A REVIEW ON DESIGN OPTIMIZATION OF PILED RAFT FOUNDATIONS

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Abstract : Due to rapid urbanization, the scope for constructing high rise building is increasing. The strength of building relies on its foundation. Raft foundations transfer the load to entire area of the building. Pile foundations transfer the load to deeper stratum and are extensively used in areas where the soil beneath is too weak to carry the super structural loads. The piles are provided along with raft foundation to reduce total and differential settlements and to improve the structural behaviour of foundation. In piled raft, pile act as settlement reducers and raft is the main bearing element. There are four interactions in piled raft foundation system which include pile- soil, pile-pile, raft-soil and pile-raft which makes its design more complex than pile groups. The optimization of piled raft aims at achieving most economical design of foundation. Artificial intelligence techniques are receiving wide applicability in various disciplines. This paper presents a review on various research works done in the area of optimization of piled raft foundations.

***IndexTerms* - Piled raft, Optimization, Artificial intelligence**

I. INTRODUCTION

Due to rapid industrialization, increasing economic development and reduction in the availability of land, the scope for construction of high rise buildings has increased. The strength of the building relays on its foundation. The foundations provide support for the structures and transfers the weight of the building to the ground. Poorly constructed foundations are dangerous to occupants and cause economic losses.

Raft foundations are shallow foundations, that are provided when the strata is unstable. Raft distributes the weight of the building over the entire area and are less effective if the structural loads are concentrated on specified areas. At the time when the strata at or just beneath the ground is highly compressible and very weak for carrying the super structural loads, pile foundation is the best choice. Pile foundations are structural elements to transfer superstructure loads deep into the ground.

In foundation design if raft foundation is not adequate to transfer the loads, pile foundations are provided instead. In situations where the foundation of high rise building is to be designed or when the strength and stiffness of foundations are not adequate to transfer loads in relatively clay and dense sand, a new approach is needed. The pile is designed to transfer whole super structural load to soil. The pile cap is designed to transfer the super structural load to piles. Thus the pile cap does not transfer any load to soil, hence more number of piles are required, which may lead to extra cost. Thus the concept of piled raft system has evolved. Such foundations make use of both piles and raft.

Artificial intelligence (AI) techniques are quick tools in solving engineering problems. AI techniques are receiving wide popularity in geotechnical engineering due to its superior predictive ability than traditional methods. AI are data driven models to determine the parameters that govern the phenomenon with less assumptions about the behavior of system. AI is a combination of math, algorithm and creativity and it consists of several techniques such as Artificial Neural Network (ANN), Genetic Algorithm (GA), Evolutionary Polynomial Regression (EPR), Support Vector Machines (SVM), Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO). Artificial intelligence techniques are receiving wide applicability in various disciplines. It mainly aims to solve real time problems in construction industry. Optimization is a mathematical technique for finding a maximum or minimum value of a function consisting of several variables subject to a set of constraints. The design of piled raft foundation involves great range of independent variables such as the number of piles, length of piles, diameter of piles pile spacing ratio, location of piles, stiffness of piles, distribution of load, level of load, raft thickness, raft dimensions, type and stiffness of soil. Therefore, the study of effect of parameters are essential for increasing the efficiency of piled raft foundation and decreasing construction cost.

II. PILED RAFT

Piled raft foundations are proven as an effective foundation system for tall buildings. These are the composite structures which consist of three elements such as piles, raft and the subsoil. Applied loads are transferred to the subsoil both through the raft as well as the piles. Load sharing between raft and piles is the main peculiar feature that diversifies this type of foundation from other type of piled foundations design. In a piled raft foundation, the total load of the superstructure is partly carried out by piles through skin friction. The remaining load is taken by raft through contact with the soil. Its behavior is determined by complex soil–structure interactions between the elements of the foundation and the subsoil.

Piled raft foundation is assumed to have four kinds of interactions. These interactions are pile-pile (P-P), pile-raft (P-R), pile-soil (P-S) and raft-soil (R-S). The (S–P) interaction is mainly governed by the pile installation procedure that is adopted. The (S–R) interaction depends on the relative stiffness of the raft–soil. The (P–R) and (P–P) interactions depend on the number of piles, on their spacing and on the piled raft geometry such as raft dimensions, pile length and diameter. The P–R and P–P interactions modify the load–bearing behaviour of each foundation component, compared to an analogous isolated element. Thus the optimization of piled raft satisfying the interactions are essential. As compared to pile foundation, piled raft has a major advantage of reduction in number of piles, thereby reducing cost and time of work. Piled raft foundations provide an economical foundation, where the performance of the raft alone does not satisfy the design requirements. Thus, the addition of a limited number of piles may improve the ultimate load capacity, the differential settlement and the required thickness of the raft.

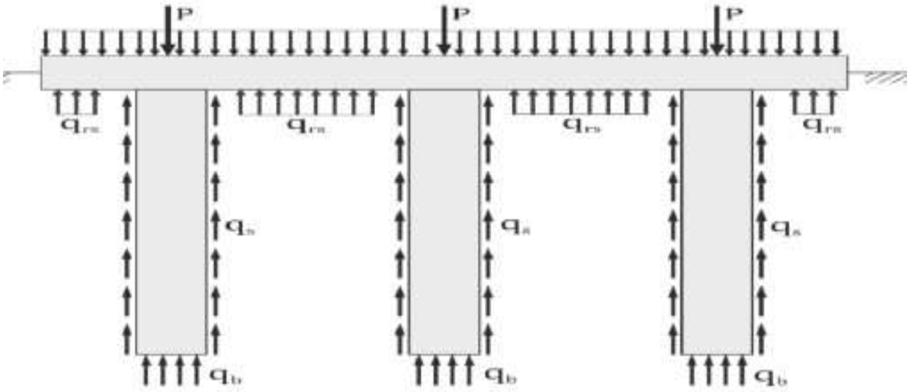

Fig.1 Simplified load transfer mechanism of piled raft foundations.

(Source: Nurullah, 2013)

III. OPTIMIZATION OF PILED RAFT

Optimal design of piled-raft foundations could significantly help minimize their construction costs. Controlling the most influencing variables on the design of piled raft in an acceptable cost, is a great challenge for designers. The interactions within the pile-soil-raft system should be analyzed and the parameters should be selected accordingly. The optimal design of piled-raft foundations includes the selection of type, number, configuration and penetration depth of the piles in addition to the thickness of the raft in conformance with the existing design and construction standards. Several factors influence the design of piled-raft foundations including the structural loads, the properties of foundation soil and the negative skin friction on piles associated with long-term settlements of a foundation underlain by soft ground.

Different models are developed to optimize the design of piled raft foundations. Main objectives of these models are to minimize cost or differential settlement. Piled rafts are provided with the aim of reducing excessive settlements. Settlements of piled raft are influenced by various mechanical properties and geometry of a piled raft foundation such as length, diameter, number, spacing, arrangement, location, aspect ratio of pile and raft thickness.

3.1 EFFECT OF PILE LENGTH

Piled raft foundation have been widely used in controlling differential settlement. In situations where settlements are large, it leads to increase in pile length and economy of foundation. Thus the study on effect of pile length is significant.

Shrestha et. al [14] conducted research work to develop design optimization procedure for piled-raft foundation to support a 130 m tall wind turbine in a clayey soil with mean undrained cohesion of 100 kPa subjected to mean wind speed of 125 mph. Wind speed (V) and undrained cohesion (c_u) are considered as the random variables. The length of piles (L_p), number of piles (N_p) and radius of raft (R_r) were selected as design variables and differential settlement of piled-raft as response. They conducted parametric study to determine the effect of variation in loading and soil properties on design outcome. Figure 2 shows that L_p, N_p and R_r decrease with increasing c_u. R_r remained same after the minimum requirement based on bottom diameter of the tower.

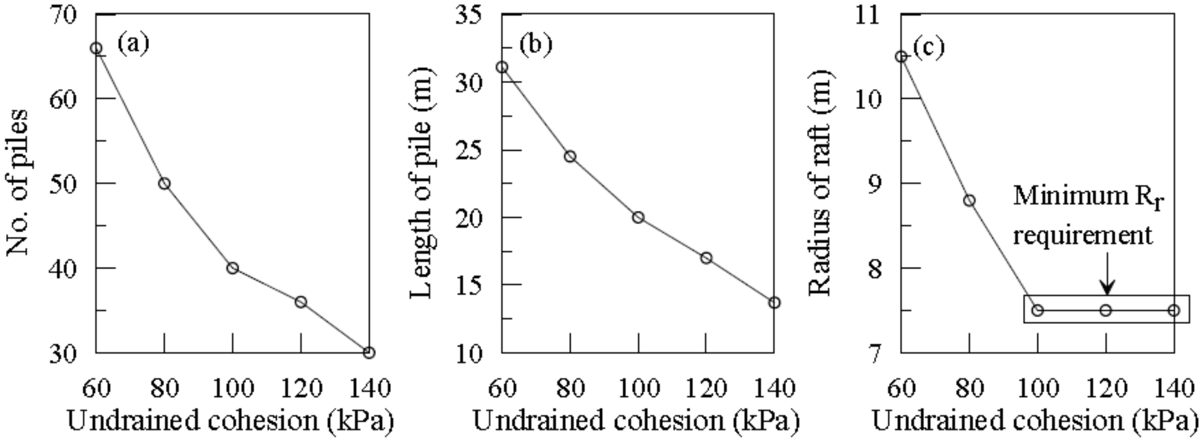

Fig.2 Effect of variation in undrained cohesion on (a) number of piles, (b) length of pile and (c) radius of raft

(Source: Shrestha et. al, 2017)

Figure 3 shows that N_p, L_p and R_r increase with increasing wind speed. The radius of the raft for the lower three wind speeds remained same based on the minimum requirement of bottom diameter of tower.

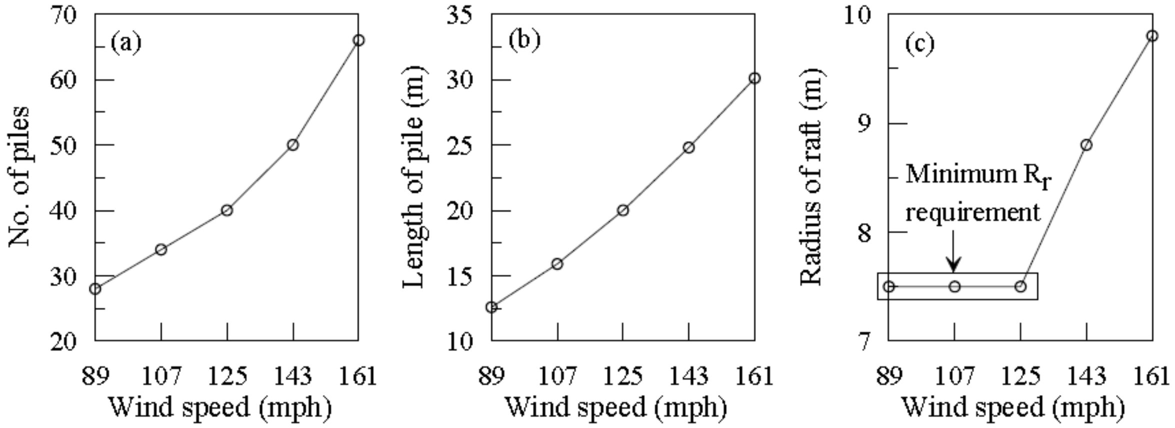

Fig.3 Effect of variation in wind speed on (a) number of piles, (b) length of pile and (c) radius of raft
(Source: Shrestha et. al, 2017)

The design requirements incorporated checks for the vertical load capacity, bending moment capacity, horizontal load capacity, total and differential settlements and the rotation of the tower. Several design sets for L_p, N_p and R_r were selected and the corresponding differential settlements were determined for variation in random variables. Regression analysis was performed to establish a response function in terms of S_{diff}, V, c_u, L_p, N_p and R_r as shown in equation 3.1. The coefficient of determination R^2 value obtained from the regression analysis was 0.91.

$$S_{diff} = \exp(19.74+3.74\ln(V)-1.87\ln(c_u)-3.04\ln(L_p)-3.66\ln(N_p)-1.28(R_r)) \qquad (3.1)$$

Design optimization was conducted using Genetic Algorithm considering the total cost of foundation and the standard deviation of the differential settlement as objectives. The Pareto front is a graphical representation of the preferred designs resulting from optimization procedure. The most optimal design was found out using Knee point concept from Pareto front. It was observed that the standard deviation of differential settlement increased from about 4.5 mm to 7.5 mm while the total cost of foundation decreased from about \$420,000 to \$360,000. The boundary line (AB) is created by connecting two extreme points in Pareto front and distance of each point in Pareto front from the boundary line is calculated. Then the point on the Pareto front with the maximum distance from the boundary line is identified, which called knee point. Optimum cost and standard deviation of response corresponding to the knee point were used to determine the optimum design. The results obtained for the optimum length of pile, number of pile and radius of raft were found to be 30.4 m, 52, and 8.01 m respectively and the optimum cost was found to be \$386,580.

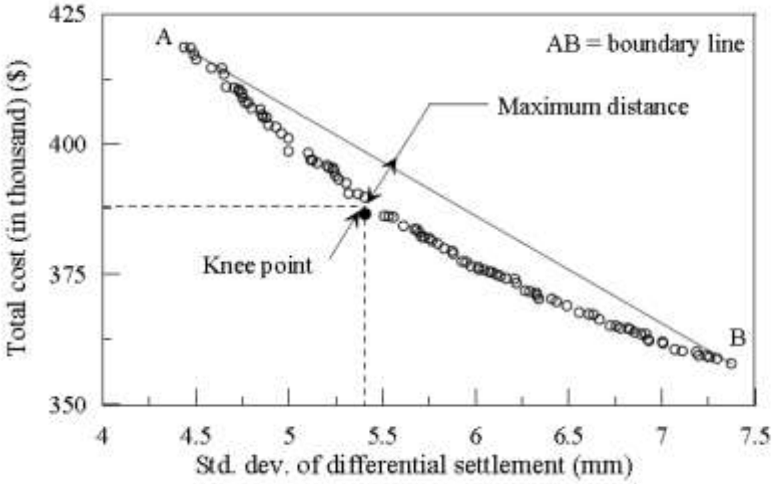

Fig.4 Pareto front optimized to both total cost and standard deviation
(Source: Shrestha et. al, 2017)

Nakanishi and Takewaki [6] presented an optimal method for determining pile length of piled raft foundations. Cost of installation of piled raft was assumed to be proportional to pile length. They considered objective function to minimize total pile length under settlement constraint. An extended sequential linear programming technique combined with an adaptive step-length algorithm of pile lengths has been adopted to solve the optimal design problem. The method incorporated raft-pile-soil interaction within an acceptable accuracy. The modelling of piled raft was carried out by Grid beam-spring model which is a hybrid model using finite element analysis. They analyzed an actual building having target settlement 30 mm, pile diameter 800 mm, the pile length 10m and 6 number of piles at one place. Three optimizations were used: (1) pile-by-pile optimization, (2) the same pile grouping as the actual one and (3) the pile grouping for 45-degree direction following the actual design. The total pile length and number of piles shortened after optimization.

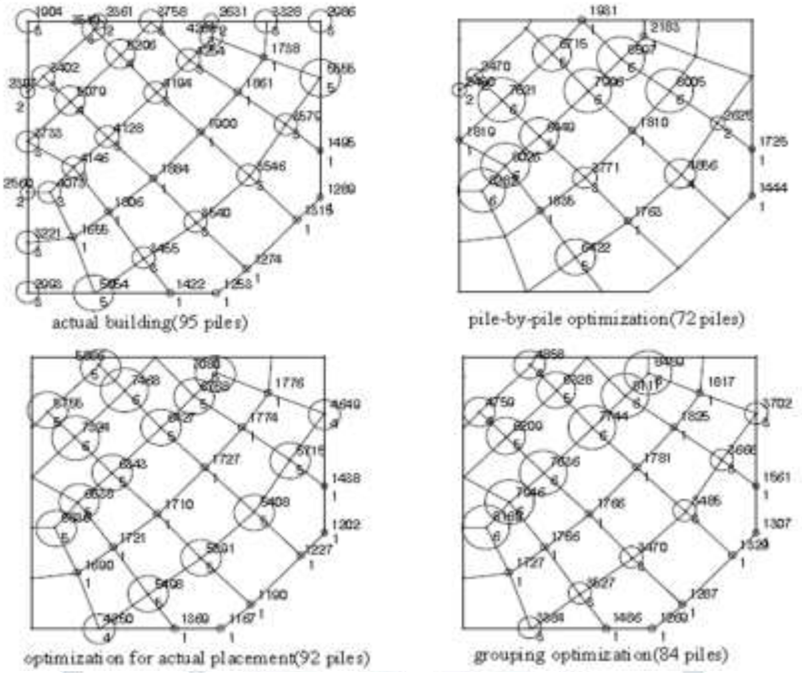

Fig.5 Optimal placement for high-rise building (upper: pile force(KN), lower: number of piles)
(Source: Nakanishi and Takewaki, 2013)

Leung et. al [8] studied the pile length optimization analysis of piled raft and pile groups in terms of average stiffness and differential settlements. The objective function was to maximize the overall stiffness and to minimize the differential settlements. Row variation (RV), piles having equal length arranged in rows and square variation (SV), equal length piles are arranged in square pattern, were considered to describe pile length layout is shown in figure.

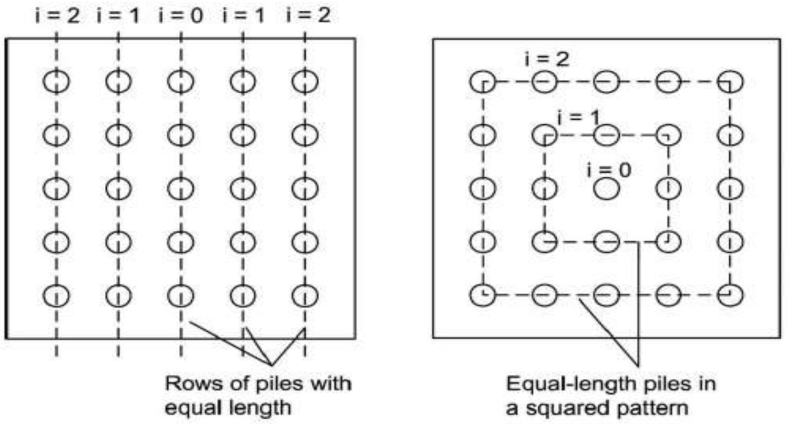

Fig.6 Pile length variation in a 5x5 pile group: plan views of (a) RV and (b) SV
(Source: Leung et. al, 2010)

In this study homogeneous soil conditions were assumed. For row variation pattern, the optimized configuration consists of longest piles at the periphery, while for the SV pattern the optimized configuration has the longest piles between the center and peripheral piles. They found that benefits of optimization increases with increasing Ep /Es ratio and decreasing pile spacing. The effect of pile group geometries like size of pile group and average pile slenderness ratios in optimization was studied. They focused in the optimization of piled raft with objective of reducing differential settlements. Settlements of a piled raft with uniform pile lengths are compared with those of an optimized configuration. They found that for most foundations designed with a FS between 2 and 3, differential settlements can be reduced through variation of pile lengths. Thus with the same consumption of total pile material, the overall foundation behavior can be enhanced by varying pile lengths across the pile group or piled raft. Depending on the degree of soil inhomogeneity, the exact length distribution of the optimized configuration can vary.

Rameez and Roshni [13] investigated the effects of pile length on piled raft foundations. In this work, piles were modeled as spring and raft as beam on elastic foundation. Raft-soil-raft interaction were taken into account. The effect of length and diameter on various parameters were evaluated. The results revealed that settlement of raft as well as pile decreases with increase in pile length. When the length of pile increased from 20m to 25m, the settlement showed reduction from 9.7mm to 5.8 mm, the load taken by the piles increased from 164082.3 kN to 217586.8 kN and load taken by the raft decreased from 313816.1 kN to 260311.7 kN. For lateral load, the percentage load taken by the raft decreased with increase in pile length. Increase in length of pile resulted in increase of load taken by piles.

Ghasemian et. al [2] evaluated the influence of structural and dimensional changes of pile and raft system in the bearing capacity of the piled raft foundation and soil settlement. Width and height of the raft and modulus of elasticity of concrete were considered as variable. The piled raft foundations were analyzed using manual methods and finite element analysis. Then design of piled raft system were done in two phases - Preliminary and detailed design phase. The general specifications of piled raft with undrained clay soil having γ_d = 1800 kg/m^3, γ_d = 1000 kg/m^3, c = 1.25 kg/m^2 and v = 0.2 were used. Piles and shallow foundations with w = 2500 kg/m^3 and v = 0.2 were modeled. From analyzing the effect of pile length on pile bearing it was found that increase in length of the pile increases the pile bearing. They found that effect of pile length increases in higher loads and a tiny proportion of the load was transferred to Raft. This increase is effective for a certain length of pile and increase it over the limit for the pile length has not effect on the percentage of piles bearing.

The review showed that optimized pile length reduces the differential settlements and cost of installation of piles. Increase in length of the pile increases the pile bearing. This increase is effective for a certain length of pile and increase it over the limit for the pile length has not effect on the percentage of piles bearing.

3.2 EFFECT OF PILE DIAMETER

The effect of changing pile diameter on piled raft characteristics have been studied. Garg et. al[11] conducted a parametric study taking space of pile to diameter ratio, settlement or differential settlement as variables. PLAXIS 3D foundation finite element program was used to evaluate the ultimate vertical load of a piled raft. Clayey soil was considered for evaluation and parametric study. Findings showed that increase in the diameter of the piles enhances the load carrying capacity of the piled-raft system. Change in the diameter of pile increases the capacity between 15 to 20%. The effect of diameter on various parameters of piled raft foundations was evaluated by Rameez and Roshni [13]. It was observed that settlement of raft as well as pile and the percentage of load taken by the raft decreased with increase in pile diameter, whereas the load taken by piles increased with increase in pile diameter. When the diameter of pile increased from 0.6m to 0.7m, the load taken by the piles is found to have increased from 228335.8 kN to 258932.9 kN and load taken by raft reduced from 249562.7 kN to 218965.6 kN.

Wei [16] et. al developed an optimization model to minimize the pile diameter with minimum differential settling of the foundation using genetic algorithm. The minimum volume corresponding to minimum settlement was analyzed to understand the minimum cost optimized profile. The implementation of pile diameter optimization model was illustrated with a 3 x 3 m piled raft foundation in uniform soil. Settlement of the foundation before and after optimization, with the reference to pile load distribution, raft bearing ratio, shear and bending moment of the raft was conducted. The influences of raft thickness, pile length, elastic modulus of pile and Poisson ratio of soil on pile diameter are studied by parameter analysis. The results showed that diameter of center pile, side pile is reduced and the radius of the corner pile is increased with increase in plank thickness but the magnitude of the change is very small. With increasing length of the pile, optimal pile diameter changed. They observed that radius of corner pile increased and radius of the center pile is reduced with slight increase in the radius of the pile side. The degree of influence of the modulus of the soil is greater than the degree of influence of Poisson's ratio. When the modulus of the soil increased, and a radius of the pile corner and side becomes larger whereas the center of the pile radius decreased. As the Poisson ration increased, radius of corner pile and side pile reduced and radius of center founded pile increased.

Table 1 Optimized pile diameter of piled raft foundation for different pile length

Pile length/m	Optimal pile diameter/m		
	Corner pile	Side pile	Corner pile
10	0.0001	0.2637	0.7476
20	0.0995	0.2611	0.7245
30	0.1621	0.2960	0.5724
50	0.2257	0.3189	0.4155

(Source: Wang et.al, 2015)

The results showed that settlement of the raft as well as pile reduced with increase in pile diameter. Also, the percentage load taken by the raft decreases and load taken by pile increases with increase in pile diameter.

3.3 EFFECT OF PILE ARRANGEMENT

The feasibility of optimal pile arrangement in reducing total and differential settlement is studied and reported. Kim et. al [7] presented an optimization method to minimize the differential settlement of piled raft foundation using optimal pile arrangement scheme. The recursive quadratic programming was adopted for optimization. The optimization was performed with respect to the locations of piles. The objective function selected was the indirect measure of differential settlement. The stiffness of piles was evaluated by the approximate analytical method considering interactions between piles through soil. The validity of proposed model was checked using three examples. It was observed that the differential settlements and bending moments of the raft reduced through optimized pile arrangement. Maximum differential settlement and average bending moment of the raft was found to be reduced by 90% and 50% when subjected to uniformly distributed load, 83% and 60% for line loads, 78% and 43% for concentrated loads.

Nguyen et. al [4] investigated the effects of changing the parameters of the piles and raft on settlements and induced bending moments of the raft. Centrifuge tests were performed with two piled raft models, one model with a uniform pile arrangement and the other with a concentrated pile arrangement and results are compared with PLAXIS 3D. The results showed that the concentrated pile arrangement with the number of piles corresponding to the column load ratio produces the best efficiency in reducing the total and differential settlements and induced bending moments.

Table 2 Maximum differential settlement and average settlement of the raft

	Initial arrangement (mm)		Optimal arrangement (mm)		Reduction ratio in differential settlement (%)
	Differential	Average	Differential	Average	
Example 1 (uniformly distributed load)	3.2	16.5	0.2	17.0	94
Example 2 (line loads)	13.2	17.0	2.2	20.6	83
Example 3 (four concentrated loads)	14.9	16.7	3.3	18.9	78

(Source: Kim et. al,2001)

Randolph [12] reported that differential settlements could be reduced effectively by placing several piles around the center of a raft. Horikoshi and Randolph [4] verified the above concept with a centrifuge model test and an extensive parametric study. The study revealed that optimal pile arrangement considerably reduces the differential settlement of piled raft foundation.

3.4 EFFECT OF PILE SPACING

Suro et. al [15] determined the optimum pile spacing of short piled raft foundation system by trial and error and by using finite element method program for simulation. Then results were compared to select the pile spacing that produced the minimum settlement. In this scenario, peat with the layer thickness of 3.5 m, constant ground water level, consolidated drained and static load was only considered. Thickness of concrete slab, length and diameter of pile was assumed to be constant. Plaxis 3D Foundation was used for the study for finite element program. Short Piled Raft foundation system with the size of 7.0 m x 7.0 m was considered as a model simulation. Concrete slab was set as 0.15 m thickness and point load varied from 0 kN to 100 kN with increment of 20kN were considered as a static load, acted on the center of the concrete slab. Piles spacing varied from 0.50 m, 0.75 m, 1.00 m, 1.50 m, 2.00 m and 3.00 m were considered. Optimization was done by comparing each numerical result of simulations. The optimum pile spacing was found to be 1.00 m which produced minimum settlement of 30.11 mm under the load of 100 kN.

Table 3 Results of Simulation for each Pile Spacing.

Pile Spacing (m)	Settlement (mm)					
	0 (KN)	20 (KN)	40 (KN)	60 (KN)	80 (KN)	100 (KN)
0.50	30.52	32.20	33.88	35.56	37.23	38.91
0.75	22.41	24.28	26.16	28.03	29.91	31.78
1.00	19.94	21.97	24.01	26.04	28.08	30.11
1.50	19.58	21.97	24.36	26.76	29.22	31.80
2.00	21.28	23.97	26.80	29.73	32.65	35.57
3.00	25.94	29.69	33.43	37.19	40.95	44.74

(Source: Suro et. al, 2015)

3.5 EFFECT OF NUMBER OF PILES

Increasing the number of piles not always brings the best performance. Thus, with an optimum number, the system will be more efficient. Increasing number beyond an optimum number does not always generate a big difference [10]. Garg et. al [11] conducted parametric study by taking number of pile as a variable. They observed that minimum number of piles may be adopted as per permissible settlement or differential settlement for optimal design in clayey soil. According to Nguyen et. al [4] it was observed that increasing the number of piles brings some benefits in reducing the settlements of the raft but it does not satisfy the economical design.

Sales et. al [9] presented an original foundation project with 25 piles, considering an imposed maximum settlement of 10 mm and a classical pile foundation approach. Results concluded that three-pile raft alternative would represent an economy of about 35% if compared with the total cost of the original 25-pile raft project or a cost reduction of 20% if compared with the 13-pile raft alternative. Thus with optimal number of piles, the total concrete volumes including piles and the raft and minimal cost can be achieved.

3.6 EFFECT OF LOCATION OF PILES

Sales et. al [9] analyzed the branch and bound optimization method to obtain the lower cost design. The results showed that position of the piles are strongly dependent on the load distribution. Edge piles were found to be more efficient in achieving the imposed constraint for uniformly distributed load was over the entire raft. Similarly, central piles are observed as more efficient for concentrated central loads.

3.7 EFFECT OF ASPECT RATIO OF PILE

Garg et. al [11] conducted parametric study on aspect ratio of pile. Aspect-ratio (l/d) of pile was varied by keeping the spacing of piles in the foundation system as a constant parameter at optimum value of five times the pile diameter. Total settlement was found be reduced up to 90% with increase of pile aspect ratio. The optimum l/d ratio of 30 was observed at lower settlement. The results showed that load carrying capacity of the piled-raft foundation system increased with pile aspect ratio. It increased by 70% when l/d ratio varied from 10 to 60. Percentage of load shared between the piles and raft component of the system was found to be increased between 50 to 650% with increase in l/d ratio from 10 to 60. The load carrying capacity of piled-raft increased, up to spacing ratio (s/d) of 5 and with raft thickness up to a limit and beyond it raft thickness does not have any appreciable effect on its carrying capacity. Ghasemian et. al [2] studied the effect of pile length to diameter ratio. They concluded that pile length to diameter ratio was not an appropriate factor to determine the percentage bearing of piles and raft.

3.8 EFFECT OF RAFT THICKNESS

Sales et. al [9] presented an optimization procedure to determine the best raft thickness, number of piles. The branch and bound optimization method was combined with a specific computational programme called Geotechnical Analysis of Raft with Piles program (GARP) for piled raft analysis. The overall foundation cost was selected as objective function and maximum absolute and differential settlements as design constraints. Applied pile load was considered to be uniformly distributed over the corresponding raft element. The optimization on a raft with up to nine piles, subjected to three different load scenarios, but with the same total vertical value was analyzed. They observed that increase in raft thickness was efficient in reducing differential settlement up to a certain point.

Nguyen et. al [4] studied the effect of raft thickness in differential settlement. They found that increasing the raft thickness considerably reduces the total and differential settlements but increases the induced bending moments. There is an upper limit for raft thickness that minimizes the differential settlement. Garg et. al [11] conducted parametric study with thickness of raft as variable. Differential settlement reduced with the increase in raft thickness and optimum thickness is found as 2.3 to 2.5 times the thickness required safeguarding against punching shear. Ghasemian et. al [2] made comparison between different states of piled raft system given the thickness variations. The effect of raft thickness on pile bearing was analyzed and found that the thickness of raft does not have significant effect on load carried by the pile. They concluded that raft can bear up to 85% load.

Yazdani et.al [3] conducted ACO algorithm to minimize the volume of the foundation by taking the number, configuration and penetration depth of the piles, as well as the thickness of the raft as design variables. The side and tip forces of the piles, the pressure applied on the underlying soil and the total and differential movements of the foundation under the serviceability limit state are the constraints adopted for the optimization problem. The piles were assumed to be drilled piles, where the pile capacity is provided by a combination of soil-pile friction and end bearing resistance at the pile tip. The underlying soil was assumed to be a homogenous, dry medium dense sand. The soil-pile interactions were taken into account. The optimization task was carried out using a mutual communication between MATLAB and OpenSees (Open Source for Earthquake Engineering Simulation. OpenSees results were imported in MATLAB to evaluate the objective function, fitness value and penalties corresponding to each solution. They considered 20 x 20m high rise building for evaluation. They found out that settlement-reducing piles are required to control the building settlements and to reduce the bending moments in the raft. The optimization was conducted and results showed that including the soil nonlinearity in the analysis results in a 5% more economical design. The 5% reduction in the volume of the raft was proved to be significant for the construction of the foundation. The review showed that with optimal raft thickness, the differential settlement can be minimized. The load carrying capacity of piled raft increased with raft thickness up to a limit and beyond it raft thickness does not have any appreciable effect on its carrying capacity.

IV. CONCLUSION

Piled raft foundations are geotechnical composite construction that combines the bearing effect of raft and piles by taking into account the soil-structure interactions. Optimization of piled raft aims to reduce the cost and differential settlement of foundation. In this report, a review on various investigations about design optimization of piled raft is presented. The optimal design of piled raft foundations depends on various parameters which includes length, diameter, spacing, arrangement, location of piles, differential settlement, raft thickness etc. The analysis showed that differential settlement reduces with increase in pile diameter, aspect ratio of pile, raft thickness, optimized pile length, arrangement, spacing, number of piles and location. Optimized pile length reduces the differential settlements and cost of installation of piles. Settlement of the raft as well as pile reduced with increase in pile diameter. It was observed that the differential settlements and bending moments of the raft reduced through optimized pile arrangement. Minimal settlement is achieved by optimal pile spacing of piled raft, increase or decrease beyond that value results increase in settlements. With an optimum number of piles, the system will be more efficient, increasing number beyond an optimum number does not always generate a big difference. Load carrying capacity of the piled-raft foundation system is found to have increased and total settlement is found to have reduced with increase in pile aspect ratio. Increase in raft thickness was found to be efficient in reducing differential settlement up to a certain point.

REFERENCES

[1] Dang Dinh Chung Nguyen, Dong-Soo Kim and Seong Bae Jo. 2014. Parametric study for optimal design of large piled raft foundations on sand, Computers and Geotechnics, 55, 14–26.

[2] Ghasemian Langroudi A., Panjalizadeh Marseh B., Heidarpour B., Ekramirad A and Hosseinnezhad A. 2015. Dimensional Optimization of Piled Raft Foundation, International Science Congress Association, 4, 28- 31

[3] Hessam Yazdani, Kianoosh Hatami & Elahe Khosravi 2013. Ant Colony Optimization Method for Design of Piled-Raft Foundations, Journal of deep foundations institute, 7, 17- 27.

[4] Horikoshi K and Randolph M. F. 1996. Centrifuge modeling of piled raft foundation on clay, Geotechnique, 46, 741–52.

[5] Horikoshi K and Randolph M. F. 1998. A contribution to optimum design of piled rafts, Geotechnique, 48, 301–17.

[6] Keiji Nakanishi and Izuru Takewaki 2013. Optimum pile arrangement in piled raft foundation by using simplified settlement analysis and adaptive step length algorithm, Geomechanics and engineering, 5, 519- 540.

[7] Kyung Nam Kim, Su Hyung Lee, Ki Seok Kim, Choong-Ki Chung, Myoung Mo Kim and Hae Sung Lee 2001. Optimal pile arrangement for minimizing differential settlements in piled raft foundations, Computers and Geotechnics, 28, 235–253.

[8] Leung Y.F., Klar A. and Soga K. 2010. Theoretical Study on Pile Length Optimization of Pile Groups and Piled Rafts, Journal of geotechnical and geoenvironmental engineering, 136, 319–330.

[9] Mauricio M. Sales, Bruno S. Lima, Sylvia Regina M. Almeida and Marcio M. Farias 2014. Automatic optimization of piled raft design based on branch and bound method, The structural design of tall and special buildings, 1-15.

[10] Poulos H. G. 2001. Piled raft foundations: design and applications, Geotechnique, 51, 95-113.

[11] Prashant Garg, Harvinder Singh, Jagadanand Jha (2013), Optimisation of piled-raft foundation, UKIERI Concrete Congress - Innovations in Concrete Construction, 1724-1735.

[12] Rameez Gahlot, Roshni J John 2015. Effect of Varying Length and Diameter of Pile in Pile Raft Foundation, International Journal of Emerging Technology and Advanced Engineering, 5, 127-133.

[13] Randolph M. F. 1994. Design methods for pile groups and piled rafts, Soil Mechanics and Foundation Engineering, 5, 61–82.

[14] Shweta Shrestha, Nadarajah Ravichandran and Parishad Rahbari 2017. Design optimization of piled raft foundation for tall wind turbine on clayey soil, Geo Risk, 403-412.

[15] Suro S. M., Bakar I. and Sulaeman A. 2016. Pile Spacing Optimization of Short Piled Raft Foundation System for Obtaining Minimum Settlement on Peat, Materials Science and Engineering, 136, 1-7.

[16] Weing Wei, Yang Min and Shanggguan Shi-qing 2015. Pile raft foundation pile by differential settlement of the path optimization analysis, Rock and soil Mechanics, 36, 178- 184.