utilisés comme fluide poreux mouillant pour produire les deux aspirations osmotiques distinctes. Les mesures sont effectuées en termes d'aspiration à la fois totale et matricielle avec une conductivité électrique connue et mesurée du fluide interstitiel pour réévaluer l'aspiration osmotique en tant que troisième composant. Selon les résultats expérimentaux, de nouvelles informations sont fournies sur le comportement de rétention d'eau des sols affaissés avec et sans potentiel osmotique.

KEYWORDS: Unsaturated soils; water retention curve; osmotic potential; filter paper method; sodium chloride

1 INTRODUCTION

Soil water retention curve (SWRC) is known as a basic unsaturated soil property mainly employed for solving two-phase flow problems under transient state (Kolahdooz et al. 2020). In addition, it has been widely used to infer and interpret more complex aspects of unsaturated soil mechanics such as the shear strength, bearing capacity and soil dynamic properties (Ng et al. 2020; Garakani et al. 2020; Jafarzadeh et al. 2021). Although the influence of many parameters such as void ratio (Gao & Sun 2017; Zhang et al. 2020), stress state (Sadeghi et al. 2016), basic soil properties (Zhou & Lu 2021), and microstructure (Sun et al. 2016; Ng et al. 2016) on water retention properties of soils were explored, the effects of some other parameters such as the pore fluid chemistry has not been fully discovered yet (Thyagaraj & Rao 2010; Sarkar & Siddiqua 2016; Estabragh et al. 2020). In other words, a significant portion of literature on this topic only considered distilled or tap water as permeating fluid (Zhang et al. 2021; Sadeghi 2016). It is to be mentioned, however, that some effort has been made to explore retention characteristics of porous media exposed to other fluids such as oil (Bazargan et al. 2015) as there has been increasing evidence that industrialization is making the fresh water polluted or impure (Taghipour & Ayati 2015, 2017; Khadir et al. 2021).

One of the key factors contributes to the impurity of permeating water is the salinity of soil water also referred to as the osmotic suction. The osmotic suction is one of the three suction components within the framework of unsaturated soil mechanics. However, the role of this component of suction has been mainly ignored in the literature purely due to the fact that the matric component of suction contributes to the strength and deformation of unsaturated soils. This assumption could be misleading as the appearance of osmotic suction can evolve soil matrix as well. The influence of osmotic suction has been the subject of some research on water retention properties. For example, the study of Thyagaraj & Rao (2010) on wetting matric-SWRC of saline and non-saline samples of compacted clay revealed a lower retention ability of the saline soil for the range of matric suction less than 2000 kPa. On the other hand, it was observed by He et al. (2016) that total-SWRC of GMZ bentonite exposed to saline water is higher than the corresponding non-saline sample for a suction range limited to 300 kPa. Recently, the experimental results of Sadeghi & Nasiri (2021) revealed that NaCl concentration suppresses the matric-SWRC and gives rise to the hydraulic hysteresis for the limited suction range of zero to 300 kPa. The observed trends were interpreted based on complementary microstructural characterization (Romero & Simms 2008) in the light of the diffuse double layer theory.

According to the brief literature reviewed, research on the SWRC of soils exposed to saline environment is rather limited. Moreover, only one component of the SWRC, i.e., matric or total suction, was considered in each study and the range of suction was too limited to be the representative of the whole practical range. Therefore, the main objective of this research is to explore the role of NaCl molar concentration on both the matric- and total-SWRC by using a combined methodology of the axis translation and filter paper techniques. In addition, the scanning electron microscopy is used to better understand the microstructure evolution due to a rise in salinity of pore fluid.

2 MATERIALS AND METHODS

2.1 *Tested soil*

The natural occurrence and geotechnical characterization of a dispersive loess stratum in southeast of Iran formed the motivation as to the reason for choosing the test material in this study (Sadeghi et al. 2019a and b). However, as the natural soil deposit contains significant amount of potassium ions and a high total dissolved salt (TDS), it is not possible to study the influence of salt concentration as an independent variable. Therefore, an artificial soil was synthesized to best mimic basic soil properties but salt concentration. The test material was hence obtained following a trial and error procedure as a combination of Firuzkuh Sand No. 181, Firuzkuh Micronized powder, and bentonite with a weight ratio of 15%, 65%, and 20%, respectively. Figure 1 shows the soil gran size distribution. The soil has a liquid limit of 44, a plastic limit of 22 and hence a plasticity index of 22 according to the ASTM D1318. The maximum dry density and the optimum water content were determined as 1.8 Mg/m^3 and 16%, respectively (ASTM D698). Further details of the collapsible test material can be found in Sadeghi & AliPanahi (2020).

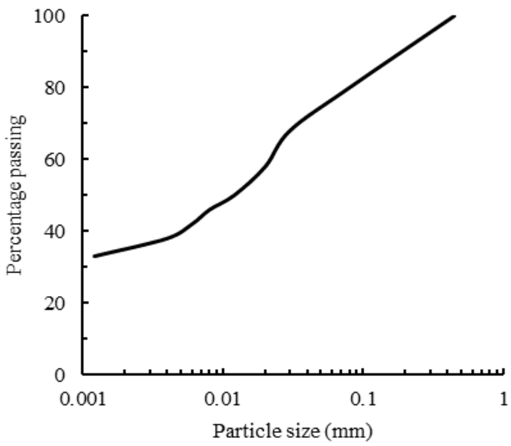


Figure 1. Grain size distribution of the soil

To make a sample, the selected soils were first placed in the oven to remove their initial moisture. Afterwards, 10% of gravimetric moisture content was added to the dry soil and the mixture was left for moisture equilibrium in plastic bag for 24 h. It is noted that distilled water or 4 mol/L sodium chloride solution were used as moistening fluid during sample preparation to remove the influence of osmotic gradient in water retention tests (Sadeghi & Nasiri 2021).

To make a sample to be used in the axis translation setup, the moist soil was placed in an oedometer ring of 50 mm in diameter, and 20 mm in height and was statically compacted to achieve the target dry unit weight of 13.5 Mg/m^3. As the drying branch of water retention curve is the focus of this study, all samples were initially submerged in de-aerated distilled water/ 4 mol/l sodium chloride solution and saturated in a vacuum aided cylindrical chamber. On the other hand, another oedometer ring of 70 mm in diameter was used to compact soil samples for filter paper tests following the same methodology.

As previously mentioned, in this study, SEM tests were performed to identify the microstructure of the samples. To make the specimens for the SEM test, the specimens were first frozen using liquid nitrogen to preserve their structure. Frozen samples were then placed in a freeze dryer chamber to completely lose its moisture content without experiencing a liquid phase transfer. Finally, the samples were cut to roughly 5 mm in cubical dimensions to take the SEM photos.

2.2 *Experimental procedure*

A combination of two methods were used to measure the full-range SWRC in this study. The procedure of the axis translation and filter paper methods are described accordingly.

2.2.1 *Axis translation method*

For experiments in the low range, i.e., zero to 300 kPa, an unsaturated oedometer developed based on the axis translation technique was used. A schematic diagram of the apparatus developed by Sadeghi & Nasiri (2021) is shown in Fig. 2. The nominal air-entry value of the embedded ceramic disk is 300 kPa. In addition, the setup was equipped with an air and water pressure control panel. It is noted that permeating fluid in each test is the same as the solution used in sample preparation. Therefore, the electrical conductivity of the exchange soil water during water retention tests can be used to obtain the osmotic suction. Indeed, the electrical conductivity is used to determine the amount of solutes in the pore fluid. Afterwards, the osmotic suction can be calculated using the van't Hoff equation (Glasstone 1951):

$$\pi = MiRT \quad (1)$$

where, π is the induced osmotic suction (kPa), i is the molar concentration of salt solution (mol/L), R is the universal gas constant (8.32 J/mol. K), and T is the absolute temperature (K).

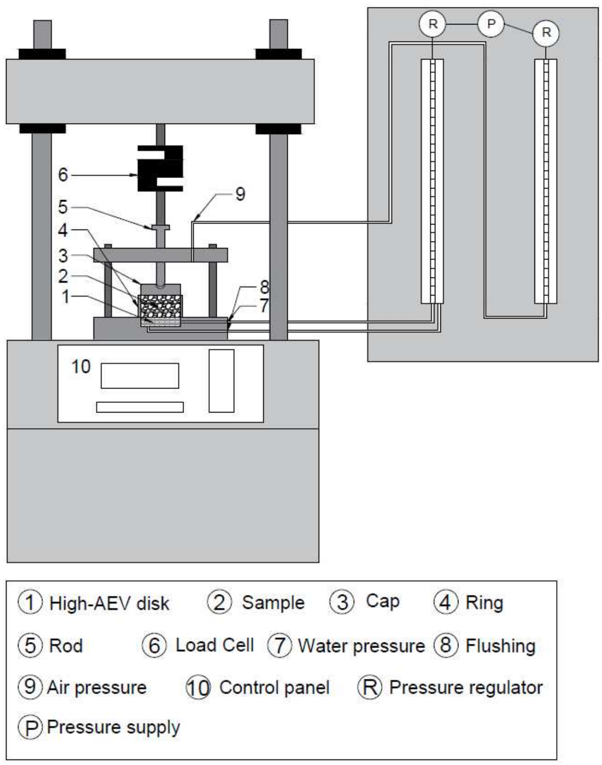


Figure 2. Schematic diagram of the developed unsaturated oedometer.

2.2.2 *Filter paper method*

The filter paper tests were carried out according to the ASTM D5298. Both contact and non-contact methods were employed to determine matric and total component of suction, respectively. To obtain the drying SWRC, the samples were first exposed to air to lose a certain amount of moisture. Afterwards, contact and non-contact filter papers were placed in contact and in vicinity of the sample and the whole assembly were wrapped in consecutive layers of clings and aluminum foil to reach moisture equilibrium after four weeks. According to the principles of this method, the moisture content at equilibrium with soil samples is measured and the corresponding soil suction is hence obtained indirectly using a predetermined calibration curve. From the results, the osmotic suction can be inferred based on the concurrent measurements of total and matric suctions.

3 TEST RESULTS

3.1 *Soil water retention curve in terms of matric suction*

According to the described methodology, the matric suction of the soil was measured using the two methods. Figs 3 and 4 indicate the matric-SWRC in terms of gravimetric moisture content and degree of saturation, respectively. It is to mention that sample volume changes were considered in derivation of the degree of saturation based on the measurements of an LVDT and a caliper during the axis translation and filter paper tests.

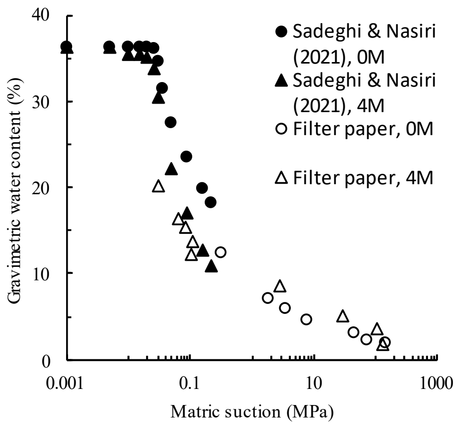


Figure 3. Gravimetric water content vs. matric suction for saline and non-saline specimens.

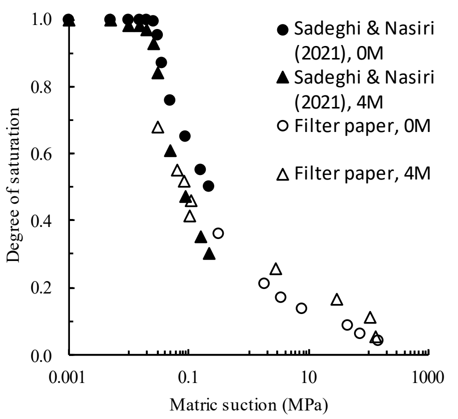


Figure 4. Degree of saturation vs. matric suction for saline and non-saline specimens.

As shown in Figs 3 and 4, in the low suction range, i.e. ≤ 400 kPa, the retention in the saline sample is less than in the non-saline sample. The observed trends are consistent with the published report of Zhang et al. (2021). The matric potential of the soil, which in the literature is considered equal to matric suction, is controlled by two physical processes referred to as capillary and absorption mechanisms (Lu 2019). Capillary is the result of the interaction of gas and liquid phases or liquid, solid and gas phases, and adsorption is the result of the interaction of solid and liquid phases. The cavitation pressure in soil pore water was conventionally considered to be -100 kPa, while it was shown by Frydman & Baker (2009) that this pressure is in the range of -100 to -400 kPa. As a result, there is a capillary process up to a pressure of -400 kPa (corresponding to a matric suction of 400 kPa); hence, water retention in this range is controlled by this phenomenon. If the soil pores are considered as capillary tubes, the Young–Laplace equation can be used to express matric suction in the lower suction range.

$$u_a - u_w = \frac{2T_s cos\theta}{R_s} \quad (2)$$

where, $(u_a - u_w)$ is equivalent to the matric suction (kPa), T_s is the surface tension (N/m), θ is the contact angle and R_s is the capillary tube radius (mm). According to Eq. 2, it can be inferred that matric suction depends on three parameters. Surface tension in saline solutions is higher than in distilled water. In other words, the surface tension for distilled water and 4 mol/L sodium chloride solution ($23\,°C$) is 72.72 mN/m, and 79.31 mN/m, respectively (Ozdemir et al. 2009). The contact angle in saline solutions is less than in distilled water. However, the effects of these two parameters are less than the radius of the pipe. According to the SEM images taken from the saline and non-saline samples and reported in Fig. 5, it is evident that the macropores are larger in the saline sample compared to the non-saline one. The controlling factor in the capillary phenomenon is the diameter of the pores and with increasing the diameter of the pores, the capillary pressure decreases. Therefore, in the low suction range where water retention in the soil is controlled by capillary, the increase in the diameter of macropores as a consequence of dissolved salts suppresses the water retention capability. Also, in soils exposed to saline solution, the thickness of diffuse double layer decreases and the ratio of free water to adsorbed water increases (He et al. 2016), which facilitates water discharge from saline samples compared with non-saline samples.

On the other hand, for higher suction range, i.e. ≥ 2000 kPa, the water retention in the saline sample is higher than in the non-saline sample according to Figs 3 and 4. At high suction range, the adsorption process controls the retention in the soil. In this range, salt acts as a component of soil grains due to significant dehydration results in salt crystallization. Therefore, salt grains can absorb extra amount of water than the clay assemblies in non-saline samples, resulted in a higher retention capacity. Therefore, the findings are quite interesting as the influence of salt concentration dissolved in the pore water is not the same over the whole range of suction, but it depends on the prevailing retention mechanisms, either capillary or adsorption.

3.2 *Soil water retention curve in terms of total suction*

Direct and indirect methods were used to obtain total suction. In the direct method, filter paper was used to obtain the total suction in the higher range. However, the matric suction was first measured in the lower range using the axis translation method. In the next step, the electrical conductivity of the solution extracted from the sample was measured and converted to the osmotic suction using the van't Hoff equation, i.e., Eq. 1. Finally, the sum of matric and osmotic suction becomes equal to the total suction in the lower range. Figure 6 shows the total-SWRC of saline and non-saline samples.

According to Fig. 6, it is clear that the amount of total suction in the whole range in the saline sample is higher than the non-saline sample. A rise in the salt content dissolved in the pore water increases the water retention capacity because the significant contribution of osmotic suction. However, this increase depends on the range of suction and the amount of matric potential. In the area of low suction, due to high humidity and the presence of salt, and according to microstructural studies, the size of large cavities increases, but with increasing suction, the moisture decreases and this effect becomes less as crystallization occurs at low moisture contents (He et al. 2019).

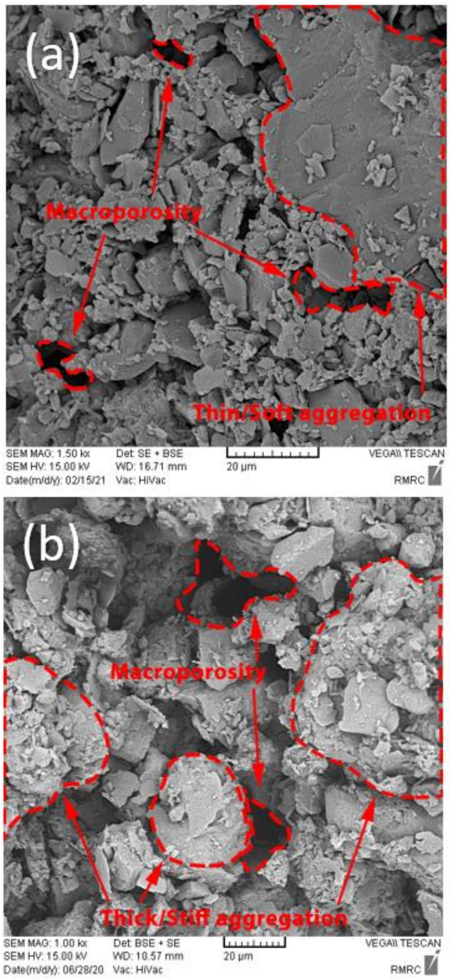


Figure 5. Microstructural images: (a) non-saline sample, and (b) saline sample (4 mol/L).

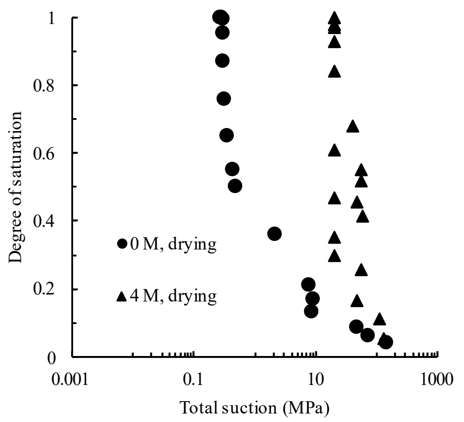
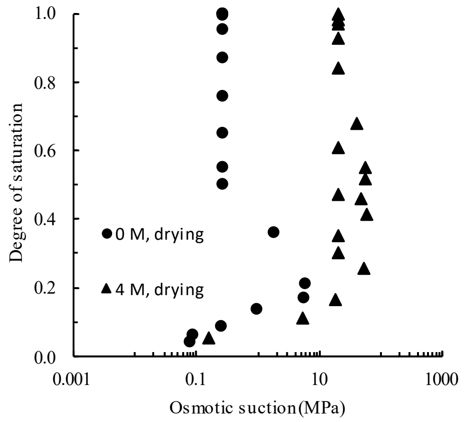


Figure 6. Degree of saturation vs. total suction for saline and non-saline specimens.

3.3 *Soil water retention curve in terms of osmotic suction*

To obtain the osmotic-SWRC at higher suction range, the difference between the two values obtained for total suction and matric suction was used. In the lower suction range, on the other hand, the electrical conductivity of the extracted solution was used. The results of osmotic-SWRC are depicted in Fig. 7. It can be revealed from the results that for the saline sample at low degree of saturation (corresponding to high suction), cation exchange and hydration cannot be occurred or occurred but at a very low rate due to the low humidity of the surrounding environment. Therefore, the amount of osmotic suction is the lowest. As moisture increases, hydration begins and cation exchange occurs between salt ions and clay soil particles to achieve a stable state. Finally, the amount of osmotic suction becomes fixed according to the concentration of the solution.

Figure 7. Degree of saturation vs. osmotic suction for saline and non-saline specimens.



3.4 *Analytical best-fit curves*

Van Genuchten (VG) has proposed a three-parameter model for the SWRC (van Genuchten, 1980). This model has been widely used to deliver a simplistic yet representative trend for variations in water content against suction (Sadeghi & Darzi 2021). The general form of the van Genuchten model is:

$$S_e = \frac{1}{(1+(\alpha\psi)^n)^m} \tag{3}$$

where, S_e is the effective degree of saturation, ψ is matric suction, and α, n, and m are the model constants that are calculated from the regression analysis of the best fit curve to the measured data. The effective degree of saturation is defined as:

$$S_e = \frac{S-S_r}{S_s-S_r} \tag{4}$$

where, S is the degree of saturation, S_r is the degree of saturation at the residual state, and S_s is the degree of saturation corresponding to the fully saturated condition ($S = 1$).

In this study, regression analyses were performed for the two series of data obtained from retention tests on saline and non-saline samples. The trends are plotted and compared in Fig. 8. In addition, the fitting parameters of the van Genuchten model for both conditions are given in Table 1. The results confirm that the saline sample has a higher residual degree of saturation (0.1224) than the non-saline sample (0.0163). Excellent coefficient of determination was obtained the non-saline sample over the whole range of suction (R^2 = 0.99). On the other hand, excellent correlation exists for the saline sample in the low suction range (R^2 = 0.98), while the correlation declines to a coefficient of determination as low as 0.4 at the high suction range. Therefore, it can be concluded that the van Genuchten model fails to give a satisfactory prediction of the SWRC of soil samples exposed to saline solutions in the high suction range well.

Another widely used retention model was proposed by (Ferdlund & Xing, 1994). The Ferdlund & Xing (FX) model considers the pore size distribution to predict the soil water retention curve:

$$\theta = C(\psi) S_s \left[\frac{1}{\ln\left(e + \left(\frac{\psi}{\alpha}\right)^n\right)} \right]^m \tag{5}$$

where, θ is the degree of saturation, $C(\psi)$ is a correction factor calculated by Eq. 6, S_s is equal to the degree of saturation corresponding to the fully saturation state ($S_s = 1$), α, n, and m are the model constants, and e is the Euler number.

$$C(\psi) = \left[1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)} \right] \tag{6}$$

where, ψ is matric suction, and ψ_r is an estimation of the residual suction. The results revealed that the residual suction in the soil is highly dependent on the osmotic potential. Therefore, the residual suction in Eq. 6 is assumed equal to the osmotic suction of the soil obtained from Eq. 1.

Figure 9 compares the fitting curves of FX and the corresponding experimental data. According to the results, it is found that the air entry value of the saline sample (AEV=22 kPa) is less than the non-saline sample (AEV=27 kPa). Also, the desorption rate of saline solution in the transition zone is more than the corresponding value of non-saline solution. Unlike the VG model, the FX equation has a much better correlation with the experimental data in the high suction range. Therefore, the FX model can give a more representative trend for retention data of saline solutions than the VG model since the influence of osmotic potential can be considered in the residual suction implicitly.

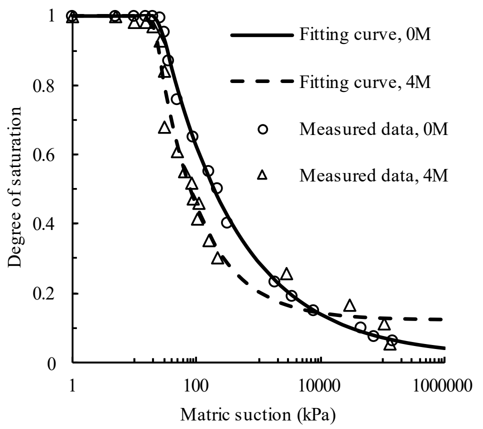


Figure 8. Best-fit VG model to the measured water retention data.

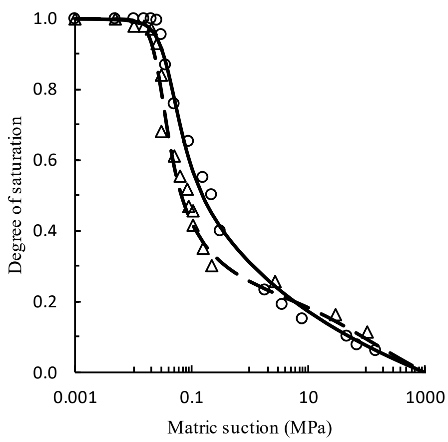


Figure 9. Best-fit FX model to the measured water retention data.

Table 1. model VG and FX parameters for saline and non-saline samples.

Parameter	VG		FX	
	saline	*Non-saline*	*saline*	*Non-saline*
θ_r	0.122	0.016	-	-
α	0.050	0.040	25	35
n	12.73	21.45	4	3.3
m	0.047	0.016	0.5	0.4
ψ_r (kPa)	-	-	19200	267

4 CONCLUSIONS

A combined methodology of water retention tests and scanning electron micrographs was employed to provide insight into the effect of osmotic suction on the full-range soil water retention curve of a collapse soil. According to the results, higher retention capacity in terms of matric suction was measured for desalinated samples compared with saline soil samples for the lower range of suction. The observed trend was attributed to the microstructural evolution caused by diffusion of salt into the clay particles, resulted in the larger macro-porosity of saline soil samples. On the other hand, matric water retention curve of saline soil samples lays above that of desalinated samples due to the contribution of salt grains in absorbing extra water molecules through vapor phase in the higher range of suction where the adsorption mechanism prevails over the capillary actions.

Regarding the water retention curves in terms of total suction, the saline soil specimens have higher retention capacity than corresponding desalinated soil samples over the whole range of suction. This is due to the significant osmotic suction component arise from the existence of dissolved salts into the pore fluid. In addition, the examination of osmotic suction revealed that hydration and cation exchange would not occur at relatively low moisture content. However, with increasing moisture content, hydration occurred and cation exchange began.

Microstructural study of saline and desalinated samples confirmed the differences in the evolution of micro- and macro-porosity in the presence and absence of salt dissolved into the pore fluid, respectively. Indeed, the average diameter of macro-pores in the soil increases due to the presence of salt. Further microstructural quantification can be insightful as concrete proof to support this postulation. Eventually, the performance of two commonly used water retention models was evaluated and discussed.

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6 REFERENCES

ASTM (2009). Annual Book of ASTM Standards. *ASTM International*, West Conshohocken, PA.

Bazargan, A., Sadeghi, H., Garcia-Mayoral, R., and McKay, G. (2015). An unsteady state retention model for fluid desorption from sorbents. *Journal of colloid and interface science* 450, 127-134.

Estabragh, A. R., Soltani, A., and Javadi, A. A. (2020). Effect of pore water chemistry on the behaviour of a kaolin–bentonite mixture during drying and wetting cycles. *European Journal of Environmental and Civil Engineering* 24(7), 895–914.

Fredlund DG, and Xing A. (1994). Equations for the soil-water characteristic curve. *Canadian Geotechnical Journal* 31, 533–46.
Frydman, S., and Baker, R. (2009). Theoretical soil-water characteristic curves based on adsorption, cavitation, and a double porosity model. *International Journal of Geomechanics* 9(6), 250–257.
Garakani, A. A., Sadeghi, H., Saheb, S., and Lamei, A. (2020). Bearing capacity of shallow foundations on unsaturated soils: analytical approach with 3D numerical simulations and experimental validations. *International Journal of Geomechanics* 20(3):04019181.
Gao, Y., and Sun, D. (2017). Soil-water retention behavior of compacted soil with different densities over a wide suction range and its prediction. *Computers and Geotechnics* 91, 17–26.
Glasstone, S. (1951). Textbook of physical chemistry. Basingstoke, UK: Macmillan.
He, Y., Ye, W. M., Chen, Y. G., Chen, B., Ye, B., and Cui, Y. J. (2016). Influence of pore fluid concentration on water retention properties of compacted GMZ01 bentonite. *Applied Clay Science* 129, 131–141.
He, Yong, Zhang, K., and Wu, D. (2019). Experimental and modeling study of soil water retention curves of compacted bentonite considering salt solution effects. *Geofluids* 2019, 1–11.
Jafarzadeh, F., Ahmadinezhad, A., and Sadeghi, H. (2021). Effects of initial suction and degree of saturation on dynamic properties of sand at large strain. *Scientia Iranica* 28(1), 156-174.
Khadir, A., Ramezanali, A. M., Taghipour, S., and Jafari, K. (2021). Insights of the removal of antibiotics from water and wastewater: a review on physical, chemical, and biological techniques. *Applied Water Science: Remediation Technologies* 2, 1-47.
Kolahdooz, A., Sadeghi, H., and Ahmadi, M. M. (2020). A numerical study on the effect of salinity on stability of an unsaturated railway embankment under rainfall. *In E3S Web of Conferences* 195, 01004.
Lu, N., (2019). Generalized soil water retention equation for adsorption and capillarity. *Journal of Geotechnical and Geoenvironmental Engineering* 142(10), 04016051.
Ng, C. W. W., Sadeghi, H., Hossen, S. K. B., Chiu, C. F., Alonso, E. E., and Baghbanrezvan, S. (2016). Water retention and volumetric characteristics of intact and re-compacted loess. *Canadian Geotechnical Journal* 53(8), 1258–1269.
Ng, C. W. W., Sadeghi, H., Jafarzadeh, F., Sadeghi, M., Zhou, C., and Baghbanrezvan, S. (2020). Effect of microstructure on shear strength and dilatancy of unsaturated loess at high suctions. *Canadian Geotechnical Journal* 57(2), 221-235.
Ozdemir, Orhan, Stoyan I. Karakashev, Anh V. Nguyen, and Jan D. Miller. (2009). Adsorption and surface tension analysis of concentrated alkali halide brine solutions. *Minerals Engineering* 22(3): 263–71.
Romero, E., and Simms, P. H. (2008). Microstructure investigation in unsaturated soils: A review with special attention to contribution of mercury intrusion porosimetry and environmental scanning electron microscopy. *Geotechnical and Geological Engineering* 26(6), 705–727.
Sadeghi, H. (2016). A micro-structural study on hydro-mechanical behavior of loess. Dual-Degree PhD thesis. *Hong Kong University of Science and Technology & Sharif University of Technology*.
Sadeghi, H., and AliPanahi, P. (2020). Saturated hydraulic conductivity of problematic soils measured by a newly developed low-compliance triaxial permeameter. *Engineering Geology* 278, 105827.
Sadeghi, H., and Darzi, A. G. (2021). Modelling of soil-water retention curve considering the effects of existing salt solution in the pore fluid. In MATEC Web of Conferences 337, 02001.
Sadeghi, H., Hossen, S. B., Chiu, A. C., Cheng, Q., and CWW, N. (2016). Water retention curves of intact and re-compacted loess at different net stresses. *Japanese Geotechnical Society Special Publication* 2(4), 221-225.
Sadeghi, H., Kiani, M., Sadeghi, M., and Jafarzadeh, F. (2019a). Geotechnical characterization and collapsibility of a natural dispersive loess. *Engineering geology* 250, 89-100.
Sadeghi, H., and Nasiri, H. (2021). Hysteresis of soil water retention and shrinkage behaviour for various salt concentrations. *Géotechnique Letters* 11(1), 21-29.
Sadeghi, H., Nasiri, H., AliPanahi, P., and Sadeghi, M. (2019b). Dispersivity, collapsibility, and microstructure of a natural dispersive loess from Iran. *In The 16th Asian Regional Conf. on Soil Mech. and Geotech. Eng.* (16ARC).
Sarkar, G., and Siddiqua, S. (2016). *Effect of fluid chemistry on the microstructure of light backfill: An X-ray CT investigation*. *Engineering Geology* 202, 153–162.
Sun, D., You, G., Annan, Z., and Daichao, S. (2016). Soil–water retention curves and microstructures of undisturbed and compacted Guilin lateritic clay. *Bulletin of Engineering Geology and the Environment* 75(2), 781–791.
Taghipour, S., and Ayati, B. (2017). Cultivation of aerobic granules through synthetic petroleum wastewater treatment in a cyclic aerobic granular reactor. *Desalination and Water Treatment* 76, 134-142.
Taghipour, S., and Ayati, B. (2015). Study of GSBAR capability in petroleum wastewater treatment. *Journal of Water Reuse* 2(2), 119-128.
Thyagaraj, T., and Rao, S. M. (2010). Influence of osmotic suction on the soil-water characteristic curves of compacted expansive clay. *Journal of Geotechnical and Geoenvironmental Engineering* 136(12), 1695–1702.
van Genuchten, M. (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44(5), 892–898
Zhang, F., Zhao, C., Lourenço, S. D. N., Dong, S., and Jiang, Y. (2021). Factors affecting the soil–water retention curve of Chinese loess. *Bulletin of Engineering Geology and the Environment* 80(1), 717–729.
Zhang, J., Niu, G., Li, X., and Sun, D. (2020). Hydro-mechanical behavior of expansive soils with different dry densities over a wide suction range. *Acta Geotechnica* 15(1), 265–278.