Micropiled-Raft Foundations for High-Rise Buildings on Soft Soils — A Case Study: Kerman, Iran

Hessam Yazdani
University of Oklahoma, Norman, OK

Mehdi Momeni
Islamic Azad University, Iran

Kianoosh Hatami
University of Oklahoma, Norman, OK

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Hessam Yazdani
University of Oklahoma
Norman, Oklahoma, USA 73019

Mehdi Momeni
Islamic Azad University
Kerman, Iran

Kianoosh Hatami
University of Oklahoma
Norman, Oklahoma, USA 73019

ABSTRACT

For the structures supported on soft soils, piled raft foundations have been shown to be more economical than conventional piled foundations. In piled raft foundations, the bearing capacity of the underlying soil is taken into account to support the superstructure loads and the piles are placed such that they increase the bearing capacity of the raft and control both the total and differential settlements of the superstructure. In the city of Kerman, Iran, the predominance of soft soils had historically hampered the construction of high-rise buildings across the city. Recently, an eighteen-story reinforced concrete building was constructed on a micropiled-raft foundation which was placed on a 30 m-thick layer of soft saturated calcareous silty soil. Conventional laboratory and plate loading test results on the foundation soil indicated that a raft foundation would have adequate bearing capacity, but would experience excessive settlements. As a remedial solution, a micropiled-raft foundation system was considered as a design option for the foundation of the structure. A prototype micropile was designed and installed based on the FHWA (2000) guidelines and tested at the site. The test results were used to design the micropiled raft foundation using a finite element program. The results of the analysis showed that micropiled-raft foundations can provide a cost-effective engineering solution for high-rise buildings constructed on soft soils. The results of this study were successfully employed to construct additional high-rise buildings in the city.

INTRODUCTION

A majority of the current foundation engineering guidelines require that the axial capacity of the piles carry the total structural load of a piled foundation (de Sanctis and Mandolini 2006; Sales *et al*. 2010). However, field monitoring of several piled foundations has revealed that the contribution of the raft foundation in the overall bearing capacity is fairly significant (Kakurai 2003). Consequently, designing a piled foundation merely as a pile group to meet the required factors of safety within the framework of the allowable stress design could often lead to overly conservative and hence, costly solutions (Poulos and Davids 2005). In contrast, the structural load in the piled raft foundations is mostly supported by the raft. The piles, known as the settlement-reducing piles, are therefore located strategically to enhance the bearing capacity of the raft besides controlling both the total and differential settlements of the superstructure. Such a design approach can significantly reduce the cost of the foundation without jeopardizing the safety and performance of the superstructure (Burland *et al*. 1977; Sales *et al*. 2010). In recent years, a new foundation system comprising of a raft foundation resting on grouted micropiles has been successfully adopted worldwide to stabilize the soft soils and reduce the settlements (Han and Ye 2006; Kempfert and Böhm 2006). The system has been proven to be very effective where the underlying soil is a normally consolidated soft clay layer with interlaminated seams of fine sand and silt (Kempfert and Böhm 2003).

The city of Kerman is located in a seismically active, semi-arid area in Southeastern Iran. The local soil generally consists of a mixture of silt and low plasticity clay (ML and CL) with a high collapse potential (Momeni and Shafiee 2005; Toufigh *et al*. 2007) which has hampered the construction of high-rise buildings in the city. This paper reports the geotechnical site investigation and the foundation design of a high-rise building in Kerman. A variety of foundation designs were considered in the early stages of the project and a micropiled-raft foundation was finally adopted in accordance with the recommendations made by the local consultants and contractors. The results of a micropile testing program and a comparison of the predicted and observed micropile performance are presented and discussed.

OUTLINES OF THE BUILDING

The Mehr project is a part of an extensive development program in Kerman and it includes five 18-story residential reinforced concrete buildings (Blocks A-E) with a podium development around the base of the buildings plus a 2-story parking garage. Figure 1 shows an artist's rendition of the project once it is completed. The seismic separation joints between adjacent blocks are shown with solid black lines on the top of the building. The design process of one of the Blocks (Block E, the hatched area in Fig. 1) is reported in this paper. Block E is of 1,250 m^2 area in plan, with a total floor area of 22,500 m^2, and a maximum height of 64.8 m.

Fig. 1. An Artist's Rendition of an 18-story Building as part of the Mehr Project.

GROUND INVESTIGATION AND SITE CHARACTERIZATION

Preliminary site investigations to determine the geotechnical characteristics of the soil included drilling 11 boreholes to 20-40 m depth below the excavation level within the construction site. The deepest boreholes were located below the building footprints and the boreholes below the low-rise areas tended to be considerably shallower. In a complementary program, detailed drilling and sampling along with the standard penetration tests (SPTs) were carried out in 12 additional widely separated boreholes within the construction site. The SPT test was chosen due to the availability of the apparatus. However it is particularly suitable for granular soils and it underestimates the shear strength of cohesive soils (Stroud 1975). A series of conventional laboratory tests, including soil classification, direct shear, and oedometer consolidation tests was also conducted in order to determine the properties of the underlying soil. Several vane shear tests were carried out at different depths across the site to compare with the undrained shear strength of the soil, S_u, obtained in the laboratory program.

The mean values of SPT, as shown in Fig. 2, generally varied over a range between 5 and 25 in the upper 20 m and increased to approximately 60 at the depths below 30 m. The site stratigraphy was found to be relatively uniform across the entire site with a highly compressible calcareous sandy soil classified as SM or ML at depths of 0-20 m and a CL-ML layer at depths of 20-30 m. Therefore, a two-layer soil model was considered to be adequate for numerical simulation of the site. The groundwater level was found to be immediately below the excavation level. The total unit weight of the soil, γ_t, was obtained from the soil samples, according to ASTM D7263. The values of undrained Poisson's ratio, ν_u, shear modulus, G, and undrained Young's modulus, E_u, of the soil at small strain were estimated using the empirical relationships with the SPT values (Das 2009). Table 1 summarizes the measured and estimated properties of the two soil layers used in the numerical model.

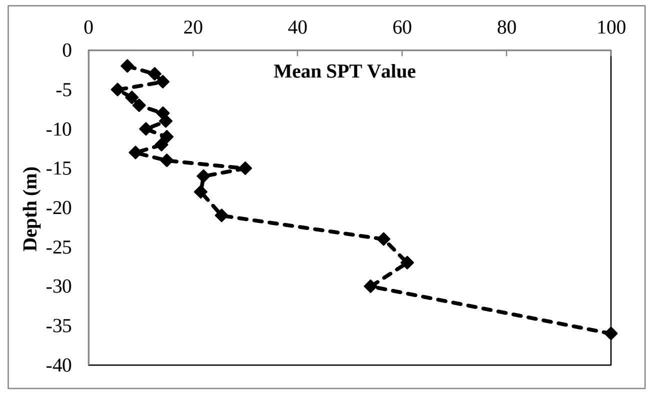

Fig. 2. Mean SPT Values in 12 Boreholes across the Site

Table 1. Soil Layer Properties used in the Numerical Model of the Site Foundation

Soil layer	Depth (m)	γ_{sat} (kN/m^3)	γ (kN/m^3)	c (kPa)	ϕ (°)	S_u (kPa)
1	0-20	18	15	10	10	91
2	>20	20	19	30	20	163

contd.

E_u (kPa)	G (kPa)	ν_u	e_0	C_c	C_s	*Constitutive Model*
2500	925.9	0.40	0.55	0.149	0.041	Mohr-Coulomb
40000	16070	0.35	0.63	0.151	0.019	Mohr-Coulomb

FOUNDATION CONSTRUCTION PROCEDURE

The foundation construction was mainly divided into four stages. First, a 200 × 53 m^2 area was excavated down to 7 m in depth to meet the architectural design requirements of the project. This stage was performed during summer (dry season) to reduce the risk of excavation failure due to precipitation. Second, a layer of well-graded soil, 0.6 m in thickness and stabilized with lime, was placed and compacted to obtain a weather resistant construction platform and also to protect the construction area from the capillary migration of the groundwater. In the third stage, 346 grouted micropiles (Type C, FHWA 2000), differing in diameter and length, were installed in pre-specified locations. Finally, all micropile heads equipped with capping plates were adequately embedded in a raft to form a rigid micropile-raft connection. The raft thickness and the dimensions of the capping plates were selected such that they would prevent punching failure and provide effective transmission of vertical loads.

FOUNDATION DESIGN

Design Approach

The micropiled raft system was designed such that the raft would alone provide adequate bearing capacity and uniformly distribute the structural load. Micropiles were used to control the total and differential settlements of the building. Preliminary studies revealed that the capacity of the micropiles would be governed by the geotechnical considerations rather than their structural capacity. The average mobilized load-bearing capacity of the micropiles was assumed to be 90% under working load conditions (comparable to the value of 80% recommended by Randolph and Clancy 1993). Also, the collective horizontal capacity of the sparsely arranged micropiles was checked to be sufficient against the lateral loads.

The limit state design approach was employed to design the foundation. The structural and geotechnical capacities of the foundation elements were ensured to be adequate to resist against various combinations of factored dead, live, and earthquake loadings for the ultimate limit state. For the serviceability limit state, the maximum total settlement and angular distortion of the foundation were limited to 50 mm and 1/500, respectively, in keeping with the local building codes.

Design Process

Finite Element and FLAC3D Modeling of the Raft Foundation. A finite element (FE) program was used to analyze the raft foundation. The raft was modeled as a 21.7 × 51.4 m^2 plate resting on an elastic foundation (Winkler model). The two important parameters in the Winkler method are the raft rigidity and the modulus of subgrade reaction, K_S. The raft rigidity influences the pressure distribution beneath the raft. A thickness of 1.5 m was assumed for the raft in order to obtain sufficient rigidity, providing uniform distribution of the structural loads and satisfactory equalization of the differential settlements. It was also deemed sufficient to prevent the punching failure below the structural columns and above the micropiles. The modulus of subgrade reaction was determined from several plate load tests carried out on the foundation soil using plates of different size according to ASTM D1194. Figure 3 shows the results of the plate load tests. It is observed that smaller values of modulus of subgrade reaction were obtained when larger plates were used. This relationship had been investigated by Terzaghi (1955) and it is generally accepted that for foundations on clayey soils:

$$K_{SB} = 0.3 K_{0.3}/B \quad (1)$$

where $K_{0.3}$ is the modulus of subgrade reaction determined with a 0.3 m plate, and K_{SB} is the modulus of subgrade reaction of a $B \times B$ footing (width B is in meters). Compared to the decreasing trend suggested by Eq. (1), a peculiar reduction in K_{SB} was observed in the performed plate load tests. The discrepancy might be due to the difference in the nature of the soil tested in the field compared to those in Terzaghi's study.

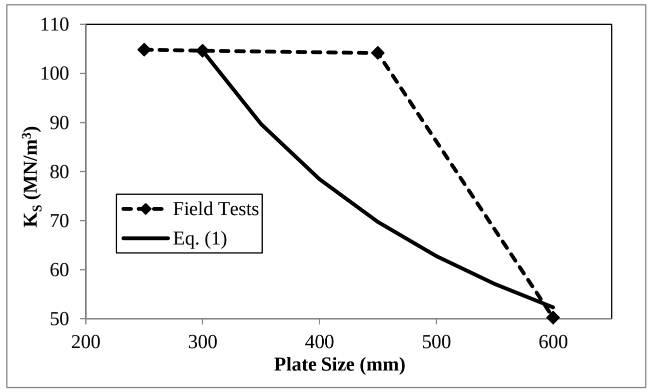

Fig. 3. The Effect of Plate Size on the Measured Modulus of Subgrade Reaction

Substituting $K_{0.3}$=104 MN/m^3 from Fig. 3 and B=21.7 m into Eq. (1), a value of K_B=1.4 MN/m^3 was predicted for the modulus of subgrade reaction. A numerical simulation study was carried out using FLAC3D (Itasca 2009) in order to calculate the settlement of the raft foundation and to determine its modulus of subgrade reaction as shown in Fig. 4.

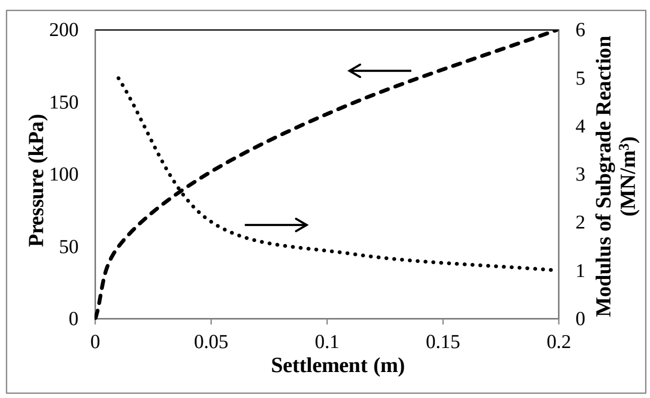

Fig. 4. Numerical Prediction of the Pressure-Settlement Response of the Raft Foundation

A trial and error approach was used to determine the modulus of subgrade reaction from numerical simulation. First, an initial modulus of subgrade reaction was selected from Fig. 4 for the raft foundation in the FLAC3D model and assigned to the FE model of the raft. Then the raft was analyzed and its settlements were calculated. A new modulus corresponding to a mean value of calculated settlements was selected from Fig. 4 and assigned to the Winkler springs supporting the raft. This procedure was repeated until the modulus assigned to the raft converged to the modulus corresponding to the mean value of predicted settlements. A value of 1.2 MN/m^3 was eventually found for the converged modulus of subgrade reaction which was in satisfactory agreement with the value from Eq. (1) and resulted in a mean predicted value of 170 kPa for the pressure beneath the raft foundation neglecting the load-bearing capacity of micropiles.

The allowable bearing capacity of the raft foundation with a factor of safety of FS=3 was estimated to be 180 kPa from the equations available in the literature (Budhu 2007). This value is greater than the predicted value of 170 kPa which indicated that the raft foundation had sufficient bearing capacity against the superstructure loads. However, the predicted maximum settlement of the raft (150 mm) was not within the tolerable limits. Therefore, it was decided to use micropiles to control the settlements of the raft foundation.

<u>Modeling and Testing of the Micropiles</u>. A combined numerical simulation (using FLAC3D) and field testing approach was used to determine the bearing capacity and stiffness of the micropiles. A "sacrificial" Type C (FHWA 2000) micropile was tested to failure in accordance with ASTM D1143 to verify the results of the numerical simulation. The micropile was of 14 m long and 0.15 m in diameter. To construct the Type C test micropile, a primary cement grout was poured under gravity and then a similar grout was injected at a pressure of 1 MPa prior to hardening of the primary grout. The grout compressive strength met or exceeded the ASTM C109 requirements. In total, 0.6 m^3 of grout was used for the micropile. The test setup included a hydraulic jack and a reaction assembly as shown in Fig. 5. The reaction assembly was comprised of a weighted platform supported on concrete cribbing and was designed to resist loads four times as great as the micropile design load. The load was applied in increments of 10% of the estimated ultimate load. The vertical displacement of the test micropile was measured using dial gauges that were mounted on independent reference beams.

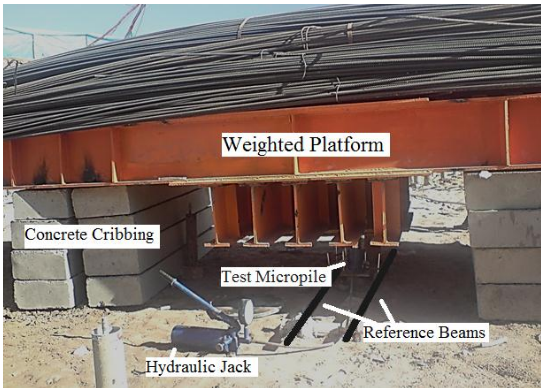

Fig. 5. Micropile Test Setup

A comparison of the predicted performance of the test micropile from the numerical modeling results and its measured performance from the field test is shown in Figure 6. It is observed that the numerical model underestimates the bearing capacity of the micropile. A possible explanation is that the high-pressure injection of the grout might have caused hydraulic fissures within the soil matrix and thereby increased the sidewall resistance of the micropile. Such effect was not accounted for in the numerical model.

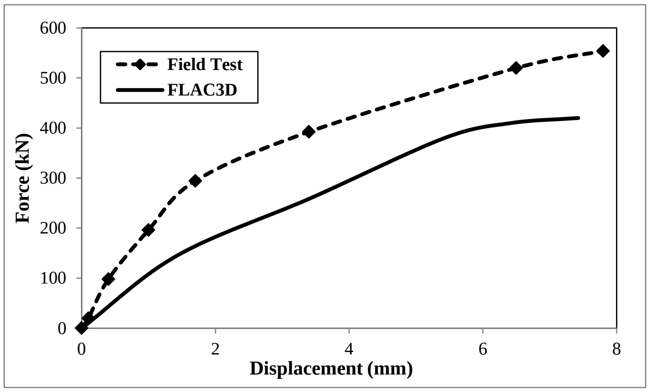

Fig. 6. Numerical Analysis of vs. the Field Test on the Micropile

<u>The Micropiled Raft Foundation Design</u>. The FE model for the raft foundation described earlier was further developed to design the foundation. The settlement-reducing micropiles were initially modeled using linear springs and their spring constant were determined from the results of the numerical modeling and the field test on the micropile. The predicted settlements of the raft were then compared against the allowable values and the stiffness of the micropiles was updated in repeated calculations until the raft settlement and the load in the micropiles were less than the allowable limits When the load in a micropile was found to be greater than its capacity (e.g. beneath the structural columns carrying large loads), a denser arrangement of the micropiles was employed in the vicinity of that micropile and the analysis was repeated. The bearing capacity of each micropile was assumed to be almost fully (90%) mobilized under working loads.

It was assumed that the large compressibility of the soil near the surface would delay the contribution of the raft in the bearing capacity of the foundation during the initial stages of the building construction and therefore, the micropiles would carry the full magnitude of structural loads. Therefore, a second round of analysis was carried out to examine the group micropile behavior of the foundation, neglecting the contribution of the raft, and the loads in the micropiles were checked against their capacity. Table 2 summarizes the predicted maximum and average magnitudes of loads in the micropiles under the most critical load combinations. The load to capacity ratio in 5% of the micropiles exceeded unity. Load redistribution in the vicinity of these overloaded micropiles was performed and the excessive load was distributed among the adjacent micropiles. It was ensured that the capacity of the adjacent micropiles outweighed their original together with the superimposed loads.

Table 2. Predicted Loads in the Micropile Group Neglecting the Contribution of the Raft

Type	Capacity (kN)	Force/Capacity Ratio		
		Max.	Min.	Avg.
1[a]	550	1.2	0.58	0.89
2[b]	1000	0.86	0.5	0.68
3[c]	3000	0.99	0.54	0.77

[a] Single Micropiles (L =10 m, D= 0.10 m)
[b] Single Micropiles (L =15 m, D= 0.15 m)
[c] Triple Micropiles (L =15 m, D= 0.15 m)

Figure 7 shows the arrangement of the micropiles underpinned the raft foundation. Instead of long single micropiles, shorter triple micropile groups, shown in Fig. 8, were located beneath the structural columns to decrease the risk of differential settlement in the case of failure in a long single pile and to improve the strength of the soil confined within the micropile group.

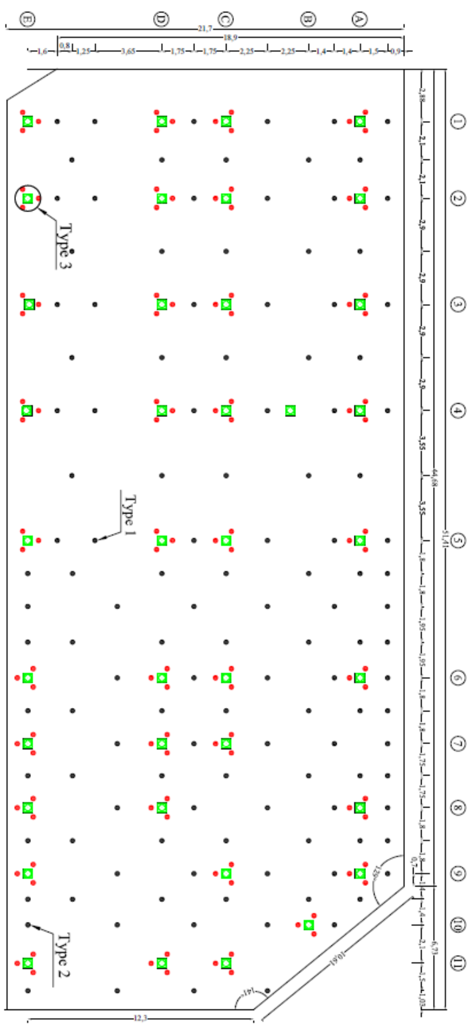

Fig. 7. Arrangement of Micropiles beneath the Raft

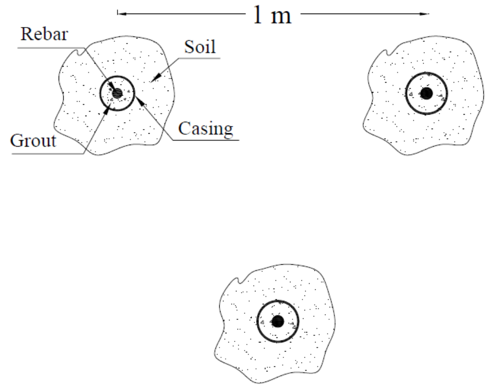

Fig. 8. Configuration of Triple Micropiles

Figure 9 shows the predicted settlement profile of the micropiled raft subjected to the combined dead load and live load (DL + LL). It is observed that maximum settlement is limited to 0.014 m which is considerably smaller than the allowable limit of 0.05 m.

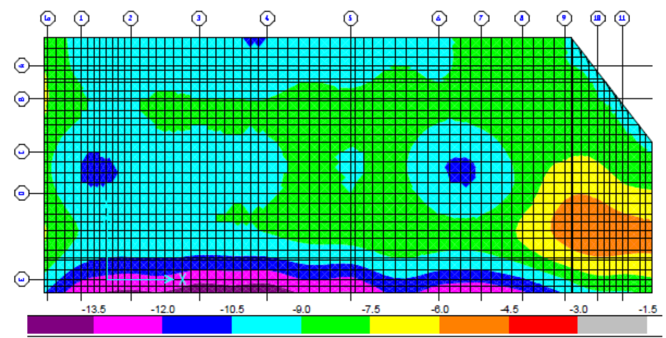

Fig. 9. Micropiled-Raft Settlement under Working Loads

CONCLUSIONS

A micropiled raft foundation system was designed for high-rise buildings constructed on very soft soils. The design approach involved numerical simulations, extensive geotechnical investigation of the project site and field testing of a prototype micropile to determine its bearing capacity and stiffness for analysis. Results of the analysis indicated that proper design of micropiles in combination with raft foundations can serve as a viable design approach for tall buildings constructed on weak and compressible soils.

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