Suction and swelling behavior of clayey soils in the presence of seawater

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ABSTRACT
Clayey soils exhibit different engineering behavior mainly depending on their mineralogical and chemical compositions. Pore fluid chemistry may significantly alter the chemical compositions of clays by means of exchangeable cations. Studies in the literature report that inorganic salt solutions have a strong impact on the engineering behavior of clays, especially on swelling clays. However, the effects of saline waters on the swelling and/or suction behavior of soils are not well known. The effects of saline waters on the engineering behavior of soils need to be determined because the salinity of pore fluid of fine-grained soils at some coastal areas increases continuously. Swelling clays such as montmorillonitic soils bring serious problems including large settlements under superstructures or hydraulically permeable in the case of change in the pore fluid characteristics. Soil suction is one of the important parameter describing the moisture condition of unsaturated soils. Changes in suction behavior in the presence of saline waters are needed to be known.

The aim of this study is to determine the rate of change in suction and swelling behavior of clayey soils when exposed to natural seawater with respect to distilled water. The six clayey soil samples were gathered with different mineralogy and plasticity characteristics and tested to determine suction and swelling characteristics in the presence of distilled water and seawater. The suction behavior of the samples was determined by the filter paper method. The modified free swell indexes of the samples were determined by free swell index methods. The total suction of the samples are higher than that of in distilled water for swelling and non-swelling soils. There are no correlations between the total suction and soil physicochemical properties (liquid limit, clay fraction, etc.). The seawater effect is most noticed on the swelling behavior for montmorillonitic soils which have high plasticity.

RÉSUMÉ
Les sols argileux peuvent représenter différents comportements d'ingénierie qui dépendent principalement à leurs compositions minéralogiques et chimiques. La chimie des fluides interstitiels peut modifier de manière significative les compositions chimiques d'argile par des moyens de cations échangeables. Les études dans la littérature rapportent que les solutions de sal inorganiques a une puissante influence sur le comportement d'ingénierie des argiles, en particulier sur les argiles gonflantes. Cependant, les effets de l'eau salée sur le gonflement et/ou La succion des argiles sont tout à fait connus. Depuis que la salinité de l'eau interstitielle des sols à texture fine près des zones côtières augmente de façon continue, les effets de l'eau salée sur le comportement d'ingénierie des sols doivent être déterminés. Les sols argileux comme sols montmorillonitiques apportent de sérieux problèmes y compris grands tassements dus aux charges élevées des superstructures ou perméabilité hydraulique dans le cas de changement des cars : Caractéristiques du fluide interstitiel. La succion du sol est l'un des paramètres importants décrivant l'état d'humidité des sols non saturés et les changements de comportement de la succion en présence des eaux salées sont également nécessaires pour être connus.

L'objectif de cette étude est de déterminer le taux de variation de la succion et le comportement de gonflement des sols argileux lorsqu'ils sont exposés à l'eau de mer naturelle à l'égard de l'eau distillée. Les six échantillons de sol argileux avec des caractéristiques différentes de plasticité et de la minéralogie ont été recueillis et aussi éprouvés pour établir des caractéristiques de la succion et du gonflement en présence d'eau distillée et d'eau de mer. Le comportement de succion des échantillons a été déterminé en utilisant la méthode du papier filtrant. Les Indices de gonflement libre modifié des argiles ont été déterminés par les méthodes d'indice de gonflement libre. Les résultats montrent que les valeurs de succion totale des échantillons sont plus élevées que celui dans l'eau distillée. Il n'ya pas de corrélations entre la succion totale et propriétés physico-chimiques du sol (limite de liquidité, la fraction d'argile, etc.). L'effet de l'eau de mer est le plus remarqué sur le comportement de gonflement des sols montmorillonitiques qui ont une grande plasticité.

1 INTRODUCTION

Clays are known to exhibit considerably different engineering behavior mainly depending on their mineralogical compositions and pore fluid chemistry. Pore fluid chemistry may significantly alter the chemical compositions of clays by means of exchangeable cations, which govern the engineering properties of clays in most cases (Sridharan, 1991).

The studies in the literature reported that inorganic salt solutions have a strong impact on the engineering behavior of clays, especially on swelling clays (Sridharan, 1991; Di Maio, 1996; Kaya and Fang, 2000; Oren and Kaya, 2003). However, the effects of saline waters on the swelling and/or suction behavior of soils are not known well.

Soil suction is one of the important parameter describing the moisture condition of unsaturated soils and changes in suction behavior in the presence of saline waters is an important phenomenon. The effects of saline waters on the engineering behavior of soils need to be determined since the salinity of pore fluid of fine-grained soils at some coastal areas increases continuously. Such increase is due mainly to lowering the groundwater level below mean sea level in coastal areas, resulting in seawater migration towards land (Don et al., 2006).

Swelling clays such as montmorillonite mineral groups bring serious problems including large settlements under superstructures or hydraulically permeable in the case of change in the pore fluid characteristics. Such problems mostly arise from changes in physicochemical state of soil particles, resulting changes in the thickness of the diffuse double layer (Yong and Warkentin, 1966). Pore fluid chemistry is one of the factors that influence the adsorbed water layer thickness surrounding the clays. That is, strong cation concentration, high cation valence and acidic environment dramatically decrease the double layer thickness around the clay particles. Hence, the performance of earth structures such as impermeable clay liners changes dramatically when the pore fluid chemistry of the system changes with time. On the other hand, double layer thickness around non-swelling clays reduces when exposed to chemicals as well. However, this is not as pronounced as swelling clays. Thus, changes in the pore fluid of the system do not significantly alter the performance of earth structures composed of non-swelling clays.

There are many studies reporting variations in engineering behavior of clays or clayey soils upon testing with pore fluids other than distilled water or tap water. A detailed summary of these studies can be found in Bowders and Daniel (1986); Sridharan (1991); Di Maio (1996); Kaya and Fang (2000) and Ören and Kaya (2003). These studies reported that inorganic salt solutions have a strong impact on the engineering behavior of clays, especially on swelling clays. However, the effects of saline waters on the swelling and/or suction behavior of soils are not known well. The saline waters may have significant effects on the engineering behavior of soils. For example, Don et al. (2006) reported that some important problems occurred due to extensive ground settlement upon salinity intrusion from pumping of groundwater in the Shiroishi lowland plain, southwestern Kyushu Island of Japan. Similarly, the groundwater level is dropping continuously in various parts of the coastal areas of Turkey, due to excessive withdrawal for industrial and agricultural purposes, causing intrusion of seawater toward land.

The amount of swelling and the magnitude of swelling pressure depend on the clay minerals present in the soil, the soil structure and the fabric, and several physico-chemical aspects of the soil such as the cation valence, salt concentration, cementation, and the presence of organic matter. Everything else being equal, montmorillonites swell more than illites, which swell more than kaolinites (Holtz and Kovacs 1981). The basic unit of the illitic clays is a sheet, which is roughly 10 Ǻ in thickness; this unit will never expand. In montmorillonite, the clay particles may consist of single sheets of 14 Ǻ, and as a result the swelling, an increase of the distance between the particles is very large. In illitic clays the particles consist of several (5-20) sheets of 10 Ǻ each which are bonded by chemical forces. The swelling of such a clay is comparatively much less than the swelling of montmorillonite, although the cause of both is the same, namely, the excess osmotic pressure in the adsorbed layer of ions. The distinction between “expanding” and “non-expanding” is a classification according to an average particle thickness or specific surface of clay (Bolt 1956). Olson and Mesri (1970) obtained that the main cause of the swelling of kaolinite is the rebound of bent particles rather than swelling of double layers. However, in the swelling of calcium and sodium montmorillonite physicochemical effects seem to dominate. Furthermore, they reported that particle shape is important because wide, flat, smooth plates allow a maximum of interaction of double layers and thus promote physicochemical effects at the same time that they tend to reduce the mechanical effects.

Soil suction is one of the important parameter describing the moisture condition of unsaturated soils (Bulut, 2001). Suction is described as negative stress in the pore water for soils. The total suction, Ψ is equal to sum of the matric suction and the osmotic suction. The matric suction is associated with the capillary phenomenon arising from the surface tension of the water. It depends on capillarity, texture, and surface adsorptive forces of the soil. Osmotic suction comes from dissolved salts contained in the soil water. The filter paper method is easily applicable and reliable method in engineering practice (Bulut, 2001). In this method, the filter paper comes to equilibrium with the soil through vapor flow, and at equilibrium the suction value of the filter paper will be same with soil. If the filter paper is allowed to absorb water through non-contact method from water vapor the total suction is measured.

The aim of this study is to determine the rate of change in some of the geotechnical engineering properties of clayey soils when exposed to seawater with respect to distilled water. Thus, six clayey soils having different clay mineralogy were gathered and subjected to swelling and suction tests.

2 MATERIALS AND METHODS

In this study, six clayey soils with different mineralogy were collected. X-Ray powder diffraction patterns were obtained using a Philips diffractometer and CuKα radiation. The dominant minerals of the soils and their physicochemical properties are given in Table 1.

All soil samples were oven-dried (80 °C-48 hours), crushed and sieved through No. 40 sieve. Grain size distribution, specific gravity and cation exchange capacity (CEC) of the samples were determined according to ASTM D-422-63, ASTM D-854-92 and Na method (Chapman, 1965), respectively. The test results are given in Table 1. Liquid limit (LL) and plastic limit (PL) were determined according to British Standards (BSI,

1990) and ASTM D-4318-98, respectively. The consistency limit tests were replicated two times, and the average values are presented here. Natural Aegean seawater and distilled water were used as reconstitution fluids in all experiments. The chemical composition of the seawater was determined using ICP (inductively coupled plasma) by ACME analytical laboratories in Canada (Table 2). Modified free swell index (MFSI) was determined from the procedure which was adapted from ASTM D-5890 and Sivapullaiah et al. (1987). In this adapted swell index method, No. 40 passing 5 g oven-dried non-swelling soil samples and 2 g swelling soil samples were used. 90 mL distilled water was transferred to the 100 mL graduated cylinder. Approximately 0.1 g increments of sample were dusted over the entire water surface in the graduated cylinder over a period of approximately 20 seconds. Sample hydration and settlement were allowed for a minimum period of five minutes. After the final increment had settled, the water volume was raised to 100 mL by rinsing the adhering particles from the sides of the cylinder. After 2 h, the hydrating clay column was inspected for trapped air. After the 24-h hydration period the volume in millilitre was recorded at the top of the settled sample.

Table 1. Characteristics of the tested soils.

Sample #	Clay fraction (< 2 µm)	Specific gravity	Cation exchange capacity (meq/100g)
1	75	2.64	38.4
2	28	2.48	24
3	46	2.63	10.7
4	82	2.50	83.7
5	80	2.76	67.1
6	90	2.72	127.9

Sample #	Liquid limit (%)	Plasticity index (%)	Dominant mineral
1	70.0	40.2	Montmorillonite
2	58.4	23.3	Halloysite
3	60.9	43.2	Illite
4	113.6	52.9	Montmorillonite
5	330.7	280.8	Montmorillonite
6	395.8	343.4	Montmorillonite

Table 2. ICP analysis of the seawater

Ion type	Concentration (100X dilution)
Ca (ppm)	547
Na (ppm)	145
K (ppm)	518
Mg (ppm)	16.2
Cl (ppm)	21321
Al (ppb)	35
Cu (ppb)	7.6

The modified free swell index is given by;

$$\mathrm{MFSI} = \frac{V - V_S}{V_S} \qquad [1]$$

where V = the soil volume after swelling and V_S = the volume of solids.

In the filter paper method, the samples were prepared at their liquid limits and then placed in plexi-glass tubes at same density of 1.6 g/cm^3. Then the samples were placed in a glass jar. At least 75 percent volume of a glass jar was filled with the soil sample. A plastic ring type support was put on the top of the soil to provide a non-contact system for total suction measurements. Two Whatman no.42 type filter papers one on top of the other are inserted on the plastic ring by using tweezers. Then, the lid of the glass jar was tightened and sealed with plastic tape. The glass jars were kept in a incubator under 20 °C for 7 days. Before weighing the filter papers, all aluminum cans were weighed to nearest to 0.0001 g accuracy and recorded. The weights of the each can with wet filter paper were recorded every quickly (in less than 10 seconds). Then, all cans with the lids half-open were placed into the oven (80 °C - 24 hours) to allow evaporation. A can was removed from the oven and put on aluminum block for about 20 seconds to cool down. After that, the can with the dry filter paper was weighed very quickly. The moisture content of the filter papers was determined and from the calibration curve suction value was determined for each sample.

In order to get the calibration curve, the soil specimens were replaced with 100 mL NaCl solution. The two filter papers were placed on a plastic platform. The obtained calibration curve is shown in Figure 1. It should be noted that, this calibration curve is in good agreement with the ASTM's calibration curve of Whatman No.42 filter paper.

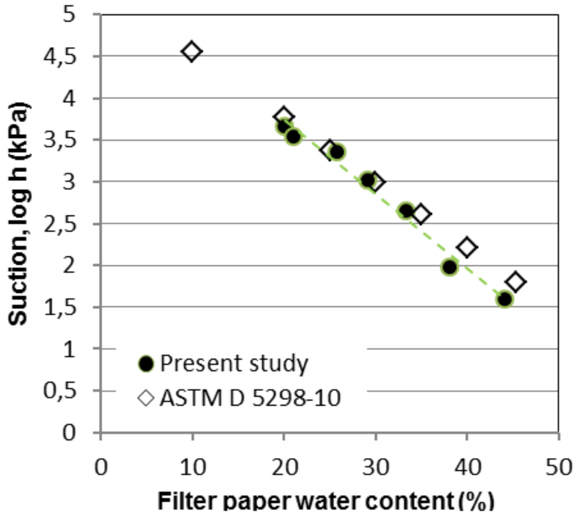

Figure 1. Calibration curve for Whatman no. 42 type filter paper

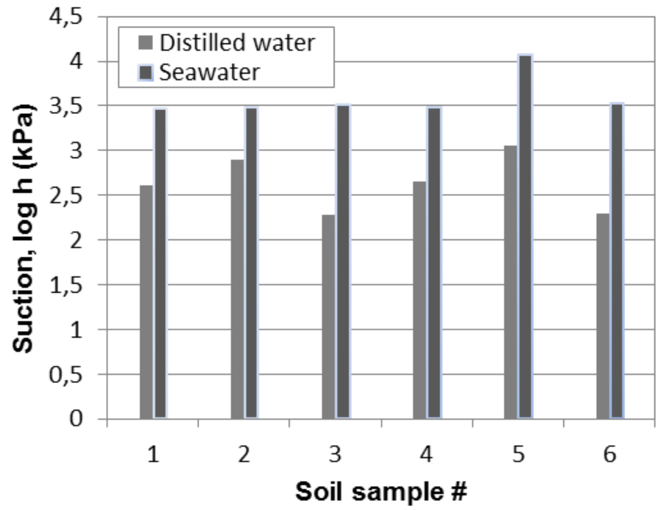

Figure 2. The effect of pore fluid on the suction behavior of the samples

3 RESULTS

3.1 Suction

The total suction of the six clayey samples were determined in the presence of distilled water and natural seawater. The natural clayey samples directly exposed to distilled water and seawater without any treatment. The determined water contents and calculated total suctions are shown in Table 3. The total suction values in both distilled water and seawater in Figure 2. The results show that total suctions in the presence of seawater are higher than distilled water. However, there is no significant difference between the swelling and non-swelling soils.

Table 3. The water content of the filter papers and total suction values of the samples

Sample #	Water content (%) / Suction (kPa)	
	Distilled water	Seawater
1	32.63 / 2.613	22.90 / 3.475
2	29.36 / 2.902	22.80 / 3.484
3	36.30 / 2.287	22.53 / 3.507
4	32.11 / 2.659	22.85 / 3.479
5	27.56 / 3.062	16.26 / 4.063
6	36.27 / 2.290	22.29 / 3.529

The correlative equations were conducted between the total suction and soil physicochemical properties. It was seen that there is no correlation between the total suction and clay content, liquid limit, cation exchange capacity, modified free swell index of the soils.

3.2 Swelling

The modified swell indexes of the samples were determined in the presence of distilled water and seawater. The results are shown in Table 4. The swelling characteristics of the soils which have low liquid limit (LL<150-200%) are not significantly affected by seawater. Furthermore, non-swelling soils have slightly higher volume in the presence of seawater than distilled water. Sridharan (1991) argue that kaolinites have an ability of making edge-to-face particle arrangements because of change in the pore fluid chemistry and form flocculated fabrics that govern the engineering properties. The air pockets occurred between the flocculated particles capped the available water during the tests and caused an increase in the liquid limit and sediment volumes of kaolinites. This phenomenon is valid to some extent for mainly kaolinitic and illitic glacial tills. In this regard, the swell volumes of this type of soils can be higher in the seawater because of the flocculated structure.

Table 4. Modified free swell index (MFSI) of the samples

Sample #	Modified free swell index (MFSI)	
	Distilled water	Seawater
1	5.18	5.42
2	2.43	2.56
3	5.10	5.26
4	6.63	7.19
5	19.79	9.19
6	51.05	7.99

The swelling behavior difference can be clearly seen in Figure 3. The amount of the clay samples are 2 g in the two graduated cylinders. However, the swell volumes of the samples are extremely different from each other. It should be noted that this difference cannot be seen for non-swelling soils.

Figure 3. Modified free swell index (MFSI) determination of the samples

The relationships between the MFSI and soil properties were examined. The coefficients of determination are shown in Table 5. The results show that MFSI has strong relationships with LL, PI, and CEC. There is no relationship between the MFSI and CF. However; the MFSI values in the presence of seawater have no significant correlations with the same soil properties. In the presence of seawater, swelling soils behave like non-swelling soils.

Table 5. The relationship between the MFSIs and soil properties

Soil property	Coefficients of determination (R^2)	
	MFSI (distilled water)	MFSI (seawater)
LL	0.83	0.63
PI	0.84	0.60
CEC	0.72	0.50
CF	0.37	0.76

4 CONCLUSIONS

In this study, the total suction and swelling behavior of clayey soils were investigated in the presence of distilled water and natural seawater. The results of the present study show that the total suction values of the samples were higher in the seawater than that of distilled water. Also, there is no difference between the swelling and non-swelling type of soils in terms of suction behavior.

The MFSIs of the non-swelling type of soils are higher in the presence of seawater than that of distilled water. However, swelling type of soils have lower MFSI in the presence of seawater. There are significant relationships between the MFSI and LL, CEC, and PI. However, these relationships are not significant for MFSIs which are determined in the presence of seawater.

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