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Performance of Shallow Foundation on Sabkha Soil

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Abstract: Sabkha or salt flat soil is one of the most unpredictable and potentially dangerous soils in the Middle East. This soil covers a large and strategically important area of the Arabian Gulf coast, as it contains the world biggest oil reserve and a number of petrochemical plants are either have been built or are scheduled to be built in this area. The performance of shallow foundations on the Eastern province of Saudi Arabia's sabkha soil is investigated numerically using the 2-D axisymmetric finite element model. The parameters used to simulate this soil in the numerical models were based on a large number of laboratory tests to determine the shear strength and stiffness parameters of the sabkha soil. In addition, the characteristics of the interface between the foundation and soil used in the numerical model were established from shear box tests that were conducted to evaluate the concrete-sabkha soil interface properties. The developed numerical model was calibrated/verified using the results of full-scale pile load testing program from an ongoing project to further enhance the accuracy of the results. A parametric study was then conducted using the verified model to establish the performance characteristics of foundations constructed on sabkha soil and provide guidelines for their design.

1 Introduction

Saudi Arabia has witnessed enormous development in the oil and petrochemical industries in the past few decades. According to The World Factbook (CIA 2009), Saudi Arabia is the largest oil producer and has the largest reserves in the world, which amounts to 266.7 billion barrels of oil in proven reserves. Major facilities have been built to support oil production and storage. Furthermore, major developments are planned for processing oil to meet the ever expanding global demand for petro-chemicals products. For example, the Royal Commission for Jubail and Yanbu (RCJY) is expanding the two presently established cities by constructing Jubail 2 and Yanbu 2. The Jubail industrial cities 1 and 2 are located in the Eastern province of Saudi Arabia where most of the oil fields and oil reserves are located. The soil in the Eastern province and particularly in the area of the Jubail industrial cities 1 and 2, widely known as sabkha soil, is one of the most unpredictable and potentially dangerous soil types from a geotechnical engineering perspective.

Sabkha is an Arabic word used to describe the large, salty flat ground that is usually underlain with silt, sand or clay. Sabkha can be found both along the sea coast where it is called coastal sabkha or inland where it is known as continental sabkha. This study will focus on coastal sabkha because it is found in a strategically important location in the Eastern province of Saudi Arabia along the Arabian Gulf coast where the oil industry is concentrated (Al-Amoudi 1995). Sabkha soil can be found in many parts of the world and is especially prevalent in hot and arid countries. While sabkha is known by different names, for engineering purposes, Fookes and Collis (1975) limit these names to: sabkha (coastal salt marsh), playa (a salty surface playa) and saline (a relatively deep area with a high salt ground water table which creates a salt crust on the surface of the ground due to a rise in the water table). Three main features characterize sabkha soils: (i) high content of salty minerals; (ii) a shallow ground water table; and (iii) a relatively hard shell (Ghazali et al. 1985). Sabkha is usually found between 15° and 45° north and south of the equator as shown in Figure 1, and at locations where the precipitation rate is less than the evaporation rate (El-Naggar 1988). Sabkha soils cover approximately 50,000 km^2 (50 km wide by 1000 km long) of the Arabian Gulf coastal strip or about 20% of its total area (Akili 2006). Additional distinguishing features that characterize sabkha soil: (i) the physical properties of sabkha soil vary in both horizontal and vertical directions; (ii) the standard penetration test (SPT) value of sabkha soil is usually low (less than 10 blows/30 cm); and (iii) upon wetting, the sabkha soil becomes vulnerable and loses a significant amount of its bearing capacity (Aiban et al. 2006). Numerous studies have examined and characterized the behavior of sabkha soil. Different approaches to stabilizing sabkha have also been investigated including the use of chemical and mechanical methods. However, to the best of the author's knowledge, no studies have yet been conducted to investigate the behavior of shallow or deep foundations founded on sabkha soil that take into account potential flooding conditions.

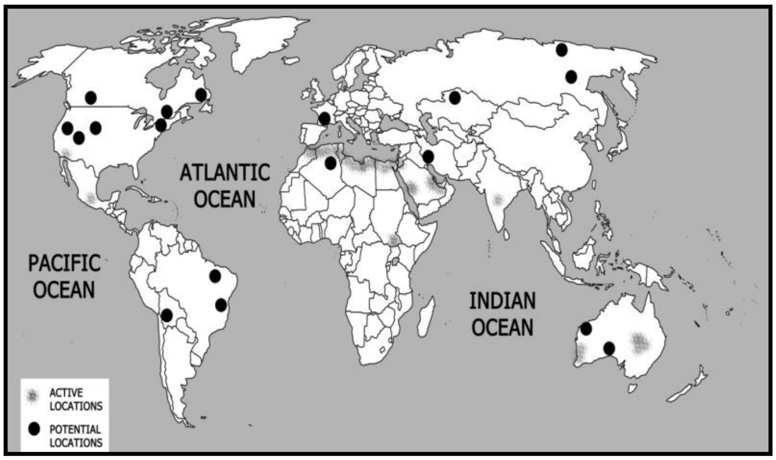


Figure 1: Distribution of sabkha soils around the world (modified from Al -Amoudi 1994).

1.1 Types and Formation of Sabkha

In general, there are two main types of sabkha soils according to their place of origin: coastal sabkha formed from the collection of marine remains caused by different tidal forces (subtidal, intertidal and supratidal); and continental sabkhas that are developed at locations where marine sediments have formed in the past (Kinsman 1969). Coastal sabkha is formed over three stages: (i) sea water covers a portion of the land during flooding and forms lagoons in the land; (ii) after the sea water retreats, marine sediments are left, which are mixed with coastal sand, and (iii) in the final stage, high temperature and wind cause the water in the area to evaporate and coastal sabkha soil is formed as shown in Figure 2 (Fookes et al. 1985).

1.2 Problems of Sabkha as Supporting Soil

Because the nature of sabkha soils, both chemically and physically, some problems may occur during construction. These problems were identified by a number of researchers: Akili and Torrance (1980), Al-Amoudi et al. (1992), Abduljauwad and Al-Amoudi (1995), and Akili (2006). The most common problems are: (i) the compressibility of sabkha soil varies from one point to another which can lead to large differential settlement, which may cause severe damage and cracking of concrete structures founded on sabkha soil; (ii) the unconfined compressive strength for surficial sabkha layers is very low (about 20 kPa), which may be further reduced because of storm tides, rainfall, rise of the ground water table or flash floods; (iii) the hydration and dehydration of unstable gypsum in a sabkha formation can lead to large volumetric change, which can cause damage in structures founded on sabkha soil (Akili 1981); (iv) sabkha soils are rich in carbonates, chloride and sulfate forming minerals such as gypsum, halite, dolomite, anhydrite and magnesite (Kinsman 1969). Most salts are concentrated in the top 200 mm of sabkha soil (Sabtan and Shehata 2002), leading to high chloride and sulfate concentrations (as high as 158 ppt and 5.24 ppt, respectively). At this level of salt concentration, the foundation reinforcement may corrode and its concrete may deteriorate (Akili 1981; Al-Amoudi 1995); and (v) the bearing capacity of sabkha soil may decrease and the foundation settlement may increase if it interacts with fresh water, since this could dissolve some of the cementing materials and thus reduce the shear strength of the sabkha (Sonnenfeld 1984; Al-Amoudi 1992).

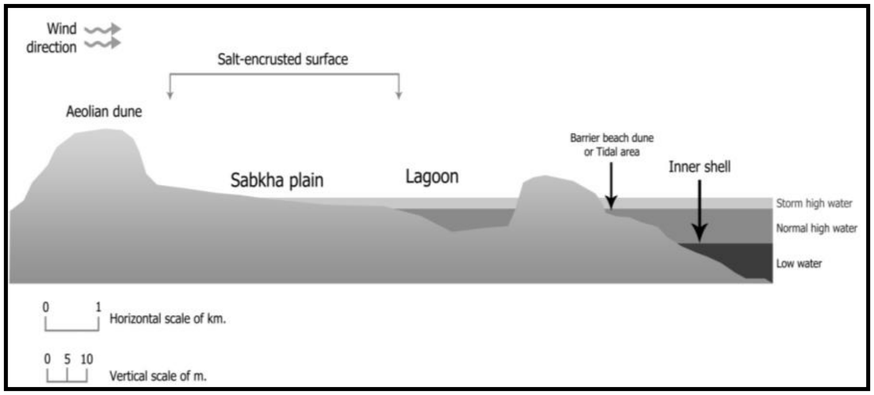


Figure 2: Formation of coastal sabkha (modified from Akili and Torrance 1981).

2 Objective and Scope

In this paper, the performance of shallow foundations in the Eastern province of Saudi Arabia's sabkha soil was investigated numerically using the commercial software, Plaxis (Brinkgreve 2002). The parameters used to simulate the behavior of the sabkha soil and the interface characteristics between the foundation and soil were based on a large number of laboratory tests to determine the shear strength and stiffness parameters of the sabkha soil.

3 Experimental Program

Numerous tests have been conducted to characterize the sabkha samples, which have been retrieved from the eastern part of Saudi Arabia. Triaxial and direct shear tests were conducted in order to measure the soil shear strength parameters which will be used in the numerical model. The interface strength between sabkha soil and different construction materials were measured as well to accurately simulate the soil structure interaction (SSI) in FEM. The soil samples used in this paper were retrieved from Ras Al-Gar, located in the eastern part of Saudi Arabia between the cities of Jubail and Dhahran. The samples were retrieved during the summer season at a temperature of 45°C and a relative humidity of 50%. Two types of samples were retrieved: disturbed and undisturbed. The disturbed samples were used mainly for the characterization of sabkha and were retrieved in plastic containers. The samples were sealed properly to maintain their moisture content. To obtain the undisturbed samples, a Shelby tube sampler was not suitable because the small diameter of the tube may have caused some disturbances in the soil, especially since it contained salt crystals that in large concentrations could damage the sampler device (Abduljawad and Al-Amoudi 1995). Therefore, the undisturbed samples were obtained using thin-walled and sharp edged 0.5 m polyvinyl chloride (PVC) tubes that had an outside diameter of 152.4 mm and 7 mm thick walls. The large diameter PVC samplers helped prevent any disturbances of the soil, especially at the sample center, which provided the soil test specimen. Five PVC tubes were used to obtain sabkha samples from randomly selected locations with a minimum distance of 2 m between the various locations. The tubes were pressed into the soil gently to avoid any disturbances at 0.5 m from the surface. After retrieving samples, the tubes were wrapped with plastic bags and sealed to avoid any changes in their moisture content, and were kept at room temperature (25°C) untill testing occurred.

3.1 Characterization Tests

Several tests were conducted to characterize the soil, including: water content, sieve analysis, specific gravity, unit weight triaxial test, and direct shear test. Different methods were used to dry the samples for these tests including the American Society for Testing and Materials (ASTM) method because the oven temperature could be more than 80˚C, which could change the sabkha structure by transforming gypsum into anhydrite (Al-Amoudi 1992). For the sieve analysis, a wet sieving and dry sieving were used along with three different drying techniques: oven-drying; air-drying, which involved spreading the samples over a large area outside the lab subjected to an ambient temperature of 45˚C for five days; and hot-room drying, which involved spreading soil in a room with a temperature of 50˚C and a relative humidity of 85% for seven days. In addition, the wet sieving was conducted by washing the samples using sieve No. 200 and weighing the amount of sabkha passing through the sieve to obtain the fine materials. The remaining sabkha was used in the sieve analysis. Moreover, both the direct shear (shear box) and triaxial tests were conducted on the undisturbed samples that were retrieved employing PVC tubes. All the tests conducted for this paper were summarized in Table 1, including the results and some comparison with results from the literature.

4 Finite Element Model

The sabkha properties established from the experimental program were used in simulating the sabkha in the numerical model used for the analysis of foundations on sabkha soil. The foundation was characterized using appropriate properties of concrete. The numerical model was calibrated/verified using full-scale pile load test data from an ongoing project involving piles installed in sabkha soil located in the same area from which the soil samples were retrieved. About forty-two borehole logs in this area were examined and most of the logs demonstrated the same soil profile with minor variations. The site consisted of 5 m of medium dense sand with silt (sabkha soil) underlain by 5 m of very loose silty sand, and 25 m of medium-stiff sandy silt. The water table elevation varied with an average depth of 3 m below the ground surface. Eight full-scale load tests were conducted on piles with different lengths at this site under different loading conditions. These pile load tests were used to calibrate and verify the numerical model. It is usually assumed that the sabkha layer is very shallow at about 1 m deep; however, this is not entirely accurate because in some locations in eastern Saudi Arabia the sabkha soil can be found to be extended up to 8 m. The elastic perfectly plastic model was used throughout this study.

4.1 Calibration and Verification of the Numerical Model

The numerical model was initially established to represent the actual site and pile foundation system for the pile load tests considered. For the pile load test, a pile with 600 mm in diameter and 15 m in length was used. The model parameters were based on the data collected from the laboratory tests and the geotechnical report for the pile load test site as presented in Table 2. As shown in Figure 3, the top 40 m comprised three soil layers. A drained condition was considered for the cohesionless materials and an undrained condition was used for cohesive materials. The initial model was calibrated considering the load-settlement curves obtained from the full-scale pile. Figure 4 compares the results from the FEM using initial soil properties with the results obtained from the full-scale pile load test. Despite the fact that the finite element model and the full-scale pile load test curves display the same pattern, it is obvious that the FEM underestimates the capacity of the soil system. This is likely because the soil strength parameters used in the FEM are less than the in-situ values. The average error in the prediction of ultimate pile load from the FEM as compared to the full-scale pile load test was approximately 30% and the maximum error was 50%. The FEM was "fine-tuned" by adjusting some of the model parameters to improve the match with the pile load test results as will be discussed later. The strength and stiffness values used to model the soils in the FEM were increased to achieve better agreement with the measured load-settlement curve from the pile load test. In addition, the reduction factor for the pile-soils interface was "fine-tuned", which helped achieve an agreement between the FEM and pile load test results. The matching process comprised several steps. First, the soil's stiffness was adjusted to improve the match for the initial part of the load-settlement curve. The soil strength and interface properties were then adjusted to improve the matching along the remaining part of the load-settlement curve. This process was repeated until the best match was achieved. Figure 4 compares the results from the initial and calibrated

FEM with those from the full-scale pile load test. The initial stiffness and pattern of the load-settlement curve are similar to those obtained from the full-scale pile load test. Table 2 summarizes the initial and final soil properties used in FEM calibration process; the final soil properties used in FEM is slight different than what reported in Table 1 due to the fine-tuning process. The Poisson's ratio,ν, for layer 1, 2 and 3 were 0.3, 0.3 and 0.45, respectively. The lateral earth pressure coefficient at rest, K_o, was 0.45 for sabkha soil and dilation angle,ψ, was 0^o The pile-soil interface reduction factor for the three layers (sabkha, very loose silty sand and medium stiff sandy silt) were 0.83, 0.61 and 0.73, respectively. The average error in the calibrated FEM as compared to the pile load test was – 5 %.

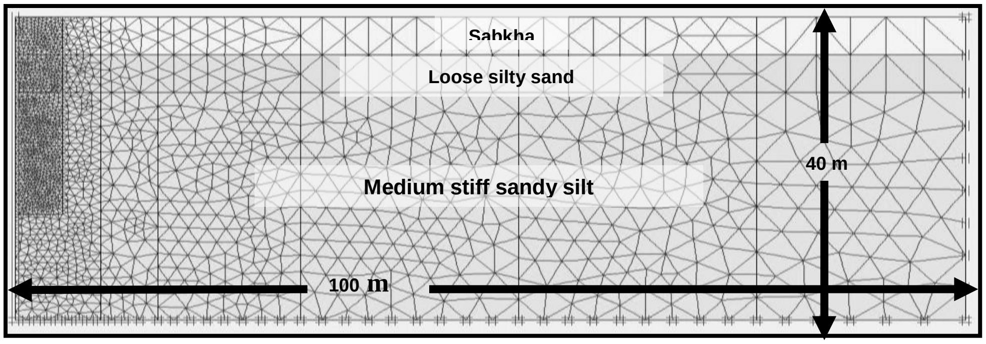


Figure 3: Geometry for FEM model and elements discretization for shallow foundation

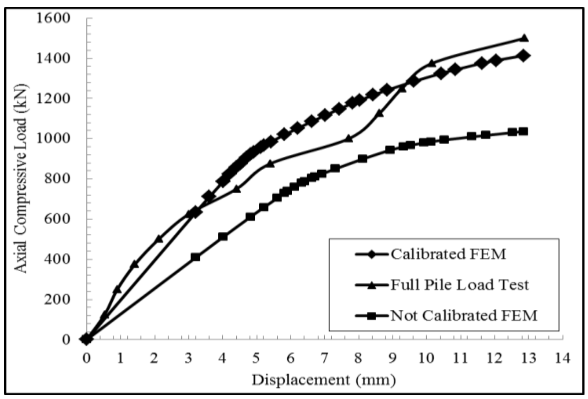


Figure 4: Comparison of load-settlement of initial FEM and calibrated FEM vs. pile load test data.

5 Parametric Study Results

The influence of some of the factors affecting the ultimate bearing capacity of shallow foundations constructed on sabkha soil examined in this study and the foundation was not embedded in the ground. The factors considered were the angle of internal friction, sabkha layer thickness, and the foundation diameter. In the FEA, the ultimate load is considered to be the maximum load on the load-settlement curve before it starts to decrease due to general shear failure. However, another failure mechanism, punching shear failure, may occur, which is particularly characteristic of footings resting on loose soil. In punching shear failure, the load-settlement curve varies in a parabolic fashion until the ultimate load is reached, after which the load-settlement curve becomes linear. In this case, the failure surface will not extend to the ground surface and the bearing capacity is reduced (Das 2004). It is worth mentioning that when sabkha soil is flooded with fresh water from any source (e.g. rainfall), it loses about 30% of its bearing capacity (Abduljauwad and Al-Amoudi 1995). This reduction was taken into consideration in this study in order to simulate a worst case scenario

Table 1: Summary of characterization tests and their results

Test	ASTM	Results	Remarks
Moisture Content	ASTM D 2216	13.31% to 15.93% (average of 14.51%)	Abduljauwad and AL-Amoudi (1995) reported sabkha water content of 17%,
Sieve Analysis dry sieving	ASTM D 422	The fine soil in the oven-dry, air-dry and hot-room-drying was 1.79%, 0.72% and 0.91%, respectively.	Similar Abduljauwad and Al-Amoudi (1995)
Sieve Analysis wet sieving	-	The fine soil in the oven-dry, air-dry and hot-room-dry were 15.89%, 15.53% and 13.64%, respectively.	-
Specific Gravity	ASTM D 854	2.74 to 2.80 (average 2.76)	Al-Amoudi and Abduljauwad (1995) reported 2.73
Field Unit Weight	-	Average for sabkha soil is 17.51 kN/m^3 and the average dry unit weight is 15.34 kN/m^3.	Abduljauwad and Al-Amoudi (1995) reported γ_d=15.69 kN/m^3.
Triaxial Test (CU)	ASTM D 2850	ϕ and c were 38° and 15 kPa, respectively. The ϕ\` and c\` were 39° and 18 kPa, respectively.	-
Concrete-Sabkha Interface	-	The angle of friction was 35° and the cohesion was 20 kPa	Reduction Factor R_{inter} = δ/ϕ= 0.8

Table 2: Summary of soil properties used in different stages of this study

#	Soil Type	γ (kN/m3)			E (MPa)			c (kPa)			(ϕ) (°)		
		PLT	FE_o	FE_f	PLT	FE_o	FE_f	PLT	FE_o	FE_f	PLT	FE_o	FE_f
1	Sabkha	18	17.5	18.5	20	10	15	14	0	14	30	30	34
2	Very loose silty sand		16			8	6		0			21	
3	Medium stiff sandy silt		19			40			44			0	

PLT: Pile load test; FE_o: initial finite element analysis; and FE_f: final finite element analysis.

5.1 The Influence of the Angle of Internal Friction

The effect of the friction angle of the soil on the footing bearing capacity depends on the depth of the soil being examined and the size of the foundation. Figure 5 shows the ultimate bearing capacity for different values of the foundation diameter and the angle of internal friction for the sabkha. As expected, the ultimate bearing capacity increased as the angle of internal friction increased; however, the rate of increase differed depending on the size of the footing. For a footing with a small diameter (i.e. 5 m), the rate of increase in the ultimate bearing capacity due to the increase in the angle of internal frictions was small compared to that of a foundation with a larger diameter. Although, the slope of the curve increased as the foundation diameter increased from 5 m to 7.5 m, the slope is substantially less for the foundation with 10 m diameter. The results presented in Figure 5 are for the sabkha layer with 8 m thickness (which is greater than the foundation diameter for a diameter of 7.5 m or less in order to eliminate any influence due to the weaker soil layer below sabkha. Therefore, the capacity of the 10 m diameter foundation was influenced by the soil layer below the 8 m sabkha soil and this influence was reflected where the angle of internal friction is greater than 26°. This is due to the fact that the strength of sabkha with a low angle of internal friction is quite similar to the weak soil layer. However, for sabkha with a higher angle of internal friction, the difference in the shear strength is obvious and the bearing capacity of a foundation with diameter greater than the thickness of the sabkha soil thickness is affected by the weak soil layer below sabkha. This is because the foundation's zone of influence extends to a depth approximately equal to its diameter (10 m in this case). All the results shown in Figure 5 were obtained for soil cohesion, c = 14 kP.

5.2 The Influence of the Foundation Diameter

The bearing capacity for a shallow footing on sabkha soil is directly related to its diameter, the angle of internal friction and the sabkha layer thickness. Table 3 presents the percentage increase or decrease of the foundation capacity for different values of the angle of internal friction and thickness of the sabkha layer. A number of observations can be made from the results presented in Table 3. As the diameter increased from 5 m to 10 m, the bearing capacity increased by an average of 21.5% for the 5 m sabkha thickness and $\phi = 24^\circ$. However, for $\phi = 27^\circ$, the bearing capacity of the foundation resting on a 5 m thick sabkha layer decreased by 11 % as the foundation diameter increased from 5 m to 10 m. This is because of the influence of the weak soil ($\phi = 21^\circ$) underlying the sabkha soil and the failure surface extended to the weak layer causing a punching shear failure. For high values of the angle of internal friction (e.g. 30° and 34°), the bearing capacity was decreased by an average of 28.2% for all values of thickness of sabkha layer considered, as the foundation diameter increased from 5 m to 10 m. Also, by increasing the diameter from 5 m to 7.5, the bearing capacity was decreased by an average of 15.7% for the 5 m sabkha thickness and $\phi = 30^\circ, 34^\circ$. The capacity of the 7.5 m diameter foundation was influenced by the weak soil underlying the sabkha soil. This influence is particularly obvious for sabkha with a high angle of internal friction and for the limited sabkha thickness (less than the diameter of the foundation). Because the soil below the sabkha was loose, the failure mechanism changed from general shear to punching shear, hence the bearing capacity of the foundation decreased. For the sabkha soil layer thickness of 8 m, the bearing capacity for the 7.5 m (which is less than the thickness of the sabkha) increased by 11.3% relative to that of the 5 m diameter foundation. In this case, the influence of the weak soil below the sabkha soil is considered to be negligible because the diameter for both foundations is smaller than the thickness of the sabkha; therefore, the bearing capacity of the foundations is mainly determined by the sabkha soil.

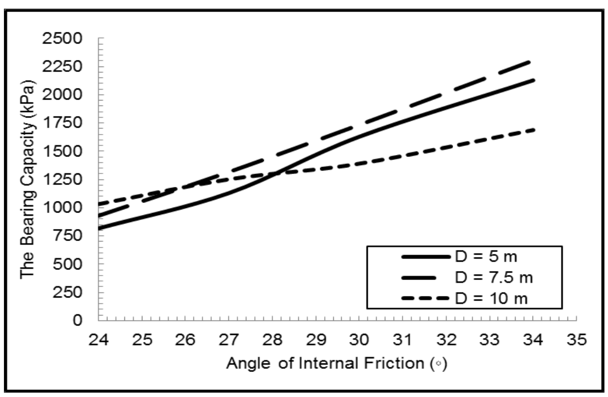


Figure 5: The capacities for different foundation diameters and different ϕ for an 8 m sabkha thickness

5.3 The Influence of Sabkha Layer Thickness

The effect of the sabkha layer thickness for different foundation diameters and angles of internal friction is shown in Table 4. For the 5 m footing diameter, the average increase in the bearing capacity was about 2.6 % with an increase in sabkha thickness. However, for the 7.5 m and 10 m footing diameter, zones of influence extended beyond the sabkha soil; thus, the foundation bearing capacity increased as the sabkha thickness increased, which depends on the ratio of the footing size to the sabkha soil thickness and the angle of internal friction. For a higher angle of internal friction, the increased rate is higher as compared to the small angle of internal friction. This is due to the fact that sabkha soil is much stronger than the underlying soil, and thus supporting most of the load transmitted by the foundation. Moreover, by reducing the ratio of the foundation size to sabkha soil thickness (D_f/h_s) to 1 or less, the influence of the soil below sabkha becomes negligible. On the other hand, for $D_f/h_s > 1$, the bearing capacity will be reduced as mentioned earlier due to the punching shear failure.

Table 3: Change in the bearing capacity due to change in footing diameter for ϕ and sabkha thickness

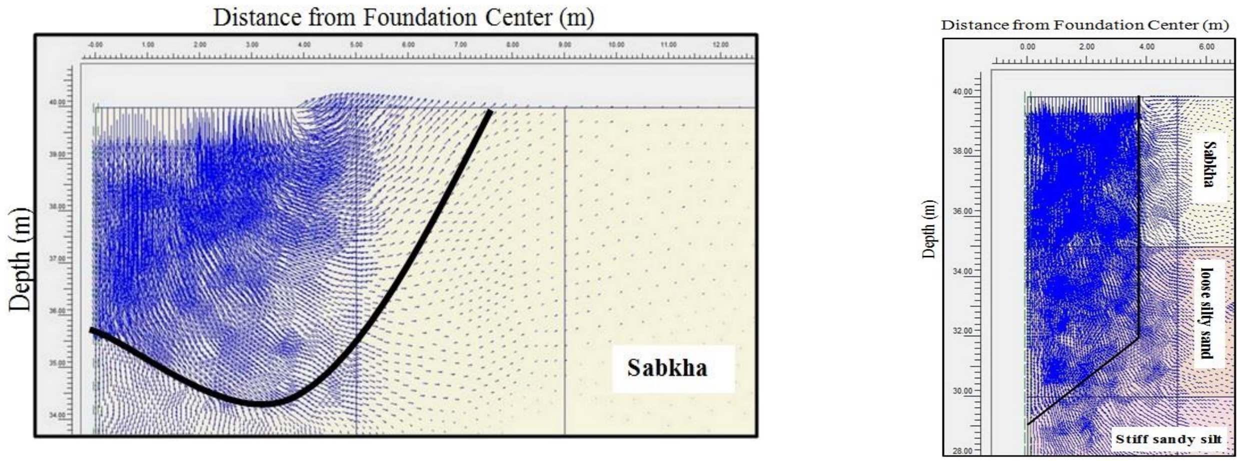
Sabkha, H (m)	ϕ(°)	% of change due increasing diameter	
		5 m – 7.5 m	5 m – 10 m
5	24	14.7	14.7
	27	7.7	- 11
	30	- 7.5	- 32
	34	- 23.8	- 43.5
6	24	14.7	23.5
	27	12.1	0.25
	30	0.2	- 21.8
	34	- 14.4	- 36.6
8	24	13.7	26.2
	27	16.5	10.8
	30	6.5	- 14.6
	34	8.2	-20.7

5.4 Failure Surface of Sabkha Soil

The soil may experience one of three shear failure modes supporting a shallow foundation: (i) general shear failure, (ii) punching shear failure, or (iii) local shear failure (Vesic 1973). For soil with high shear strength (e.g. medium dense or dense sand), the failure mode is usually general shear. On the other hand, very weak and compressible soil experiences punching shear failure. Each failure mode has a unique failure surface, so it is easy to identify the particular shear failure mode by identifying the failure surface. The failure surfaces for the different foundation configurations considered in this study are discussed below. In the case of the sabkha soil considered in this analysis, two shear failure modes were observed. First, general shear failure which was exhibited in all sabkha thicknesses for the 5 m foundation diameter as well as for the 7.5 diameter supported by 8 m sabkha soil thickness. This failure mechanism occurred in these cases due to the fact that the thickness of the sabkha (medium dense sand) was greater than the foundation diameter, and hence was not influenced by the compressible (weak) soil underlying the sabkha layer as shown in Figure 6a. Second, the punching shear failure, which was exhibited in all sabkha thicknesses for the 10 m foundation diameter as well as for the 7.5 diameter was supported by the 5 m and 6 m sabkha soil thicknesses. This failure mechanism was dominant in these cases because the diameter was larger than the thickness of the sabkha, and the foundation behavior was influenced by the compressible (weak) soil underneath the sabkha layer. Thus, the failure surface penetrated the weak soil as shown in Figure 6b. Figure shows the load displacement curves for 7.5 m footing supported by 8 m and 5m sabkha thickness. There is a noticeable decrease in load carried by the foundation supported by 5 m sabkha soil due to the influence of weak soil underline.

Table 4: Increases in capacity due to increase in sabkha thickness for different ϕ and footing diameters

Footing Diameter (m)	ϕ(°)	Increases in Bearing Capacity (%)	
		Sabkha Soil Thickness Increase	
		5 m – 6 m	5 m – 8 m
7.5	24	0.4	0.1
	27	7.75	7.9
	30	11.65	18.35
	34	15.9	45
10	24	8.6	11.2
	27	16	24
	30	19.1	29.7
	34	15.65	43.53



(a) (b)

Figure 6: Incremental displacement for 7.5 m footing supported by (a) 8 m and (b) 5m sabkha thickness.

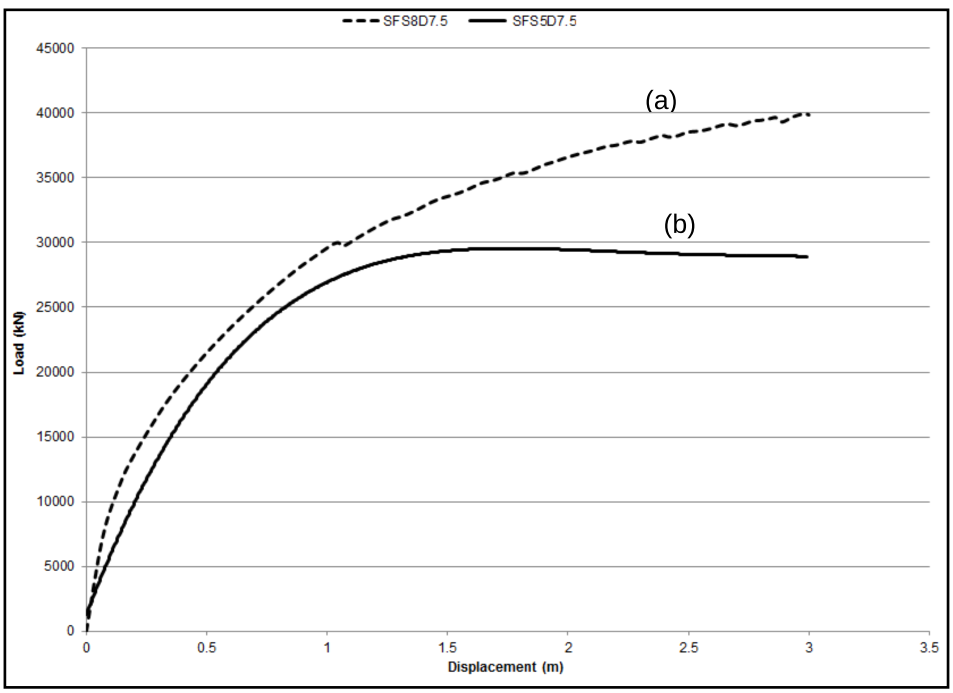


Figure 7: load vs. displacement curves for 7.5 m footing supported by (a) 8 m and (b) 5m sabkha thickness.

6 Conclusions

An experimental program was conducted to characterize the sabkha soil and its stiffness and shear strength parameters. The results from the experimental study were incorporated in finite element models to perform a parametric study in order to examine the performance of a shallow foundation in sabkha soil. A number of observations can be drawn based on the results of the experimental program and the numerical analyses. First, the parameters of the sandy sabkha, which was used in the paper, were compatible with the parameters reported in the literature. Second, the failure mode was generally a general shear failure for footing diameter to sabkha thickness ≤ 1, and the punching shear for ratios greater than 1 due to the presence of the loose soil layer underneath the sabkha. Thus, the general bearing capacity equation can be used to predict the capacity of footings founded on sabkha as long as the footing diameter ratio to sabkha thickness is < 1. Moreover, increasing the diameter of a shallow foundation will not necessarily produce more sufficient bearing capacity.

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