4th International Conference on New Developments in Soil Mechanics and Geotechnical Engineering
2-4 June 2016, Near East University, Nicosia, North Cyprus

3-D numerical assessment of rammed aggregate pier (RAP) group effects: a geothermal power plant case history site

Lale Oner
M.Sc., Civil Engineer, Sentez Insaat, loner@sentezinsaat.com.tr

Ece Kurt Bal
M.Sc., Civil Engineer, Sentez Insaat, ekurt@sentezinsaat.com.tr

K. Onder Cetin
Professor Dr., Civil Engineering Department, Middle East Technical University, ocetin@metu.edu.tr

KEYWORDS: Impact rammed aggregate piers, rigid columns, group effects, settlement

ABSTRACT: Within the confines of this manuscript, the results of three dimensional finite element assessments of a geothermal power plant site, which is improved with 50 cm diameter rammed aggregate piers (RAP) are presented. The soil profile is composed of a fill layer with a thickness of 0.3-0.5m over medium stiff to stiff silty clay to a depth of 22 m with interlayers of loose to medium dense clayey, gravelly sand / clayey gravel layers. Below this clay layer, there rests dense clayey sand layer. Power plant facilities are composed of a number of structures with gross foundation stresses varying in the range of 25 kPa to 160 kPa. 17 m long RAP elements are installed with a square grid spacing, in the range of 1.3 to 2.75 m. Design lengths and patterns are governed by i) the allowable settlement criterion of 7-25 millimeters, ii) factor of safety against seismic soil liquefaction, defined as 1.2. The long term consolidation settlements of cohesive layers, which are estimated in the range of 12 to 50 cm before improvement, are reduced to 5-20 mm after the improvement with RAP elements. RAP load tests are performed to test the conformity of bearing capacity and stiffness responses. Series of three dimensional numerical assessments were performed by using RS^3-Rocscience software to assess the load distribution among group of RAP elements and the corollary settlements. The results of these analyses are presented in the form of load and settlement distribution factors, which address the group response of RAPs. The findings are then compared with available literature, widely used to assess concrete pile group effects.

1 INTRODUCTION

Ground improvement solution alternatives are widely studied as part of foundation design of engineering structures and comprise numerous different applications, including deep soil mixing, bored piles, sand drains, vacuum consolidations or stone columns. While a number of soil improvement solutions may be effective for a project, the decision about the selection of a particular alternative is usually governed by cost and/or schedule constraints. Among existing alternatives, the rammed aggregate pier (RAP) solution has been listed and served as an alternative to deep foundations or over excavation replacement of compressible soils. RAP or impact pier terminologies will be used interchangeably to refer to 50 cm diameter piers constructed by bottom-fed dry displacement method. The diameter of the RAP elements are monitored in real time through sensor monitored quality control system with volume measurements. Hence, 50 cm diameter is confirmed within ±2 cm production accuracy. The effectiveness of the piers is attributed to the lateral prestressing that occurs in the matrix soil during pier construction and to the high strength and stiffness of the piers.

Within the scope of this manuscript, the results of three dimensional finite element assessment of a geothermal power plant raft foundation system, which is improved by 50 cm diameter, 17 m long rammed aggregate piers, are presented. The results of these analyses are given in the form of load and settlement distribution factors, which address the group response of RAPs. These analyses results are compared with available literature mostly focused on the performance of concrete piles and pile groups. This outline flow of discussions will be presented next.

2 GEOTHERMAL POWER PLANT SITE SOIL PROFILE

In the western part of Turkey, a series of geothermal power plant facilities was to be constructed. The facility is composed of a number of structures with gross foundation stresses varying in the range of 25 kPa to 160 kPa. Due to facility requirements, allowable settlement criteria were defined to vary in the range of 7 to 25 mm. A schematic view of the facilities is shown in Figure 1 and the performance of RAP supported raft foundation of Unit 1 will be scope of this manuscript.

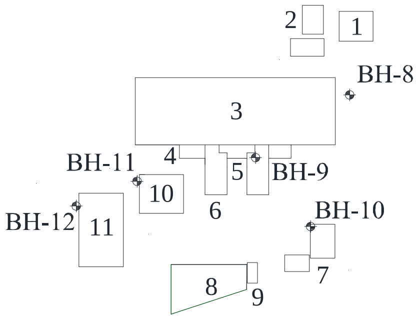


Figure 1. Plan view of the project site

A detailed site investigation program was implemented including the execution of in-situ penetration tests, disturbed and undisturbed soil sampling. Following the site investigation studies, on the extracted disturbed and undisturbed soil samples, a laboratory testing program was executed. The generalized soil profile, as well as a summary of laboratory test results is shown in Figure 2.

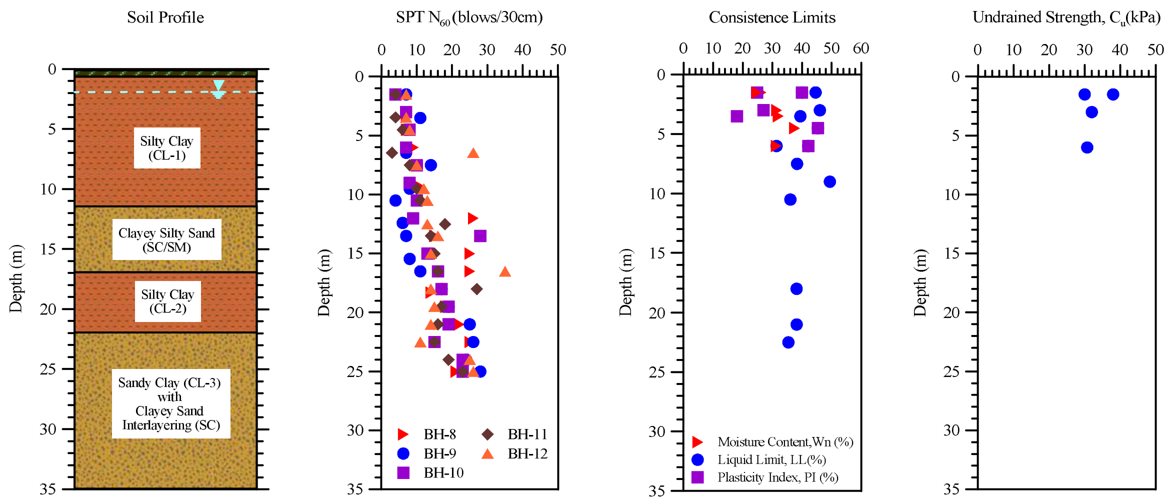


Figure 2. Generalized soil profile and a summary of laboratory test results

The soil profile is composed of a fill layer with a thickness of 0.3-0.5 m overlying medium stiff to stiff silty-clay layer up to a depth of 11.5 m, with thin inter layers of loose to medium dense clayey, sand and clayey gravel layers. Below this clay layer, there rests a 5 m thick medium dense to dense clayey, silty sand layer. Stiff to very stiff silty clay and medium dense clayey sand layers are observed, respectively. The ground water table is reported to be 1.7 meter below natural ground surface.

The ground improvement before the construction of facility structures of various kinds were needed due to extremely restricted post construction settlement criteria. When compared to other ground improvement techniques, rammed aggregate pier solution was determined as one of the most cost effective solution for this project. Hence 17 m long RAP elements were installed with a square grid spacing, varying in the range of 1.3 to 2.75 m. Design lengths and patterns are governed to specifically comply with the i) the allowable settlement criteria varying in the range of 7 to 25 millimeters, ii) minimum factor of safety criterion of 1.20 against seismic soil liquefaction. After the installation of RAP elements, the long term consolidation settlements of cohesive layers and immediate settlements of cohesionless soil layers, which are estimated in the range of 12 to 50 cm before improvement, are reduced down to 5-20 mm range, consistent with allowable settlement criteria.

3 CONSTRUCTION of IMPACT PIERS

In the field, rammed aggregate piers are installed using the Impact® System construction procedure: (1) a closed ended mandrel with a diameter of 36 cm is pushed into the design depth using hydraulically applied static force assisted with vertical dynamic energy, (2) the mandrel and hopper are filled with aggregate, (3) the ramming action is applied with 100 cm up / 67 cm down compaction efforts, during which vertical energy is also introduced (Figure 3). The ramming actions expand the diameter from 36 cm to 50 cm if 100 cm up and 67 cm down compaction procedure is chosen. The significant increase in lateral stress combined with the high density of the stone created by the installation process provides the unique strength and stiffness of the RAP system (Handy 2001, Wissmann et al., 2001).

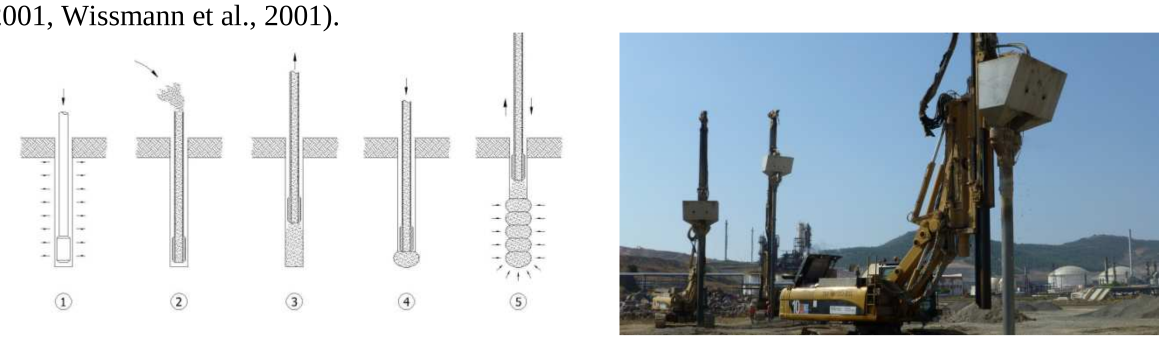


Figure 3. Construction methodology of Impact Pier® and a view from the field construction

4 FIELD LOAD TEST

RAP field load tests are widely referred to "quick" tests due to relatively rapid application of the loading scheme. The test procedure is very similar to pile load tests defined by ASTM D 1143. As part of the test, test load is directly applied on the pier as shown in Figure 4a, as opposed to alternative distributed application of the load on both the site soil and the pier, which is widely referred to cell loading. The modulus load tests of Impact Pier elements often incorporate tell-tales at different elevations within the pier (Brian et al., 2006). The tell-tale elements consist of a horizontal steel plate that is attached to two sleeved vertical bars extending to the top of the pier. During the load test, displacements at top of the pier and at the tell-tale plate were recorded, which enable relative displacement (straining) of the pier element. Depending on the location of tell-tales, the displacement response along the RAP element can be assessed. Staged loading starting with 5% of the service load was continued until 150% of the service load. Then, an unloading procedure was followed. With the exception of the load increment representing approximately 115% of the design maximum top of rammed aggregate pier stress and the rebound load increments, all load increments shall be held for a minimum of 15 minutes and until the rate of deflection is less than 0.254mm per hour, or for a maximum duration of 1 hour. The load increment that represents approximately 115%

of the design maximum stress on the rammed aggregate pier shall be held for a minimum of 60 minutes and until the rate of deflection is less than 0.254mm per hour or less, or for a maximum duration of 4 hours. The rebound load increments shall be held for a minimum of 5 minutes.

The load settlement (pressure-strain) curves corresponding to the tip and the base of the RAP element are shown in Figure 4b.

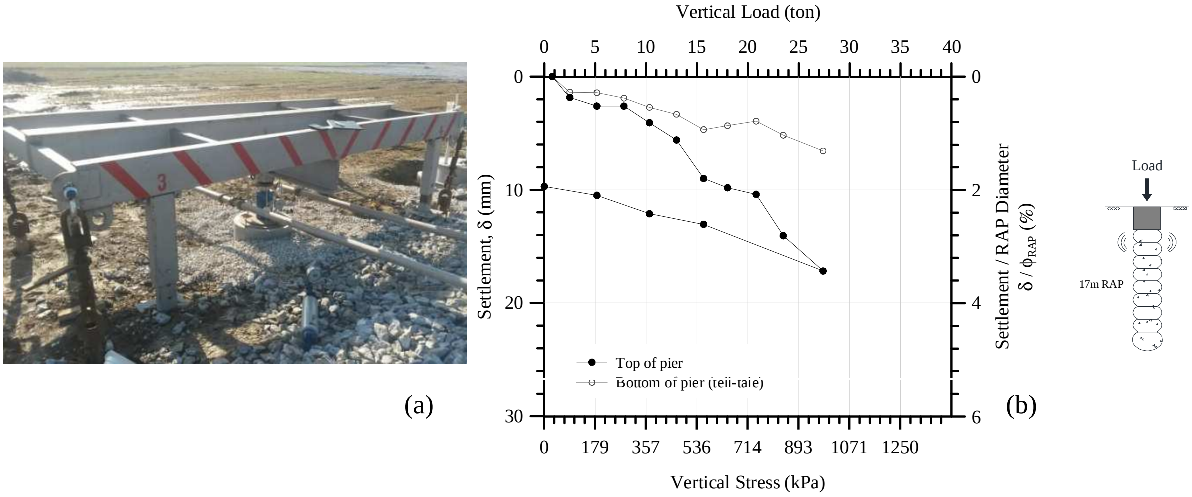


Figure 4. a) The single RAP load test set-up b) the field load test results

5 3-D NUMERICAL (FINITE ELEMENT) SIMULATION OF THE SINGLE RAP FIELD LOAD TEST AND MODEL CALIBRATION

For the numerical simulation of the field load tests, and calibration of soil parameters, 3-D finite element modeling is employed by using Rocscience RS^3 software. For the purpose, a 3-D model mesh was prepared as shown in Figure 5.

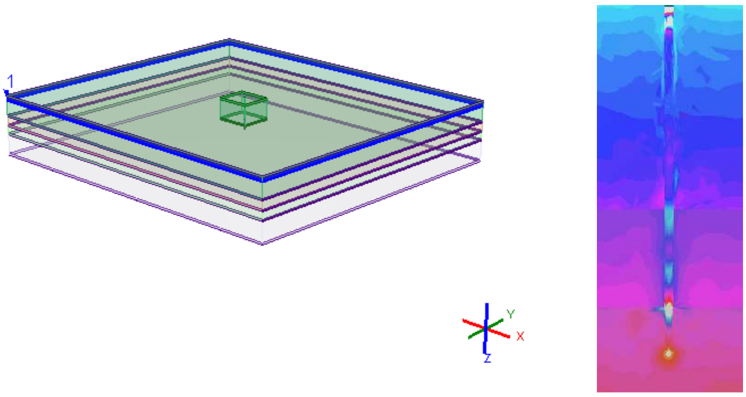


Figure 5. 3-D model of the field load test

Initial stresses are generated consistent with at rest stress conditions by using K_o values. The effect of rammed aggregate pier installation method is taken into account in the FE model. For this purpose, cavity formation in the surrounding soil during pier installation is attempted to be modeled by increasing the lateral earth pressure ratio K to 2.5. This simulated the effects of particle inter-locking and induced increase in horizontal stresses due to bulging of the pier element after compaction. A 60 cm diameter concrete cap, with a thickness of 60 cm was defined consistent with the field construction procedure. Due to lack of extensive laboratory testing, a simple constitutive model was decided to be used for the simulations. Hence, soil elements were modeled as elastic-perfectly plastic elements, for which Mohr-Coulomb failure criterion was used to define shear-induced failure. For concrete RAP cap, elastic elements were defined. A complete summary of input parameters used for numerical analyses is given in Table 1. Undrained loading parameters for the site soils (not for RAP element) were used due to rapid nature of the single RAP loading test. However, as will be discussed later, for the assessment of the long-term response of the RAP-improved raft system, an effective stress-based drained analysis was performed.

Table 1. Drained and undrained constitutive model input parameters

No	Material	Material Type	Thickness	γ	E'	E_u	c'	c_u	ϕ'	ν'	ν_u
		-	(m)	(kN/m^3)	(MPa)	(MPa)	(kPa)	(kPa)	(˚)	-	-
1	Silty Clay (CL-1)	Elasto-Plastic	11.5	18	4.8	8	0	40	29	0.34	0.50
2	Clayey Silty Sand (SC-SM)	Elasto-Plastic	5.5	19	17.8	-	0	0	35	0.30	0.30
3	Silty Clay (CL-2)	Elasto-Plastic	5	18	11	18	0	90	29	0.34	0.50
4	Sandy Clay (CL-3) with Clayey Sand Interlayering (SC)	Elasto-Plastic	12	19	20	-	10	10	33	0.30	0.30
5	RAP element	Elastic	17	22	165	-	-	-	-	0.25	0.25
6	RAP Concrete Cap	Elastic	ϕ 0.6	-	35.000	-	-	-	-	0.15	-
7	Raft Foundation	Elastic	0.6	-	35.000	-	-	-	-	0.15	-

γ - unit weight; E' - drained elastic modulus; E_u - undrained elastic modulus; c' - effective cohesion; c_u - undrained strength; ϕ' - effective friction angle; ν' - effective Poisson`s ratio; $\nu_u$ - undrained Poisson`s ratio

The field loading scheme was simulated as part of 3-D finite element analyses, and the field-monitored and simulated settlement-load responses are comparatively shown in Figure 6.

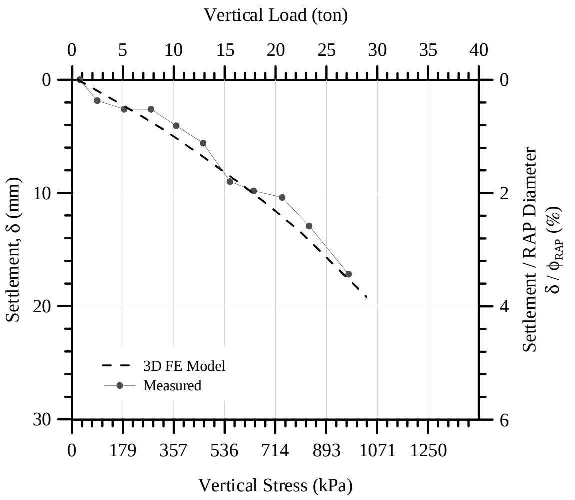


Figure 6. Comparison of measured and calculated pressure-settlement curves

The fit of the monitored field and 3-D finite element simulated settlement vs. load responses are surprisingly satisfactory, which did not leave much room for further calibration. Hence no additional calibration studies were performed.

6 3-D NUMERICAL (FINITE ELEMENT) SIMULATION OF LONG TERM RESPONSE OF RAP SUPPORTED RAFT FOUNDATION

Inspired and motivated from the satisfactory fit between the field monitored and finite element simulation results, the 3-D assessment of raft foundation was performed following the same modeling details. A finite element model with overall model dimensions of 170 m x 190 m x 34 m was generated, as shown in Figure 7.

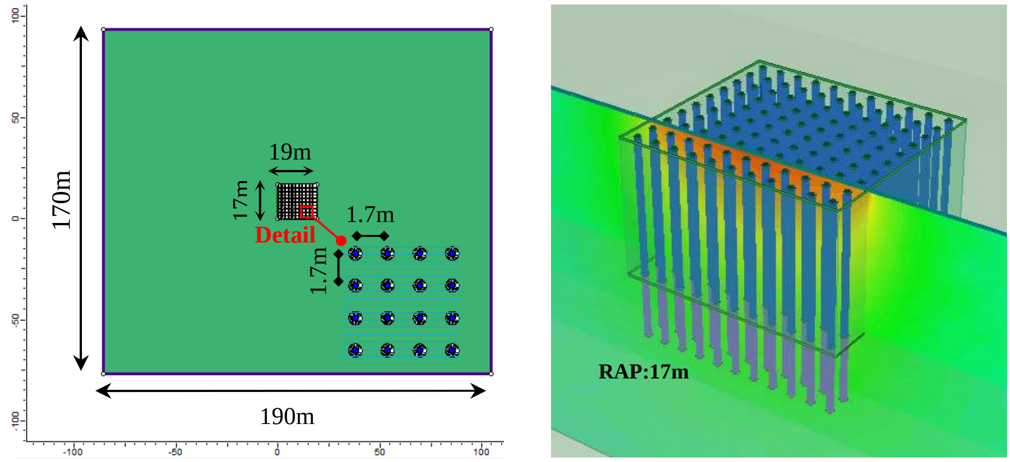


Figure 7. 3-D finite element mesh of the RAP-improved raft foundation

Drained constitutive model parameters, as summarized in Table 2, were used. An unstructured mesh that consists of 10-noded, tetrahedron elements is used. The model comprised of 10 rows and 11 columns of RAPs (=110 RAP elements) of 50 cm diameter installed at 1.7 m x 1.7 m square pattern. RAP elements extended to a depth of 17m beneath the foundation. A uniformly distributed gross foundation stress of 100 kPa was applied on 60 cm thick, 17 m x 19 m raft foundation.

7 DISCUSSION OF NUMERICAL ASSESSMENT RESULTS

For the purpose of comparing responses of perfectly flexible and 60 cm thick rafts, supported by 17 m long RAP elements, series of figures were prepared.

Figure 8 shows the distribution of vertical loads among RAP elements for the 60 cm thick raft foundation case. It is clearly seen that the RAPs located in the vicinity of the middle of the raft are subjected to less of a vertical loads as compared to the elements at the edges. The most corner RAP element was subjected to about 13-14 tons whereas the middle RAP elements to 9-10 tons. This suggests a difference defined by a factor of 1.4.

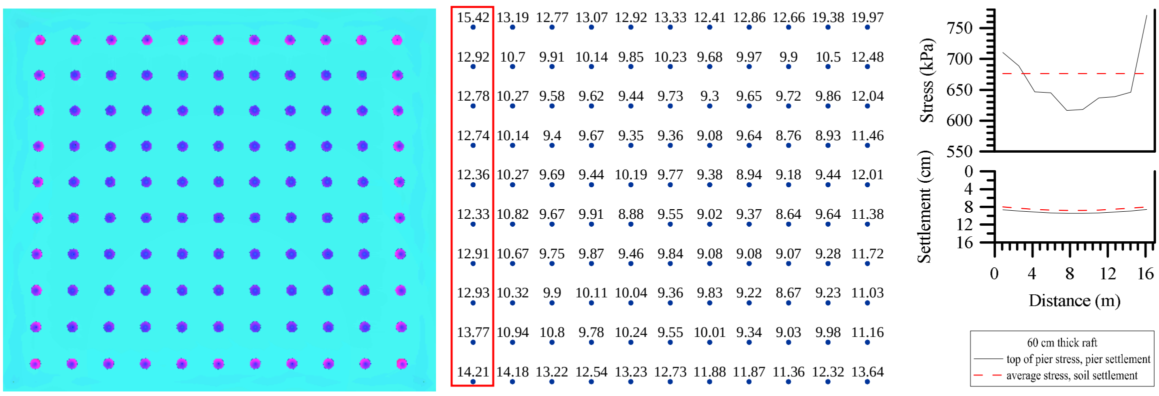


Figure 8. Vertical load distribution (in tons) on RAPs under 60 cm thick raft

Figure 9 shows the distribution of vertical loads among RAP elements for the flexible foundation case. It is clearly seen that as expected from a flexible foundation loading case, the vertical load distribution among RAPs are observed to be rather uniform. However, the vertical settlement at the midpoint of the raft is significantly more than the edges, which is again consistent with flexible foundation response.

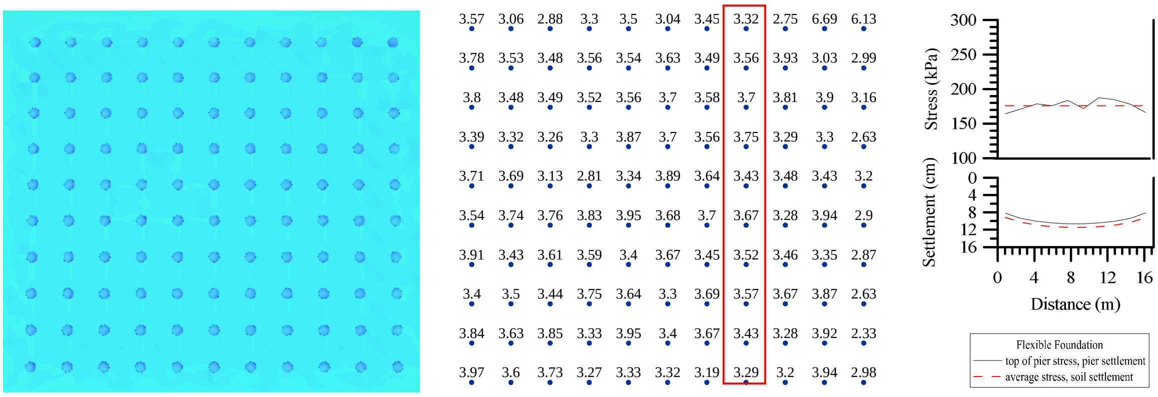


Figure 9. Vertical load distribution (in tons) on RAPs under a flexible foundation

Poulos and Davis (1980) studied the response of 5x5 pile groups and observed a similar trend as also shown in Figure 10.

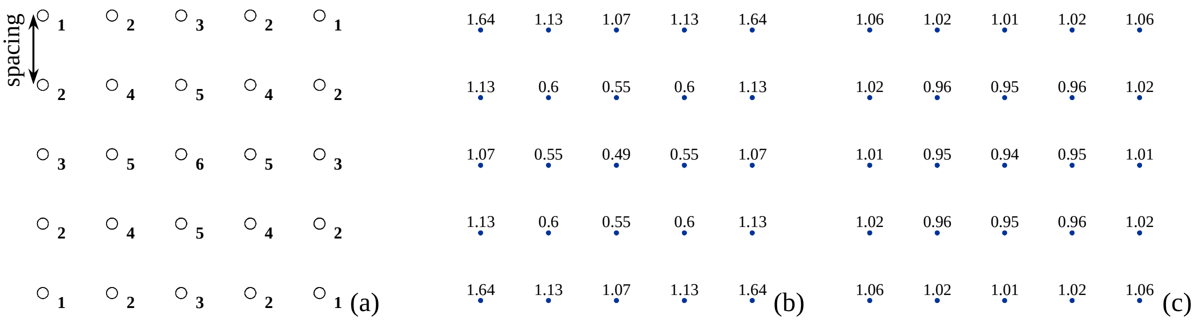


Figure 10. a) Identification of piles in 5x5 square groups, vertical load distribution 5x5 pile group for b) rigid cap c) equally loaded, Poulos and Davis (1980)

The effect of raft rigidity on settlement is illustrated in Figure 11. It is found that the settlement of raft foundation decreases with increasing rigidity of the raft agreeing with the available literature (e.g.: Gandhi and Maharaj, 1995).

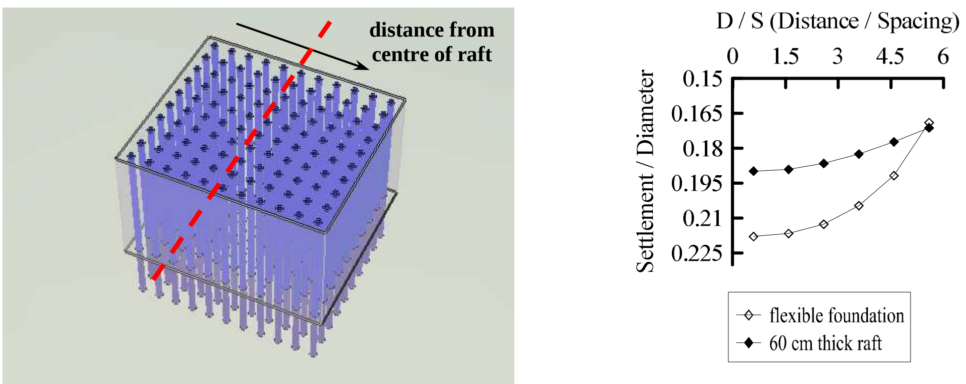
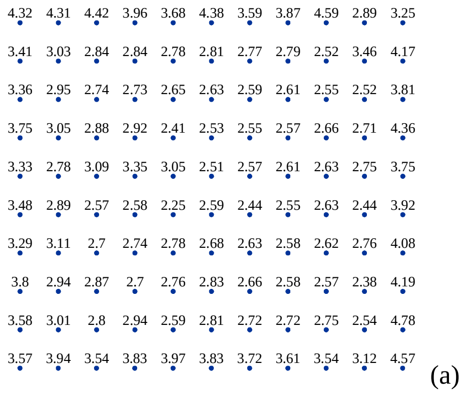


Figure 11. Effect of raft rigidity on settlement

The ratio of the vertical load on RAPs beneath a 60 cm thick raft and a flexible foundation are presented in Figure 13. RAPs under 60 cm thick raft are subjected to 2.5 to 4.8 times more loads as compared to RAP under a flexible foundation. Consistent with this finding, also the ratio of foundation stresses on the soils beneath foundations in between RAPs is given in Figure 12. As shown in this figure, soil element under a flexible foundation is subjected to approximately 2.5 times more stresses. Consistent with this observation, vertical settlement of cases with a more rigid raft is about 25 % less than the settlements under flexible foundation.



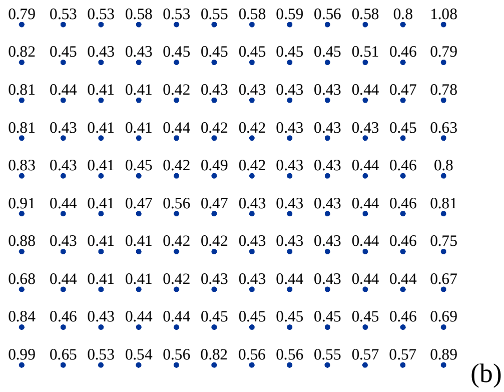


Figure 12. a) Vertical load ratio for RAPs under a 60 cm thick raft and flexible foundation b) Vertical stress ratio for soils beneath foundations in between RAPs for a 60 cm thick raft and flexible foundation

8 CONCLUSIONS

Within the confines of this paper series of 3-D dimensional numerical assessments were performed by using RS^3 Rocscience software to assess the load distribution among group of RAP elements and the corollary rigid element settlements. RAP field load test results were used to calibrate numerical simulations. The results of these analyses are presented in the form of load and settlement distribution factors, which address the group response of RAPs. The findings are then compared with available literature, widely developed for pile groups. Followings are the specific conclusions of the assessments performed:

i) For the 60 cm thick raft foundation case, the RAPs located in the vicinity of the middle of the raft are subjected to less of vertical loads as compared to the elements at the edges. The most corner RAP element was subjected to about 13-14 tons, whereas the middle RAP elements to 9-10 tons. This suggests a difference defined by a factor of 1.4.
ii) The vertical load distribution among RAPs beneath perfectly flexible raft is observed to be rather uniform. However, the vertical settlement at the midpoint of the raft is significantly more than the edges, which is again consistent with flexible foundation response.
iii) The differential settlement of raft decreases with increasing rigidity of the raft.
iv) RAPs under 60 cm thick raft are subjected to 2.5 to 5 times more loads as compared to RAP under a flexible foundation.
v) The soil element under a flexible foundation is subjected to approximately 2.5 times more stresses, when compared to the 60 cm thick raft foundation case.
vi) The vertical settlement beneath 60 cm thick raft foundation is about 25 % less than the settlement beneath the flexible raft foundation.

REFERENCES

ASTM D1143 – 81 (Reapproved 1994). Standard Test Methods for Deep Foundations Under Static Axial Compressive Load, Annual Book of ASTM Standarts.

Brian, C.M., FitzPatrick, B.T. and Wissman., K.J. (2006). Specifications for Impact® Rammed Aggregate Pier Soil Reinforcement. Geopier® Foundation Company, Inc., Mooresville, NC.

Gandhi, S. R. and Maharaj, D. K. (1995). Behaviour of Piled Raft under Uniform Loading. Indian Geotechnical Conference (IGC-95), Bangalore, Vol.1, 169-172.

Handy, R.L. (2001). Does Lateral Stress Really Influence Settlement?. ASCE Journal of Geotechnical and Goenviromental Engineering, 127(7), 623-626.

Poulos, H. G. and Davis, E. H., 1980. Pile Foundation Analysis and Design. John Wiley & Sons, New York.

Wissmann, K.J., Moser, K. and Pando, M.A. (2001). Reducing Settlement Risks in Residual Piedmont Soils Using Rammed Aggregate Pier Elements. Proceedings, ASCE Specialty Conference, Blacksburg, Virginia.