PROPERTIES AND BEHAVIOR OF ARID CLIMATE SOIL DEPOSITS IN KUWAIT

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ABSTRACT

The properties and behavior of natural soil deposits in Kuwait and their spatial variability are examined. These deposits include the windblown surface dune sands, cemented sand (Gatch), and coastal salt bearing soils (Sabkha). Typical soil profiles from comprehensive site investigations are examined along with details of the basic properties, soil composition date, strength and compressibility with depth. The response of these deposits to structural loads, and their unique characteristics will be presented based on the results of plate load tests and the instrumentation monitoring data on recently completed structures. The volume changes occurring in these soils will be discussed and related to the environmental factors in arid lands, which affect the deposits mineral and chemical composition.

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INTRODUCTION

With major economic development in arid lands, and oil and mineral exploration, interest in the properties and behavior of the ground soils has intensified. Numerous environmental factors affect the characteristics of these soils and their response to structural loads. Among these factors are the hot weather during the long summer months which reduces the moisture content of near surface soils to very low values. The excess of evaporation over rain fall, even in the winter months, leads to upward movement of the ground water of high salinity, precipitation of carbonates, sulphates and other salts in the soil matrix and the formation of crusts or layers of cemented sands. The strong dry wind in the desert results in the formation of fine rounded or subrounded sand grains in the surface layers.

The three main soil deposits in Kuwait include surface windblown sands, cemented sands, and coastal salt bearing soils (Sabkha). Over the past 20 years these deposits were investigated in great detail, and their geotechnical properties and behavior were determined.

This paper presents a review the geotechnical properties, composition and natural spatial variability of these deposits. Emphasis is placed on the unique and interesting characteristics of each deposit, and the relation between the soil behavior and its density, moisture content, stress state, and composition.

SURFACE DESERT SANDS

The soil profile in Kuwait typically consists of a surface layer of windblown dune sand underlain by a more competent deposit of silty fine to medium sand known locally as gatch. The gatch is usually cemented with varying degrees of cementation. Below this layer limestone bedrock is encountered at a depth of 80 to 100 m in Kuwait city and suburbs.

The surface deposit varies in thickness from 0 to 7 m deep. The material is predominantly fine sand with some medium sand, no gravel, and very little fines. The percent of fines passing the No. 200 U.S. sieve ranges between 5 and 15% and on average it constitutes 10% of the total composition. The Unified Soil Classification designation of the majority of samples is SP $\rightarrow$ SM (dual classification of poorly graded sand to silty sand).

The physical properties of five selected samples from a test corridor, in Kuwait city, are summarized in Table 1 (1). The samples were taken from undisturbed block samples at a depth of 1.0 to 1.5 m where the soil displayed very slight cementation. This cementation is not real interparticle or structural cementation but rather a suction or water soluble cementation can be destroyed with slight disturbance or light hand pressure. Examination of Table 1 reveals that the subsoils are in a relatively dry condition with natural moisture contents below 2%, and degrees of saturation between 4 and 8%. The median grain diameter ranges between 0.14 - 0.16 mm, and the specific gravity varies between 2.67 and 2.72. The relative density averages nearly 60 to 70% indicating medium dense soil. The coefficient of permeability values were in the range of 10^{-3} to 10^{-4} cm/sec. indicating a free draining soil.

Chemical analysis was performed on the windblown sand specimens taken from a depth of 0.5 m at five sites. The tests were carried out on the natural samples, the coarse fraction only, and the fines fraction alone. A summary of the average values obtained for each component is given in Table 2. As shown both the natural samples and the coarse fraction consist predominantly of silica. However, the fines fraction is calcareous having approximately 40% silica, and 30% carbonates and sulphates. The composition data is highly important and will be used to explain the soil behavior later on.

The Standard Penetration Resistance 'N' values in this layer ranges between 10 and 35 and they generally increase in magnitude with depth. Typical soil profiles along a test corridor in Kuwait city are shown in Figure 1. Allowable pressures for foundations supported on this deposit generally range between 100 kN/m^2 - 300 kN/m^2 (1,2). Static cone penetration tests indicate that the average ratio q_c/N of the cone penetration resistance to the standard penetration values is 480 where q_c is in kN/m^2 (3).

One of the interesting characteristics of this layer is its sensitivity to saturation or ground wetting. In one out of four sites modest collapse occurs upon wetting (4, 5). This is more pronounced for compacted fill material at low and medium relative density. For compacted ground at high relative density, the material is not collapsible. The extreme desiccation and the poor gradation characteristics and the lack of fines to fill the voids make the soil matrix occasionally unstable and susceptible to deformation and collapse upon wetting.

Figure 2 shows the variation of the collapse potential with applied pressure for windblown dune sand tested in the consolidation apparatus (5). Several factors were investigated in this study including the applied pressure, relative density, the effect of remolding, and stabilization using 5% cement as additive. Figure 3 shows a comparison of the collapse potential for undisturbed and remolded samples at the same relative density. The collapse potential decreases linearly with the relative density and increases with the applied pressure at a decreasing rate. Soil disturbance leads to higher collapse potential. The use of cement as an additive in small quantities of 5% resulted in a significant decrease in the collapse potential. The influence of soaking on the angle of friction ϕ for remolded samples is depicted in Figure 4.

Cement stabilization of the surface sands in Kuwait was examined by means of an extensive laboratory compressive strength testing program (6). Typical results are shown in Figure 5 and Table 3. The strength increased linearly with cement content which varied from 2% to 10%. The strength decreased sharply by about 50% when the relative compaction decreased from 100% to 95%. Mixes compacted on the wet side of the optimum moisture content yielded generally more favourable strength values than mixes compacted on the dry side. Some other factors were examined including the effect of delayed compaction and the durability of stabilized mixes. The results were encouraging and the stabilized soils can be used for a variety of engineering purposes, such as road bases, paving slopes and lining ditches, embankment protection, cement-treated pipe bedding and backfilling (7).

Because of the very low natural moisture content of the surface sands which ranges from 1 to 2%, underground electric cables may be subject to unfavorable conditions. This is due to the high thermal resistivity of the soil around the cable, and the possible overheating. It is thus important to assign a proper value for the thermal resistivity of the soil based on laboratory and field test results (8). The use of soil cement with 2% cement as an additive resulted in a great improvement in the thermal properties, with a thermal resistivity of 20°C cm/W after drying for samples compacted to the maximum standard proctor density (8).

Loading tests were carried out to on square concrete shallow footings with a width varying from 0.25 m to 1 m at seven sites in Kuwait (2). The purpose being to examine the pressure settlement curves, and to determine the most accurate method for predicting the allowable soil pressure corresponding to a given permissible settlement (2, 3). The results indicated that most methods based on the standard penetration resistance are conservative by a ratio of 2 to 3. However, the methods proposed by Schmertmann (9) Schmertmann, et al (10) yielded very accurate predictions of the elastic settlement. The coefficient of subgrade reaction was also calculated from the results of these footing tests and compared with other tests around the world. Recommendations regarding this coefficient for surface desert sands are given based on the field test results (11).

CEMENTED SANDS

Competent deposits of cemented sands exist in Kuwait and in many places of the world where arid or semi-arid conditions prevail (12). The degree of cementation vary with depth from very weak or uncemented to strongly cemented material at the same location. Recently published research dealt only with the laboratory determination of the geotechnical properties of few cemented sand samples and the role of cementation in increasing the strength parameters c, ϕ (13, 14). The variability of these deposits with depth and its response to foundations loads have not been investigated or adequately examined.

Several structures were placed recently on cemented sands in Kuwait. By detailed site investigation and foundation monitoring, the unique and interesting characteristics of these deposits were explored. One of these structures is the 370 m high antenna tower founded on a ring shaped raft, 55.5 m in diameter and embedded 18 m below the ground surface in down town Kuwait. The soil profile at this site consists of dense to very dense, calcareous, fine to medium sand with little coarse sand and gravel. A special feature in the soil profile is the presence of several layers or horizons of cemented sand underlain by uncemented cohesionless sand. Figure 6 shows a summary of the soil conditions at the test site (15). Indicated from left to right are the soil description, location of the cemented layers, bulk unit weight, moisture content, SPT blow count corrected for overburden pressure as per Peck et.al (16) and the soil composition.

Examination of Figure 6 reveals several interesting points including the presence of cemented and uncemented layers. The degree of cementation varies and is certainly related to geological and environmental factors during the formation of these deposits. The SPT values usually exceeded 50 below 18 m depth, and frequently it was not possible to drive the spoon the required 0.45 m of penetration. There is also a concentration of very high N values within the cemented layers.

The bulk unit weight measured by the sand cone at the excavation level ranged between 19.8 and 20.7 kN/m^3, and the moisture content was 8 to 10%. The maximum and minimum dry density revealed a high relative density which ranged between 85 and 93% (15).

Mineralogical analysis on 36 samples from borehole 1 revealed that the major mineral phase is quartz which is always larger than 60%. The remaining components include calcite, dolomite, and gypsum. Clay minerals were found in very small quantities which ranged from 5-10%. Analysis of the gradation characteristics and mineral composition of the samples reveals that both cemented and uncemented sand layers are of fluvial origin (17).

Deformation moduli, E_M, obtained from pressurementer tests are reproduced in Fig. 7 (15). It is evident that the pressurementer moduli increase with depth and fall within the ranges of 30-50 MPa at the foundation level located 18 m below ground level. The range of moduli derived from plate load tests is also indicated in Fig. 7. The reloading modulus was found to be about 2 - 2.5 times larger and 4 times larger than the virgin modulus as determined from the plate load tests and the pressurementer tests respectively.

The foregoing results indicate that cemented sand deposits are nonhomogeneous with cemented and uncemented or partially cemented layers or bands in succession. Within each cemented stratum, the degree of cementation is not constant or uniform. Nevertheless, the soil stiffness increases rapidly with depth as demonstrated by the pressurementer test data, Fig. 7. Below a depth of 43 m no modulus values were measured. Instrumentation monitoring at the Antenna tower site (17) revealed that the modulus increase below depth of 43 m, which was back calculated from extensometer data, was significantly larger than what was assumed based on the measurements shown in Fig. 7. Consolidation tests on selected samples from the boreholes revealed very low compressibility, with the compression index below 0.1 and the term $C_c/1+e_0$ limited to a maximum of 0.05 for all samples. The increased strength and stiffness with depth is similar to those measured for deep soft rock ground in the suburbs of Tokyo (18) and for raft foundations on the bouldery clay of Singapore (19).

Settlement and Bearing Capacity

Plate loading tests were carried out recently on cemented sands at sites of various cementation levels to examine the bearing capacity and settlement of cemented sands (15, 20, 21). The results of these tests indicated very competent soils with high bearing capacity and smaller settlement as compared to granular sandy soils with similar relative density and resembles the behavior of overconsolidated sands. The failure is also progressive in nature with no clear ultimate load. Typical load settlement curves at the tower site are depicted in Fig. 8 (22). The observed failure mode in all these tests is punching shear failure below the plates with no heave or ground surface movement adjacent to the plates. The soil modulus values ranged from 40-60 MPa near ground surface increasing sharply with depth. The variation of the settlement ratio with the width ratio at two sites is shown in Figure 9 (21). Additional field tests are required to examine in detail the variation of the settlement ratio with the width ratio. This can be done by testing larger size plates since the width ratio in the tests conducted so far was limited to a maximum value of 4.

Other Comments

The use of crushed cemented sand as a subgrade soil in road construction, in arid areas, was investigated by laboratory tests on near surface samples taken from six sites in Kuwait (23). Several findings from this study are presented briefly herein. The amount of fines ranged from 20 up to 50% of the total weight. Most of the cementing agents, with lower mineral hardness compared to quartz, break into smaller sizes and are included in the fines fraction. The clay size fraction is nearly 50% of the fines for all soils. however, clay minerals are only one-fourth of the clay fraction and consist mainly of illite and chlorite. The chemical analysis of the fines is similar to that shown in Table 2 for the fines fraction of the surface windblown sands. The fines are classified as MH and A-7-5 according to the Unified and AASHTO soil classification systems respectively (23).

If the fines content of compacted crushed cemented sand exceeds 35%, large or uncontrollable swelling occurs upon saturation or ground wetting due to the increase surface area, disturbance of the soil fabric, and the low moisture content coupled with a high suction potential. This is depicted in Figure 10 based on laboratory tests at six sites (23). However, undisturbed cemented sand deposits have generally a stable structure which displays little or no volume change upon saturation or wetting.

Because of the low permeability (10^{-4} - 10^{-6} cm/sec) and non homogeneity of cemented sand deposits construction dewatering may be difficult to achieve on large projects. At the tower site the use of deep wells alone along the perimeter of the excavation was not sufficient to bring the water level down the required 10 m depth of dewatering. A line of sand drains was installed later on to help drain the site and speed the dewatering process.

COASTAL GROUND

Salt bearing soils exist along the coast-line of Kuwait and the Gulf States. It is locally called "Sabkha" which defines coastal flat areas that extend above the high tide level and are covered by evaporate-rich clastic sediments (24). Due to the high salinity of the near surface ground water and the excess of evaporation over rain fall, 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 (25).

With the presence of these deposits in areas of potential development in Kuwait, an extensive, field and laboratory testing program was carried out at the site of the proposed Olymbic village in Doha, Kuwait. The work included sampling, classifications, static, and dynamic cone penetration tests, basic properties, chemical analyses, consolidation and triaxial tests on undisturbed samples. Plate load tests were also performed employing a 0.3 m diameter plate.

The field and laboratory test results are presented herein. Emphasis is placed on the special and unique geotechnical characteristics of salt bearing soils. The change of the soil properties with depth is noted and discussed along with the influence of the environmental factors on the soil properties.

Site Characterization

The soil conditions at the test site are summarized in Fig. 11 (26). Indicated from left to right are soil description, basic properties, dynamic and static cone penetration test results. 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 upper layer contains lenses of gypsum particularly near the ground surface and can be classified as ML according to the Unified Soil Classification System. Groundwater was encountered At a depth of 0.5 m below the ground level.

A close examination in Figs. 11 reveals that the upper layer has lower specific gravity and higher moisture content than most granular soils. The specific gravity ranges between 2.3 to 2.5 and the moisture content varies up to 35%. The dynamic penetration resistance with depth indicates a hard salt crust up to a depth of 1.0 m followed by very low penetration resistance to the bottom of the layer. Similar tendency is visible in the static cone penetration resistance measurements. These low values range between 200 to 600 kPa for the point resistance q_c, and 0 to 150 kPa for the frictional resistance f_s.

Figure 12 shows the main soil components as determined from the chemical analysis on samples of borehole (26). As shown sulphates exceeded 60% of the soil composition at ground surface and decreased sharply with depth reaching 20% at a depth of 1 m and zero at a depth of 2.5 m. Carbonates consisting mainly of calcium carbonate ranged between 15 to 20% in the upper layer. Silica constituted 25% increasing to 40% below a depth of 1 m.

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. It has been found herein that oven drying the gypsum soils tested at 60°C or use of a vacuum desiccator and a temperature ranging between 23°C and 60°C for drying in accordance with ASTM D2216 (27) resulted in identical results. However, drying at temperatures between 80°C and 110°C resulted in significant loss of hydrated water and large moisture contents. Drying also, affected other properties including specific gravity and Atterberg limits. The values shown in Figure 11 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 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 clearly in Fig. 13 where the variation of the moisture content and the specific gravity is plotted for samples from borehole 1 (26). 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.

Compressibility and Strength

Consolidation tests were carried out on undisturbed samples from borehole 1 to determine the consolidation parameters of the upper salt bearing layer. The e log p plots for samples at different depths are shown in Fig. 14. A summary of the consolidation and strength parameters is given in Table 4. Examination of Figure 14 and Table 4 reveals that both the compression index c_c and the swelling index c_s increased substantially with depth in the upper layer. The increase in c_c is nearly two fold 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 $c_c/(1+e_0)$ is considered as an index of compressibility, this ratio was 0.058 - 0.059 at a depth of 0.3 m increasing to 0.099 at a depth of 1.5 m. This is nearly a 70% increase in compressibility within the layer.

Consolidated undrained triaxial tests with pore pressure measurements were conducted on 71.8 mm diameter and 150 mm length undisturbed samples from the borehole. Figure 15 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 ϕ' were determined from Fig. 15 as (20 kPa, 37°) for sample at 0.5 m depth. The presence of a small cohesion intercept is typical of cemented sands in the area. However, the presence of large concentration of gypsum near the surface of this deposit leads to nonhomogenity and some variations in the measured strength characteristics for points in the vicinity of each other at the same depth.

The strength envelope for samples from borehole 1 at a depth of 1.5 m is superimposed in Fig. 15. It indicates strength parameters of (0, 28°). Lower strength is obtained from similar samples from borehole 2, Table 4. Thus softer conditions exist below the surface crust in the zone located permanently below the ground water level. These results are compatible with the dynamic penetration resistance plotted in Fig. 11

indicating a surface crust of one meter with high penetration resistance reaching 15 to 20 blows/0.3 m underlain by softer ground with very low penetration resistance.

Since the water level is located 0.5 m below ground at the time of measurements in November and considering tidal and seasonal fluctuations, it is evident that the portion of this deposit located permanently below the ground water level approximately 1 m deep remains very 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.

Bearing Capacity

Plate load tests were carried out at the sites of boreholes 1 and 2 to examine the bearing capacity of the near surface Sabkha. The tests employed a circular steel plate 0.3 m diameter and a ten ton hydraulic jack attached to a hand pump. A calibrated pressure gage 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 herein to provide reaction. Each load increment was maintained for at least 15 minutes and until all settlements had ceased. Settlements were measured by three dial gages attached to the plate from a reference beam. Each test was repeated to ensure accuracy and consistency of the test data.

Test results are plotted in Figure 16 in the form of pressure-settlement curves. Each curve is the average of two plate load tests. Since the failure load was not well defined the slope tangent method was employed 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 or 3 mm. The pressure-settlement curve at this depth, Fig. 16 indicates a well defined failure, followed by large settlement due to 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 indicated very low bearing capacity for the salt bearing soils. Considering the results of the unconfined compression strength tests which 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.

Special Characteristics

The presence of 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 (28). 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 cone penetration (CPT) tests before and after leaching by fresh water indicated a reduction of 40 to 50% in the bearing capacity and penetration resistance within a shallow depth of 1 to 1.5 m. However, no visible change was recorded below this depth (28).

Many other problems are associated with these soils and should not be underestimated. These 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. It is common to reach temperatures exceeding 50°C in the months of 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 by a bituminus binder or other suitable inert material to prevent deterioration of concrete and corrosion of steel due to the agressive action of salts in the soil and ground water (29).

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

If construction is necessary over salt bearing soil, such as road construction over large areas covered with Sabkha, soil improvement techniques may be necessary including stabilization with additives or geosynthetics. However, these methods must be successfully tested and short and long term performance monitoring should be carried out to ensure safety and stability.

DISCUSSION

From the proceeding sections it is evident that the windblown dune sand having very little fines, medium density, and low moisture content is sensitive to saturation leading to possible collapse at low relative density. In contrast cemented sands are very dense and competent deposits, containing an appreciable amount of fines, and lacking homogeneity and uniformity. The cementation level could vary with depth with the presence of cemented and uncemented layers in succession.

Coastal salt bearing soils (Sabkha) are softer, very compressible, and highly corrosive with extremely low bearing capacity. The large fines fraction consisting of carbonates, sulphates, chlorides and other salts are softer than quartz and dissolve to varying degrees upon saturation, or ground wetting. As result, these deposits are usually very soft, problematic, susceptible to salt leaching, and not suitable for foundation support.

A comparison between the classification, basic properties, and characteristics of the local deposits is given in Table 5. It is intended as a useful summary and a guide for the practicing soil engineers in the Gulf region.

CONCLUSIONS

The properties and behavior of arid climate soil deposits in Kuwait were examined along with the influence of the prevailing environmental factors. The deposits examined include the windblown dune sands, cemented sands, and coastal ground. The following conclusions are made :

1) The surface windblown dune sands are very dry, loose to medium, dense predominantly fine poorly graded sand. It is sensitive to saturation and may collapse at some locations due to ground wetting. The collapse will be evident for compacted sand at low relative density.

2) Cemented sands are competent deposits of very dense silty sand. It is not homogeneous or uniform, however its strength and stiffness usually increase with depth. Due to its high density, the presence of appreciable amount of fines (20-50%), and low permeability dewatering techniques normally used for free draining soils may be insufficient requiring the use of additional measures such as sand drains.

3) Crushed cemented sand may be used for backfilling. However, if the amount of fines exceed 35%, large or uncontrollable swelling may occur upon saturation. Therefore, the amount of fines should be checked before the use of this material in practical applications such as road construction or backfilling.

4) Coastal ground consists of loose gypsiferous fine sandy silt with little clay (Sabkha). It has a large content of salts in the form of carbonates and gypsum. It is soft, corrosive, and problematic soil. It is often capped with a cemented crust that becomes soft upon saturation of ground wetting. This is due to the leaching of soluble salts and the softening of the cementation bonds.

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Table 1. Summary of physical properties of the windblown dune sands (Depth = 1 - 1.5 m) [after Ismael et al (1)]

Location	Moisture content w(%)	Bulk unit weight γ_b(kg/m^3)	Dry unit weight γ_d(kg/m^3)	Specific gravity of solids G_s	D_{50} (mm)	Void ratio (e)	Degree of saturation S_r(%)	Minimum* dry density $\gamma_d$min(kg/m^3)	Maximum* dry density $\gamma_d$max(kg/m^3)	Relative density R_d(%)	Coefficient of permeability (x10^{-3}cm/sec)
A-1	1.8	1717	1687	2.72	0.15	0.612	8.0	1521	1789	65.7	2.0
R-1	1.0	1727	1710	2.69	0.14	0.591	4.6	1541	1769	76.7	1.73
Y-1	1.1	1734	1715	2.72	0.15	0.586	5.1	1574	1783	70.1	0.93
J-1	0.9	1719	1704	2.72	0.16	0.596	4.1	1564	1792	64.6	0.26
S-1	1.5	1766	1740	2.67	0.16	0.561	7.2	1577	1779	72.4	0.64

* As per ASTM D 2049 using the dry method for maximum density.

Table 2. Summary of the chemical analysis of the windblown dune sand

Component Oxides	% *Composition		
	Natural Sample	Coarse Fraction	Fines Passing # 200 Sieve
$S_i O_2$	76.15	82.79	42.46
$AL_2 O_3$	6.39	5.17	12.14
$Fe_2 O_3$	0.91	0.72	2.93
C_aO	7.41	5.1	17.06
MgO	2.92	1.03	5.94
CL^-	0.06	0.05	0.14
SO3	0.16	0.85	2.67
Loss on Ignition (Organic Matter, Moisture)	5.36	4.64	16.92
Compounds	**% *Composition**		
C_aCO_3	8.7	7.92	27.43
$M_g CO_3$	0.00	0.43	0.19
C_aSO_4	0.27	0.97	3.3
$M_g SO_4$	0.00	0.42	1.08
Total carbonates & Sulphates	8.97	9.74	32.00
pH value	7.67	7.95	7.83

* Based on the average value for samples taken from five sites at a depth of 0.5 m. These sites are located in the following areas: Jahra, Rabiya, Sulaibiya, Shuwaikh, and Khaldiya.

Table 3. Comparison between test results at 100% and 95% relative compaction [after Ismael (2)]

Site Location	Cement Content %	90-Day Strength (psi)			% of Maximum Strength	
		γ=100% (Optimum)	γ=95% (Dry)	γ=95% (Wet)	γ=95% (Dry)	γ=95% (Wet)
Ardiyah	10	2117	980	1173	46	55
Ardiyah	5	709	345	527	49	74
Ardiyah	2	256	192	223	75	87
Mushrif	10	2130	1304	1361	61	64
Mushrif	5	1164	382	545	33	47
Mushrif	2	514	307	426	60	83

Table 4. Summary of the consolidation and strength parameters - for Sabkha [after Ismael (26)]

Borehole No.	Sample Type	Depth m	γ_B Mg/m^3	W (%)	γ_d Mg/m^3	e_o	P_c kPa	c_c	c_s	$c_c/1+e_o$	c' kPa	ϕ'
1	L_1	0.3-0.5	1.693	19.6	1.42	0.893	60	0.11	0.01	0.058	20	37
1	L_2	0.3-0.5	1.804	24.5	1.45	0.849	60	0.11	0.01	0.059	20	37
1	S_1	1.5-2.4	1.909	43.6	1.33	1.016	80	0.2	0.015	0.099	0	28
2	S_2	0-0.8	1.76	23.0	1.43	--	--	--	--	--	20	37
2	S_3	1.5-2.4	1.84	43.2	1.28	1.086	50	0.22	0.020	1.055	0	13
2	S_4	4.5-53	2.09	21.5	1.72	0.564	60	0.10	0.01	0.064	0	36.9

L Pushed Linear
S Shelby Tube
-- Not Measured

Table 5. Comparison between the characteristics of the local deposits

	Windblown Sand	Cemented Sand	Coastal Sabkha
Description	Loose to medium dense, fine to medium sand, with little silt (Predominantly fine sand).	Very dense, silty sand or clay sand with cemented bands or layers.	Loose Gypsi-ferous fine sandy silt with little clay.
Classification	SP → SM	SM, SP → SM, SC	ML
Strength parameters	$c' = 0$ $\phi' = 32° - 35°$	$c' = 10 - 200$ kPa $\phi' = 35° - 40°$	$c' = 0$, $\phi' = 25° - 28°$, For cemented crust $c' = 10 - 20$ kPa, $\phi' = 34° - 37°$
Coefficient of permeability, K,cm/sec.	$1*10^{-3} \rightarrow 2*10^{-3}$	$\sim 10^{-4} - 10^{-6}$	$2*10^{-3} - 4*10^{-3}$
Percent Fines	5 → 15%	18 → 50%	> 50%
Clay Size	----	~50% of the fines.	----
Composition of Fines	Calcareous with ~32% carbonates & sulphates, 40~45% silica.	~30% carbonates, 40~45% silica.	Mostly sulphates & carbonates.
Classification of Fines	MH	MH	----
Undesirable Characteristics	Possible collapse upon wetting, specially if not well compacted.	- Possible swelling if it contains >35% of fines specially if used as compacted backfill. - Non homogeneous with depth.	- Very soft, not good for foundation support. - Loses strength upon wetting. - Aggressive to ward concrete and steel. - Salt leaching affect soil properties. - Subject to volume changes.
Advantages	- Suitable as backfill material. -Can support light to moderate pressures. - Can be stabilized or improved using cement.	- Competent very dense deposit. - Can support large pressures. - Can be used as backfill. - Small settlement under working loads	- None.

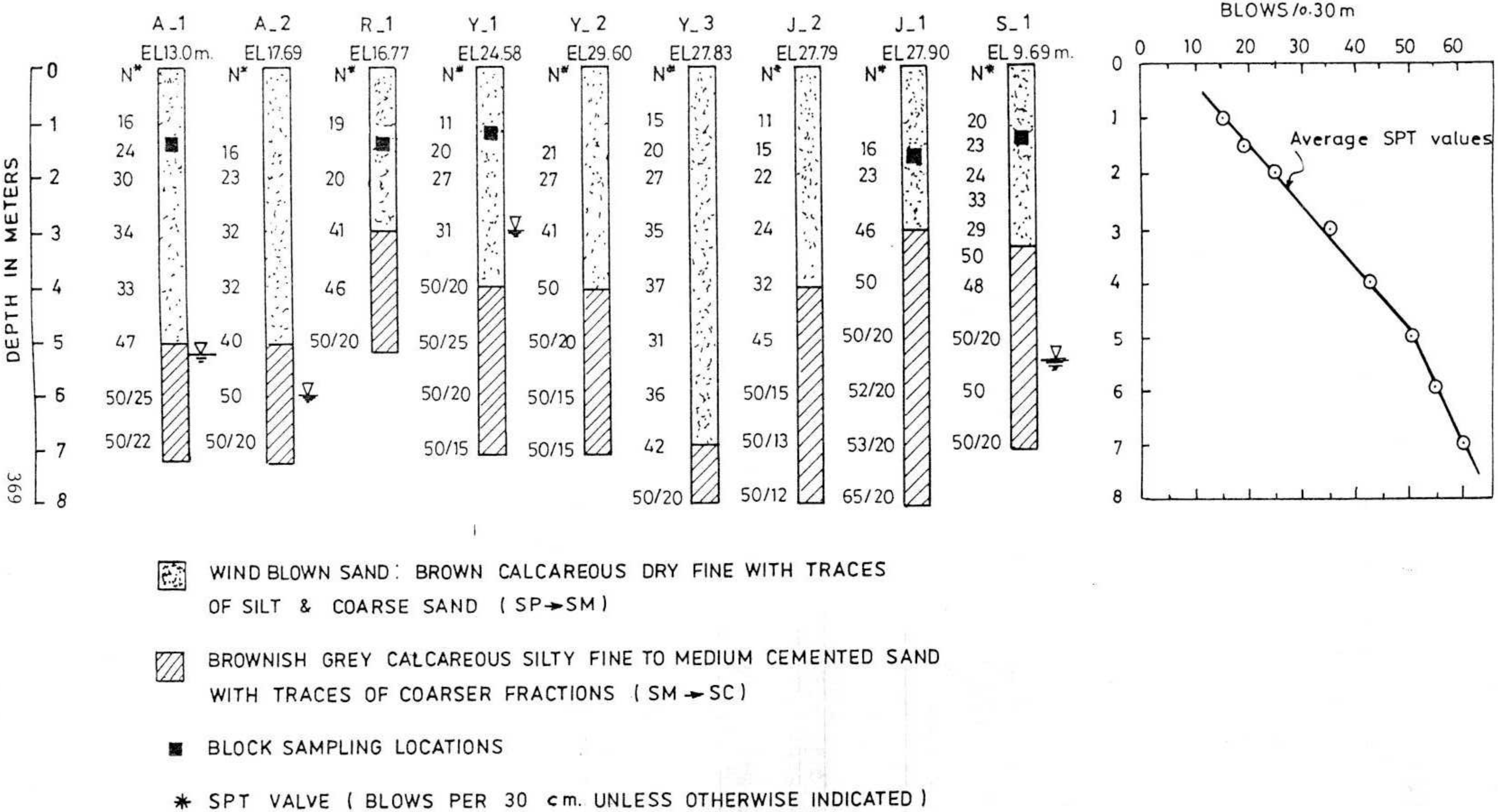

Figure 1 Soil profiles at the wind blown sand test sites [after Ismael (1)]

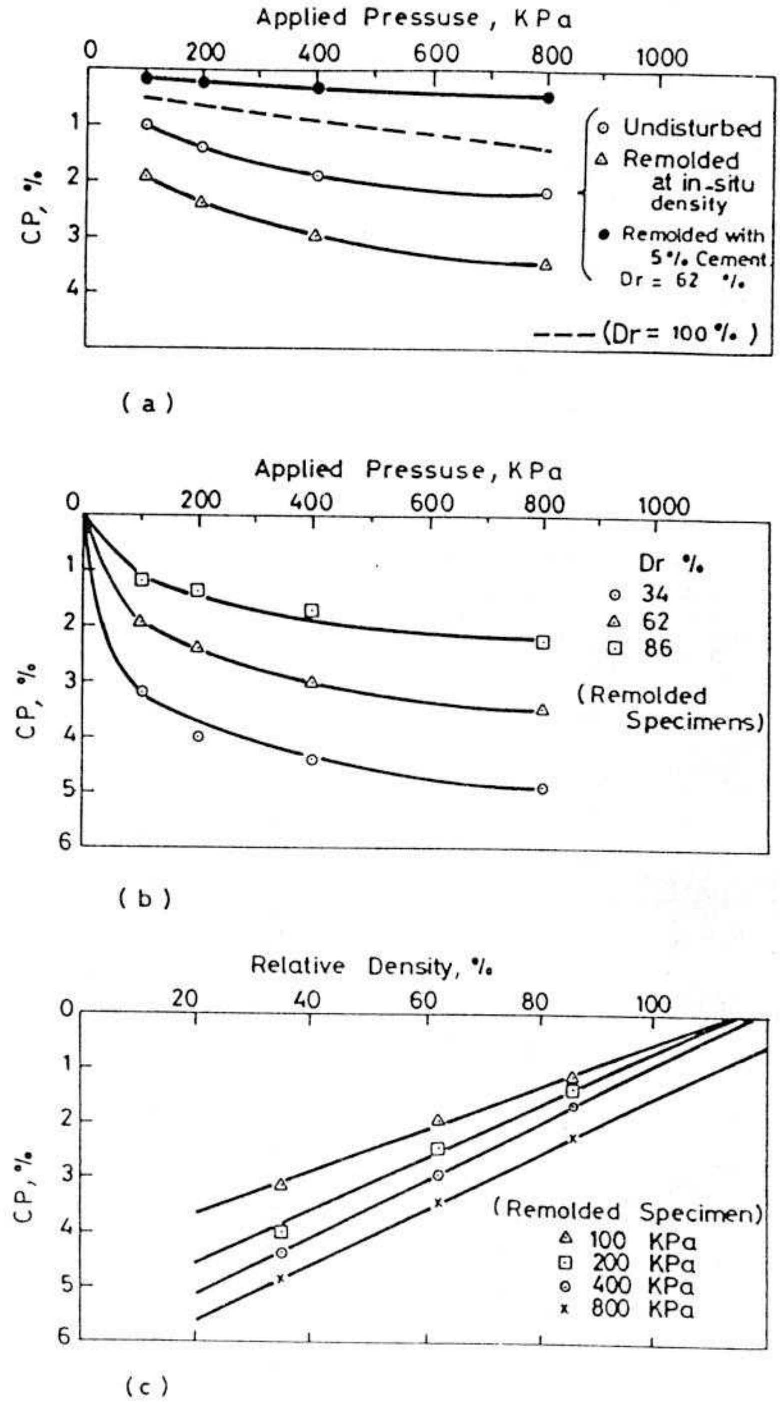

Figure 2 Variation of the collapse potential with applied pressure [after Ismael et al (5)]

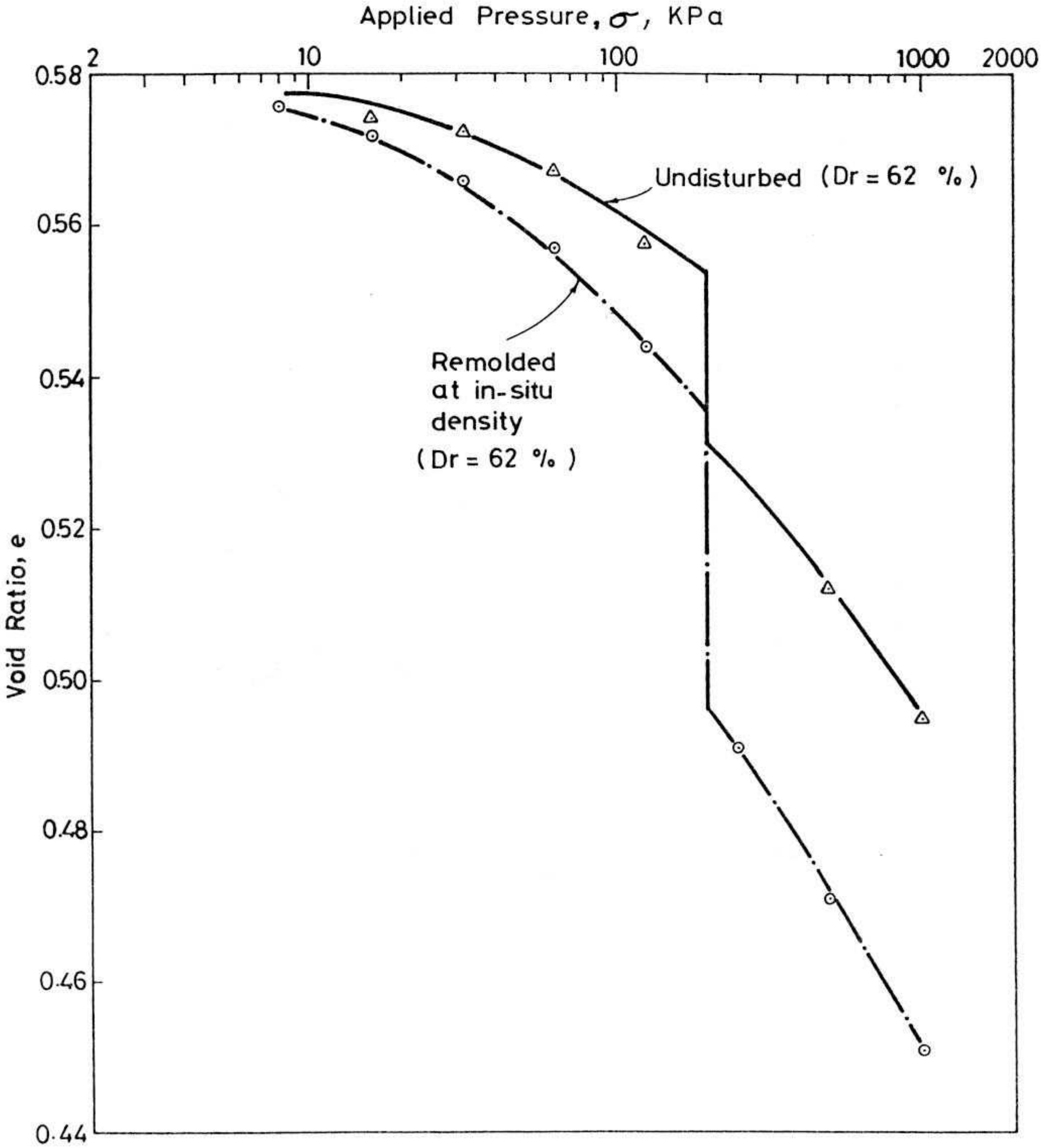

Figure 3 Comparison of the collapse potential for undisturbed and remolded samples on e log σ plots [after Ismael et al (5)]

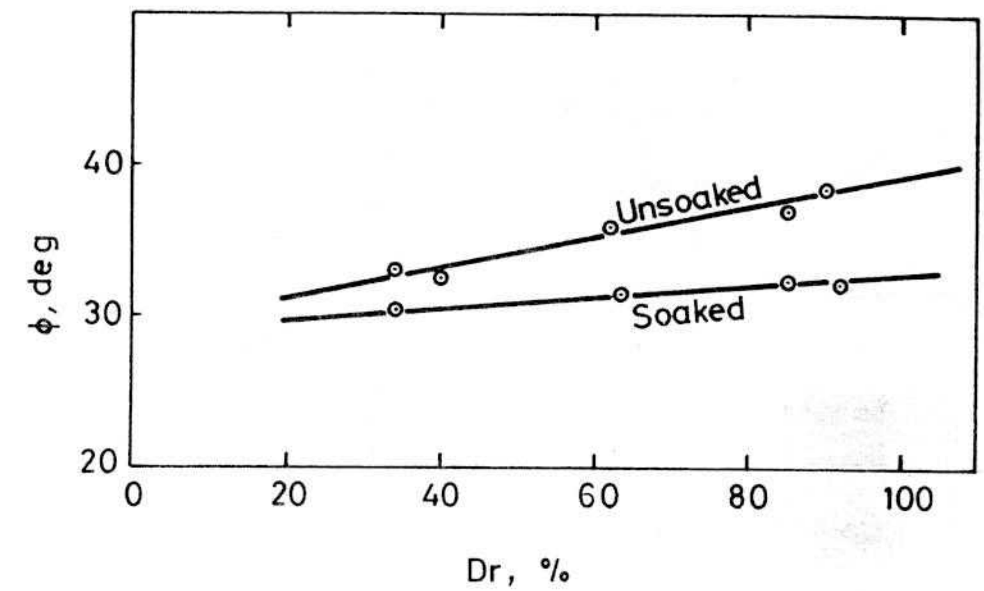

Figure 4 Angle of friction versus relative density for soaked and unsoaked remolded samples [after Ismael et al (5)]

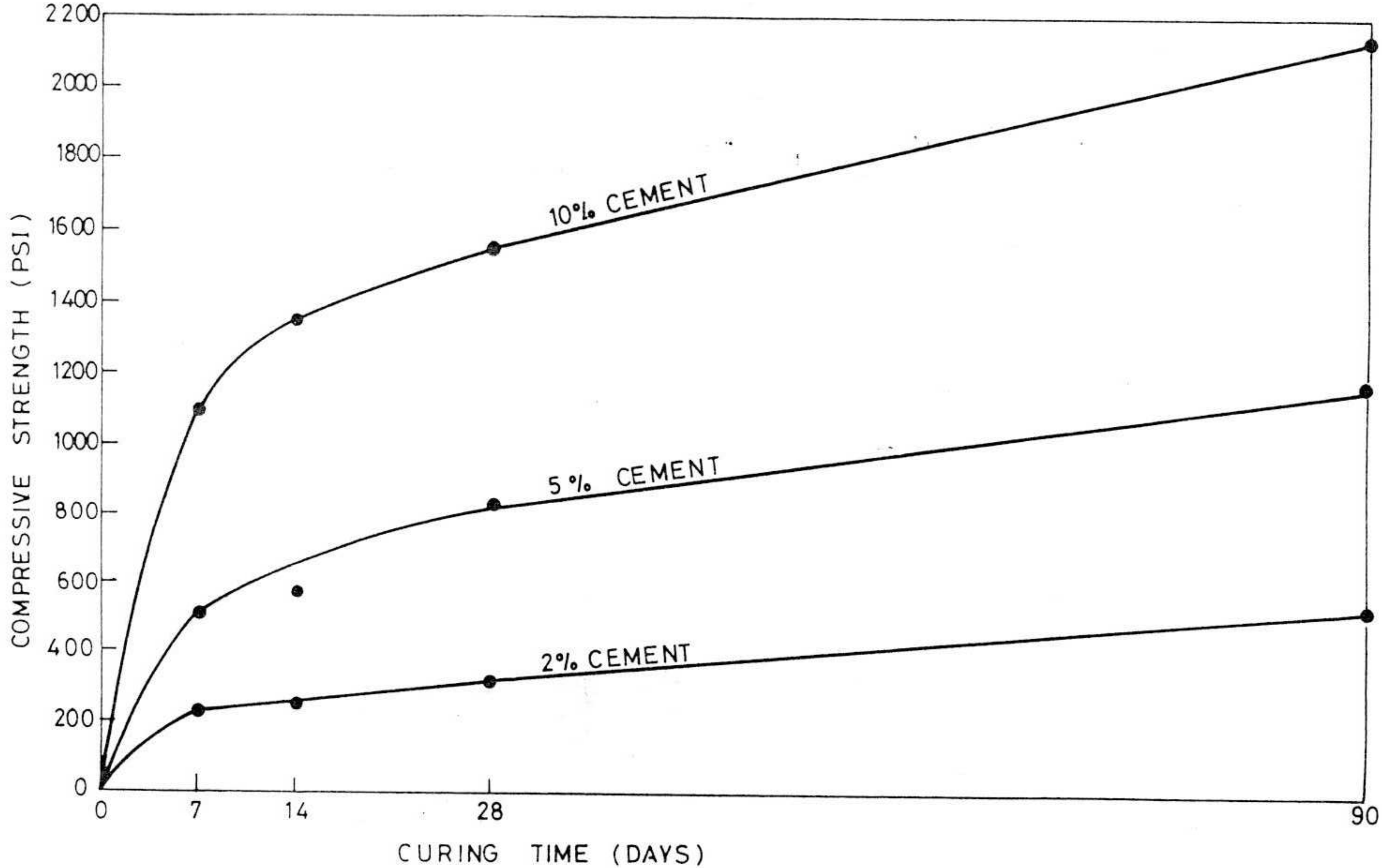

Figure 5 Compressive strength versus curing time for cement stabilized mixes from Mushrif [after Ismael (6)]

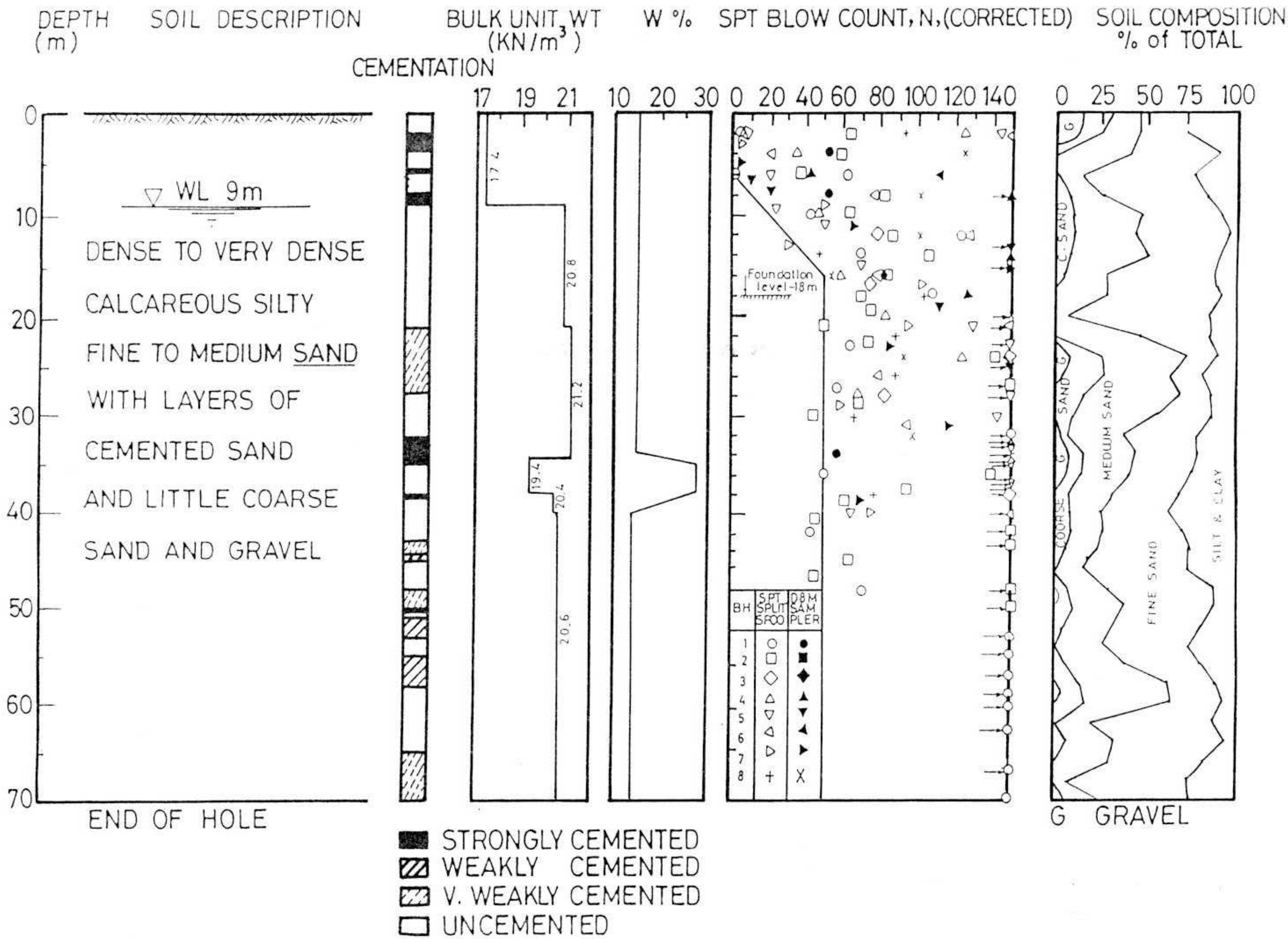

Figure 6 Soil conditions at the site of the Antenna tower [after Al-Sanad et al (15)]

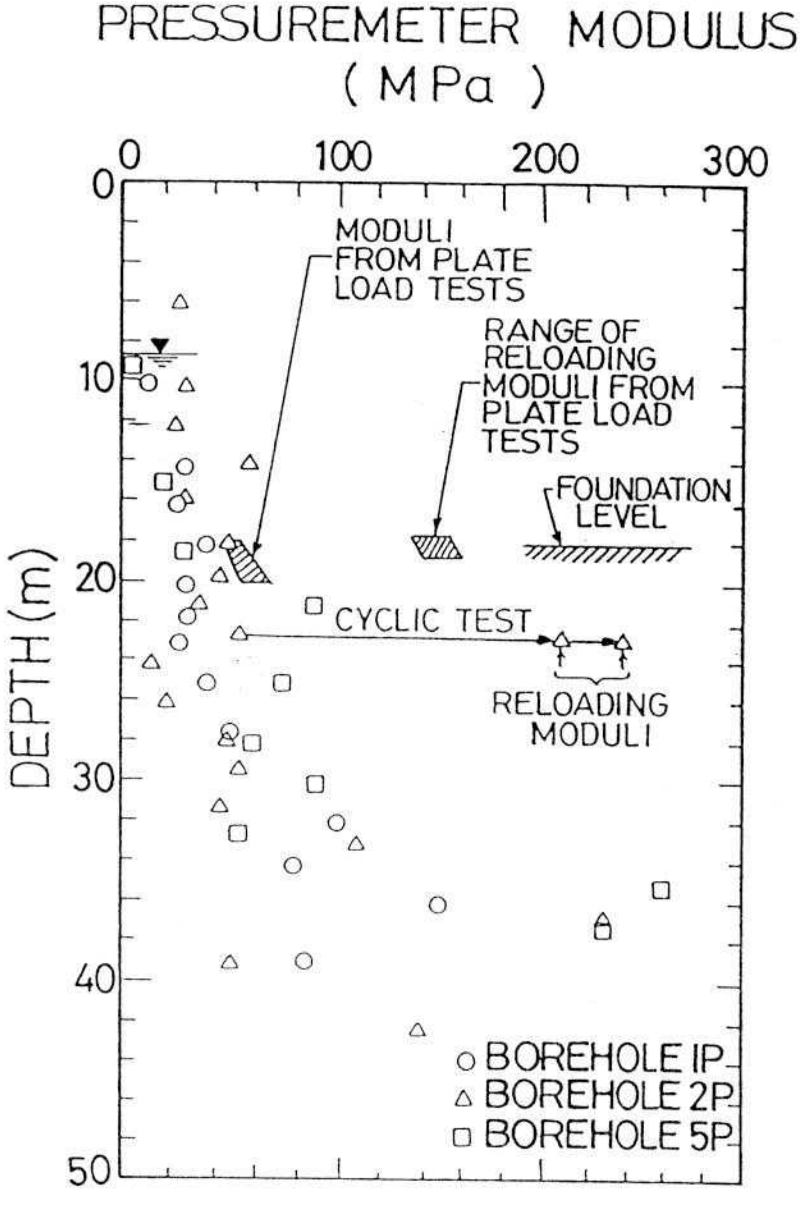

Figure 7 Pressuremeter moduli with depth and range of moduli obtained from plate load tests at the Antenna tower site [after Al-Sanad et al (15)]

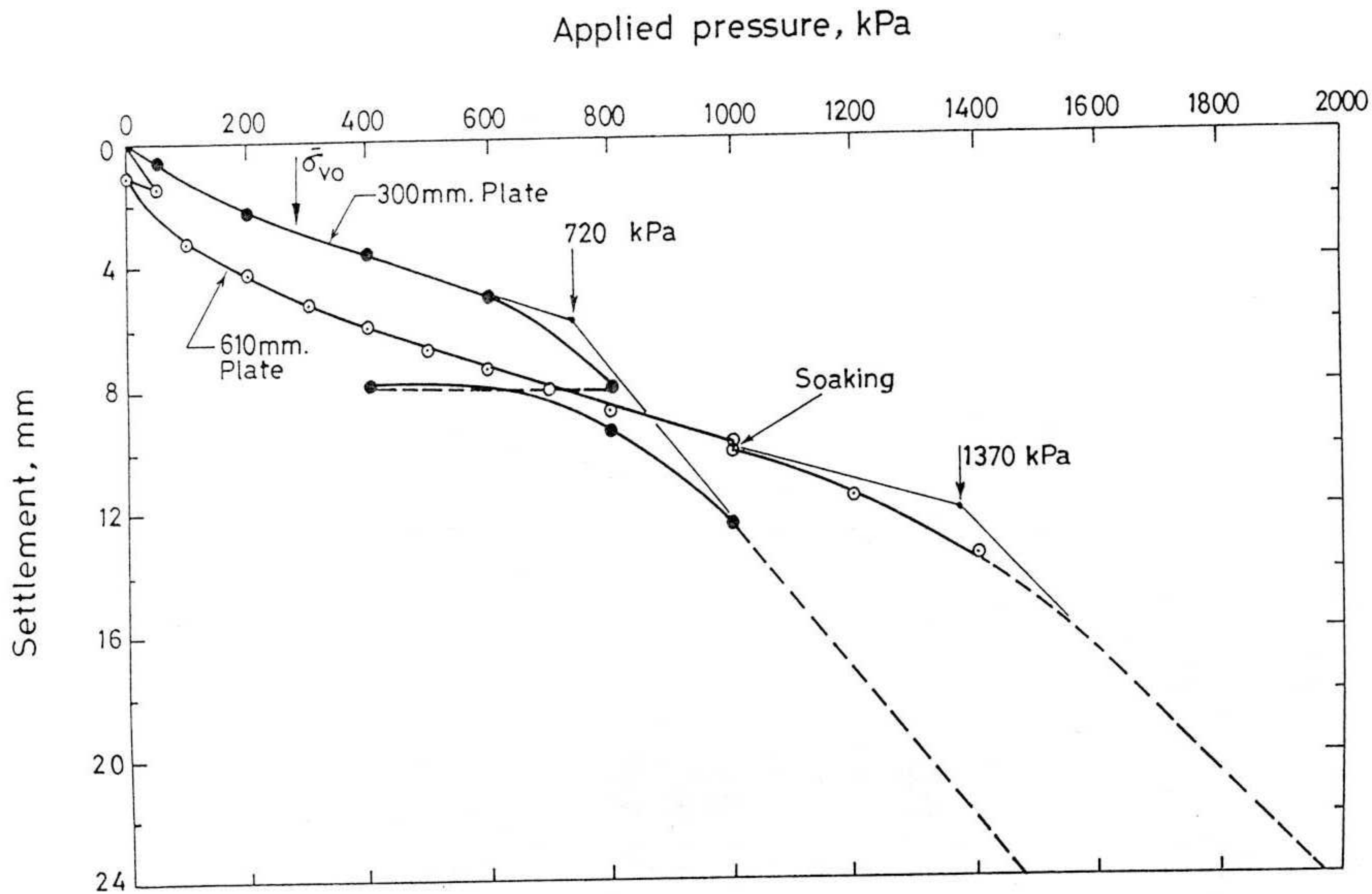

Figure 8 Pressure-settlement curves for circular plates on cemented sands at the Tower site, depth = 18 m [after Ismael (22)]

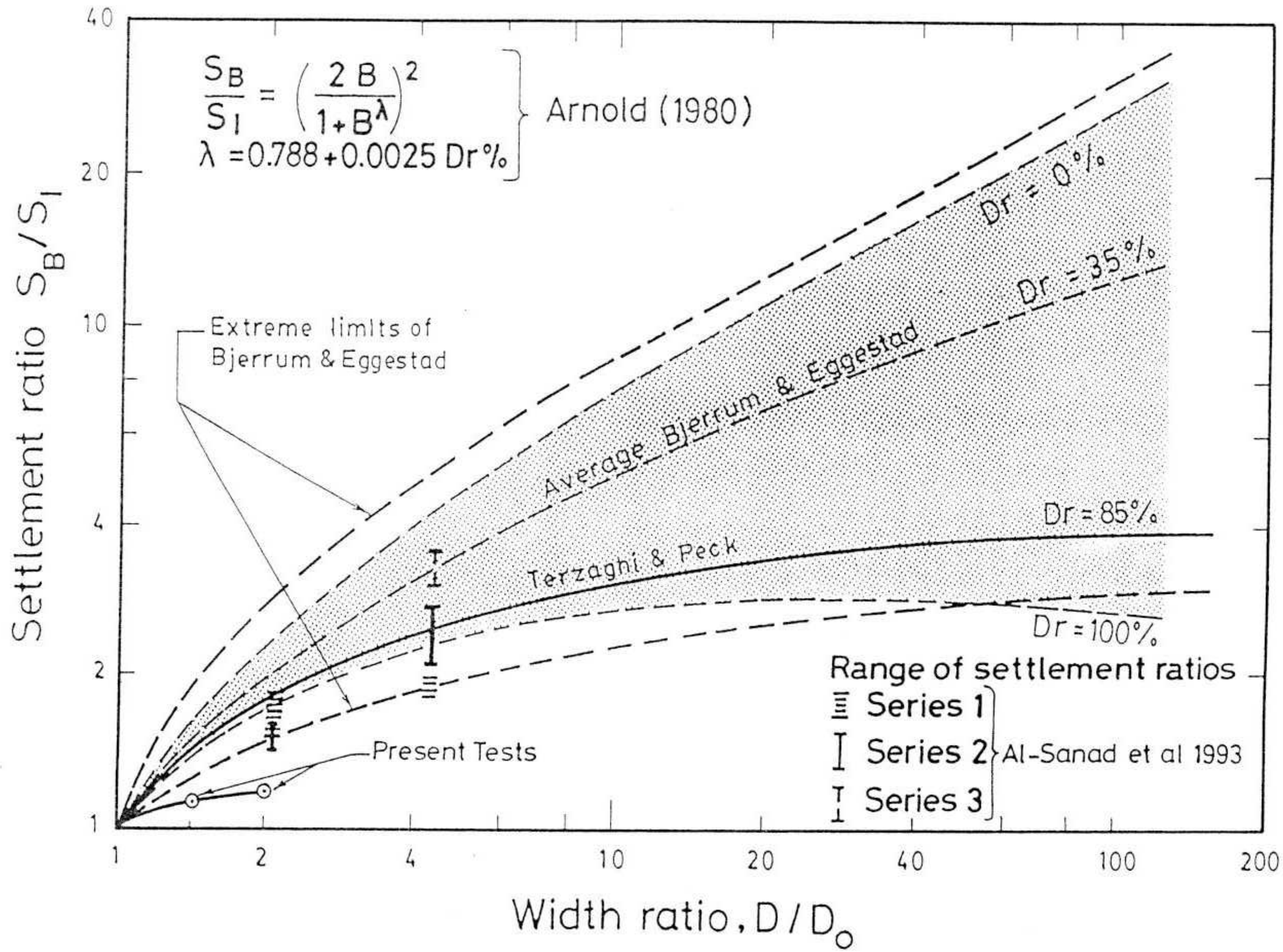

Figure 9 Settlement ratio vs. width ratio for cemented sands at two sites [after Ismael (21)]

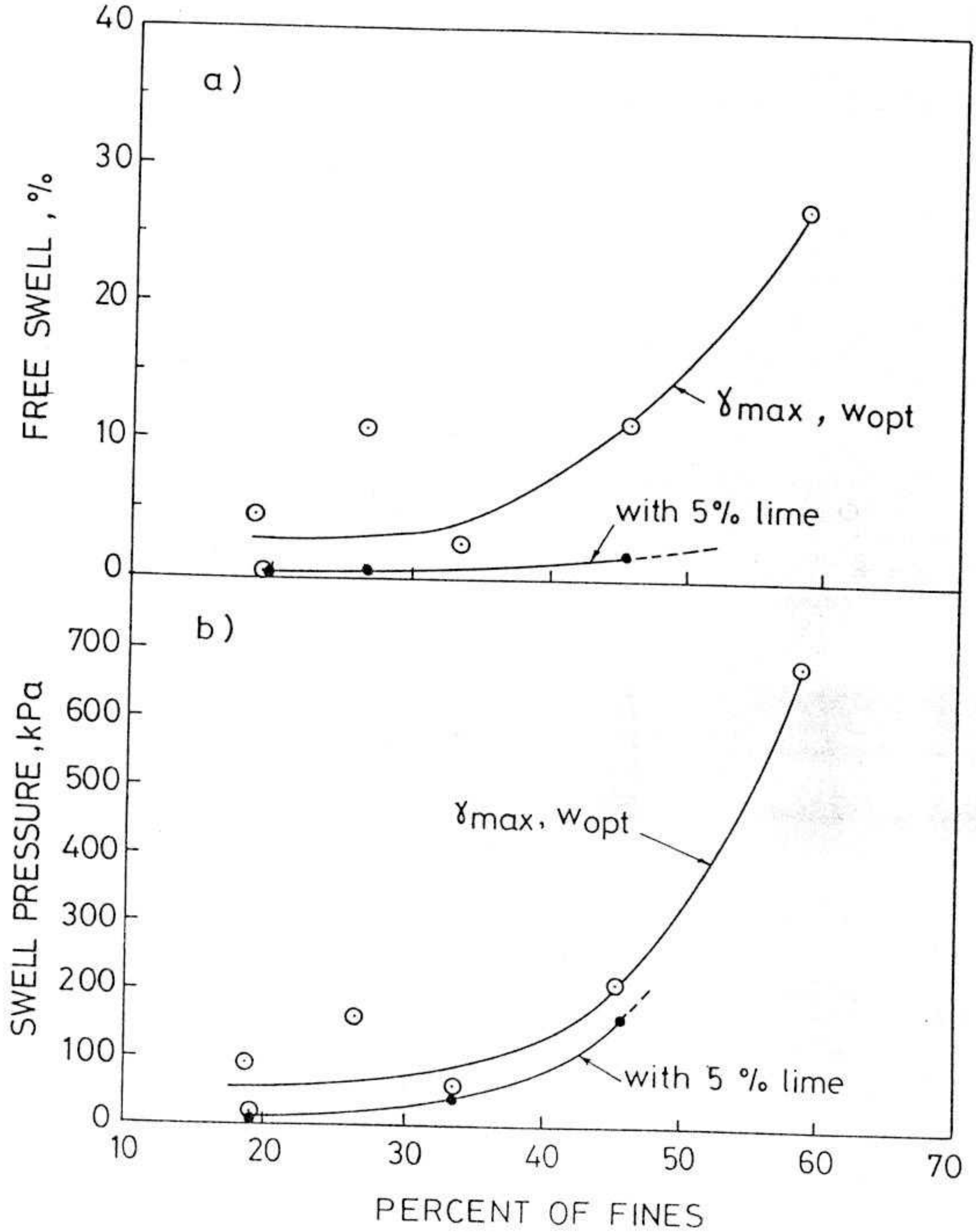

Figure 10 Free swell and swell pressure vs. percent of fines for remolded cemented sands [after Ismael at al (23)]

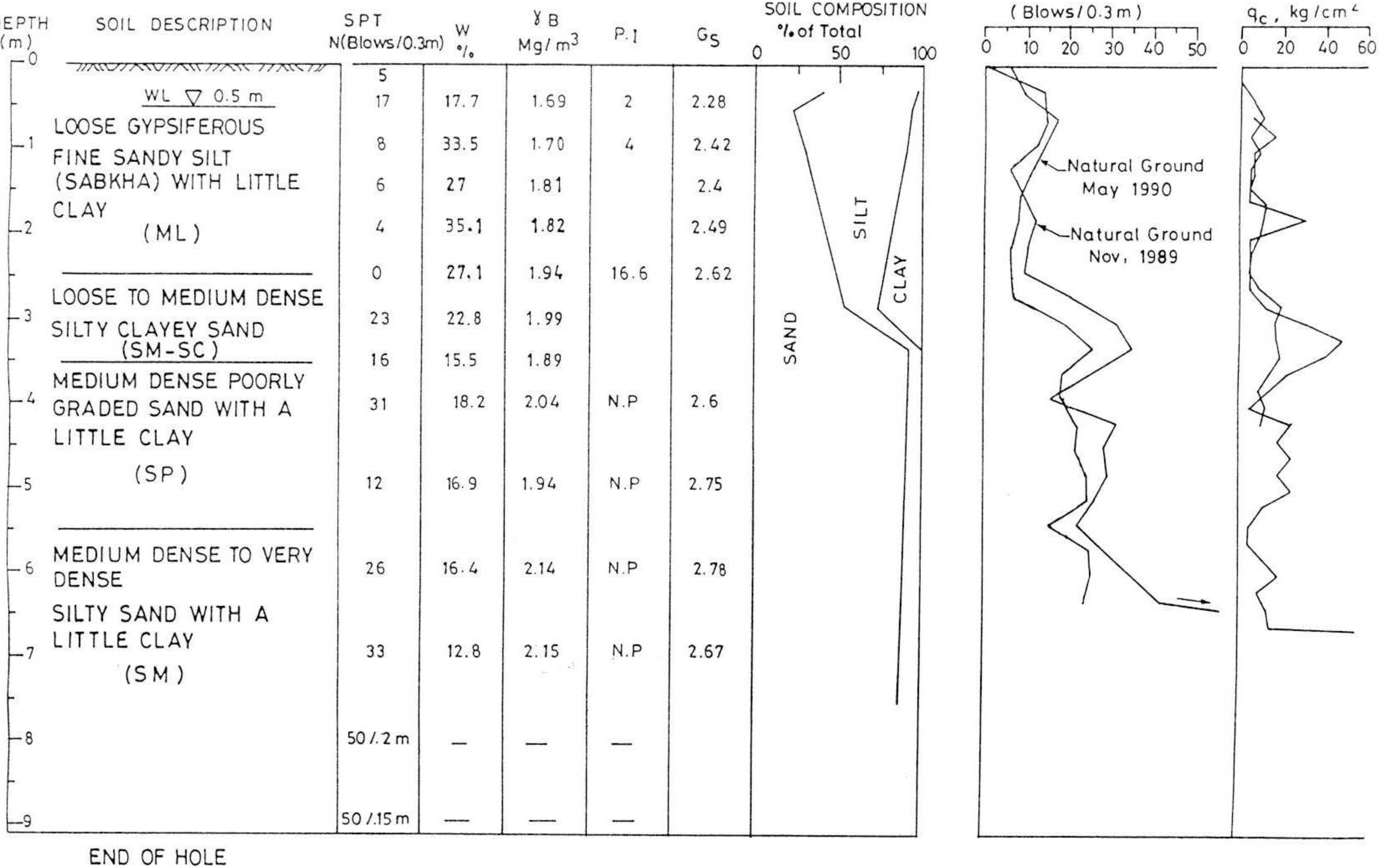

Figure 11 Soil conditions at the Sabkha test site in Doha [after Ismael (26)]

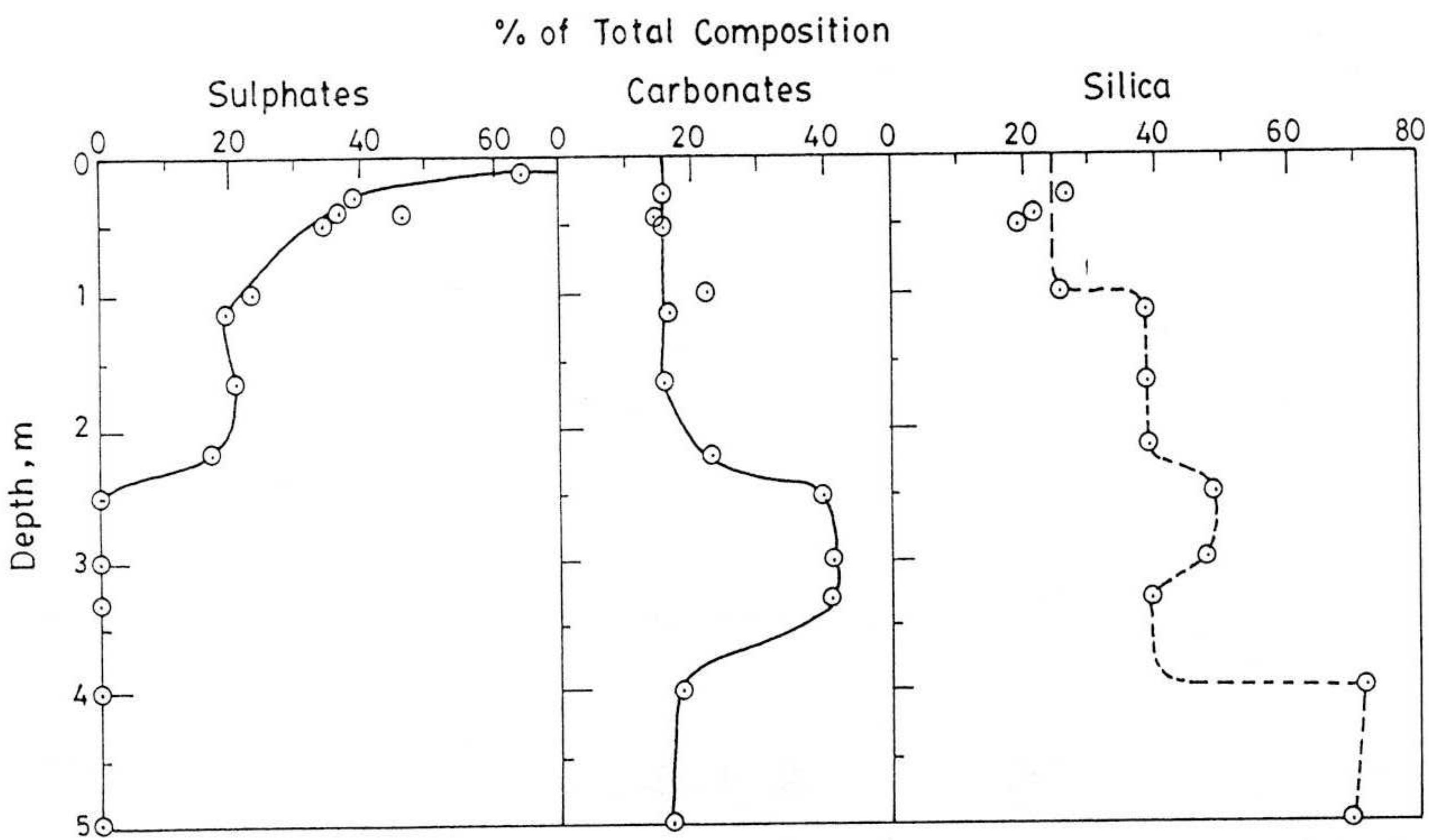

Figure 12 Main components of Sabkha as determined from chemical analysis [after Ismael (26)]

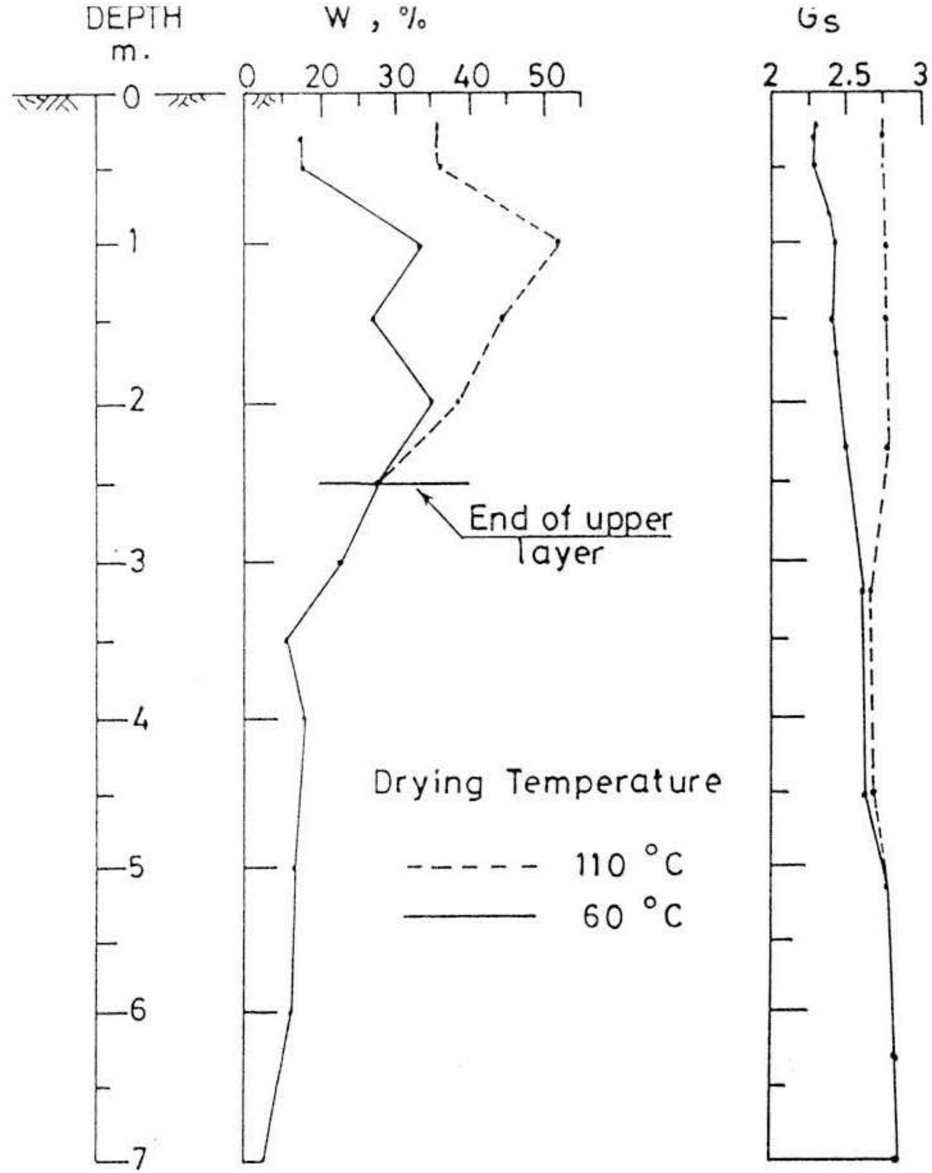

Figure 13 Moisture content and specific gravity with depth at the Sabkha test site - Borehole 1 [after Ismael (26)]

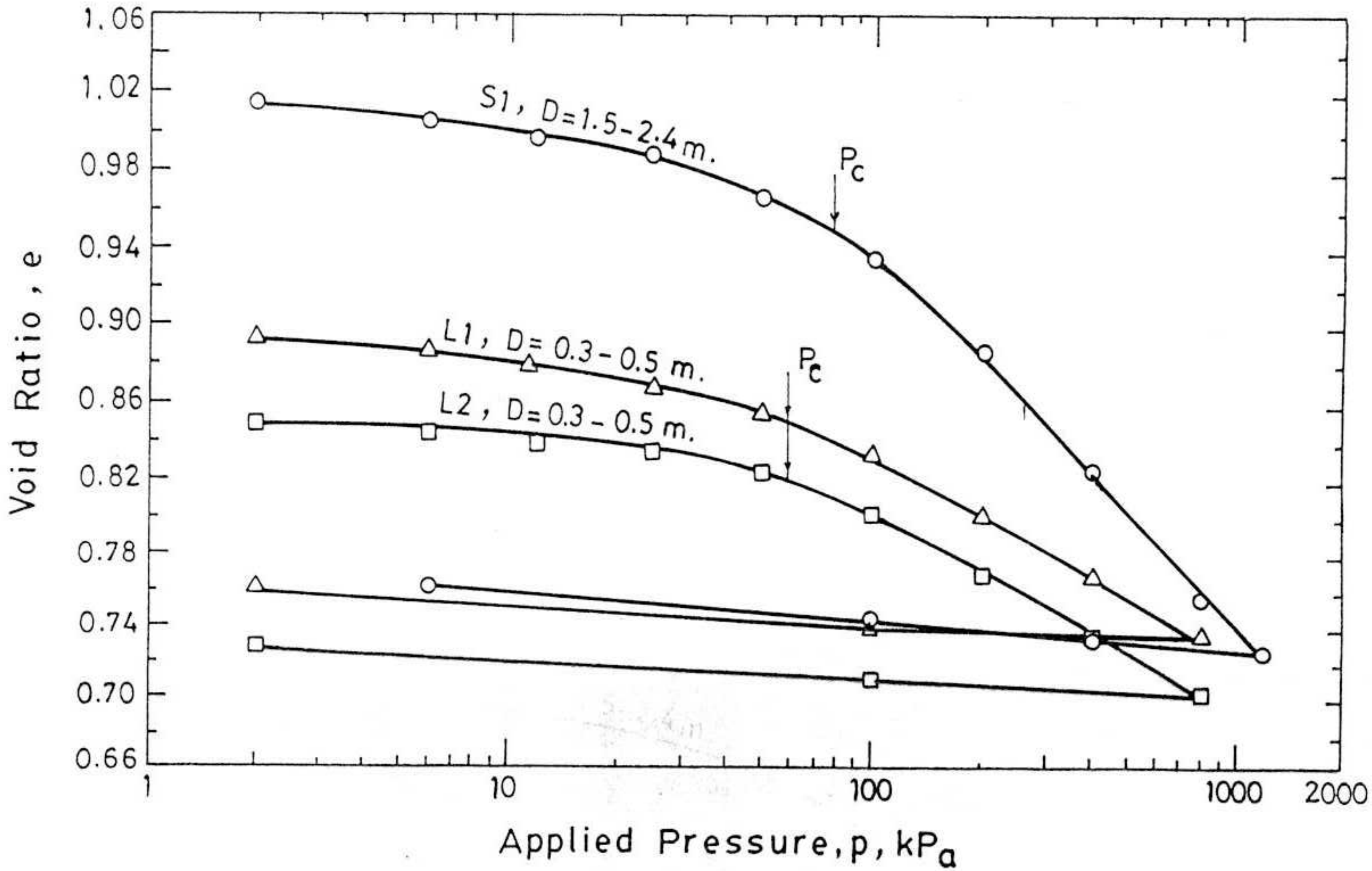

Figure 14 e - log p curves for samples from borehole [after Ismael (26)]

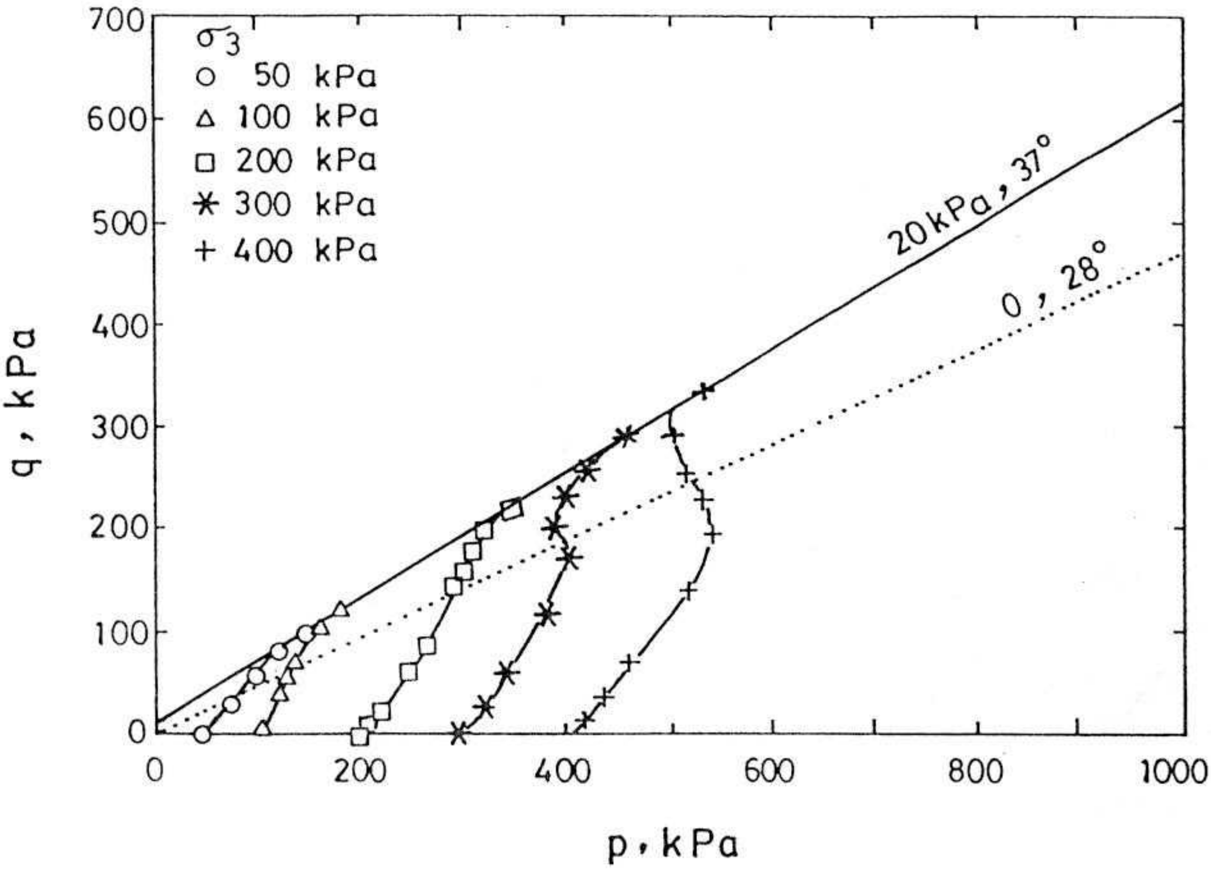

Figure 15 Effective stress path and failure envelops for two samples from Borehole 1 - Sabkha test site [after Ismael (26)]

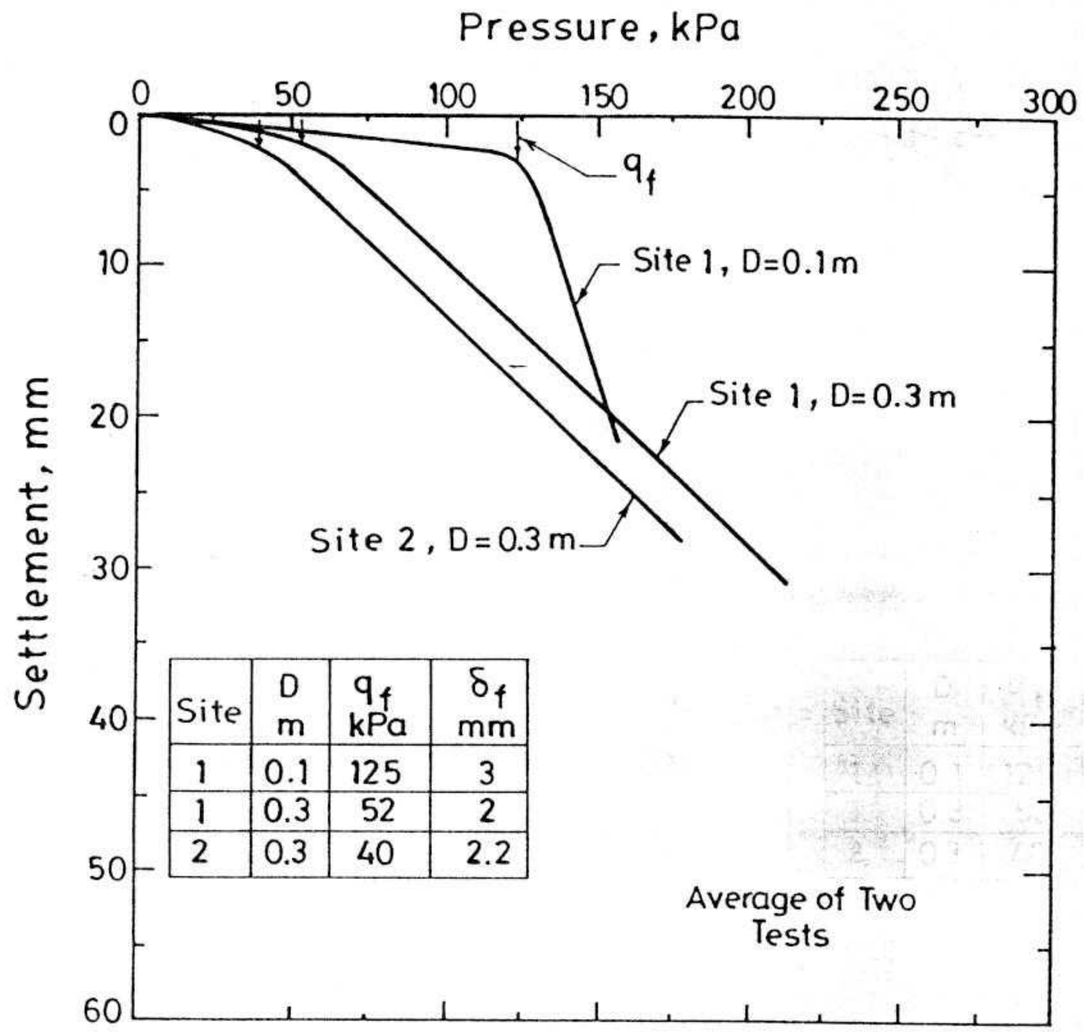

Figure 16 Pressure-settlement curves for 0.3 m diameter plates at the Sabkha test site [after Ismael (26)]