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FOUNDATIONS OVER SALT-ENCRUSTED FLATS (SABKHA): PROFILES, PROPERTIES, AND DESIGN GUIDELINES

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ABSTRACT

The evaporative and sedimentary environment that has prevailed over the southern shores of the Arabian Gulf region (eastern Saudi Arabia, Qatar, and United Arab Emirates) has produced salt-encrusted flat areas known in Arabic as "sabkha". Building activities on sabkha areas have posed problems and challenges to the construction industry triggered primarily by the excessive salts present in both the sediments and their shallow ground waters. The paper sheds light on the general setting of sabkha, including: its development, its geology, its hydrogeology and the make up of its sediments. In general, sabkha sediments are cemented and uncemented layers of sand /silt material, interbedded with pockets of clay and mud, where calcium carbonate and more recent digenetic minerals (gypsum, anhydrite) serve as the principal cementing agent.

The geotechnical aspects of sabkha are addressed with particular reference to building foundations. Simplified soil profiles from selected sabkha sites with Standard Penetration Test Results are shown. The effectiveness of some soil densification methods, as a means of improving engineering properties of sabkha sediments, is explored. Arrival at appropriate foundation recommendations hinges on a properly conducted site investigation, consistent with field conditions, with a geochemical component as an essential part of the investigation. The most likely problems created by chemical changes within sabkha sediments are: settlement and strength loss due to solution of flowing ground water, and the creation of a chemically aggressive environment in foundations.

INTRODUCTION

Salt-encrusted flat surfaces, known as "sabkha" in the Arabic-speaking countries, are common in the coastal and inland areas of the Arabian Peninsula. These features are products of the evaporative environment that has dominated the Arabian (Persian) Gulf area for several thousand years. See Fig. 1 for location of major sabkhas along the southern shores of the Arabian Gulf. Conditions leading to the formation of these salt flats and their properties in the coastal and inland areas are different, and Kinsman & Park (1969) refer to these features as "coastal sabkha" and "continental sabkha" respectively.

The geomorphology, the geochemistry, and regional environmental parameters that influence the nature of sabkha sediments have been reported on by a number of investigators (Kinsman 1969; Bush 1973; Evans *et al*.1969; Butler 1969; Hsu & Seigenthaler 1969). In general terms, coastal sabkha sediments are loose to moderately dense silt/sand material of varying: size, composition, texture, and origin. Mud and clays are often interbedded with the sands and silts, as seams or pockets, or may be found down below towards the bottom. Some distinguishing features of sabkha deposits may include some or all of the following:

- puffy and hard surface often dotted with halite,
- lack of any vegetal cover over the surface,
- highly saline ground water table (usually within two meters from surface), and
- readily visible precipitated salts (halite, anhydrite, gypsum, and calcite) within the upper portion of the profile.

At most times, and in open terrain, sabkha's hard surface is sufficiently strong and durable to serve as a substitute for surfaced roads. Unfortunately, if the surface becomes wet due to occasional rainfall, flash floods or storm tides, the soluble salts (mainly halite)- which provide the cementation in the crust, dissolve and the sabkha becomes impassible (Ellis 1973; Fookes 1976).

Documented engineering type information on sabkha with reference to foundations and potential problems associated with buildings on sabkha sediments has remained scanty. Ellis (1973) and Fookes (1976) have evaluated coastal sabkha in the United Arab Emirates as road bases. Akili & Torrance (1981) have simulated sabkha sands in the laboratory and have assessed strength associated with cementation using different percent cement in the sand. Further work on cemented sands with reference to sabkha layers, using a laboratory penetrometer, was presented by Akili & Al-Joulani (1986).

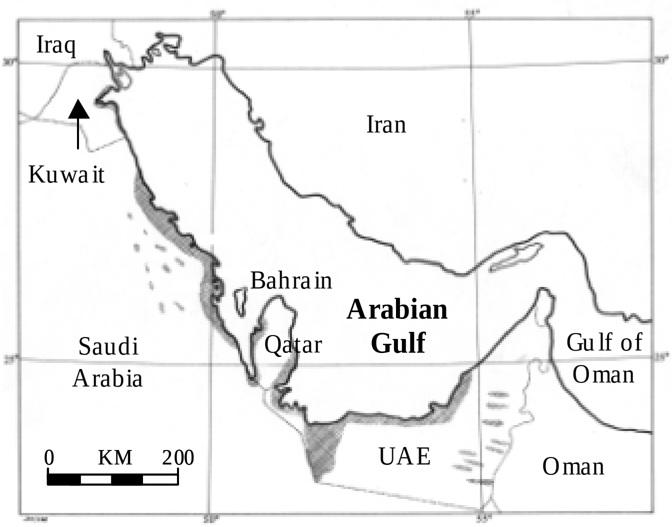

Fig. 1. Map showing location of major sabkha flats along the southern coast of the Arabian Gulf.

Fookes *et al.* (1985) have addressed chemical processes and geotechnical changes in sabkha soils and its waters, and have cited relevant case histories. Akili (1997) has evaluated some of the sabkhas along the western coast of Qatar Peninsula, by means of open pits and borehole samples. The materials encountered in Qatar were, by and large, similar to those of the sabkhas of eastern Saudi Arabia.

This paper is a further extension of earlier work by the author (Akili & Torrance 1981; Akili & Ahmad 1986; Akili & Jackson 1998) on foundations in the arid coastal margins of the southern shores of the Arabian Gulf. Use is made of extensive field data collected from sabkha cites in eastern Saudi Arabia and Qatar, with particular reference to building foundations.

In this paper, the author touches on the geological and hydro-geological setting of sabkha, shows typical profiles in sabkha sediments, and examines the effectiveness of soil improvement methods deployed in densifying sabkha sands. As such, the paper provides pertinent observations on foundations built over sabkha. The paper concludes by offering relevant recommendations for geotechnologists involved with foundations over sabkha, and argues for the need to carry out an "appropriate" site investigation prior to design and construction of foundations in sabkha terrain.

BACKGROUND

Sabkha(s) are equilibrium geomorphic surfaces whose levels are largely determined by local ground water. The mode of development and the dominant features of the sabkha in the coastal areas are different from those in inland areas. Coastal sabkhas are supratidal and are commonly a wedge of sediments overlain by supratidal facies that are overlain by eolian facies. Figure 2 presents diagrammatically a generalized cross-section from the Gulf waters to the inland margin of a coastal sabkha. The inland portion of the sabkha plain tends to have a brownish, salt-encrusted surface while that portion which is only slightly above the high tide level is commonly covered with a greenish- black algal mat. Coastal sabkha brines are primarily derived from the evaporation of percolating sea waters at or below sabkha surface.

Continental sabkhas are located inland and are often associated with areas of dune sands. They are considered as equilibrium deflation-sedimentation surfaces situated a set height (about a meter) above the ground water table (Kinsman 1969). Brines are the result of extensive evaporation losses of water vapor at the surface. Groundwater in nearby dune areas may have very different ionic concentrations from the sabkha brines. However, because the sabkha surface is very near the groundwater table, evaporation of incoming groundwater contributes to brine formation (Fookes *et al.* 1985).
Sabkha sediments, whether coastal or continental, reflect several sequences of sedimentation processes that are known to have occurred in the Arabian Gulf region during recent geologic history. Coastal sabkha sediments contain sands, silts, mud and clays that are either totally marine derived, or have been affected by marine environment during a sequence of ingressions and regressions of Gulf waters over the coast. As a result of these transgressions, the sands and silts were reworked by the waters and intermixed with marine sediments which resulted in the formation of: carbonate sands and silts, the bioclastic sands, the grey mud, and some of the clays. The most notable process occurring today is the deposition of wind-transported sands over coastal and continental sabkhas (Fookes e*t al.*1985). The depositional environment has produced quartzitic sand layers over original marine-derived and/or marine- affected sediments.

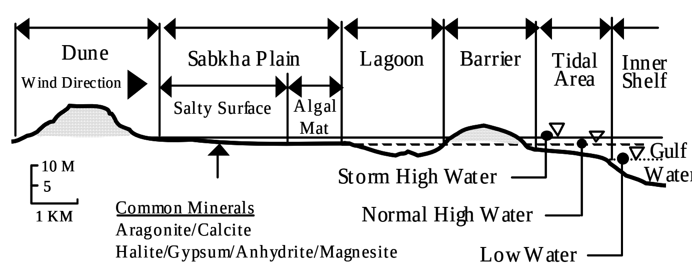

Fig. 2. Generalized cross section across a typical coastal sabkha with typical surface features.

Secondary minerals (salts) have formed within host sediments (sands, silts, insoluble salts, clays, etc.) by precipitation from concentrated brines (as in the case of gypsum) or by reaction between the brines and the host sediments (as in the case of dolomite). The most prevalent secondary minerals in sabkha are: calcite, gypsum, anhydrite, dolomite, magnesite, aragonite and halite. New secondary minerals continue to form while older secondary minerals may undergo chemical and physical changes in response to the complex geochemical environment of the sabkha.

The formation of secondary minerals and their relative positions in sabkha sediments are largely dependent on the hydrology of the particular sabkha and the means by which the sabkha ground waters are replenished. The principal means of replenishment in coastal sabkha are horizontally moving sea water and/or vertical downward water which inundate the surface of the sabkha as a result of flash floods, high tides, or occasional rainfall. Continental sabkha waters are replenished from continental water sources (perched water) or rainfall. When the vertical water is rainwater, it will dilute the interstitial waters thus causing dissolution of soluble secondary minerals within the sabkha matrix.

The evaporative pumping mechanism appears to be the most effective mechanism involved in causing the concentration of brines in sabkha waters, and in the formation of evaporite (secondary) minerals (Butler 1969; Hsu &Schneider 1973). Evaporation from the sabkha surface provides the energy for the upward movement of the saline interstitial waters by capillary action. In the absence of flood tides and rainfall (both of which are infrequent and probably inadequate), the water thus lost would be replenished by water entering laterally from the sea side. Hsu and colleagues (1969, 1973) have demonstrated that the amount of water that can be evaporated from the sabkha surface is substantial and is governed by the evaporation conditions of the atmosphere; since almost all of the sediments are capable of supplying water to the surface by capillarity at the necessary rate. The upward movement of saline ground water and its evaporation from the surface readily accounts for the development of the crust dominated by halite and other soluble minerals, and in the evaporative regime there would be evaporation and solution concentration at all levels above the water table such that some secondary minerals would form within the sediment from the water table to the surface. Back diffusion of ions along the concentration gradient combined with the periodic reflux associated with storm tides could lead to additional concentration of the saline interstitial waters (Hsu & Schneider 1973).

PROFILES AND PROPERTIES

The shores of eastern Saudi Arabia, Qatar peninsula, and the United Arab Emirates have extensive sabkha flats, both coastal and continental. They occupy roughly 20% of a coastal strip (50 km wide by 1000 km long) that extends from Kuwait in the north to the Sultanate of Oman in the east. See Fig. 1. For engineering purposes, the sabkha sediments of eastern Saudi Arabia and those on the western shores of Qatar are mostly sands and silts except in the shoreline extremities, where mud and clays tend to be more prevalent. The fines' content in the sands (silt & clay size) is significant. The sands are layered and often cemented Degree of cementation varies from lightly cemented to strongly cemented. Carbonate soils have been located at various sites within sabkha sediments, at different depths. Readily visible crystalline salts are wide spread at the surface and below. The salts often encountered include: anhydrite, gypsum, calcite, and halite.

The author has examined a number of foundations investigations' reports and a fairly large number of boreholes in sabkha terrain of eastern Saudi Arabia, and in the state of Qatar, looking for common characteristics, distinctive features and anomalies. Despite the complex nature of sabkha sediments, i.e. varying: particle size, shape, soil origin, degree and type of cementation, etc. it was possible to broadly view the sabkha profile as made up of **three zones:**

An **upper zone:** extends from the crusty puffy surface down past the water table. This zone, one to three meters in depth, includes the water table and the stratified thin cemented sand/silt layers. Based on the Standard Penetration Test (SPT) values, the encountered sediments in this zone are generally medium dense to dense unless the surface has been inundated with rain water or high tide, which tends to wash away readily soluble salts responsible for particles' cementation. Dissolution invariably lowers the strength of the sediments and creates loose density conditions.

An **intermediate zone:** may contain some or all of the following: loose quartzitic sands, calcareous sands, cemented sand-silt layers, clay layers interbedded with sands, mud, carbonate sands, and other marine-derived sediments. The general condition in terms of SPT varies from very loose to medium dense. Based on available borehole logs, this zone may vary in depth from few meters to over twelve meters. Within this zone, foundations (mostly shallow) are laid; thus its geotechnical characteristics are critical in arriving at appropriate decisions and/or foundation geometries.

A **lower zone:** In this zone, sediments tend to exhibit high resistance to penetration by SPT. Materials encountered have included: dense to very dense sands and silts, strongly cemented sands, shale, stiff clays, or diagenetic rock. Based on SPT results, refusal is within one or two meters of penetration.

Range of SPT values, side by side with prevalent description of materials encountered, for three selected sabkha cites, are shown in Fig. 3.The SPT profiles shown tend to support the categorization of sabkha deposits into the three broad zones referred to earlier as: upper zone, intermediate zone, and lower zone respectively.

DESIGN AND CONSTRUCTION CONSIDERATIONS

It seems appropriate when considering the broad categorization of sabkha, in terms of the three zones listed earlier, to focus attention on conditions and sediments within the intermediate zone. This zone is the most critical when foundations recommendations are to be made.

The decision on the type of foundation and the selection of an appropriate site improvement method is highly dependent on: the type of sediments and their relative density; degree of cementation and the evaporites providing the cementation;

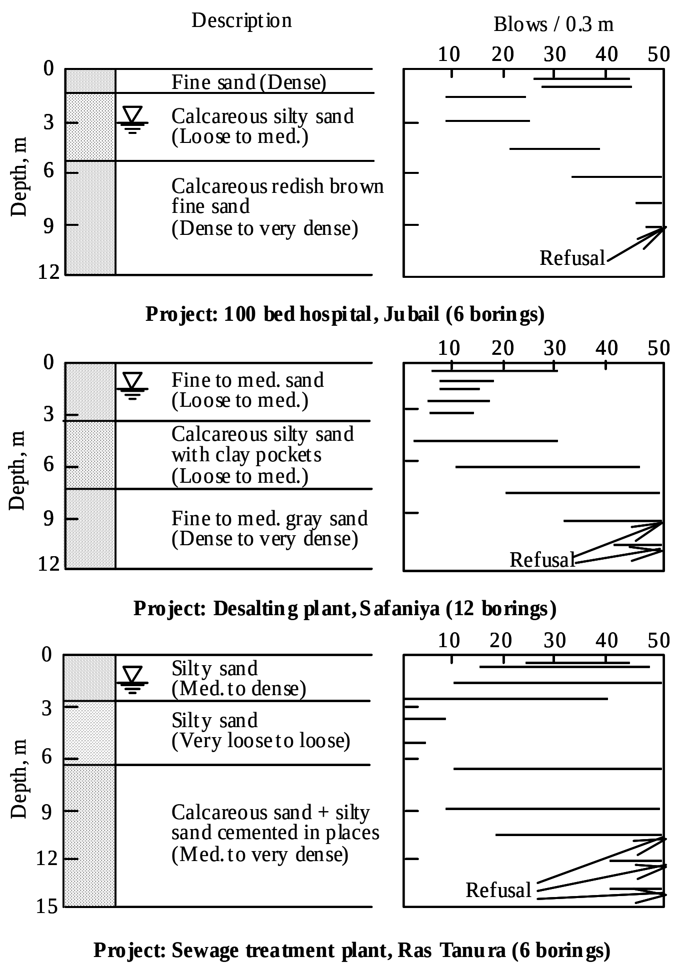

Fig. 3. Simplified soil profile data from three selected sabkha sites typical of material encountered, showing ranges of standard penetration test results (SPT) in terms of blows per 0.3 m.

percent fines within the uncemented layers; and percent carbonates, chlorides, and sulphates in the brines. Some of the noted problems and potential safe guards may include some or all of the following:

- Because sabkha sediments are highly variable materials in vertical and horizontal extents, chances are that these variations (layer thickness, relative density, degree of cementation, and type and percentage salts in sediments) would manifest themselves in extreme variations in compressibility characteristics. Precautionary measures and safeguards during site exploration, design, and construction, need to be taken to minimize and/or avert excessive differential settlement.

- The potential adverse reactions and chemical changes that may influence sediment properties and foundations embedded in them. This would invariably include the corrosion problems in the concrete and steel, resulting from high concentration of chlorides and sulphates in sabkha brines.

- The inability to properly assess by conventional probes the degree of cementation of sabkha sands, particularly in the light to moderately cemented range. Cementation has, both, positive and negative attributes in the context of foundation design over sabkha sites.

- Due to the high water table of sabkha and the nature of sabkha sediments, drainage of wastewater and irrigation water of built facilities (housing, industrial parks, etc.) is difficult and requires a well- planned disposal system. Discharge of waste and irrigation water through soak ways, as currently practiced, could cause a rise in groundwater level coupled with intermixing of water sources, leading to dissolution of some soluble salts thus undermining the strength and stability of the layers supporting the foundation.

- The evaporative pumping mechanism moves soluble salts from the water table towards the surface where they precipitate when water evaporates. The salt crystals thus developed may form blisters at man-made surfaces (pavements, concrete foundations, basements) causing cracking particularly in pavements (Fookes & French, 1977) but potentially in any porous material. Counter measures to deal with this problem and help reduce blistering have been outlined (French et *al.* 1982).

- Carbonate and gypsum contents in the sabkha sediments could be a trouble source of shallow foundations. High carbonate content (above 20 percent by total weight) may undermine foundations by carbonate leaching. Alternate hydration and dehydration of gypsum-rich layers under the hot and humid conditions that characterize the sabkha environment, is usually accompanied by volume changes that could contribute to differential settlement and foundation instability.

- The combination of loose sands with lightly cemented grains in sabkha sediments may be susceptible to collapse upon wetting or due to an increase in vertical stress. The collapse, referred to here, is not necessarily the sudden or the catastrophic break down of soil structure, but rather the slow type (years versus months) of relatively small magnitude(less than 1% percent). It is therefore highly recommended that the collapse potential of the sabkha site be addressed.

- Chemical reactions, precipitation and solution within sabkha sediments, are greatly enhanced if ground water flow- in and/or out of these sediments is relatively high. In the long range, these on-going activities (reactions, precipitation, solution) could undermine the stability of a foundation unless precautionary measures are taken. It is highly recommended that the anticipated flow regime of groundwater, in and out of the site, be mapped out and parameters such as: hydraulic conductivity, porosity and flow velocity, be estimated.

As noted above, sabkha sediments are extremely sensitive to changes in conditions that, directly or indirectly, affect the equilibrium chemistry of the sediments and their physical properties. It is highly recommended that extreme caution be exercised when considering foundations over sabkha. It makes a lot of sense when design decisions are in the making; that they are preceded by: proper soil investigation, appropriate tests, and assuming worst scenarios.

DENSIFICATION OF SABKHA SEDIMENTS

Sand/silt material encountered in sabkha (with particular reference to the intermediate zone referred to earlier) may be in very loose to medium dense state, thus requiring densification to sustain design loads safely, within tolerable settlement limits. Experience to date with construction on sabkha flats has shown that some form of densification is generally required when shallow foundations are considered. The densification methods that have been attempted in the sabkhas have included:

(A) Placement and compaction of selected fill material over the sabkha surface,
(B) Compaction without additional fill,
(C) Vibro-compaction, and
(D) Dynamic compaction.

For highly settlement-sensitive structures, piled foundations have been used. The piles are generally end-bearing supported on rock, in dense sand, or on a hard pan. These materials are usually encountered within the lower zone of the profile. Following is a brief discussion of the densification methods deployed in the region, and factors governing the choice of a method, based on outcome.

Sabkha compaction by vibratory rollers

This widely used approach is usually suitable for relatively small structures such as one to three story residential or commercial buildings. Such structures are usually supported on shallow footings with width rarely exceeding one or two meters. The stress influence zone of such footings is normally contained within two to four meters below footing grade. Adequate density is normally achieved by a predetermined number of passes using heavy rollers. Light rollers are generally not effective at a depth greater than two meters.

In order to increase the effectiveness of the compaction process, and consequently the relative density of loose sabkha sands within the intermediate zone, the sabkha crust should be broken down prior to compaction. Excavation to depth slightly above groundwater, replacement by a granular fill, and compaction of the fill by vibratory rollers, is practiced and appears effective in densifying deeper strata of sabkha sediments. However, if dewatering is required, this approach becomes uneconomical.

In sabkhas where the crust is firm and the soil is medium dense to dense in the upper zone all year round, the placement and compaction of a select fill on top of the surface may prove effective in sustaining the loads of a light structure. The final thickness of the fill placed shall be such that the pressure bulb developed by the footing is contained within the fill. This approach may be considered only when structural and architectural constraints do not preclude raising site grade.

Deep compaction of sabkha sediments

When sabkha deposits are loose and relatively thick, compaction at the surface is not effective. Deep compaction methods may be applied. Under this category, vibrocompaction and dynamic compaction are included. Vibrocompaction refers collectively to all methods involving the insertion of a vibrating probe into the ground with or without the addition of backfill material. The ability of any of these methods to accomplish the required improvement in density depends largely on:

(1) soil gradation and fines content,
(2) degree of saturation and position of water table,
(3) initial relative density of the deposit,
(4) soil structure and degree of cementation, and
(5) characteristics of the method applied.

Densification requires that the soil structure be broken down in order for particles to rearrange into new packing. In saturated cohesionless deposits, this is accomplished by inducing liquefaction by means of dynamic loading. Liquefaction occurs due to sudden release of energy upon impact of the probe into the soil, which greatly reduces its shear strength. Vibrocompaction and dynamic densification have been used on sabkha deposits with mixed results. A brief description of each, and results obtained are given below.

<u>Vibroflotation</u> This is one of the methods categorized under vibrocompaction and consists of inserting a vibratory probe into the deposit at predetermined intervals. The vibration induced causes the loose or medium dense granular soils to liquefy leading to subsequent densification. This method works well when the deposits are clean with little or no fines. Experience has shown that this method is ineffective when the percentage by weight of fines (particles finer than 0.075mm) exceeds 20%. This is because the hydraulic conductivity of materials containing fines is too low to permit rapid drainage of pore water- a requirement for densification which follows

liquefaction under the action of the vibratory forces. Details on vibroflotation's equipment and the process are discussed by Brown (1977). This method has worked in densifying some loose sabkha deposits of eastern Saudi Arabia, down to about 6 meters below surface. However, presence of silt layers or cemented sand-silt layers would reduce the effectiveness of this technique. Results of pre- and post-treatment of a sabkha site by vibroflotation are shown in Fig.4.

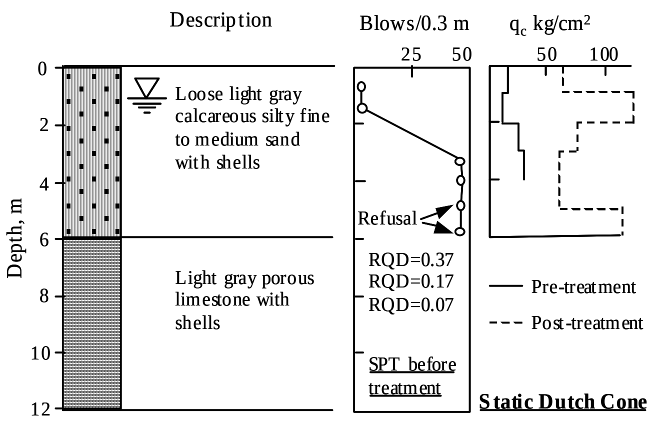

Fig. 4. Simplified soil profile, SPT and static Dutch Cone test results before and after vibroflotation on a sabkha site in Rahima, eastern Saudi Arabia.

Vibro-replacement (stone column) Most stone column installations are accomplished using the vibro-replacement method in a manner similar to vibroflotation. A cylindrical vertical hole is made by a vibrating probe penetrating by means of jetting action and under its own weight. Gravel and/or gravel-sand backfill is dumped into the hole in increments of 0.4 to 0.8 m and compacted by the probe which simultaneously displaces the material radially into the soft (or loose) soil. Column diameters are usually in the range of 0.6 to 1.0 m. Stone columns are placed in a grid pattern with center to center spacing of 1.5 to 3.5 m. The column should extend into a firmer stratum below. A blanket of sand and/or gravel, 0.3m or more in thickness, is usually placed over the top. This blanket has two functions; it acts as a drainage layer, and aids in distributing stress resulting from structures above. Useful guidelines on the application of this method are presented by ASCE Committee on Placement and Improvement of Soils (ASCE, 1978). The vibro-replacement method has been used on several sabkha sites in conjunction with vibroflotation application. Reports made available to the author appear favorable, and tend to support its use with caution.

Dynamic compaction Soil compaction by heavy tamping, termed dynamic compaction, involves repeated dropping of heavy weights onto the ground surface. Pounders range from 6 to 25 tons, are dropped repeatedly from heights ranging from 10 to 20 m. The repeated application of high energy impacts at the same impact points, causes densification/compaction of the soil mass to depths ranging from 3 to 8 m. Energy is typically applied in several passes, with the initial pass on a 3 to 6 m grid, followed by either additional passes, or at a tight grid at footings' locations. The technique was pioneered by Menard (Menard & Bruise 1975). When applied to saturated cohesionless soils, liquefaction can be induced, and the densification process is somewhat similar to that occurring during vibrocompaction. The effectiveness of the method in saturated fine-grained soils is uncertain. Successes, as well as failures, have been reported. Of particular importance when this method is under consideration, are: the depths of influence and the level of improvement anticipated. The level of improvement, within the projected depth of influence, depends primarily on: soil type, water conditions, and input energy. This technique has been applied onto several sabkha sites and has not been effective at all locations. The main difficulty arises from extreme variability in sabkha deposits, which are not always detected by routine soil investigation that precedes the improvement work. The presence of undetected silts and clay pockets, cemented sand-silt layers, and thin gypsum layers tend to inhibit densification of the cohesionless material in sabkha. A review of a number of cases suggests that there may be a definable maximum level of improvement that could be achieved for a particular soil. It has been suggested that this limit is equivalent to a cone penetration resistance (q_c) of about 150 kg/cm^2 (Leonards *et al.* 1980). The data presented in Fig. 5 of pre- and post-treatment with dynamic compaction of a selected sabkha site, show maximum improvement in value of SPT of 20 blows/0.3m, in q_c of 160 kg/cm^2, in Pressuremeter limit pressure of 22 kg/cm^2, and in Pressuremeter modulus of 350 kg/cm^2. The sediments densified in this case were relatively clean sands. Based on the field data (Fig.5), the level of densification achieved appears satisfactory.

SITE INVESTIGATION

To aid in planning of ground investigation of a sabkha site, preliminary information on the geology, geomorphology, and brine chemistry of the specific location, should be made available. Relevant information under this category may include:

i. The land forming processes: past processes, present processes, and those that may be controlling after construction and development of the proposed site;
ii. Predominant sediments and whether marine or continental: types of sediments and their characteristics, bedrock/ hard pan information, and buried algal mats, if any;
iii. Salts in sediments: their type, amounts, presence of continuous and discontinuous cemented layers, particularly gypsum layers;
iv. Groundwater flow characteristics: gradient, potential water ingress, capillary zone, surface water courses, and water table fluctuations; and,
v. Groundwater chemistry: major ions and their concentration, potential reactions, and the impact of construction and site development on: precipitation, dissolution, and crystal growth.

For large-size projects, it is recommended that site investigation work be carried out in stages. Table 1 outlines a four- stage strategy; proven useful when sufficient lead time is available. Preliminary stage (Stage I), using walk over survey and/or widely spaced sampling procedure, will aid in the planning and execution of the latter three stages to follow.

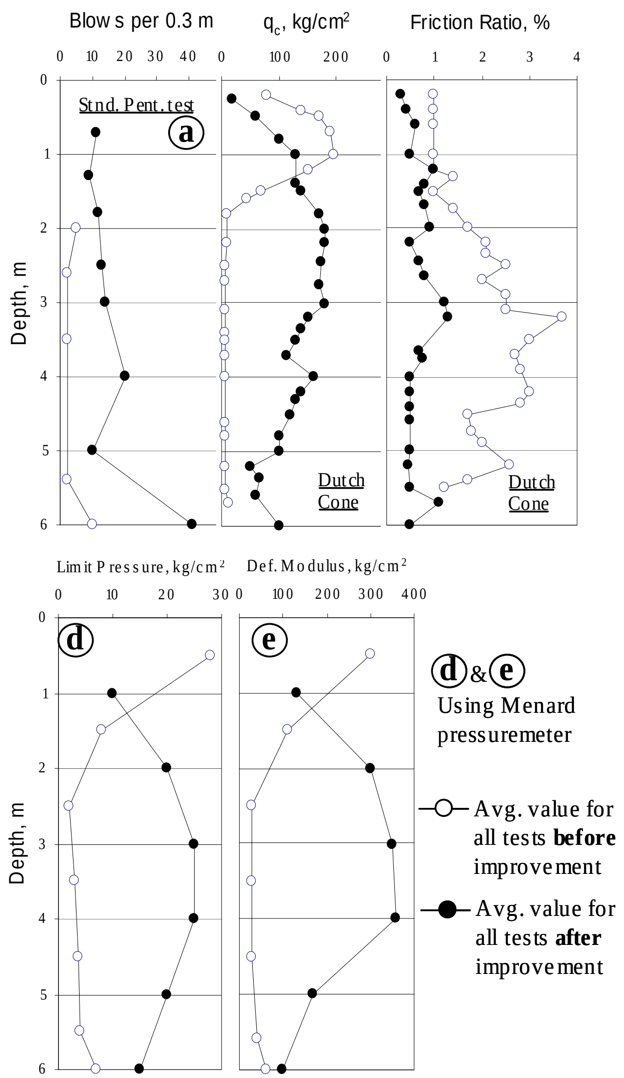

Fig. 5. Test results before and after dynamic compaction of a sabkha site in Rahima, eastern Saudi Arabia.

Because the soil-structure, and therefore stability of layers within the sabkha profile, are dependent on chemical cementation due to the presence of salts (chlorides, sulphates, carbonates); it is useful to identify those layers that appear sensitive to the presence of salts versus those that are less affected. Therefore, it is imperative that chemical testing be carried out (Stage IV) to assess: type, percentage, and manner in which these salts are present within soil grains.

Examination of relatively large exposures in open test pits, trenches, or through large diameter shallow borings, will aid in delineating sediments and layering, help identify crystalline salts, and at the same time, allow extraction of bulk and undisturbed samples. Specimens for determination of mechanical properties of soils are often obtained with open-end drive samplers which can be placed directly in consolidation or triaxial devices. In some cases, high quality Denison and Pitcher specimens are needed Block samples from open test pits have also been utilized. Ordinarily, however, the presence of salts makes it extremely difficult to obtain good samples. Thus because of the difficulty of sampling, insitu testing is recommended for major projects involving: chemically sensitive layers, relatively heavy loads, dynamic loads, and the use of heavy construction equipment.

Table 1. A proposed four-stage geotechnical investigation for a sabkha terrain

Stage	Purpose	Major Tasks
I Preliminary	To plan subsequent stages	• Desk study • Walk over survey
II Defining	To determine type and extent of required field and lab work	• Identify land forms and controlling processes • Obtain preliminary in-depth information through open pits
III Main	To obtain all field and lab data at a standard, justified by size and complexity of project	• Mapping including: topography, outcrops, hydrology, water gradient • Perform fieldwork by: boreholes, sampling, in-situ testing • Perform lab tests: strength, compressibility, conductivity, etc. • Properties and classification
IV Auxiliary	Addressing chemical equilibrium of sediments and brines	• Chemical testing of soils and brines • Assessing chemical stability due to construction and development • Effect of leaching on stability and strength

Field tests including: plate bearing tests, CBR tests, Pressuremeter tests, foundation and embankment loading tests, dewatering, seismic surveys, etc. have been used, with varying degrees of success, to investigate sites of major structures or to generate useful parameters for foundation design over sabkha sites. Proper planning and relatively long time (one to two years) are usually required to generate useful field data that could be relied upon.

When examining the behavior of granular materials in sabkha, it is important to distinguish between stable and metastable structures. The former derive their strength predominantly from particle interlock, while the latter are dependent to a large degree on weak cementation bonds derived largely from the presence of sulphates, chlorides, and/or carbonates

(Fookes & Higginbottom 1980). Some of the sand-silt layers in a sabkha possess metastable particle structure that makes them extremely susceptible to collapse upon loading or inundation. The author has observed collapse behavior on several sabkha sites, triggered by embankment loading coupled with increase in moisture content (Akili 1997).

CONCLUDING REMARKS

The brisk pace of construction activities over many of the sabkha flats along the southern shores of the Arabian (Persian) Gulf, has necessitated consideration of their geological setting and their geochemical properties. Sabkha sediments are unusual deposits characterized by highly saline groundwaters, presence of significant amount of crystalline salts, high evaporation rate through the surface, rapid crystallization in the upper portion (crust), and complex chemical reactions between the brines and the sediments.

Examination of a large number of boring logs and related field tests from several sabkha sites in eastern Saudi Arabia and Qatar, has confirmed that granular soils tend to dominate sabkha profiles. Quartzitic sands, calcareous sands and silts, mud and clays make up the unconsolidated portion of the sabkha profile. Based on the standard penetration test data, sabkha's granular sediments are generally dense within the **upper zone**, which contains also the cemented crust. This upper layer may extend to the water table. Below the crust, an **intermediate zone** comprised of: loose to medium dense conditions of a granular matrix, a mixture of continental and marine-derived sediments, extends down to a probable maximum depth of about twelve meters below surface. Below the intermediate zone, dense sands, strongly cemented sands, diagenetic limestone or occasionally stiff clays are usually encountered and referred to, in here, as the **lower zone**.
Difficulties noted when using sabkha as building sites have been attributed to: (*1*) sediments variability, which makes sabkha sites extremely susceptible to differential settlement; (*2*) sabkha's complex and changing geochemical setting, which appears to influence mechanical properties of sabkha sediments; (*3*) the difficulty in assessing, by conventional probes, the degree of cementation of sabkha sands particularly, in the light to moderately cemented range; and (*4*) potential carbonate leaching in high carbonate content sediments, along with, potential volume changes that are known to occur in layers containing gypsum.

Experience has shown that some form of site improvement is necessary for sabkha to sustain shallow foundations. Improvement methods applied have included surface densification by vibratory rollers (with and without a select fill on top), deep compaction by vibroflotation, vibro-replacement technique, and dynamic compaction. Observations, based on available case studies, show some degree of success in increasing relative density on most jobs performed. Difficulties with deep compaction are bound to arise with higher fines content and presence of undetectable cemented layers and cemented pockets.

Site investigation in sabkha terrain should include an appraisal of the geochemical setting and potential chemical changes that are likely to occur in sabkha sediments after construction. Although many of the chemical and physical processes that occur in sabkha are not fully understood, it is believed that sufficient knowledge exists to assess the probable risks that may result in most situations, and to be able to design and construct safe foundations in sabkha deposits.

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