Appendix E

"Pile Foundation in Al-Hasa Area, Saudi Arabia"

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Pile Foundation in Al-Hasa Area, Saudi Arabia

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ABSTRACT: The main problem for construction in Al-Hasa area of Saudi Arabia is the presence of clay layers, which extend to a depth of some 50 meters below the ground surface. Shallow foundation on this type of clay generally causes considerable consolidation settlements, which are taking several years for reaching their final values. Therefore, to overcome this problem a pile foundation is considered as an alternative foundation system. The theoretical and practical knowledge are to be examined and advanced through numerical analyses and analytical studies of the geotechnical characteristics and geological conditions of the area. Field and laboratory tests are carried out in some places in Al-Hasa area. Case study is documented and application of value engineering to foundations is investigated. The results of this research formed a base for pile design guidelines in Al-Hasa area of Saudi Arabia.

Key words: Field testing, pile foundations, soil structure interaction, clay

INTRODUCTION

Al-Hasa is about 70 to 80 km from the sea coast of the Eastern Province of Saudi Arabia. The main Problem associated with the *Al-Hasa* region in terms of its subsoil structure is that it contains a thick layer of clay with large variations from place to place (inconsistent thickness). Therefore, surface foundation systems such as footing or raft may not be suitable for heavy loaded structures in this area. To add to this, there is limited accurate information available about the geology and the subsoil conditions of the region. This is more serious when the information is required about the subsoil conditions for depths greater than 15 m. The results presented in this paper are part of a larger study by the authors on the suitability of the pile foundation for large scale structures within the *Al-Hasa* region. It is envisaged that the findings of this study could potentially lead to certain recommendations within the context of the introduction of pile foundations for large structures in the region.

The problem of soil containing clay layers extended to depths, such as in *Al-Hasa* could be found in many locations throughout the globe, among which London Clay in the UK and the Frankfort Clay in Germany. It is famously known that the city of London in England and the city of Frankfurt in Germany are lying above a thick layer of clay. The behavior of the London Clay and the Frankfurt Clay for the pile foundation purposes have been the subject of many studies by researchers within the discipline. In the case of London Clay the following examples could be referred to within the literature: Cooke et al. (1981), Padfield & Sharrock (1983), Hong et al. (1999) and Hemsley (2000), while for the Frankfurt Clay: Sommer et al. (1985), Katzenbach et al. (2000) and Reul & Randolph (2003) could be mentioned.

Numerical analysis of pile foundation in clay is a relatively complicated nonlinear problem. Pile foundation has attracted many researches during the last four decades. Early researches focused on hand calculation techniques with the help of empirical charts and formula for single piles and pile groups. With the advent of the computers and numerical procedures, finite element techniques were developed to solve problems associated with pile foundations. Recent years have seen major advances in understanding the manner in which pile foundations interact with the surrounding soil. This work shall present some of the modern analytical methods available; concentrating on those areas that could be used in design calculations. The introduction of certain developed methods for analyzing the pile foundation could be easily found within the literature of Wong & Poulos (2005), Lee & Xiao (2001), Butterfield & Banerjee (1971), Hain & Lee (1978), Liu & Novak (1991), Lee (1993), Sayed & Bakeer (1992) and Chow & Teha (1991). In this study the numerical analysis has been carried out by a computer package (program) called ELPLA, which is developed by Kany et al. (2007). This Package allows a full interaction between the pile-soil-pile caps to be considered.

In this paper, the results of some theoretical, practical and numerical/analytical studies together with the geological conditions and geotechnical characterization of the soil have been presented. In order to materialize this it deemed necessary to carry out some field and laboratory tests on the soil samples taken from certain parts of the region. Then, the typical soil stratification and the study of their properties were carried out. The required input parameters for the analytical work were directly calculated from the pile load tests. The numerical results obtained from the pile studies then were compared with those obtained from the field tests. The presented "case study" includes the application of the "value engineering" to foundations. The results of this research forms a base for pile design guidelines in Al-Hasa area of Saudi Arabia.

MATHEMATICAL MODELING

The numerical study of this research is carried out by the commercial program ELPLA, which can analyze single pile, pile groups, piled raft and raft using different subsoil models. In the analysis, pile cap and raft are analyzed by the finite element method. Single pile is also analyzed by finite element method, while pile in a pile group is treated as a rigid member having a uniform settlement on its nodes. Soil is modeled as a three dimensional continuum medium. The nonlinear analysis of pile foundation is taken into account using hyperbolic function. The theoretical bases of the methods in ELPLA are well documented by El Gendy (2007) and Kany et al. (2007).

NUMERICAL RESULTS

A case study about pile foundation of Al Ahsa Holiday Inn Hotel has been carried out to examine the pile foundation system in Al-Hasa area. The calculated results have been compared with in situ measurements of single piles and pile groups. In addition, the calculated settlement for the whole structures is compared with the recorded one. The purpose of these studies is to verify the analysis and design of pile foundation system in Al-Hasa area.

Description of the Project

Al-Hasa Holiday Inn Hotel is the first building in Al-Hasa area with a foundation designed as a pile foundation, Figure 1. The hotel has an area of 30,000 m^2 and locates in Al-Hasa city at the east region of Saudi Arabia. It is a ten storey reinforced concrete building with 30 m high. The hotel is constructed between 1997 and 1999. The building has no underground floors. The foundation of the building is composed of pile caps connected together with tie beams in both directions. Pile caps are founded at a depth of 1.65 m under the ground surface. A total of 542 bored piles with lengths range between 9 and 21.5 m are located under the building. Two pile diameters are considered according to column loads and minimum number of piles, where 378 piles have a diameter of D = 0.6 m and 164 piles have a diameter D = 0.8 m. Spacing between piles varies from 2.5 D to 3.0 D. The subsoil at the location of the building consists of clayey silty sand up to 4.5 m below the ground surface, followed by layers of Al-Hasa clay extending to great depth. The groundwater level lies below pile caps.

Subsurface Condition

To investigate the site of the project, 15 boreholes to a depth of 20 m below the natural ground surface were carried out, which indicated that the soil stratification at the site consists of two homogeneous layers. The subsurface conditions as revealed from the boreholes indicated that from the ground surface until an average depth of 4.5 m a brown to gray, fine to medium grained, loose to dense, silty clayey SAND, was encountered. Below the sand layer and down to the final depth of investigation (20 m) dark gray to brown, very soft to hard silty CLAY with low plasticity is found.

In Figure 2, a trial is carried out to compare the clay at this site with other clays found in Europe in order to provide a degree of comfort in the analysis process. Based on the average plasticity index of samples recovered during the supplementary investigation (22-27%) and an extrapolated SPT N value of 60, the clays may be seen to be similar to the overconsolidated clays of Central and Southern England. A relationship of undrained cohesion to SPT N value of c_u/N = 300/60= 5.0 is reasonable.

London clay is classified as an over-consolidated clay. The undrained cohesion of London clay increases with depth and can be approximated according to Hong et al. (1999) by the following linear relation:

$$\left[c_u = 150 + 6.67z\right] \quad (1)$$

where c_u is the undrained cohesion of London clay, kN/m^2, and z is the depth measured from the clay surface, m.

Fig. 1. Al-Hasa Holiday Inn Hotel

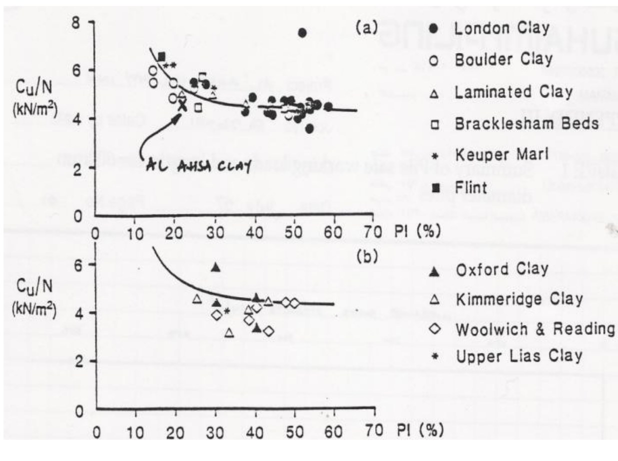

Fig. 2. Correlation of undrained cohesion with SPT value (Stroud, 1974)

Figure 3 compares between the profile of the correlated undrained cohesion with depth for Al-Hasa with the undrained cohesions obtained from Eq. 1 for London clay. The comparison is acceptable and the soil properties those are available in many literatures for London clay may be used here for any missed soil data.

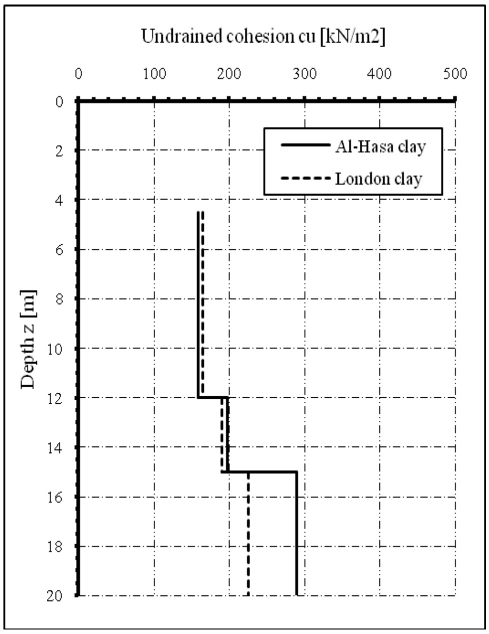

Fig. 3. Undrained cohesion against depth

Analysis of the Foundation

Using available data and measurement results of Al-Hasa Hotel pile foundation, the present pile foundation analysis is evaluated numerically and verified for analyzing a pile foundation in Al-Hasa area.

Bearing Capacity of the Pile

The calculation of bearing capacity of piles using c_u obtained from soil tests in the hotel location is carried out at different pile lengths for piles of diameters d = 0.6 and 0.8 m. The same calculation of bearing capacity is carried out using c_u obtained from Eq. 1. Comparison between the two calculations for allowable bearing capacity of piles at different lengths is shown in Figures 4 and 5. From these figures, pile length can be determined according to the applied load. Both calculations give nearly the same results. The above analysis of bearing capacity of piles shows that the net allowable load capacity of 0.8 m and 0.6 m diameter piles with a length of about 15-16 m embedded into silty clay layer is estimated is about 2000 kN and 1400 kN, respectively. For estimating pile load, the skin friction around the pile shaft according to Tomlinson (1957), is estimated by $\alpha\ c_u$, where an adhesion factor of α= 0.456 has been adopted. The end bearing capacity is estimated by $N_c\ c_u$, where an appropriate value of bearing capacity factor N_c is 9 according to Skempton (1951) is considered. To determine the allowable pile load an overall safety factor of 2.0 is used.

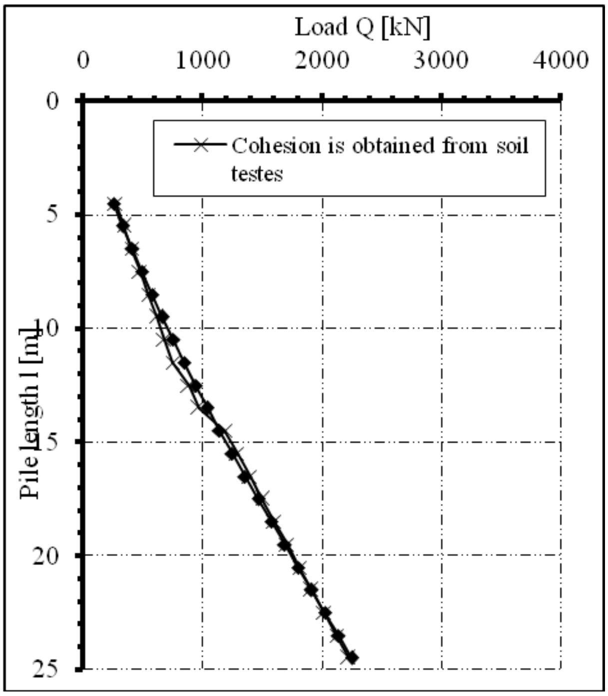

Fig. 4. Allowable bearing capacity with pile length (d = 0.6 m)

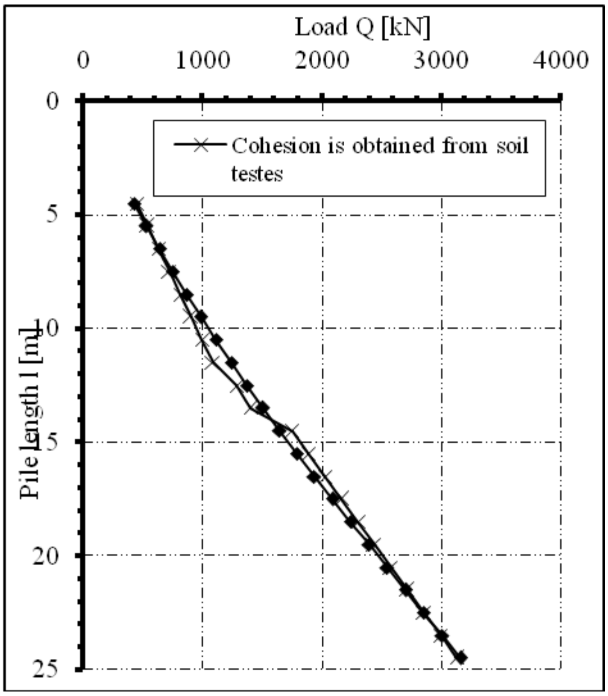

Fig. 5. Allowable capacity with pile length (d = 0.8 m)

Single Pile Analysis

In order to verify the effectiveness of numerical procedure and to check the estimated model parameters, a single pile analysis was first performed to simulate the pile load test. Analysis was carried out using two different pile diameters; as those used in the project.

The diameter of the first pile is d = 0.8 m, while that of the second is d = 0.6 m. Pile length ranged between l = 15 and 16.5 m. Most of the pile length is embedded into silty clay layer. According to the weakness of the upper layer, the effect of this layer is neglected in the analysis. The analysis of single pile was performed considering both linear and nonlinear analyses. Nonlinear analysis is an important consideration since piles may be loaded close to their full capacity, even under working condition. The nonlinear relation between the load and settlement of the pile is determined by considering a hyperbolic relation between load and settlement; see El Gendy (2007).

Comparison between calculated and measured settlements for two selected piles with two different loading is plotted in Figures 6 and 7. The figures show the load-settlement relation for analyzing piles for the both linear and nonlinear analyses. Results of load-settlement relation obtained from numerical analyses are compared in the figures with those of measurement in case of loading cycles. It can be observed from these figures that there is good agreement between the nonlinear load-settlement and those of measurement. From the above evaluation of single pile analysis, it can be concluded that the proposed soil parameters can be used safely in the analysis of pie groups or piled raft of Al-Hasa Hotel.

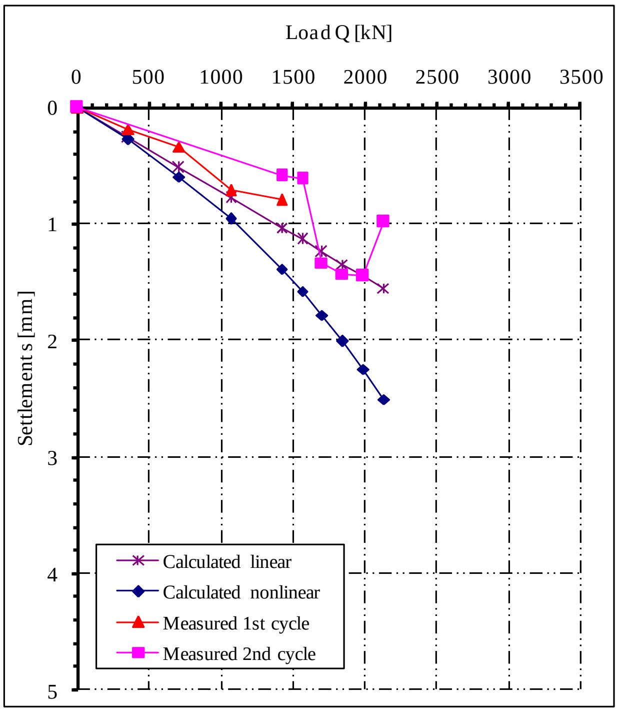

Fig. 6. Comparison between calculated and measured settlements for pile P126

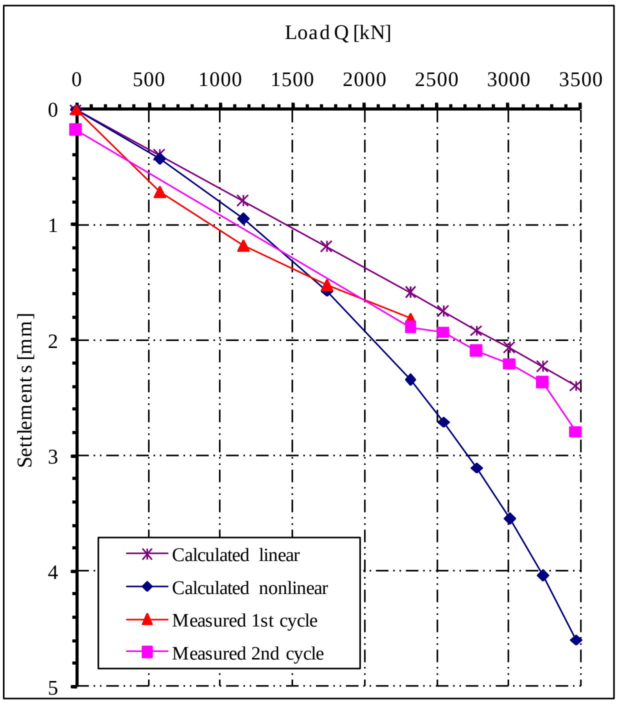

Fig. 7. Comparison between calculated and measured settlements for pile P274

Pile Group Analysis

As mentioned before, the foundation of Al-Hasa Hotel was analyzed as isolated pile caps. Each pile cap rested on a number of pile groups depending on the applied load on the cap. In the original analysis of pile cap, piles were considered as non-settled supports and there was no contact between the pie cap and the soil. Besides, there was no connection among pile caps. In realty, pile caps are located directly on the soil and connected together by tie beams in both x- and y-directions. Therefore, the assumptions of the previous analysis lead to overestimated design results. To show the difference between results when analyzing pile foundation of Al-Hasa Hotel with neglecting some of the above considerations, two typical pile caps as shown in Table 1 from the original design are selected and studied.

Piled Raft Analysis

Although, Al-Hasa Hotel foundation consists of only pile caps, a piled raft is also analyzed to show the behavior of piled raft in Al-Hasa Hotel area. The piled raft is a rectangular and has a length of L = 14.40 m and width of B = 6.0 m. Raft thickness is 1.0 m. The raft rests on 21 bored piles. Each pile is 16.0 m long and 0.6 m diameter. Piles are spaced at 2.2 m centers on a square grid as shown in Figure 8. The raft is supposed to have a uniform load of p = 340 kN/m^2.

Carrying out the Analysis of Pile Caps and Piled Raft

Caps and raft are divided into rectangular plate elements. Element sizes range between 0.45 and 0.60 m. Piles are divided into line elements with 2.0 m in length. The pile caps and raft are considered as elastic plate supported on piles, each has a uniform settlement along its length. The effective depth of the clay layers in the analysis is taken to be H = 30 m. Foundation depth is d_f = 1.5 m under the ground surface. The applied centric load on pile cap includes self weight of cap and piles. Also, the uniform load on raft includes self weight of the raft and piles.

Pile caps and piled raft are analyzed four times as follows:

- Linear analysis without soil contact
- Nonlinear analysis without soil contact
- Linear analysis with soil contact
- Nonlinear analysis with soil contact

Furthermore, the above analyses for pile cap and piled raft, pile cap is analyzed as an isolated footing, while piled raft is analyzed as an un-piled raft, both are with the same dimensions, load and soil condition of pile foundation.

Recorded Settlement

Reordered settlement of the Al-Hasa Holiday Inn Hotel on April 2008 was trivial. The expected settlement from the analysis is about 5 mm. It can be concluded that results obtained from numerical analysis and measurement of the project are in a good agreement.

RESULTS AND DISCUSSIONS

Table 2 to Table 4 summarize results of settlements, contact pressures, moments, shear forces and pile forces for the four analysis types and compare with them. In general, it can be noticed from the figures of results in the tables below that:

Settlement

As the assumed load on pile cap or raft is the full load capacity, the actual expected settlement will be less than that calculated. Furthermore, the settlement of a single pile is due to only soil-pile interaction. Therefore, considering the interaction between pile-pile and pile-cap (or pile-raft) in pile groups (or piled raft), settlement obtained from a single pile analysis is less than that obtained from pile groups (or piled raft). For linear analysis, settlement of pile cap ranges between 5.38 mm and 5.64 mm and for piled raft is 8.75 mm. Samples of settlement results are presented in Fig. 8 for pile cap and in Fig. 9 for piled raft.

As it is expected, settlement from nonlinear analysis for pile cap or piled raft is greater than that obtained from linear analysis. The nonlinear settlement exceeds linear settlement by 25 to 27% for cap without soil contact and by 21 to 23% for cap with soil contact. For piled raft, the nonlinear settlement exceeds linear settlement by 31% for raft without soil contact and by 18% for raft with soil contact. For a single analysis, either linear or nonlinear, the difference in settlement obtained from analyzing pile cap or piled raft with or without soil contact is small. This means any of the analysis can be used for estimating the settlement. Comparing between settlements obtained from pile cap with and without soil contact, which were analyzed linearly or nonlinearly, it is observed that considering soil contact in the analysis exceeded settlement. This is related to the first soil layer is a weak layer. Settlement of pile cap as an isolated footing exceeds the maximum allowable settlement for isolated footing. If it is known that according to ECP, the maximum allowable settlement for isolated footing on pure sand is 3.0 cm and on pure clay is 5.0 cm. It can be concluded that isolated footing is not a suitable foundation type for Al-Hasa Hotel area in such cases of structures.

Comparing between settlements obtained from isolated footing and pile cap with soil contact, those were analyzed linearly, observed that the pile cap type reduced settlement by 99% and comparing between settlements obtained from un-piled raft and piled raft with soil contact, those were analyzed linearly, observed that the piled raft type reduced settlement by 98%. Also differential settlement obtained from isolated footing type is greater than that obtained from pile cap type.

Although the applied load is centric, the contour line of settlement for isolated footing and un-piled raft takes unsymmetrical shape (see Fig. 10). This is related to the high rigidity of the cap and the raft thickness. One can see this action obviously for contour lines of settlement of pile cap as an isolated footing and of piled raft as raft. The great value of settlement when analyzing pile foundation as isolated footing or un-piled raft is related to the first weak soil. This means in any way isolated footing or un-piled raft are not suitable for this area.

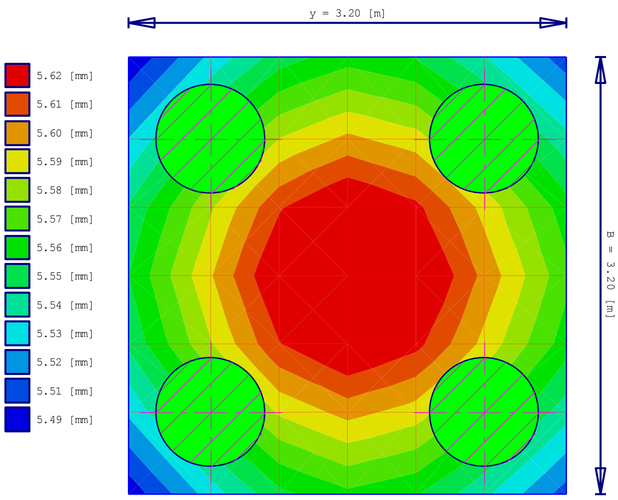

Fig. 8. Settlement for pile cap 1
(linear analysis with soil contact)

Table 1. Selected pile cap types

Pile cap No.	No. of piles	Cap dimensions		Pile spacing		Cap thickness	Pile diameter
		Length L m	Width B m	x-direction S_x m	y-direction S_y m	t m	d m
1	4	3.2	3.2	2.0	2.0	1.50	0.8
2	4	2.8	2.8	1.9	1.9	1.30	0.6

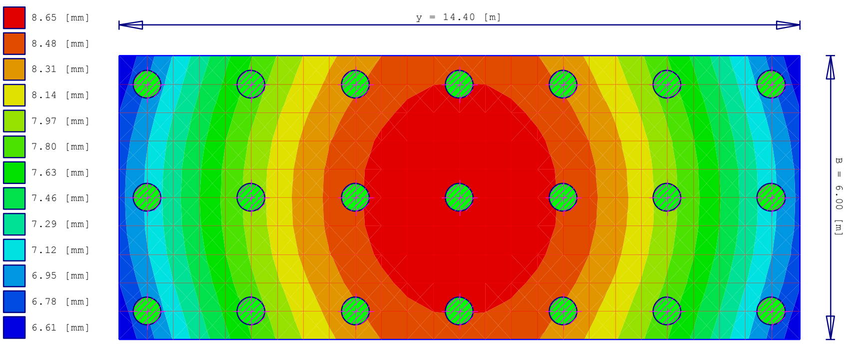

Fig. 9. Settlements for piled raft (linear analysis with soil contact)

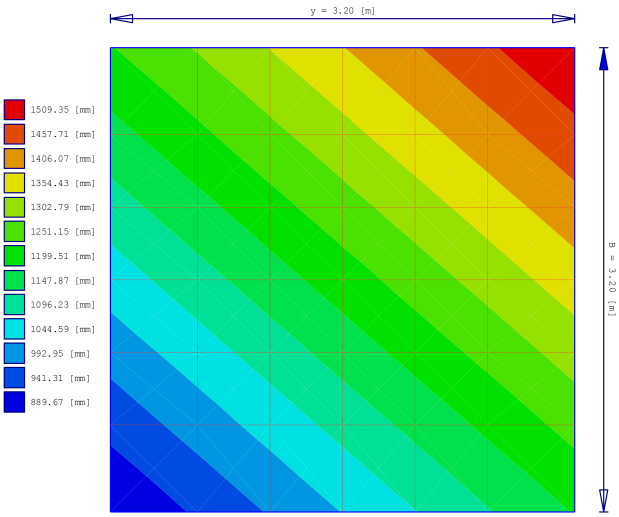

Fig. 10. Settlement for Pile cap 1 as a footing

Force on Pile Head

Linear analysis gives a pile load at edge of the piled raft greater than that at the inner. Consequently, pile load at the edge may exceed the allowable pile load capacity. Therefore, care must be taken when estimating the arrangement and number of piles. In addition, using nonlinear analysis redistributes pile loads by increasing values of inner piles and decreasing values of edge piles. Comparing between pile loads obtained from pile cap with and without soil contact, which were analyzed linearly, it is observed that considering soil contact in the analysis reduced pile load by 6%, while for piled raft reduced pile load by 51%.

Bearing Factor of Piled Raft

Bearing factor is the ratio between loads carried by piles to the total applied load. Bearing factor of pile cap and piled raft from nonlinear analysis is less than that obtained from linear analysis. For pile caps the difference in bearing factor ranges between 3 and 4%, while for piled raft is 6%. And considering soil contact between the cap and soil for linear analysis gives a bearing factor of 95-96%, while that for nonlinear analysis gives a bearing factor of 92%. While considering soil contact between the raft and soil for linear analysis gives a bearing factor of 87%, while that for nonlinear analysis gives a bearing factor of 83%. It means that piled raft distributes loads on the soil better than the pile cap.

Contact Pressure

Using pile cap type reduced the maximum contact pressure by 96%, while using piled raft type reduced the maximum contact pressure by 93%. The nonlinear analysis redistributes the contact pressure under the foundation, the difference between contact pressure obtained from linear analysis and that obtained from nonlinear analysis is 21-25% for pile caps and for piled raft 20%.

Internal Forces

For the different analysis types of pile caps, it is found that there are no great differences in bending moments and shear forces. And the designed sections of pile caps and piled raft in this study are great enough to resist internal forces. Consequently, the soil settlement and soil reaction are considered as the main problem of the foundation in Al-Hasa area.

Table 2. Comparison of results for different analysis types for pile cap 1

Type of analysis		Pile cap as a footing	Cap without soil contact		Cap with soil contact	
			Linear	Nonlinear	Linear	Nonlinear
Central settlement s_{center} cm		74.629	0.308	0.422	0.564	0.736
Corner settlement s_{corner} cm		60.397	0.308	0.422	0.549	0.721
Max. differential settlement Δs [%]		19	-	-	2.66	2.04
Bearing factor α_{kpp} [%]		-	100	100	95	92
Pile force P_P [kN]		-	2000	2000	1890	1848
Contact pressure q [kN/m^2]	Max.	2151	-	-	77	102
	Min.	329	-	-	0	0
Bending moment m_x [kN.m/m]	Max.	2478	2551	2551	2546	2541
	Min.	-52	-167	-167	-143	-134
Shear force Q_x [kN/m]	Max.	3554	3521	3521	3519	3516
	Min.	-3476	-3520	-3521	-3519	-3514

Table 3. Comparison of results for different analysis types for pile cap 2

Type of analysis		Pile cap as a footing	Cap without soil contact		Cap with soil contact	
			Linear	Nonlinear	Linear	Nonlinear
Central settlement s_{center} cm		60.490	0.221	0.294	0.552	0.699
Corner settlement s_{corner} cm		48.035	0.221	0.294	0.538	0.683
Max. differential settlement Δs [%]		20.59	-	-	2.54	2.29
Bearing factor α_{kpp} [%]		-	100	100	96	92
Pile force P_P [kN]		-	1400	1400	1322	1297
Contact pressure q [kN/m^2]	Max.	2061	-	-	82	104
	Min.	289	-	-	0	0
Bending moment m_x [kN.m/m]	Max.	1782	1811	1811	1805	1801
	Min.	-55	-125	-125	-110	-104
Shear force Q_x [kN/m]	Max.	2650	2581	2580	2578	2579
	Min.	-2625	-2181	-2581	-2578	-2579

Table 4. Comparison between results of different analysis types for piled raft

Type of analysis		Un-piled raft	Piled raft without soil contact		Piled raft with soil contact	
			Linear	Nonlinear	Linear	Nonlinear
Max. settlement s_{max} cm		46.726	0.502	0.726	0.875	1.065
Min. settlement s_{min} cm		41.916	0.502	0.726	0.653	0.814
Max. differential settlement Δs [%]		10.29	-	-	25.37	23.57
Bearing factor α_{kpp} [%]		-	100	100	87	83
Max. pile force P_P [kN]		-	2644	2248	1304	1235
Contact pressure q [kN/m^2]	Max.	1340	-	-	96	120
	Min.	238	-	-	0	0
Bending moment m_x [kN.m/m]	Max.	519	116	116	351	389
	Min.	-2	-386	-386	-180	-173
Bending moment m_y [kN.m/m]	Max.	302	116	117	294	284
	Min.	-6	-401	-401	-179	-167
Shear force Q_x [kN/m]	Max.	163	674	674	493	485
	Min.	-171	-674	-673	-488	-484
Shear force Q_y [kN/m]	Max.	155	645	645	535	507
	Min.	-153	-645	-644	-538	-508

CONCLUSIONS

A study was carried out for the subsoil condition of Al-Hasa area to get the soil parameters that can be used in numerical and analytical analyses of Al-Hasa foundations. A comparison of Al-Hasa clay with London clay shows an identical in properties between them. Consequently, the available experience of London clay can be benefited in Al-Hasa area. A case study was examined with different analyses and foundation systems. It showed that the suitable foundation system for Al-Hasa area is pile foundation. The comparisons between calculated values and measured ones show that the recommended analysis and investigated soil parameters can be used successfully for analysis of pile foundation in Al-Hasa.

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