Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilimleri Dergisi

Afyon Kocatepe University Journal of Science and Engineering

AKÜ FEMÜBİD **21** (2021) 025601 (399-407) AKU J. Sci. Eng. **21** (2021) 025601 (399-407)

DOI: 10.35414/akufemubid.863095

Araştırma Makalesi / Research Article

Experimental Investigation of Pile Addition and Length on Bearing Capacity and Settlement of Rafts on Loose Sandy Soil

Bayram ATEŞ[1*], Erol ŞADOĞLU[2]

[1] Karadeniz Teknik Üniversitesi, Mühendislik Fakültesi, İnşaat Mühendisliği Bölümü, Trabzon.

[2] Karadeniz Teknik Üniversitesi, Mühendislik Fakültesi, İnşaat Mühendisliği Bölümü, Trabzon.

**Sorumlu Yazar, e-posta[1]: bayramates61@hotmail.com ORCID ID: http://orcid.org/0000-0002-1251-7053*

e-posta[2]: esadoglu@ktu.edu.tr ORCID ID: http://orcid.org/0000-0003-3757-5126

Geliş Tarihi: 17.01.2021 Kabul Tarihi: 13.04.2021

Keywords
Raft; Piled Raft Foundation; 1g Physical Model Test; Bearing Capacity; Settlement

Abstract

Foundations are important parts of many construction projects. Piles or piled foundations are used in the cases where the structural loads cannot be carried safely with the shallow foundations. In this study, it is aimed to investigate and compare the bearing capacity and sitting settlement of rafts and piled raft foundations. For this purpose, a test setup was formed and loading tests were carried out on a model raft and a model piled foundation. The results can serve as a reference for the preliminary assessment of bearing capacity and settlement of driven piles embedded in sandy soils without conducting expensive and time-consuming field trials.

Gevşek Kum Zemine Oturan Radyelerin Taşıma Gücü ve Oturmasına Kazık İlavesinin ve Uzunluğunun Etkisinin Deneysel Olarak İncelenmesi

Anahtar Kelimeler
Radye; Kazıklı Radye Temel; 1g Fiziksel Model Deney; Taşıma Gücü; Oturma

Öz

Temeller, çok sayıda inşaat projesinin önemli bir parçasıdır. Yapısal yüklerin yüzeysel temellerle güvenli bir şekilde taşınamadığı durumlarda, kazıklar veya kazıklı temeller kullanılır. Bu çalışmada radye ve kazıklı radye temellerin taşıma gücü ve oturmasının belirlenmesi incelenmesi ve karşılaştırılması amaçlanmıştır. Bu amaçla bir deney düzeneği oluşturuldu; model radye ve model kazıklı radye temeller üzerine yükleme deneyleri gerçekleştirilmiştir. Sonuçlar, pahalı ve zaman alıcı saha denemeleri yapmadan, kumlu zeminlere gömülü kazıkların taşıma kapasitesinin ön değerlendirmesi ve oturması için bir referans görevi görebilir.

© Afyon Kocatepe Üniversitesi

1. Inroduction

Over the last decades, huge structures have been built with developments in civil engineering. The loads transferred from these structures to soil reach very high values. If it is not possible to carry these loads with shallow foundations, usage of piled foundations becomes compulsory. Unlike shallow foundations, the load transfer mechanism from piles to soil layers is complicated. In general, the axial loads applied to the piles are transferred into the soil by two mechanisms: end bearing and skin friction.

The tips of piles can be rested on the rock surface Where rocky soils or very stiff soil layers are expected at shallow depth of the site during soil exploration. Most or entire applied axial load of the piles is carried by underlying rock layer in this case, these types of piles are called end-bearing piles. Where rock layers or rock-like materials are not available at a reasonable depth of a site the lengths of the piles will become very long and the end bearing piles will not be economical. In this case, the piles can be constructed into the soil at a limited depth. This type of piles is called as friction piles, because most of the resistance is due to friction between surface of pile and soil. The ultimate bearing capacity (Q_u) of a pile is given by the equation below:

$$Q_u = Q_p + Q_f \qquad (1)$$

Where; Q_u = ultimate bearing capacity of pile, Q_p = end bearing capacity of pile, Q_f = skin resistance of pile.

Determination of pile bearing capacity is not simple, but quite complex; a lot of theories and empirical methods are available at the present time but they do not give the same value of bearing capacity especially for friction piles because there are many uncertainties in soil properties and at the interface of soil-pile materials. Many methods and empirical equations achieved from experimental work are available for calculation of ultimate bearing capacity of pile foundations and most of them are based on the equations of shallow foundation (Terzaghi and Peck 1948; Janbu 1976; Meyerhof 1963; Vesic 1963; Coyle and Castello 1981). Design of pile foundations is based on the assumption that the all weight of the superstructure is supported by the piles, even when the second design criterion is more critical. A different approach, involving the use of piles as settlement reducers, has been postulated by Burland et al. (Burland et al. 1977; Padfield and Sharrock 1983; Hansbo and Jendeby 1983; Cooke 1986).

The piled raft foundation is a geotechnical composite structure that consists of the three elements, namely: piles, raft and soil. The foundations have high bearing capacity and reduce settlements in an economical way as compared to other foundations. Also, strategic placement of piles results in improvement of the bearing capacity and reduction of differential settlements to an allowable level. The piled raft foundation has become a prominent foundation system in recent years due to that it combines load bearing capacities of piles and raft. Therefore, comprehensive analytical and experimental studies are carried out for reliable and economic design of piled raft foundations. Horikoshi et al. (2003) investigated load-settlement behavior and load sharing mechanism between piles and raft with centrifuge tests (horizontal and vertical loading) in a granular soil. Lee and Chung (2005) studied pile groups with experiments on single pile, single-loaded center piles in groups, raft foundation, free standing pile group, and piled foundations in granular soil and pointed out that factors such as mutual effect between piles, mutual effect between raft and piles and influence of calculation method, all need to be considered for a proper pile group design. Bajad and Sahu (2008) determined the effect of number of piles and pile length on settlement and load sharing behavior of piled raft foundations resting on soft clay with 1 g model tests. Fioravante et al. (2008) examined behavior of rigid circular rafts on settlement reducing piles with centrifuge model tests. The experimental program involved an unique raft, rafts on 1, 3, 7 and 13 piles for loose silica sand. Phung (2010) presented the data of three extensive series of large scale field tests performed on piled foundation in granular soil in order to clarify pile cap-soil mutual effect and load-settlement behavior of piled foundations. All the pile groups were square and consisted of five piles (four at the corners and one at the center).

Al-Mosawi et al. (2011) conducted some laboratory tests in order to investigate the behavior of model piled raft. The experiments were performed with a cubical soil tank with a length of 60 cm, filled with medium dense sand. The dimensions of the tank were selected in a way that the boundaries did not limit the failure zone of the foundation. The material of piles and the raft were aluminum alloy. Piled raft design was changed in each test. Pile spacing was selected as 5 cm and kept constant for all the tests. Thickness of raft was determined as 5 mm and 2.5 mm. The pile diameters were 9 mm, 12 mm and 15 mm. The length over diameter ratio (L/D) was varied as 20, 25 and 30. The pile configurations were formed as 2x1, 3x1, 2x2 and 3x2. The vertical load applied on foundation was either 5 kN or 10 kN and unpiled raft is also examined for comparison. For the unpiled raft, thickness of raft slightly influenced the load bearing capacity. The increment in raft size enhanced the load bearing capacity. Elwakil and Azzam (2016) performed 23 small scale laboratory tests to examine the piled raft foundations. Medium dense sand was used in the tests. The raft was a steel square plate and included 16 piles with a diameter of 1.6 cm and spacing of 3.75 cm. Different pile lengths were used as 10 cm, 20 cm and 40 cm. Number of piles was also changed as 4, 8, and 16. For each pile length and number of piles, tests were repeated for the cases of that the raft is in contact with the soil surface or free from the soil surface. In addition, the piles were placed in both square and staggered configurations. The test results proved that the average load supported by the raft is 39%, as length of piles are reduced the contribution of the raft to bearing capacity increases, the settlement of the foundation decreases with increasing number of piles and L/D ratio.

Numerous researchers have performed computational analysis of raft and piled rafts foundation (Russo and Viggiani 1998; Viggiani 2001; Randolph et al. 2004; Sanctis and Mandolini 2006; Sanctis and Russo 2008; Ponomarev et al. 2020; Gotman and Alekhin 2020). However; less information is available in literature about experimental studies on piled raft foundations. Therefore, it is aimed to determine bearing capacity and settlement of raft and piled raft foundations experimentally in this study. For this purpose, a test setup was formed and loading tests were performed including the piled raft and the raft cases. The effect of pile length on bearing capacity and settlement also investigated.

2. Materials and Method

Study of piled foundation with field tests needs high cost. For this reason, studies on the behavior of piled foundation can usually be done with model laboratory experiments and case studies. In this study; an experiment setup was made in order to observe bearing capacity and settlement of vertically loaded piled raft and raft foundations resting on sandy soil. The main parts of the experimental setup consist of a test tank, model raft, model piles, a loading apparatus, linear variable differential transformers (LVDT's), a load cell, a sand surface leveling tool and sand. A gear driven loading press of a triaxial test device was used as the loading apparatus. In addition, a compaction device was used to compact the sand in some tests. A digital camera and a computer were used to record data during tests. The model experiments were performed in the Geotechnical Laboratory of Karadeniz Technical University.

The inside of the test tank is a cube prism with edge lengths of 100 cm. The tank sizes were selected by considering similar studies and the results of the numerical analysis so that no boundary effect occurs (Fig. 1). The frame of the tank was made of steel profiles. The steel braces were welded at certain points around the tank and supported by bolts to ensure stability of test tank. The horizontal lines with 5 cm intervals were drawn inner surfaces of test tank to place granular soil homogeneously and to obtain desired relative density of the sand easily. The movements of both the tank and the surface were observed with the help of dial gauges in order to control the boundary effect during loading. In addition, a steel beam was mounted to the test tank to connect the loading apparatus.

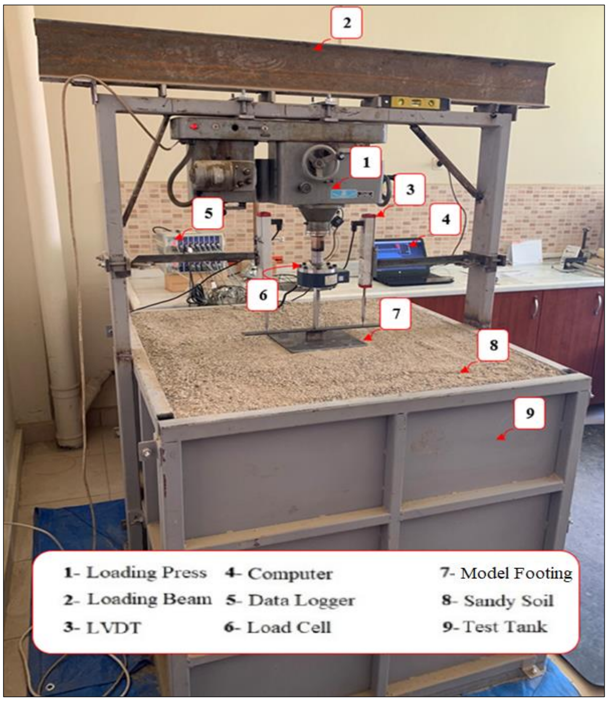

Figure 1. A view of experimental setup

Literature survey and preliminary tests were performed to determine sizes of model raft foundation used in laboratory tests. The length and width were determined as 240 mm and 240 mm, respectively (Fig. 2 (a)). The holes, which were compatible with the loading head, were drilled in the model raft to ensure vertical loading and the large diameter holes were also drilled to assemble the model piles. A thick abrasive paper is adhered to the base of the model raft foundation in accordance with friction and practical conditions.

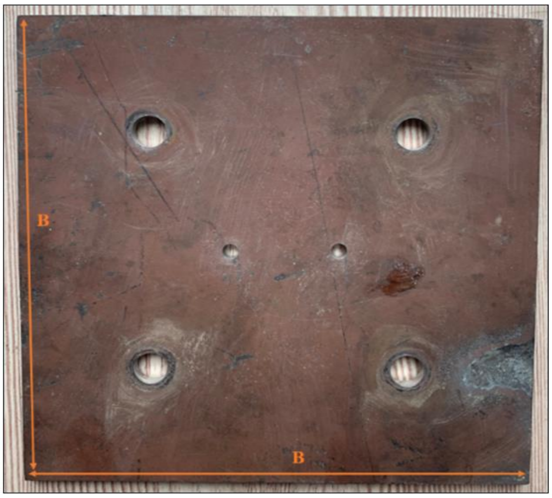

Figure 2. Model raft foundation (B=240 mm)

The pile lengths (L) and diameter were determined from preliminary tests as 200, 300 mm and 30 mm, respectively. Aluminium molds were prepared to manufacture the model piles (Fig. 3 (a)). The model composite piles were prepared by using concrete and steel bar to obtain real soil-concrete friction behaviour between the model pile and the sand (Fig. 3 (b) and (c)).

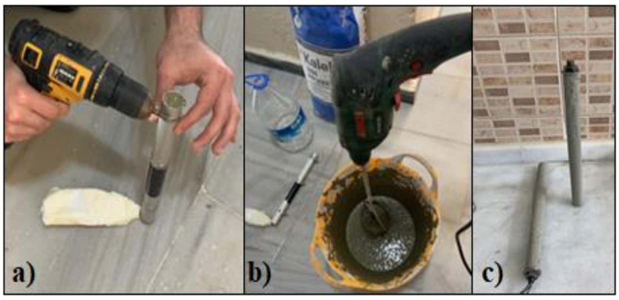

Figure 3. Model pile foundation; a) placing the concrete in the aluminum mold b) concrete preparation for production of model pile, c) model piles

The piled raft foundation used in the laboratory scale experiments was formed by combining the model piles and the model raft with the help of bolts. Figure 4 shows the connection detail.

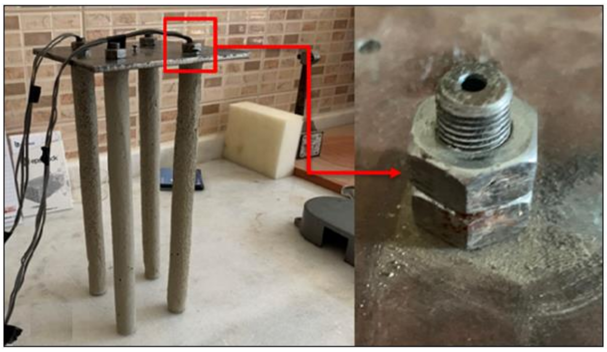

Figure 4. Model piled raft and rigid connection detail

The sand, taken from the east coast of Black sea adjacent to Iyidere district (Rize), was used in the tests. The grain size distribution of the sand was determined in accordance with ASTM D-6913 (2017). In addition, uniformity coefficient and curvature coefficient were calculated as C_u=6.11 and C_c=1.1, respectively. The grain size distribution of the sand is between 0.1-5.0 mm (coarse-medium) and it is classified as well graded sand in accordance with the Unified Soil Classification System (ASTM D-6913; 2017). The geotechnical specifications of granular soil used in tests are given in Table 1. The dry unit weight of the sand was calculated with help of the following equation for the relative densities of D_r=0.30. The angle of internal friction of granular soil for different relative densities was obtained by shear box test.

$$D_r = \frac{\gamma_{d\max}}{\gamma_d}\left(\frac{\gamma_d - \gamma_{d\min}}{\gamma_{d\max} - \gamma_{d\min}}\right) \quad (2)$$

Table 1. Geotechnical properties of sandy soil

Specifications	Unit	Value
Grain specific gravity, Gs, (ASTM D-854; 2006)	-	2.64
Maximum dry density, ρ_{dmax}, (ASTM D4253-16; 2016)	Mg/m^3	1.89
Minimum dry density, ρ_{dmin}	Mg/m^3	1.58
Effective diameter, D_{10}	mm	0.28
D_{30}	mm	0.73
D_{60}	mm	1.71
Coefficient of uniformity, C_c	-	6.11

Coefficient of curvature, C_r	-	1.10
Internal friction angle, ϕ	Degree	37.00

The press of a triaxial test equipment was used for application of vertical load during the tests. The press is capable of loading at various speeds (0.50 mm/min-1.50 mm/min) thanks to the electric motor and was mounted on the steel frame fixed to the test tank for vertical loading (Fig. 5(a)). A 50 kN load cell was mounted vertically at the end of the press to measure applied loads. The load cell was calibrated before the tests. The vertically mounted loading head with a sharp end was used to load the model raft and the model piled raft. The applied loads were measured precisely with the help of the load cell. Fig. 5(b) shows the LS-5T model load cell with a capacity of 50 kN manufactured by CAS Corporation. The displacement transducers (linear variable differential transformers, LVDT) manufactured by OPKON which can measure displacements up to 150 mm, were used to measure the settlement of the model piled raft foundation due to the vertical loading (Fig. 5(c)).

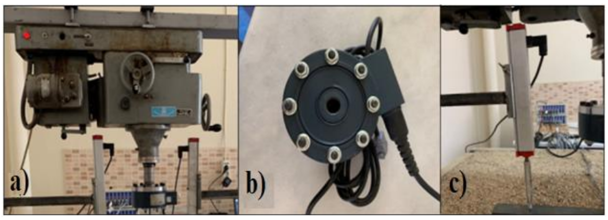

Figure 5. Loading assembly; a) the load press, b) the load cell, c) LVDT

The settlements were measured at two different points that were equal distance to the center of the pile. The settlement of the raft and piled foundation were determined as the average of the two measurements. During the experiments, the quantities measured by the load cell and the LVDTs were transferred to the computer with the aid of TDG branded data logger of Ai8b model with 8 channels input and RS-485 model gateway of the same brand (Fig.6 (a) and (b)). These data were converted to numerical values with the help of CoDA Locomotive program (Fig. 6(c)).

Figure 6. Data collection units; a) data logger, b) gateway, c) CoDA Locomotive

The sand was placed and compacted in the test tank in layers. For 30% relative density (ρ_d=1.66 Mg/m^3), the sand required (M_d=83kg) for 50 mm layer was poured into the test tank at a close distance to prevent compacting, the surface of the sand was made horizontal with a water balance, and thus the sand was homogeneously placed. The height of the sand layer was controlled by the horizontal lines indicating the layer thickness on the inner surfaces of the tank (Fig. 7).

Figure 7. The placement of the sand a typical test

After placement of the sand into the tank, model raft rested on sand was loaded. Then, the model piled raft foundation was inserted into the sand at a constant penetration rate of 0.50 mm/min (Bajad and Sahu 2008; Nguyen 2013). While the model piled raft foundation was being inserted into the sand, its verticality was checked with water balance. Before starting the test, all measurement devices were placed in the experimental setup. The measurement devices consist of LVDTs placed on both sides of the loading head, the load cell mounted to the load press (Fig. 8 (a) and (b)).

Figure 8. A typical test; a) insertion of the model piled raft b) the start of loading

The initial values of the measurement devices were reset zero and the load was applied vertically and very slowly. A constant loading speed of 0.50 mm/min was applied until the desired settlement was achieved. The data were recorded during the experiments with the help of the data logger and the gateway and they were converted to numerical values with the help of CoDA Locomotive program. With the help of experimental data, vertical load-settlement curves were obtained. As we had seen in the literature studies; nonlinear load-settlement behavior was observed in the loading stages of the model raft and piled raft foundations. If the bearing capacity cannot be determined precisely from the load-settlement curves, some methods, (0.1B method, (B=width of raft), Tangential intercept method, Log-Log method and Hyperbolic method) can be used in geotechnical engineering to investigate the bearing capacity (Briaud and Jeanjean 1994; Debeer 1970; Trautmann and Kulhawy 1998). Different bearing capacity values can be obtained in each of these methods. Therefore, a single method should be selected to determine the value of bearing capacity. Since an apparent bearing capacity could not be determined from the vertical load-settlement curves, the 0.1B method, which is more practical in comparison with other methods, was used. The tests were repeated three times for each relative density of soil, and the results were recorded.

3. Results and Discussions

The results of the laboratory scale experiments for the parameters that can be effective on bearing capacity and settlement of raft and piled raft foundations are presented and discussed in this section. The foundations were placed in loose sandy soil subjected to vertical load. Figure 9 shows the load-settlement curves obtained for the model piled raft in case of D=30 mm, L=200 and 300 mm, D_r=30% and B=240 mm. There are significant differences between the load-settlement curves of the raft and the piled raft foundation. Increasing the pile length by 50% (L=300mm) significantly affected the load bearing capacity of piled raft foundation. It was determined that piles are significant parameters in terms of bearing capacity of piled raft foundation. Usage of piles increased bearing capacity by 72-130 % depending on pile length. Also, 50% increment in pile length increased bearing capacity by 33 % (Table 2).

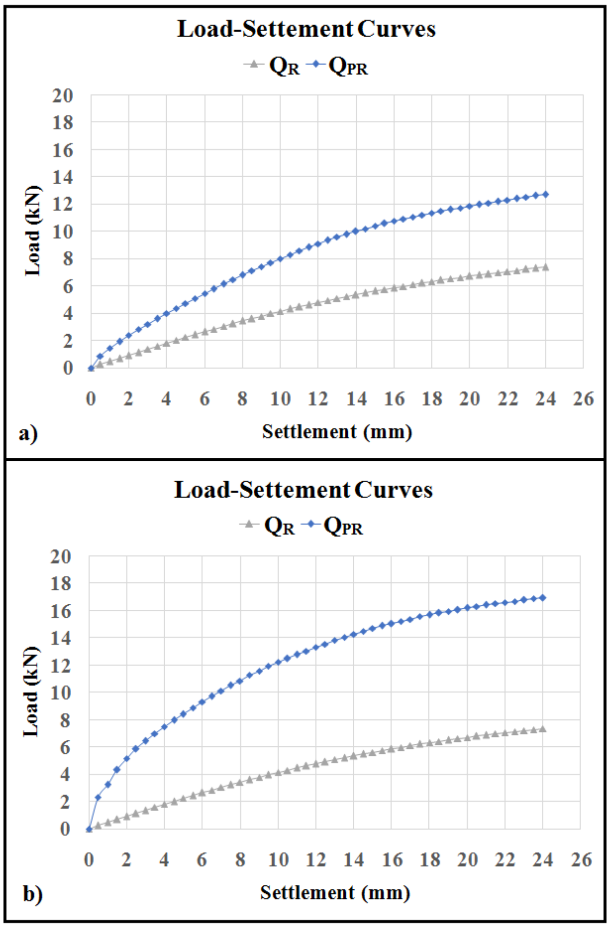

Figure 9. The load-settlement curves in case of D_r=%30 a) L=200 mm, b) L=300 mm

Table 2. Result of tests

Width of Raft (B, mm)	Pile Length (L,mm)	Relative Density (D_r)	Model	Load (kN)	Settlement (mm)
240	-	D_r=0.30	raft	7.359	24.00
240	200	D_r=0.30	piled	12.688	24.00
240	200	D_r=0.30	piled	7.359	8.90

240	300	D_r=0.30	piled	16.916	24.00
240	300	D_r=0.30	piled	7.359	3.91

Figure 10 shows the pile length-settlement curves obtained for piled raft in case of D=30 mm, L=200 and 300 mm, D_r=30% and B=240 mm. Adding piles to raft and increasing the pile length by 50% (L=300mm) significantly affected the settlement of raft. Adding the piles (L=200mm) to the model raft reduced the settlement of the raft by 63% for the same load level. Also, increasing the pile length by 50% (L=300mm) contributed the reducing settlement reduction by 84% for the same load level.

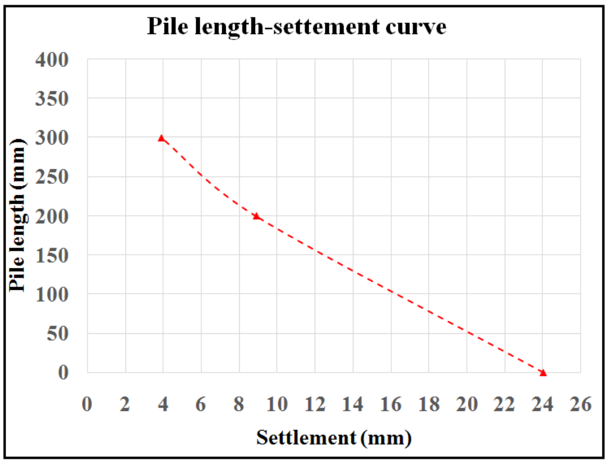

Figure 10. The pile length-settlement curves

4. Conclusion

In this study, it is aimed to determine settlement and bearing capacity of raft and piled raft foundations. For this purpose, a test setup was made and loading tests were carried out with the model raft and the model piled raft. The addition of the different model piles to the model raft was done to examine effects of pile length on settlement and bearing capacity. The main results obtained from the experimental study are as follows:

- It was determined that piles are significant parameters in terms of bearing capacity of piled raft foundations.
- Addition of the model piles to the model raft increased bearing capacity by 72-130% and 50% increment of the model pile length increased bearing capacity by 33%. Pile length is an important factor for piled raft design.
- Addition piles to raft and increasing the pile length by 50% (L=300mm) significantly affected the settlement of the model raft. Addition of the model piles (L=200mm) to the model raft reduced the settlement of the model foundation by 63%. Also, increasing the pile length by 50% (L=300mm) reduced settlement by 84%. The use of piles and increasing pile length are effective in reducing the settlement of foundations.

5. References

Al-Mosawi, M.J., Fattah, M.Y. and Al-Zayadi, A. A. O., 2011. Experimental Observations on the Behavior of a Piled Raft Foundation, Journal of Engineering, **17(4)**, 1–11.

ASTM D-854, 2006. Standard test methods for specific gravity of soil solids by water pycnometer, *American Society for Testing and Materials*, West Conshohocken.

ASTM D3080M-11, 2011. Standard test method for direct shear test of soils under consolidated drained conditions, *ASTM International*, West Conshohocken.

ASTM D4253-16, 2016. Standard test methods for maximum index density and unit weight of soils using a vibratory table, *ASTM International*, West Conshohocken.

ASTM D-6913, 2017. Standard test methods for particle-size distribution (gradation) of soils using sieve analysis, *American Society for Testing and Materials*, West Conshohocken.

Bajad, S.P. and Sahu, R. B., 2008. An experimental study on the behavior of vertically loaded piled raft on soft clay, *The 12th Intl. Conf. Of International Association for Computer Methods and Advances in Geomechanics* (IACMAG), 84–90.

Burland, J.B., Broms, B.B. and De Mello, V.F.B., 1977. Behaviour of foundations and structures, *In Proceedings of the 9th International Conference on*

Soil Mechanics and Foundation Engineering, Tokio, **2**, 495-546.

Briaud, J.L. and Jeanjean, P., 1994. Load settlement curve method for spread footings on sand, *ASCE*, **2**, 1774-1804.

Cooke, R.W., 1986. Piled Raft Foundations on Stiff Clays, *Geotechnique*, 35, **2**, 169-203.

Coyle, H.M. and Castello, R.R., 1981. New design correlations for piles in sand, *Journal of Geotechnical and Geoenvironmental Engineering*, 107.

Debeer, E.E., 1970. Experimental determination of the shape factors and the bearing capacity factors of sand, *Geotechnique*, 20, **4**, 387-411.

Elwakil, A.Z. and Azzam, W. R., 2016. Experimental and numerical study of piled raft system, *Alexandria Engineering Journal,* 55, **1**, 547–560.

Fioravante, V. Giretti, D. and Jamiolkowski, M., 2008. Physical modeling of raft on settlement reducing piles, *In: From Research to Practice in Geotechnical Engineering*, 206–39.

Gotman, N.Z. and Alekhin, V.S., 2020. Calculation of the ultimate resistance of the pile basis in pile groups, *Soil Mechanics and Foundation Engineering*, 57, **1**.

Hansbo S. and Jendeby, L., 1983. Case Study of Two Alternative Foundation Principle; Conventional Friction piling and Creep Piling, *Vag-och Vatten by garen*, **7-8**, 29-31.

Horikoshi, K., Matsumoto, T., Hashizume, Y., Watanabe, T. and Fukuyama, H., 2003. Performance of piled raft foundations subjected to static horizontal loads," *International Journal of Physical Modeling in Geotechnics,***3**, 37–50.

Janbu, N., 1976. Static bearing capacity of friction piles, *In Sechste Europa Eische Konferenz fuer Boden Mechanik und Grundbau*, 1.

Lee S.H. and Chung, C.K., 2005. An experimental study of the interaction of vertically loaded pile groups in sand, *Canadian Geotechnical Journal*, **42**, 1485–93.

Meyerhof, G.G., 1963. Some recent research on the bearing capacity of foundations, *Canadian Geotechnical Journal*, 1**, 1**, 16-26.

Nguyen, D.D.C., Jo, S.B. and Kim, D.S., 2013. Design method of piled-raft foundations under vertical load considering interaction effects, *Computers and Geotechnics*, **47**, 16-27.

Padfield, C.J. and Sharrock, M.J., 1983. Settlement of Structures on Clay Soil, *Construction Industry Research and Information Institute*, Special Publication **27**, London.

Phung, D.L., 2010. Piled raft –a cost-effective foundation method for high-rises, *Geotechnical Engineering Journal of the SEAGS&AGSSEA,* 41, **3**, 1–12.

Ponomarev, A.B., Akbulyakova, E.N. and Ofrichter, Y.V., 2020. Prediction of bearing capacity of driven piles in semi-rocky soils, *Soil Mechanics and Foundation Engineering*, 57, **2**.

Randolph, M.F., Jamiolkowski, M.B. and Zdravkovic, L., 2004. Load carrying capacity of foundations, *Advances in Geotechnical Engineering—the Skempton Conference*. London: Thomas Telford Limited, 207–40.

Russo, G. and Viggiani, C., 1998. Factors controlling soil-structure interaction for piled rafts, *In: Darmstadt Geotechnics,* Darmstadt: Darmstadt University of Technology, 297–322.

Sanctis, L.D. and Mandolini, A., 2006. Bearing capacity of piled rafts on soft clay Soils, *International Journal of Geotechnical and Geoenvironmental Engineering*, 132, **12**.

Sanctis, L.D. and Russo, G., 2008. Analysis and performance of piled rafts designed using innovative criteria, *International Journal of Geotechnical and Geoenvironmental Engineering*, 134, **8**.

Terzaghi K. and Peck, R.B., 1948. Soil Mechanics in Engineering Practice, *John Wiley and Sons*, USA.

Trautmann, C.H. and Kulhawy, F.H., 1998. Uplift load-displacement behavior of spread foundations, *Journal of Geotechnical Engineering*, 114, **2**, 168-183.

Vesic, A.S., 1963. Bearing capacity of deep foundation in sand, *Highway Research Record*, National Academy of Sciences, **39**, 113-151.

Viggiani, C., 2001. Analysis and design of piled foundations, *1st Arrigo Croce Lecture*, Rivista Italiana de Geot, 47–75.