# Geotechnical Characteristics of Salt-Bearing Soils in Kuwait

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Salt-bearing soils exist along the shorelines of Kuwait and the Persian Gulf states. Many areas inland are also covered by these sediments, which are locally called "Sabkha." The geotechnical properties and behavior of these soils were examined by a comprehensive field and laboratory testing program. The program included penetration tests, sampling, basic properties, consolidation and triaxial tests at two locations within one site in Doha, Kuwait. In addition, plate load tests were conducted using a 0.3-m diameter plate to determine the bearing capacity. The variation of the soil properties with depth was assessed. Test results indicate that a cemented crust develops at ground surface because of the arid climate, which causes continuous evaporation and precipitation of salts in the soil matrix. Below this crust, the soil remains loose with low strength. Sabkha consists of loose gypsiferous fine sandy silt with little clay. It has lower specific gravity and higher moisture contents than other granular soils. Sulphates exceed 60 percent of the soil composition at ground surface and decrease sharply with depth. Consolidation and triaxial tests indicate increased compressibility and decreased strength with depth. The static cone penetration values ranged from 200 to 600 kPa for the point resistance and 0 to 150 kPa for the frictional resistance. The bearing capacity varied from 40 to 50 kPa at 0.3 m depth with a higher value at the ground surface. The problems associated with these soils, including volume changes, corrosive behavior, and low strength, are discussed.

Salt-bearing soils extend along the coastline of Kuwait and the Persian Gulf states as well as throughout the Middle East, Central Asia, the western coast of South America, and parts of the United States. This soil is locally called "Sabkha," which defines coastal flat areas that extend above the high-tide level and are covered by evaporate-rich clastic sediments (*1*). Due to the high salinity of the near-surface ground water and the excess of evaporation over rainfall, salts (particularly gypsum, chlorides, and carbonates) are precipitated in the surface layers, leading to salt crusts. Under dry conditions, the Sabkha provides an excellent running surface for wheeled vehicles, but under high water table conditions, or as a result of heavy rainfall, the soluble salts dissolve and the surface becomes impassable (*2*). Vehicles can break through the surface crust, but they are then up to their axles in liquid mud (*3*).

Several geological studies were conducted on these deposits to determine origin and deposition (*4,5*). The damage to bituminous-paved roads following construction on these soils has long been well recognized (*6*). The problems associated with volume changes due to dehydration of gypsum at high temperatures followed by rehydration in the presence of water are documented (*7*). Parameters for pavement design purposes were determined recently by field and laboratory tests on these soils (*3*). However, there is no detailed or comprehensive geotechnical investigation of the properties and the characteristics of these deposits that provides a clear understanding of their behavior under load. Such an understanding is essential to design and construct structures on these soils and to improve or stabilize soil if necessary.

With the presence of these deposits in areas of potential development in Kuwait, such as Al-Subbiyah, Al-Doha, and Al-Khiran (Figure 1), an extensive field and laboratory testing program was conducted at the site of the proposed Olympic village in Doha, Kuwait. The work included sampling, classifications, static and dynamic cone penetration tests, basic properties, chemical analyses, and consolidation and triaxial tests on undisturbed samples. Plate load tests were also performed using a 0.3-m diameter plate. Other tests involving laboratory and field leaching tests are included in a separate paper (*8*).

In this paper, the author presents and discusses the field and laboratory test results, emphasizing the special and unique geotechnical characteristics of salt-bearing soils. The change of the soil properties with depth is noted and discussed, as is the influence of environmental factors on the soil properties.

## SITE CHARACTERIZATION

The testing site location in Doha, Kuwait, and the locations of major Sabkhas in Kuwait are shown in Figure 1. Two points within the site located along a line 2.9 km from the shoreline and spaced 400 m apart were selected for the detailed soil investigation. At each location, one hollow stem auger boring was advanced to a depth of 9 m. Standard penetration tests and linear samples were taken at 0.5 m intervals to a depth of 4 m and at 1 m intervals below this depth. Another boring was drilled nearby to obtain undisturbed thin-walled Shelby tubes at the different depths in the boreholes. The field tests included dynamic and static cone penetration tests (CPTs) at two points 3 m apart in the vicinity of the boreholes. To carry out the tests, the Dutch cone penetrometer conversion kit was used. The kit easily converts the CME 750-XL drill rig to a mechanical Dutch cone penetrometer tester. Details of the test procedure can be found elsewhere (*9*).

The soil conditions at the two test locations are summarized in Figures 2 and 3. The soil profile consists of a surface layer of loose gypsiferous fine sandy silt with a little clay (Sabkha) to a depth of 2.5 m. This is underlain by silty clayey sands, sands, and silty sands to the bottom of the boreholes. The

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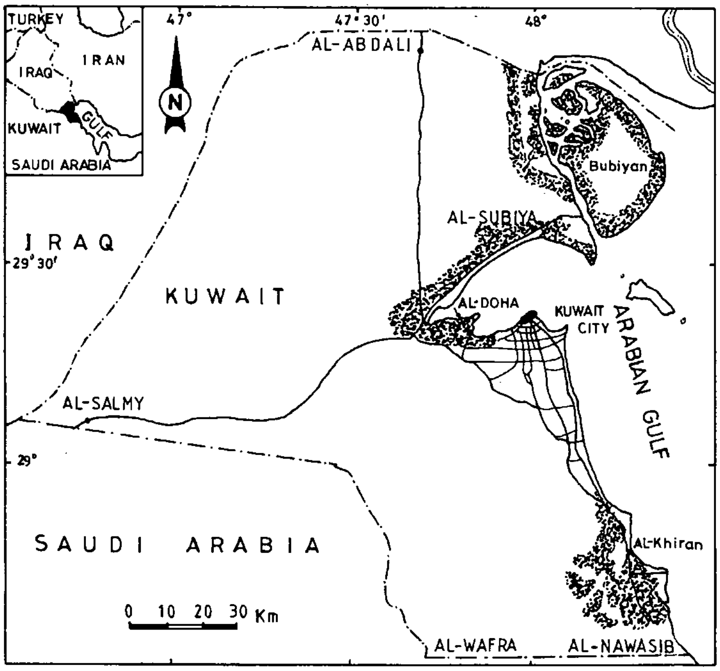

FIGURE 1 Map of test site and location of Sabkhas in Kuwait.

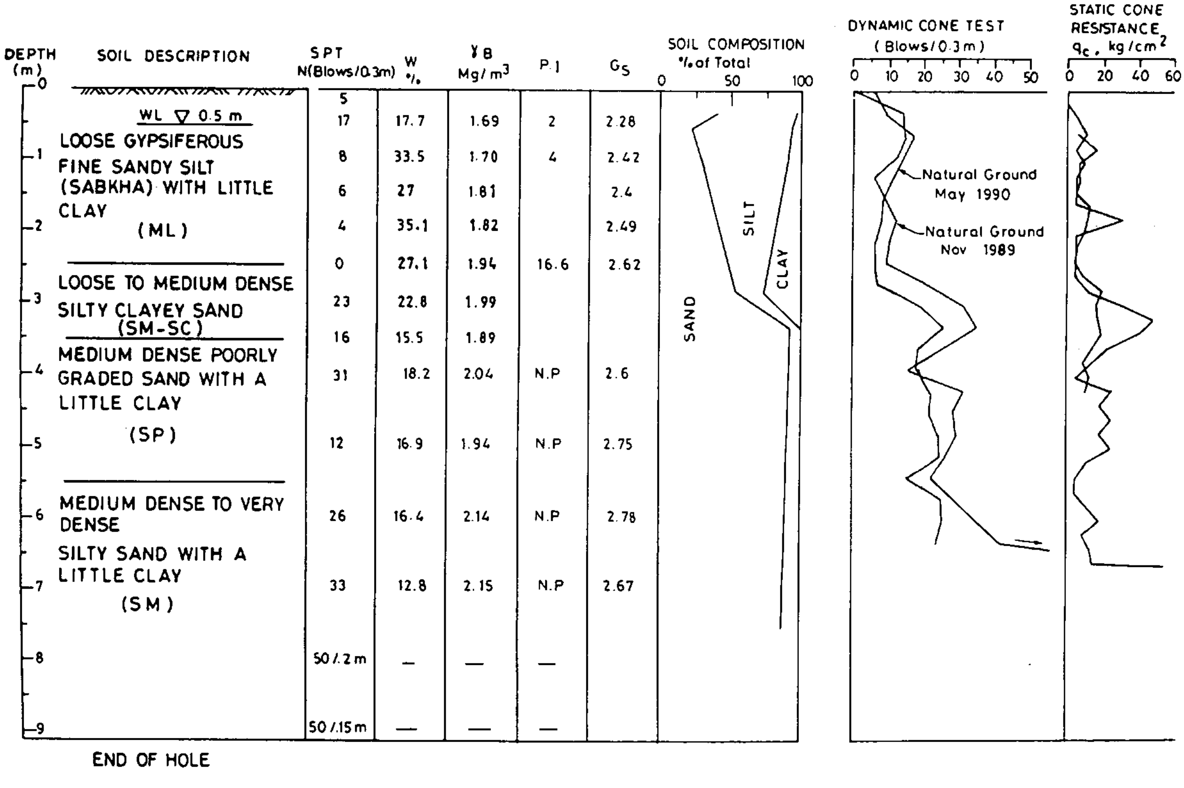

FIGURE 2 Soil conditions at test site—Borehole 1 (*8*).

upper layer contains lenses of gypsum, particularly near the ground surface. Groundwater was encountered at a depth of 0.5 m below the ground level.

A close examination of Figures 2 and 3 reveals that the upper layer has lower specific gravity and a higher moisture content than most granular soils. The specific gravity ranges from 2.3 to 2.5, and the moisture content varies up to 35 percent. The dynamic penetration resistance with depth indicates a hard salt crust up to a depth of 1.0 m, followed by low penetration resistance to the bottom of the layer. A similar tendency is visible in the static cone penetration resistance measurements, which are shown in Figure 3. These low values range from 200 to 600 kPa for the point resistance ($q_c$), and 0 to 150 kPa for the frictional resistance ($f_s$).

Figure 4 shows the main soil components as determined from the chemical analysis on the samples of Borehole 1. As

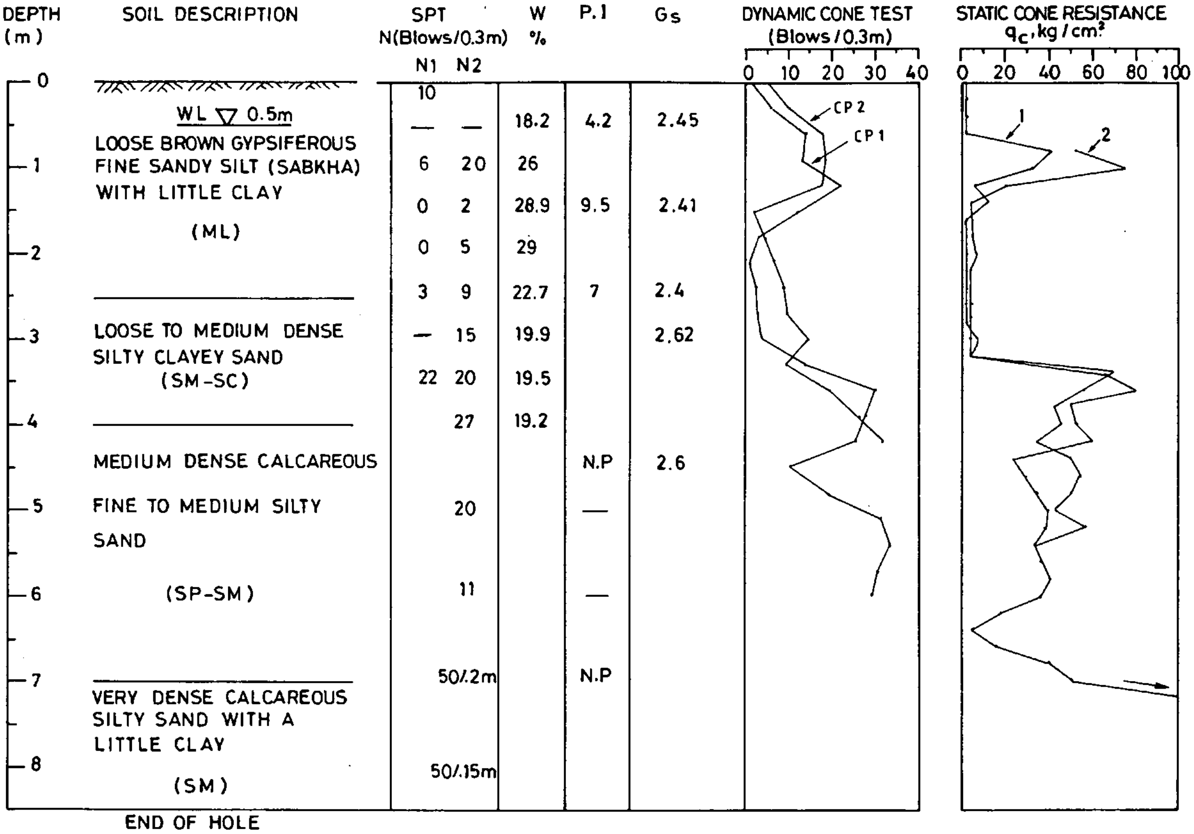

FIGURE 3 Soil conditions at test site—Borehole 2.

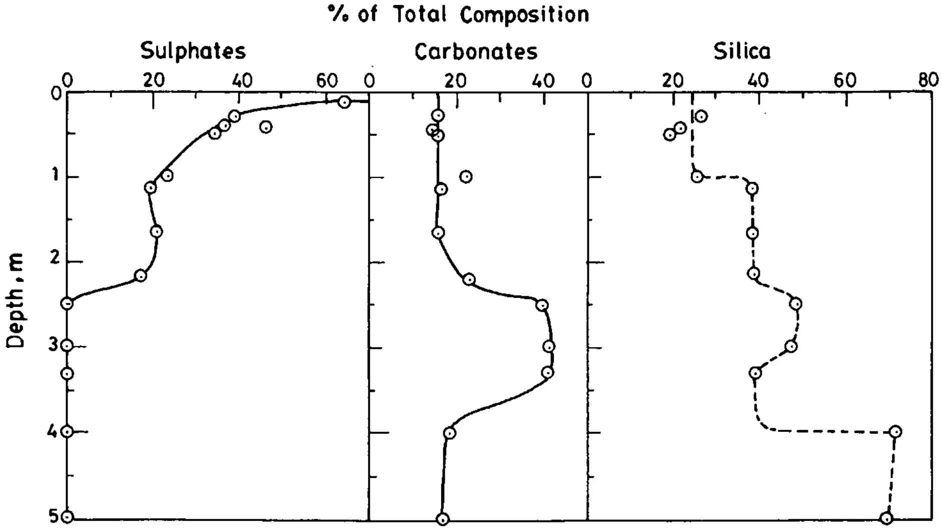

FIGURE 4 Main components of Sabkha as determined from chemical analysis (8).

shown, sulphates exceeded 60 percent of the soil composition at ground surface and decreased sharply with depth, reaching 20 percent at a depth of 1 m and zero at a depth of 2.5 m. Carbonates consisting mainly of calcium carbonate ranged from 15 to 20 percent in the upper layer. Silica constituted 25 percent, increasing to 40 percent below a depth of 1 m.

The presence of sulphates affects the behavior of salt-bearing soils (*8*). The sulphates consist of either gypsum or anhydrite. The main difference between the two minerals is that gypsum has two weakly bound molecules of water, whereas anhydrite has no such molecular water (*7*). The properties of gypsum and anhydrite are summarized in Table 1. The molecular water in gypsum is unstable and at high temperature dehydrates to form anhydrite. A volume decrease of 39 percent occurs with this reaction if the molecular water evaporates. The hydration of anhydrite results in a 63 percent volume increase.

One of the more interesting characteristics of salt-bearing soils is the influence of the drying temperature in the laboratory on the moisture content and other basic properties. Oven drying the gypsum soils tested at 60°C or using a vacuum desiccator and a temperature ranging from 23°C to 60°C for drying in accordance with ASTM D2216 brings identical results. However, drying at temperatures from 80°C to 110°C results in significant loss of hydrated water and large moisture contents. Drying also affects other properties, including specific gravity and Atterberg limits. The values shown in Figures 2 and 3 were obtained for samples that were oven dried at 60°C. It is interesting to note that one way to find the thickness of these deposits is by determining the moisture contents by oven drying the soil at temperatures of 60°C and 110°C. The layer ends where there is no difference in the moisture content obtained from the two methods. This is shown in Figure 5 where the variation of the moisture content and the specific gravity are plotted for samples from Borehole 1. At a depth of 2.5 m, the moisture content is the same for the drying temperatures of 60°C and 110°C, indicating the end of the gypsum deposit.

Wherever possible, the soils used for Atterberg limit tests should not be oven dried at temperatures exceeding 60°C before testing. Higher liquid and plastic limits are obtained from oven drying gypsum and tropical soils at high temperatures compared with air drying preparation. A 30-percent increase, for both liquid and plastic limits, is measured from tests on the present soils. Conversely, lower liquid and plastic limits are usually associated with oven drying organic soils.

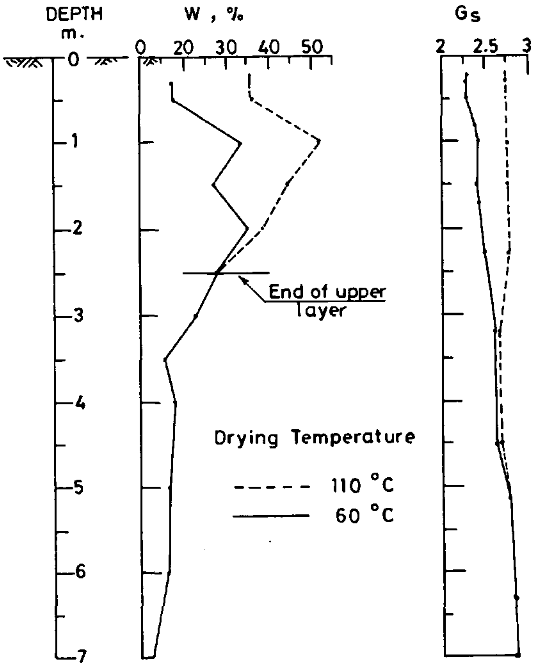

**FIGURE 5 Moisture content and specific gravity with depth—Borehole 1.**

The preceding results emphasize the importance of the drying temperature on the properties of salt-bearing or gypsum soils. Oven drying at a high temperature also causes the soil particles to subdivide, changing the grading characteristics of these soils. Figure 6 shows the grain-size distribution curves of two natural samples taken at a depth of 0.3 m from Borehole 1. One sample was air dried, whereas the second was oven dried at a temperature of 110°C prior to sieving. The difference in the grading curves for these samples is significant.

**TABLE 1 Properties of Gypsum and Anhydrite (*7*)**

| | Gypsum ($CaSO_4H_2O$) | Anhydrite ($CaSO_4$) |
|---|---|---|
| % $CaSO_4$ (by weight) | 79.1 | 100 |
| Mohs Hardness | 1.5 - 2 | 3 to 3.5 |
| Specific gravity | 2.3 to 2.4 | 2.92 to 2.98 |
| Weight kg per $m^3$ | 2,250 to 2,400 | 2,885 |
| Crystal system | Monoclinic | Orthorhombic |
| Dilute HCl | Soluble without effervescence | Slightly soluble without effervescence |
| At temperatures above 42°C | Converts to hemihydrate or anhydrite | No reaction |
| At temperatures below 42°C | No reaction | Converts to gypsum in the presence of water |

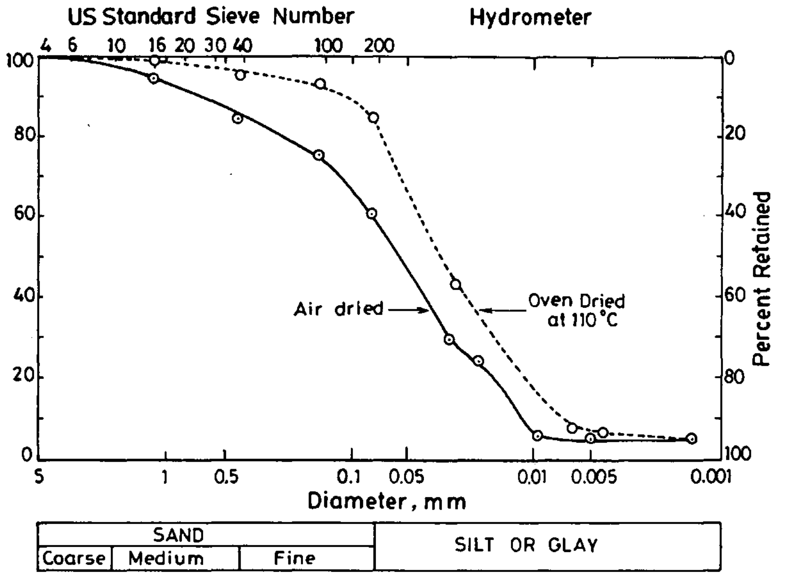

**FIGURE 6 Grain-size distribution curves—Borehole 1 (depth = 0.3 m).**

## CONSOLIDATION TEST RESULTS

Consolidation tests were conducted on undisturbed samples from Boreholes 1 and 2 to determine the compressibility characteristics of the upper salt-bearing layer. The specimens were 71.8 mm in diameter and 20 mm in height. Initially all specimens were saturated with fresh water and seated under a pressure of 2 kPa. The *e* log *p* plots for samples from Boreholes 1 and 2 are shown in Figures 7 and 8, respectively. The consolidation and strength parameters are summarized in Table 2. An examination of Table 2 and Figures 7 and 8 reveals that both the compression index ($c_c$) and the swelling index ($c_s$) increase substantially with depth in the upper layer. The increase in $c_c$ is nearly twofold, with a magnitude of 0.11 at the sampling depth of 0.3 m increasing to 0.2 at a depth of 1.5 m. The corresponding values of $c_s$ are 0.01 and 0.015, respectively. If the ratio $c_c/(1 + e_o)$ is considered as an index of compressibility, this ratio was 0.058 to 0.059 at a depth of 0.3 m and increased to 0.099 at a depth of 1.5 m. This is nearly a 70 percent increase in compressibility within the layer. Results on samples from Borehole 2 are similar to those from Borehole 1. However, tests in the upper layer were conducted on samples at a depth of only 1.5 m. Other samples tested from this borehole were taken from a depth of 4.5 m in the lower medium-dense calcareous silty sand layer.

These findings and the penetration resistance shown in Figures 2 and 3 indicate that a harder cemented crust usually exists in the upper half to 1 m of these deposits, which is

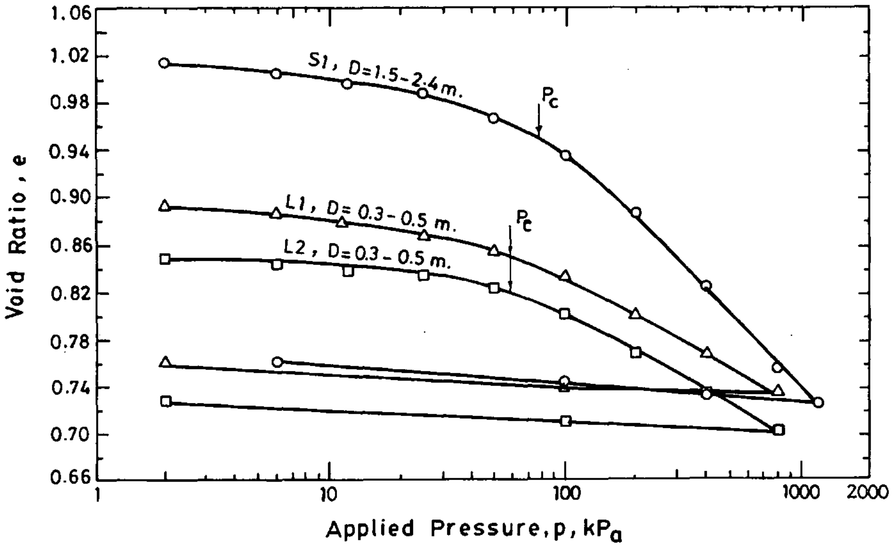

**FIGURE 7 *e* log *p* curves for samples from Borehole 1.**

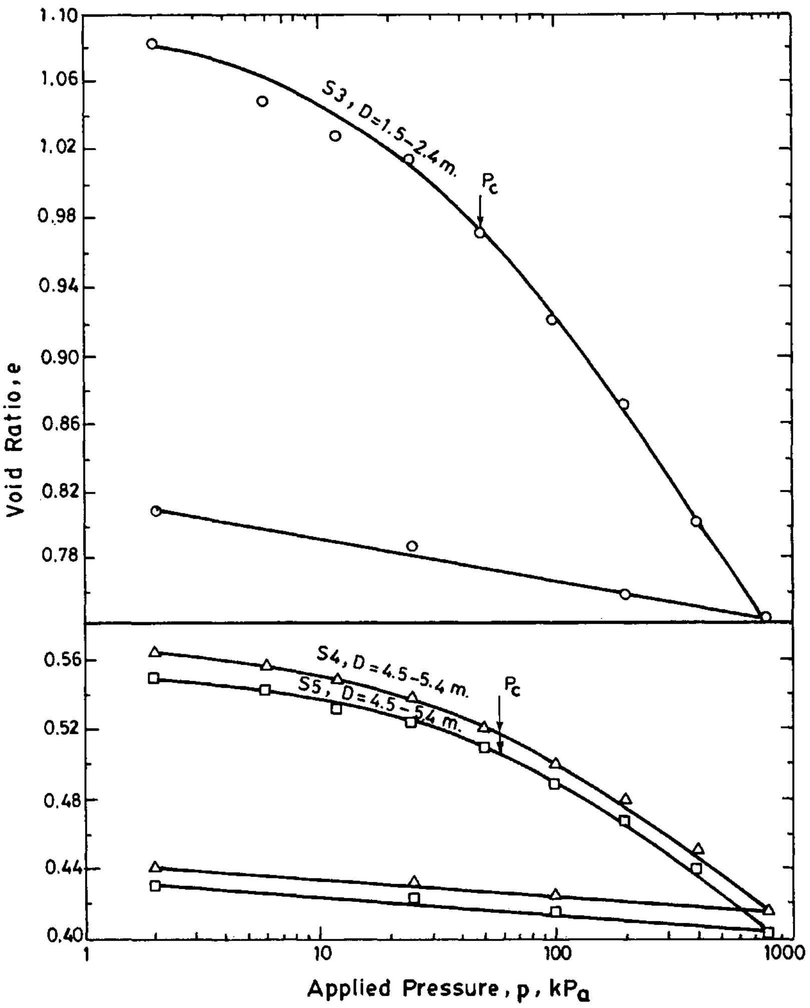

**FIGURE 8** *e* log *p* curves for samples from Borehole 2.

**TABLE 2** Summary of the Consolidation and Strength Parameters

| Bore-hole No. | Sample Type | Depth m | $\gamma_B$ Mg/m³ | W (%) | $\gamma_d$ Mg/m³ | $e_o$ | $P_c$ kPa | $C_c$ | $C_s$ | $C_c/1+e_o$ | c′ kPa | φ°′ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 35 | $L_1$ | 0.3-0.5 | 1.693 | 19.6 | 1.42 | 0.893 | 60 | 0.11 | 0.01 | 0.058 | 20 | 37 |
| 35 | $L_2$ | 0.3-0.5 | 1.804 | 24.5 | 1.45 | 0.849 | 60 | 0.11 | 0.01 | 0.059 | 20 | 37 |
| 35 | $S_1$ | 1.5-2.4 | 1.909 | 43.6 | 1.33 | 1.016 | 80 | 0.2 | 0.015 | 0.099 | 0 | 28 |
| 36 | $S_2$ | 0-0.8 | 1.76 | 23.0 | 1.43 | -- | -- | -- | -- | -- | 20 | 37 |
| 36 | $S_3$ | 1.5-2.4 | 1.84 | 43.2 | 1.28 | 1.086 | 50 | 0.22 | 0.020 | 1.055 | 0 | 13 |
| 36 | $S_4$ | 4.5-5.3 | 2.09 | 21.5 | 1.72 | 0.564 | 60 | 0.10 | 0.01 | 0.064 | 0 | 36.9 |

L Pushed Liner

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-- Not Measured

usually above the groundwater level. This is due to the abundance of sulphates in the form of gypsum close to the ground surface. Below this zone, the deposit is much softer and more compressible with virtually little or no penetration resistances as evident in Figures 2 and 3. After continuous flooding by heavy rain, soluble salts dissolve and leach down, and the upper crust becomes softer and more compressible (*8*).

## STRENGTH PARAMETERS

Consolidated, undrained triaxial tests with pore pressure measurements were conducted on undisturbed samples from Boreholes 1 and 2. The testing program was implemented using a fully computerized triaxial testing system supplied by Engineering Laboratory Equipment Limited, England in accordance with the procedure described by Bishop and Henkel (*10*). The specimens with nominal dimensions of 71.8 mm diameter and 150 mm length were saturated with fresh water under an incrementally applied back pressure of 200 kPa. The sequence of isotropically applied consolidation pressures was 50, 100, 200, 300, and 400 kPa. End and radial drainage was allowed by using porous stones and filter paper strips, respectively. The specimens were left for 24 hr under the full back pressure of 200 kPa and a slightly elevated cell pressure of 205 kPa. This precautionary measure was adopted to eliminate the chances of possible collapse of the specimens. It was followed by an application of isotropic consolidation pressure. Earlier, a saturation check performed on each specimen indicated that the degree of saturation was 98 to 100 percent. After full consolidation was ensured, the specimens were sheared at a strain rate of 4 percent per hour under undrained conditions. Correction was applied for the rubber membrane using the method suggested by Bishop and Henkel (*10*).

Results of the triaxial tests (Figure 9) show the stress strain curves and pore pressure versus axial strain curves for samples from Borehole 1 at a depth of 0.5 m. Figure 10 shows the effective stress path and failure envelope for the same samples on a *q-p* plot. The cohesion ($c'$) and angle of shearing resistance ($\phi'$) were determined from Figure 10 as (20 kPa, 37°). The presence of a small cohesion intercept is typical of cemented sands in the area. However, the presence of a large concentration of gypsum near the surface of this deposit leads to nonhomogeneity and some variations in the measured strength characteristics for points in the vicinity of each other at the same depth. Other measurements made (*8*) indicated strength parameters of (0, 36.5°).

The strength envelope for samples from Borehole 1 at a depth of 1.5 m is superimposed in Figure 10. It indicates strength parameters of (0, 28°). The lower strength is obtained from similar samples in Borehole 2 (Table 2). Thus, softer conditions exist below the surface crust in the zone located permanently below the groundwater level. These results are compatible with the dynamic penetration resistance plotted in Figures 2 and 3, indicating a surface crust of 1 m with high penetration resistance reaching 15 to 20 blows/0.3 m underlain by softer ground with low penetration resistance.

Because the water level is located 0.5 m below ground at the time of the measurements (November) and considering tidal and seasonal fluctuations, it is evident that the portion of this deposit located permanently below the groundwater level—approximately 1 m deep—remains soft and experiences no cementation, in contrast to the surface zone. The surface crust, displaying higher strength and lower compressibility in the dry season, becomes softer and weaker upon wetting.

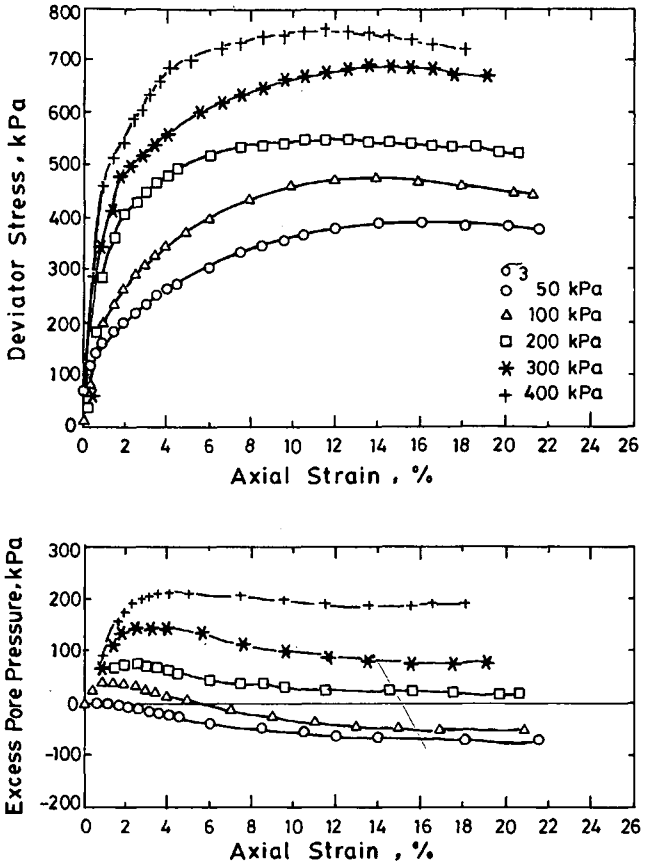


**FIGURE 9 Stress and pore water pressure versus axial strain from consolidated undrained triaxial tests—Borehole 1.**

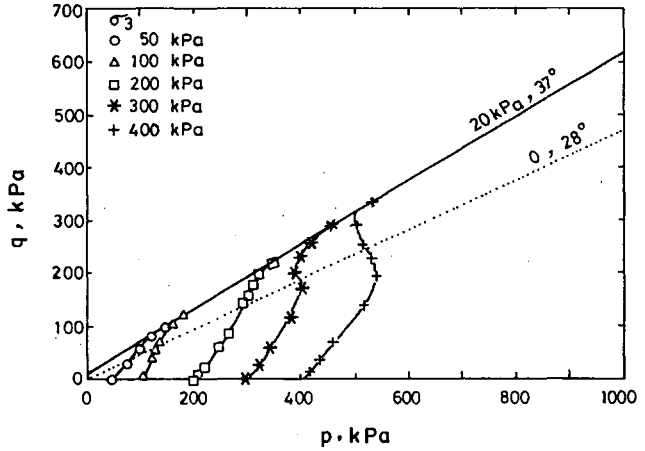


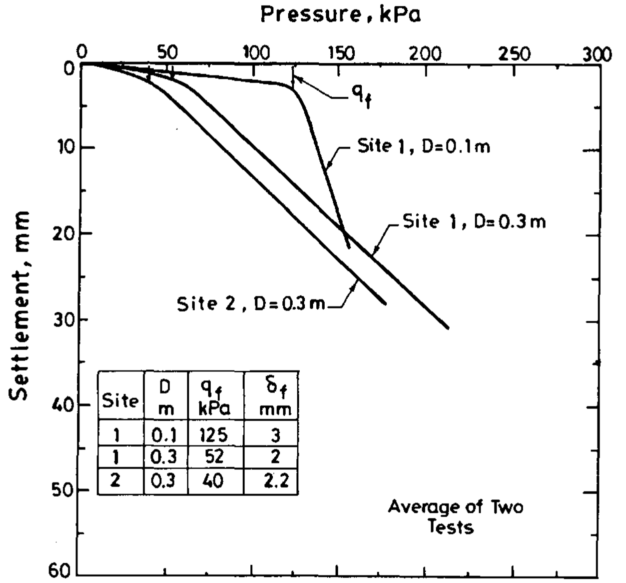
**FIGURE 10 Effective stress path and failure envelopes for two samples from Borehole 1.**

## BEARING CAPACITY

Plate load tests were conducted at the sites of Boreholes 1 and 2 to examine the bearing capacity of the near-surface Sabkha. A circular steel plate 0.3 m in diameter and a 10-ton hydraulic jack attached to a hand pump were used for the tests. A calibrated pressure gauge was connected to the pump, and equal load increments of 10 kPa were applied to the plate. The weight of the CME 750-XL drill rig was sufficient to provide a reaction. Each load increment was maintained for at least 15 min and until all settlements had ceased. Settlements were measured by three dial gauges attached to the plate from a reference beam. Each test was repeated at least once to ensure accuracy and consistency of the test data.

The test results are plotted in Figure 11 in the form of pressure-settlement curves. Each curve is the average of two plate load tests. Because the failure load was not well defined, the slope tangent method was used to determine this load, denoted by $q_f$. The failure loads were determined as 52 kPa and 40 kPa at Sites 1 and 2, respectively, at a depth of 0.3 m. The corresponding settlements were 2 mm and 2.2 mm, respectively. Tests at Site 1 (at a very shallow depth of 0.1 m) resulted in a higher bearing capacity of 125 kPa, which occurred at a settlement of 3 mm. The pressure-settlement curve at this depth (Figure 11) indicates a well-defined failure, followed by a large settlement caused by the breaking of the plate through the upper highly cemented crust. Punching failure was clearly evident below the plates in all tests.

The preceding results indicate a low bearing capacity for the salt-bearing soils at the test site. Considering the results of the unconfined compression strength tests that indicated an average undrained shear strength ($c_u$) of 25 kPa within a depth of 1.5 m, it is evident that failure occurs under undrained conditions. Furthermore, the measured bearing capacity is less than that calculated by the bearing capacity theory due to the high compressibility of the soil and the occurrence of punching shear failure.



| Site | D<br>m | $q_f$<br>kPa | $\delta_f$<br>mm |
|---|---|---|---|
| 1 | 0.1 | 125 | 3 |
| 1 | 0.3 | 52 | 2 |
| 2 | 0.3 | 40 | 2.2 |

**FIGURE 11 Pressure-settlement curves for 0.3-m diameter plates.**

The lack of homogeneity of the deposit near the ground surface is reflected by the decreasing bearing capacity with depth in the upper crust. The bearing capacity decreased from 125 kPa at a depth of 0.1 m to 50 kPa at a depth of 0.3 m. This is due to the cementation caused by the large salt concentration at ground level (Figure 4).

## SPECIAL CHARACTERISTICS

The presence of a large concentration of salts in these soils raises questions as to the influence of leaching soluble salts on their properties and behavior. A program of field and laboratory tests was carried out recently to investigate this problem (*8*). Identical undisturbed samples were taken from a depth of 0.3 m and tested before and after leaching. The results indicated that leaching led to reduced unit weight, plasticity, and specific gravity, and to increased permeability and void ratio. Leaching also resulted in increased compressibility and reduced shear strength. Field plate load tests and dynamic CPT before and after leaching by fresh water indicated a reduction in the bearing capacity of 40 to 50 percent and penetration resistance within a shallow depth of 1 to 1.5 m. However, no visible change was recorded below this depth (*8*).

Many other problems are associated with these soils and should not be underestimated. These problems include dehydration and volume decrease, which occur in the summer at high temperatures, and hydration and volume increase in the winter due to rain and the presence of water. Temperatures often exceed 50°C during July and August in Kuwait, thus initiating the process of dehydration.

The corrosive reaction of these soils should also be dealt with carefully if any concrete or steel structures are placed on it. Sabkha is not considered a suitable soil for backfilling, and foundations should not placed in direct contact with it. Moreover, foundations should be coated with a bituminous binder or other suitable inert material to prevent deterioration of concrete and corrosion of steel due to the aggressive action of salts in the soil and groundwater (*11*).

For locations that have deep deposits of Sabkha, driven piles may be necessary, particularly for multistory structures and heavy axial loads. The piles will develop their support from point resistance in the underlying competent deposits.

## CONCLUSIONS

A program of field and laboratory tests were conducted to establish the basic properties and behavior of salt-bearing soils in Kuwait. On the basis of the test results, the following conclusions and recommendations were reached:

1. The soil investigated is loose, gypsiferous sandy silt of low plasticity. It extends from ground surface to a depth of 2.5 m at the test site.
2. A hard surface crust occurs to a depth of 1 m. Below this crust, the deposit remains soft and compressible.
3. Salt-bearing soils are characterized by low specific gravity and large moisture contents. They are generally loose,

having low penetration resistance, except for the upper surface crust.

4. Salt-bearing soils are sensitive to the method of drying used to perform the laboratory tests. It is recommended that salt-bearing or gypsum soils be oven dried at 60°C or with a vacuum desiccator at a temperature from 23°C to 60°C.

5. Cementation of a surface crust leads to increased shear strength and decreased compressibility above the groundwater level.

6. Salt-bearing soils (Sabkha) have low bearing capacity. The values measured were 40 to 50 kPa at a depth of 0.3 m.

7. Several environmental factors affect the properties and behavior of salt-bearing soils. Leaching of soluble salts causes loss of strength and increased compressibility. Volume changes resulting from dehydration at high temperatures followed by hydration in the presence of water are undesirable conditions for construction.

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*Publication of this paper sponsored by Committee on Soil and Rock Properties.*