

# UNSATURATED SOIL PROBLEMS IN THE KINGDOM OF SAUDI ARABIA

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## ABSTRACT

The arid climate, the geology and the severe weathering conditions in Saudi Arabia have produced a wide distribution of unsaturated soils. These soils are dry and desiccated near the ground surface. The most common two types of problematic unsaturated soil in Saudi Arabia are expansive clay and saline sabkha soil. The matric suction was very significant to study the behavior of the expansive clay and gave a better prediction of heave than the other methods. Furthermore, results of control heave tests indicated that a slight movement in structure caused a major reduction in constant pressures. For sabkha soil, osmotic suction is several orders of magnitude larger than the matric suction and is very important to describe the behavior of sabkha due to the large forces which may be generated by hydration of salts in very dry sabkha. Results indicate that the percolation of distilled water through sabkha causes destruction of natural cementation leading to collapse, reduction in strength and increase in settlement.

## KEYWORDS

Unsaturated soil, arid, expansive, sabkha, suction, cementation, heave, collapse.

## INTRODUCTION

Arid and semi-arid regions of the world comprise more than one-third of the earth's surface. Soils in these regions are dry and desiccated near the ground surface. These conditions may exist to a considerable depth below the ground surface (Abduljauwad, 1994). Even under humid climatic condition, the groundwater table can be well below the ground surface and the soil used in construction is unsaturated. The portion of the soil profile above the groundwater table is called the vadose zone. This zone can be broadly subdivided into a portion immediately above the water table which remains saturated even though the pore-water pressures are negative, and a portion where the soil becomes

unsaturated. The desaturation in the upper portion may be due to exceeding the air entry value of the intact soil or due to the formation of fissures and cracks (Fredlund and Rahardjo, 1993).

Unsaturated soil mechanics problems can be categorized into three main categories, namely seepage, shear strength and volume change. This subdivision, along with examples associated with each category, are shown in Fig. 1. This categorization shows that the same types of problems are of interest for both saturated and unsaturated soils. Soil suction can be described as a measure of soil's affinity for water. The total suction in a soil consists of two parts, osmotic and matric suctions. The osmotic suction in a soil is related to forces from osmotic repulsion mechanism arising from the pressure of soluble salts in the soil water (Chen, 1988). The process of osmosis is illustrated in Fig. 2. The matric suction is the result of two phenomena, adhesion and capillarity. The attraction of soil solids and their exchangeable ions for water along with the surface tension of water accounts for the capillary force. Fig. 3 shows air-water interface in soil and the concept of matric suction. Osmotic suction typically is neglected in a practical definition of the stress state of an unsaturated soil, with no profound consequences. Krahn and Fredlund (1971) concluded that for water content changes within the normal range of water contents encountered in most geotechnical engineering applications, the change in total suction is due primarily to changes in matric suction. But in situations where significant changes in pore fluid salt concentration will occur, there may be an associated change in osmotic suction that cannot be neglected.

In this study the most common two types of unsaturated soil in Saudi Arabia will be investigated, namely expansive clay and sabkha soils. The geological and environmental conditions of these two soils will be presented and their geotechnical problems will be investigated.

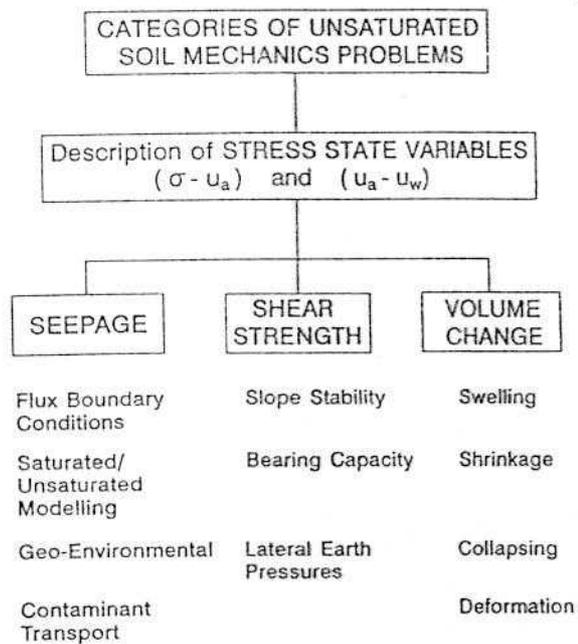


Fig. 1. Categorization of unsaturated soil mechanics based on the type of engineering problem (Fredlund and Rahardjo, 1993)

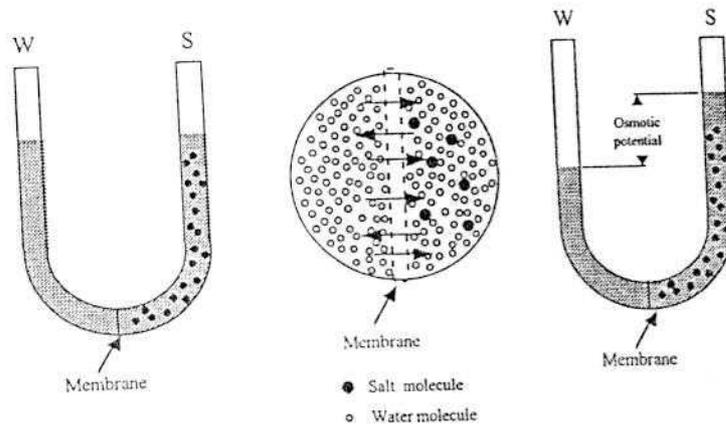


Fig. 2. Concept of osmotic suction

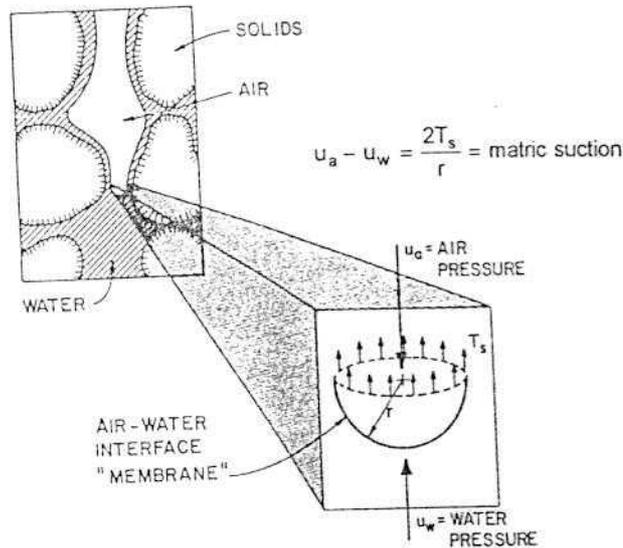


Fig. 3. Air-water interface in soil

## GEOLOGICAL AND ENVIRONMENTAL CONDITIONS

Arabian Gulf region is part of a rectangular depression known as Mesopotamia. The elevation of this region rises gradually inland at a rate of about one meter per kilometer. The Arabian Gulf basin lies in the northern tropical zone and falls within the hot-arid climate. Butler (1969) quoted an average annual rainfall of less than 5 cm, compared with an average annual rate of evaporation of approximately 125 cm. Such a large difference between the moisture received by the area and the moisture loss indicates an extreme degree of aridity, as defined by Fookes (1978). Rainfall is scanty and sporadic, and is mostly thinly spread between December and March, but it is not unusual for the region to go for several successive months without any rain. The range of temperature generally varies from about 15°C to 44°C, but it can be much wider in the inland margins of the Gulf, where the temperature can reach 50°C during summer

days and drop almost to 0°C during winter nights. Relative humidities range from 50% to 80%.

The surface rocks of the Eastern Province of Saudi Arabia include formations of consolidated sediments ranging from Palaeocene to middle Eocene age and Miocene to Pliocene age. Unconsolidated materials include various sediments of Quaternary age, comprising beach sand and gravel, basin deposits of gravel and silt, sabkha sediments, shale and claystone. The expansive clays encountered in the areas are derived mainly from beds of marl, limestone and chert in the underlying Cretaceous bedrock, by processes of weathering and erosion. The setting for the formation of expansive smectite clay minerals is extreme disintegration, strong hydration, and minimal leaching (Tourtelot, 1973). This is usually aided by an alkaline environment, the presence of sulphates (McMahon, 1989) and magnesium, calcium, sodium and iron cations. Such conditions are common in the Eastern Province of Saudi Arabia with its relatively low rainfall.

The Arabian Peninsula has a large number of sabkhas, both coastal and inland. Along the western coasts of the Arabian Gulf, coastal sabkha soils extend intermittently for more than 1700 km with average inland extensions of about 20 km. These soils normally have loose, rather porous and permeable, sandy to gritty textures. The outer surface is usually composed of hygroscopic salts, which, when dampened, can render the normally stable sabkha surfaces unstable. The sedimentary features, mineralogical composition and the chemistry of the interstitial brines in such coastal sabkhas vary greatly in both horizontal and vertical directions. Extensive research carried out by Imperial College, Shell Research BV and Keele University on the Arabian Gulf sabkhas during the 1960s and early 1970s (Purser, 1973) indicated that these sabkha deposits are of Holocene age and represent the remnants of a marine regression (retreat) that followed a middle Holocene high sea level in the region. Evidence of such a relatively high sea level is given by a number of raised beaches, as well as by the vast coastal sabkhas that fringe the Arabian Gulf coast with large inland extensions. Fig. 4 shows a generalized cross-section across a typical coastal sabkha; Fig. 5 shows the cross-section of a natural sabkha in Jizan, Saudi Arabia.

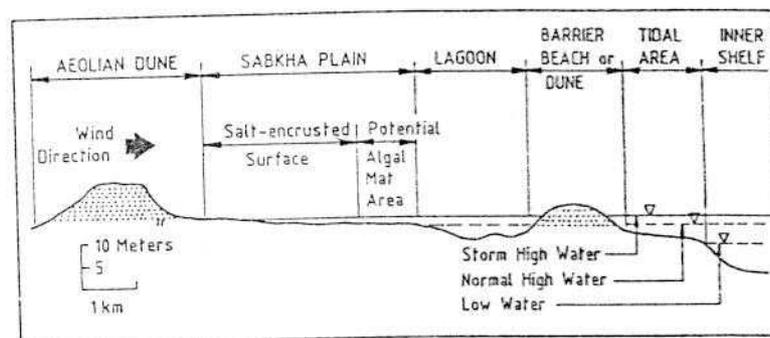


Fig. 4. Generalized cross-section across a typical coastal sabkha (Akili and Torrence, 1981)

Studies on the sequence of salt precipitation from the direct evaporation of sea water leads to the deposition of calcium carbonate, first when sea water is evaporated to about half of its original volume, followed by calcium sulphate (gypsum) at 19% of the original volume. Next in succession comes sodium chloride (halite), and at about 4% of the original volume the highly soluble salts of potassium and magnesium - the so-called bitterns or polyhalites - start to

develop as a co-precipitate with halite (Borchet and Muir, 1964). Most sabkha deposits, however, show major discrepancies. Commonly, there is a much greater proportion of carbonate and calcium sulphate than would be expected. This anomalous precipitation, with regard to the sea, is attributed to diurnal variations in temperature, overburden pressure and relative humidity of the system, and to the availability of trace elements in it. Moreover, incomplete evaporative concentration and the difficulty of achieving equilibrium precipitation in a system as large as a sabkha, added to the complex diagenetic changes, may lead to sharp deviation from the results of evaporating sea water.

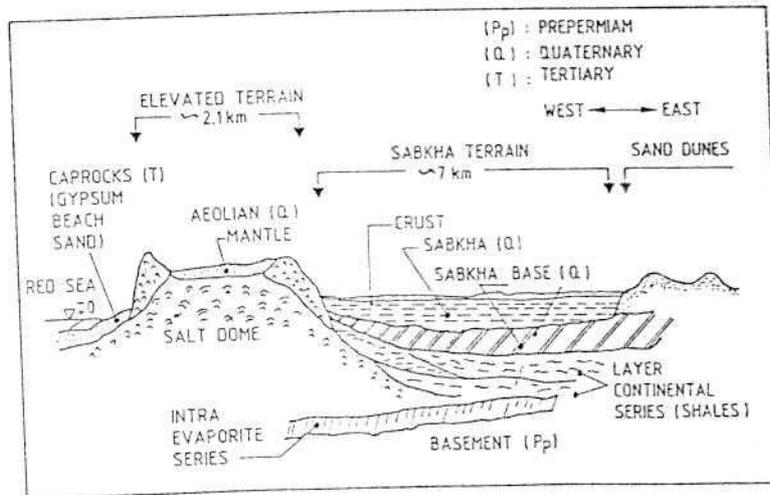


Fig. 5. Naturally-existing sabkha cross-section in Jizan (Erol, 1989)

## EXPANSIVE SOIL

The arid climate, the geology and the severe weathering conditions in Saudi Arabia have produced a wide distribution of expansive soils (Abduljawad, 1993). A site was selected in Al-Qatif, a city of Eastern Province of Saudi Arabia, for detailed investigation. The strata exposed at the investigated site are Tertiary or Cretaceous sedimentary rocks, which down to 4 m comprise green clayey shale with an intercalation of limestone. Below this the strata comprise hard greenish brown clay interbedded with layers of silty sand and moderately strong light gray limestone. X-ray diffraction analysis of a green clay sample from a depth of 3 m indicated that the main soil constituents are smectite (52%), illite (23%), palygorskite (5%), dolomite (9%), gypsum (6%) and quartz (5%). The clay at depth is moist, but the uppermost 1 to 3 m becomes desiccated in the summer months (Abduljawad, 1994). A survey of fissures in an exposed cutting showed quite a variation in the dip angles of fissures to the horizontal.

The investigated clay has a significantly high swell potential as indicated by the high consistency limits shown in Fig. 6. In the top 2 m, the liquid limit of 130% and the plasticity index of 70% are exceptionally high. This behavior is in conformity with the high values of the percentages of swell and swelling pressures obtained using the conventional oedometer. A typical result is shown in Fig. 7. The percentage of swell was obtained by using the simple oedometer test, while the swelling pressure was obtained from both the simple oedometer and constant volume tests (Abduljawad and Al-Sulaimani, 1993; Johnson and Sneath, 1978). In the simple oedometer test, after the sample reached a maximum volume change under a 6.8

kPa surcharge, it was reloaded gradually to cancel the deformation due to saturation. The swelling pressure is calculated from the sum of the load increments divided by the cross-sectional area of the sample. The test was repeated under a surcharge of 48 kPa. In the constant volume test, the volume of the specimen is forced to remain constant throughout the test, and the pressure developed when saturation is completed gives the swell pressure. A percentage of swell of 36% was recorded for the sample obtained from a depth of 3.0 m from the ground surface at 40% initial moisture content, while the swelling pressures obtained from the simple oedometer and constant volume tests were 3100 kPa and 800 kPa respectively. The percentage of swell for the sample subjected to 48 kPa surcharge was 10%. Complete details of the geotechnical properties and swelling characteristics of this soil were presented by Abduljauwad (1994).

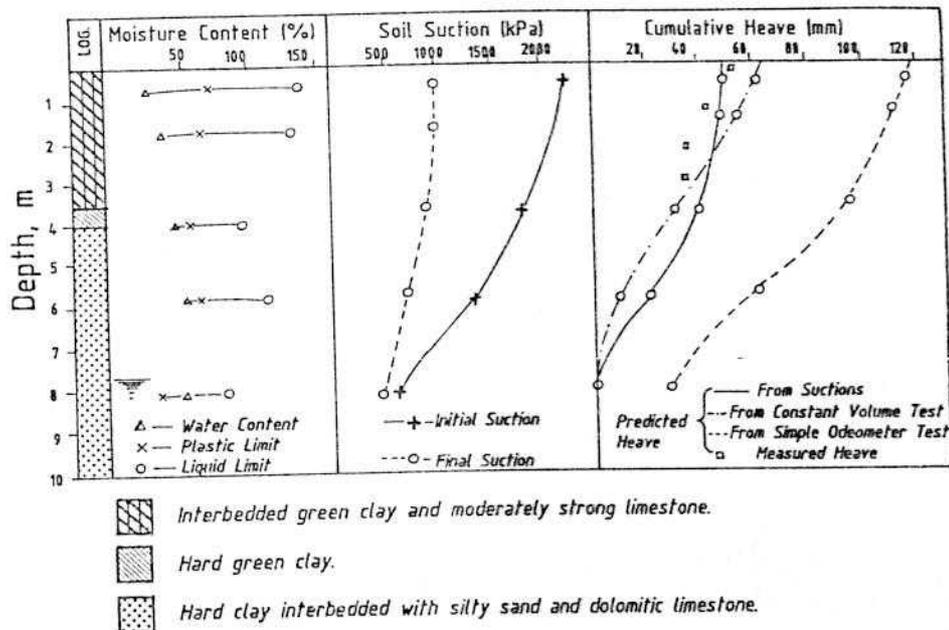


Fig. 6. Soil profile and heave comparison

Soil suctions were measured before and after the field swelling test using a transistor psychrometer developed by Soil Mechanics Instrumentation (Woodburn et al., 1993). Soil samples were obtained by using a Shelby tube and, while maintaining the natural water content and density, suction was measured in the laboratory. The high value of the initial total suction of up to 2,300 kPa (Fig. 6) corresponding to a moisture content of 22%, indicated that the uppermost 1 to 3 m becomes desiccated during the summer period, during which time the drilling was conducted. The final suctions for samples obtained 4 months after flooding the site reduce with depth from 800 kPa to 400 kPa.

Additional tests were conducted to investigate the effect of heave rate on swelling pressures. Samples of clay were trimmed to 100 × 100 × 250 mm blocks and four sides plates were screwed around them to contain the sample. Fig. 8 shows the complete setup for the controlled rate of heave test. A pressure transducer, which was embedded inside the clay sample, and a load cell, which was placed between the top rigid steel plate and a loading frame, were used to monitor the swelling pressure. All samples were subjected initially to a surcharge of 6.8 kPa. Water was then added and the bottom plate was allowed to move down at certain rates to simulate different tests conditions. The rates were selected based on results of slab tests and field interaction conducted by the author (Abduljauwad et al., 1997).

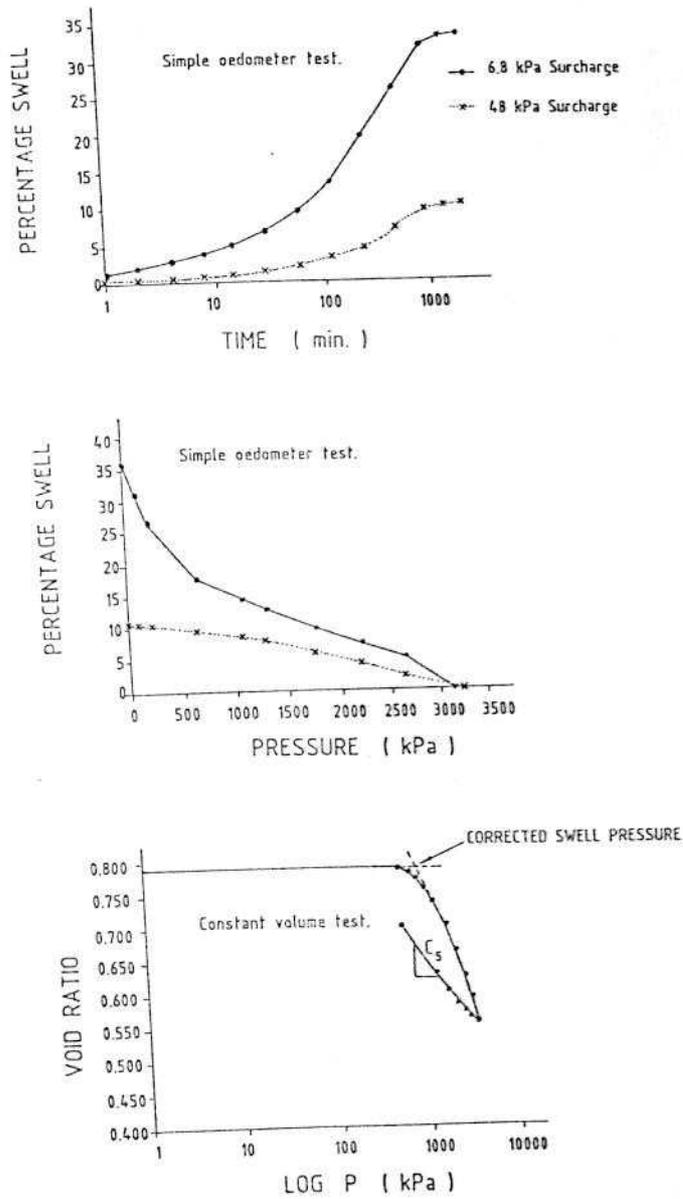


Fig. 7. Percentage of swell and swelling pressure for selected soil sample

Fig. 9 shows the effect of sample size on the percentage of swell. The percentage of swell was measured in the controlled heave device, while the sample is free to move upward under a surcharge of 6.8 kPa. It is very clear that the rate of heave for the small sample (100 mm × 100 mm in cross section) is higher than the large sample (500 mm × 500 mm in cross section), which was tested in the floating slab setup (Abduljauwad et al., 1997). The thickness and boundary conditions are the same for both samples. However, the maximum percentage of swell for both tests are identical (16%).

Fig. 10 shows the variation of pressure with time, while no vertical movement was allowed. A maximum swell pressure of 1000 kPa was recorded. This is the average of the pressure gauge and load cell readings. The rate of heave during the primary swelling was  $3.5 \times 10^{-3}$  mm/hrs under a pressure of 6.8 kPa as depicted in Fig. 9. The test was repeated twice and the bottom

plate was allowed to move downward with the rates of  $3.5 \times 10^{-2}$  and  $3.5 \times 10^{-1}$  mm/hrs, respectively. The movement of the plate was allowed after 10 hrs of sample inundation. The tests were terminated when a reduction in pressures was observed. Fig. 10 indicates that the pressure before the plate was allowed to move was 270 kPa and an increase of 50 kPa in pressure was obtained in the sample in which the rate of heave was 0.35 mm/hr compared to an increase of about 700 kPa in the sample in which the vertical movement was not allowed. The reduction in pressure was about 93%. This is a significant observation in the explanation of a behavior of structures built on expansive clay, where a slight movement will have a significant effect on the pressure generated between the soil and structures (foundation, ground beams and grade slabs).

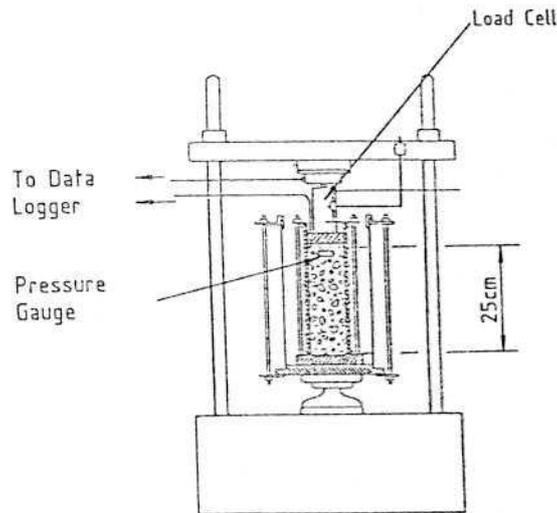


Fig. 8. Controlled heave rate device

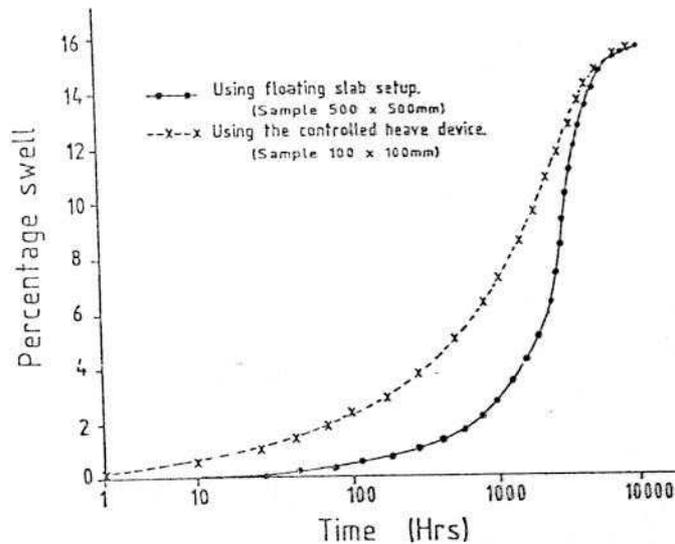


Fig. 9. Percentage of swell versus time for floating slab and controlled heave test

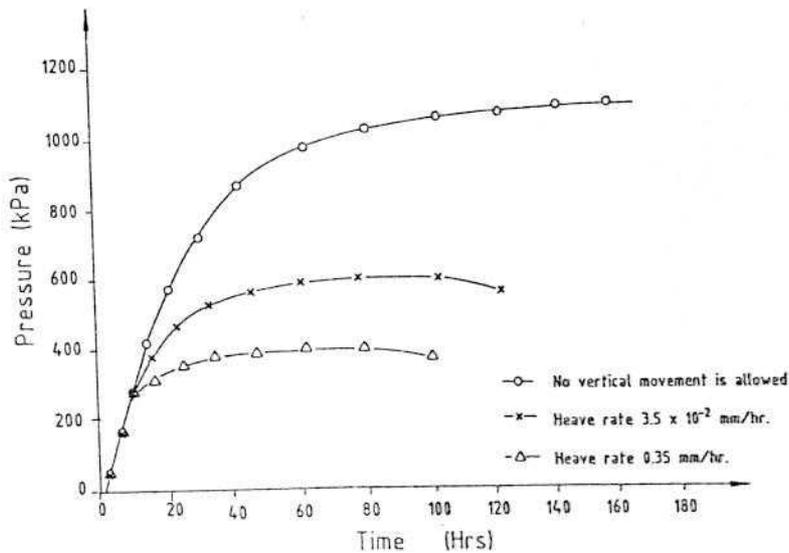


Fig. 10. The effect of heave rate on swelling pressure

## GEOTECHNICAL FEATURES OF SABKHA

Sabkha soils are distinguished by their heterogeneous nature and the presence of concentrated brines in their matrix. The highly variable nature of sabkhas is evidenced in terms of grain size and shape, texture, degree of cementation, diagenetic minerals, layering, etc. These soils generally exist in the form of alternating cemented and uncemented layers, as well as in the form of lumps of quartz and/or carbonate sand. In the cemented layers, the main cementing materials vary according to the location and the prevailing ambient conditions. Fig. 11 shows the subsurface soil conditions of a sabkha site located in Ras Al-Ghar region, eastern Saudi Arabia. The soil profile consists of a surficial layer of loose, brown, fine to medium sand with salt crystals. This layer is characterized by low SPT values and the presence of high moisture coupled with salt pockets of very soft diagenetic minerals. This layer is underlain by a rock salt layer with high SPT values. The retrieved salt samples had a bright color and were composed of pure halite. The bottom layer is characterized by the presence of light, gray, calcareous sand which increases in density with depth.

The sabkha sediments are predominantly composed of cemented silica sand. X-ray diffraction analysis indicated that sabkha sediments are mainly quartz (49%) cemented with halite (23%), calcite (21%), gypsum (6%) and traces of clay and iron oxides. Scanning electron microscopy (SEM) was carried out on undisturbed samples of sabkha. Fig. 12 shows a microphotograph at split mode magnification of 150/900X which depicts a columnar like halite porefilling the intergranular micropores. The quartz (Q) grain is cemented with halite (H) and slightly dissolved calcite/gypsum (C/G).

Several laboratory tests were conducted on disturbed and undisturbed samples of the surficial sabkha soil according to standard ASTM procedures. The average values for the natural moisture content and dry density were 17% and  $1.6 \text{ Mg/m}^3$ , respectively. A wet grain size analysis was conducted using the natural groundwater (sabkha brine). The classification of sabkha according to the unified soil classification system is SW-SP. Due to the unsaturated characteristics of surficial sabkha sediments, the total suction was measured using two different

techniques. The first technique was based on the filter paper method (McKee, 1981; Abduljawad and Al-Sulaimani, 1993) and the second one by using the transistor psychrometer (Woodburn et al., 1993). Both techniques gave the same value of 5.7 PF (where PF = log (centimeters of water)) or approximately 50 MPa. A matric suction of 1.5 PF, or about 3 kPa, was measured using the filter paper technique, suggesting a value of about 50 MPa (5.7 PF) for the osmotic suction. This indicates that the osmotic suction is several orders of magnitude larger than the matric suction and will be the important state variable which describes the behavior of sabkha. This reveals that large forces may be generated by hydration of the salts in very dry sabkha. Miller and Nelson (1993) presented interfacial thermodynamics and micromechanical equilibrium in a colloidal system to illustrate the fundamental roles of matric, osmotic and total suction in the stress state and volume change behavior of unsaturated soils. On the basis of their results, it was hypothesized that osmotic suction constitutes an additional stress on the soil and can be treated as an independent stress state variable particularly for soils with high salt concentrations like sabkha.

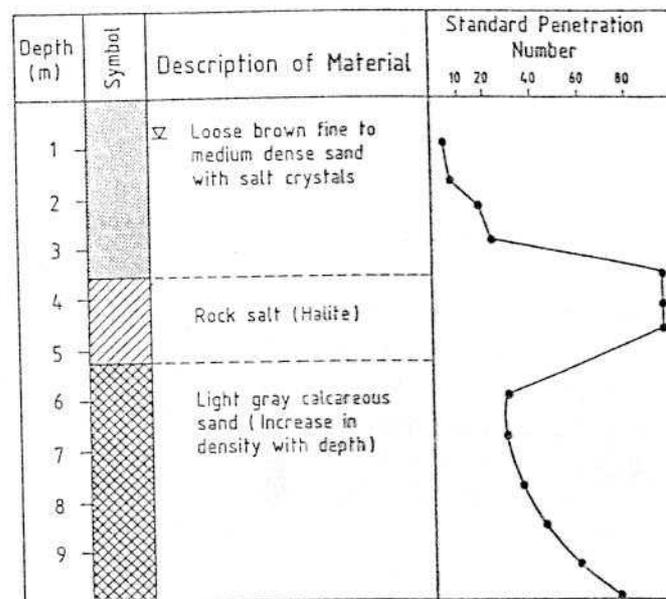


Fig. 11. Subsurface soil conditions

The retrieved undisturbed sabkha samples were subjected to a set of tests to assess the compressibility and collapse potential of sabkha in accordance with ASTM D 2435 using a fixed-ring oedometer. In all tests, the specimens were first loaded to the overburden pressure at the natural moisture content then flooding or leaching took place for a period sufficient for the settlement to cease. The leaching phase of these tests required permeating distilled water through the specimens. This was achieved by modifying the conventional oedometer to permit water percolation through the specimens under a constant head of 3.6 cm by providing inlet and outlet valves for the water supply and the overflow of excess water (Abduljawad and Al-Amoudi, 1995). Two holes were made under the bottom porous stone from which percolating water can be collected using a graduated cylinder. Fig. 13 shows the test results in the form of the void ratio ( $e$ ) versus the logarithm of vertical total stress ( $\sigma_v$ ) plot. The preconsolidation pressure for the natural sample was determined as 320 kPa. This high value might be attributed to the combined effect of desiccation, cementation and aging. The preconsolidation pressure for the soaked and leached samples are 180 and 80 kPa,

respectively. This is an indication that dissolution of salts and leaching of the cementing material caused a major reduction in the overconsolidation ratio of the tested samples.

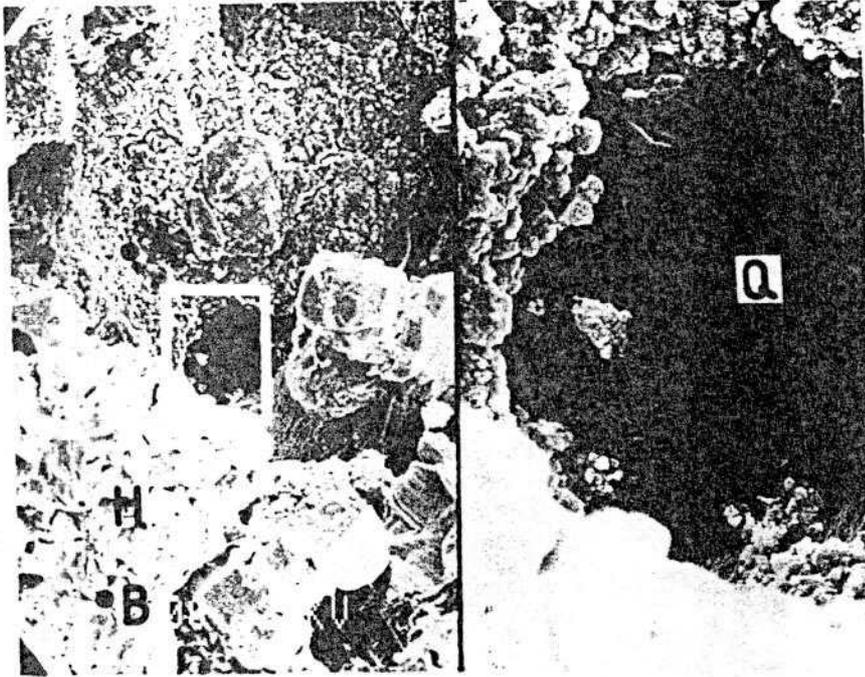


Fig. 12. SEM microphotograph for natural undisturbed sabkha sample

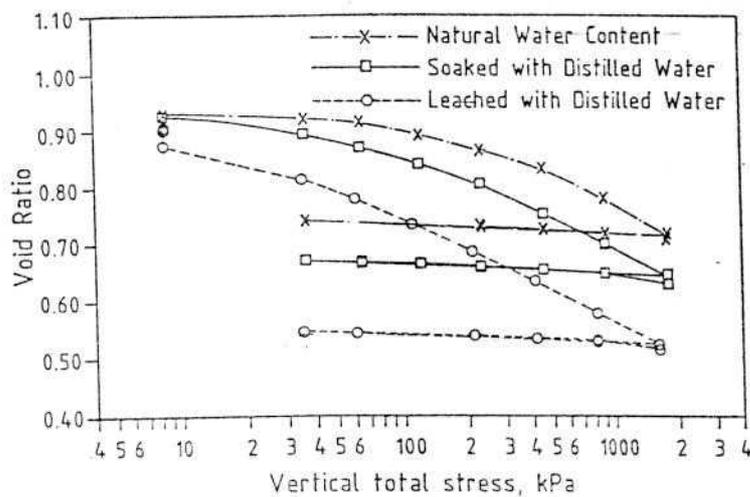


Fig. 13. Natural sample and samples soaked and leached with distilled water

Samples tested at their natural moisture content and thereafter soaked with or leached by water can be used to predict the magnitude of collapse over a wide range of pressures. The curves for the soaked samples are lower than the ones tested at their natural moisture content. A sharp reduction in the void ratio was observed for the samples through which percolation of water (leaching) was permitted. The collapse potential for samples soaked or leached with distilled water at a pressure of 1800 kPa are 4.2% and 10.4%. It can be observed that the

major collapse of sabkha occurs only when it is exposed to percolation by water that has the ability to dissolve the natural cementation. The SEM microphotographs for the sample leached with distilled water showed that all cements, including the easily soluble halite, gypsiferites and calcarenites, were completely destroyed or washed away with the percolating water. After loading, the quartz grains are covered by a thin loose mat of illitic clay (IC) (Fig. 14).

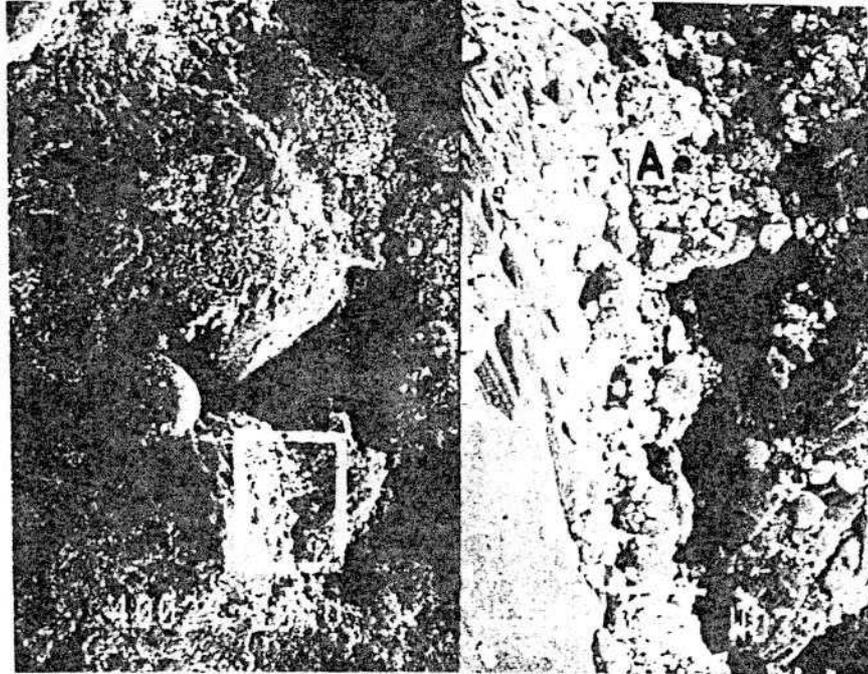


Fig. 14. The structure of sample leached with distilled water

Two plate load tests were conducted at the Ras Al-Ghar sabkha site: (i) at the natural condition, and (ii) while leaching with water. A 460 mm diameter plate was placed at a depth of 40 cm in an excavated test pit with a diameter of about 4 times the diameter of the plate. Small trench was excavated around the plate and water was poured in the trench from a tank through plastic hoses. Tests were conducted in accordance with ASTM D 1194. The results shown in Fig. 15 reveal that leaching the sabkha with water reduced the bearing capacity and increased settlement at all applied pressures. The bearing capacities estimated by the intersecting tangent methods were found to be 100 kPa and 70 kPa for natural conditions and leaching with water, respectively. The reduction in bearing capacity was 30% when the sabkha was leached with water.

## CONCLUSIONS

1. The arid climate, the geology and the environmental conditions in Saudi Arabia have produced a wide distribution of unsaturated soils, including both expansive and collapsing saline sabkha soils.

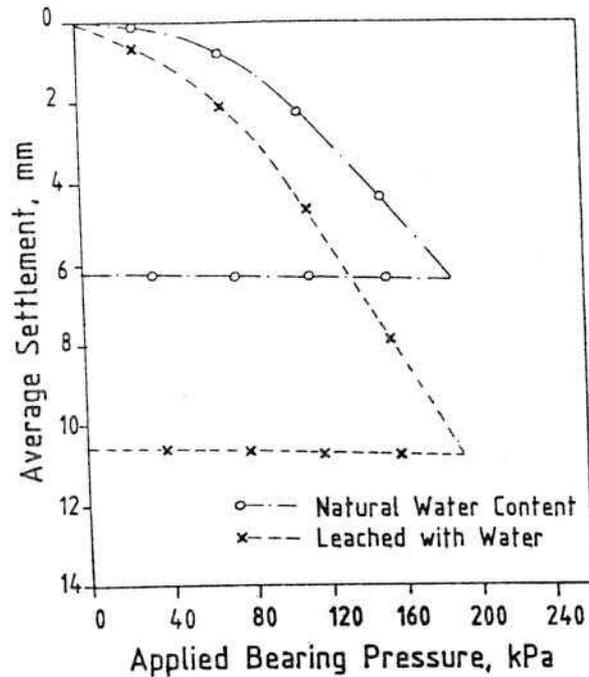


Fig. 15. Results of plate load test

2. Measurement of soil suction can significantly help in the evaluation of the behavior of unsaturated soils. Heave predicted based on the change of matric suction was better than the other methods, while osmotic suction was useful to study the large forces generated in sabkha soil due to hydration of salts.
3. The controlling heave rate test indicated that a very slight vertical movement will have a significant effect on swelling pressure.
4. Soaking the sabkha with distilled water caused a small collapse potential while leaching it with the same water produced a severe collapse potential.
5. The percolation of distilled water and leaching of salts lead to breakdown of the crystalline and cementation bonds and produce irreversible structural changes in sabkha microstructures that result in residual deformation of considerable magnitude. This is due to the large reduction in osmotic suction and dissolution and leaching of the natural cement that holds the quartz grains together.

#### ACKNOWLEDGEMENTS

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