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Effect of Pile Spacing in the Behaviour of Pile Groups

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Abstract
Bridges are the most important structure that needs to be constructed to provide passage over an obstacle in a highway project. Most of the bridges that are being built in highway projects in Nepal have a pile foundation. Piles are seldom used as a single pile, it is mostly used as pile groups. Hence, the study of pile groups is important for the proper design and construction of pile foundation. This study attempts to study the behaviour of pile groups subjected to a vertical load by numerical modelling for a soil type of Nepal. The effect of pile spacing has been considered in this study. The study is conducted by developing a model in a software based on finite element method, Plaxis-3D V21. The soil has been modelled as a Mohr-Coloumb model, the pile and the pile cap as embedded beam and plate element respectively. A gap has been maintained between the pile cap and the ground level so that the system behaves as a piled group rather than as a piled raft and the load is transferred only to the piles and not the underlying soil. The created model is then subjected to a vertical load and the study of behaviour of the pile group foundation was conducted by varying pile spacing.

Keywords
Pile spacing, axial load distribution, pile groups, Plaxis-3D

1. Introduction

The most important infrastructure for a developing country like Nepal is transportation which for the most part refers to construction of highways. For a country having differing geographical features in a short stretch, bridges are required to be constructed in various parts to provide a passage over the obstruction. The bridge should fulfil both structural and functional requirements. In order to fulfill these requirements, the foundation of a bridge should be strong enough to bear the loads during its design life and also its settlement should be within the permissible limits. Hence, most of the bridges in Nepal where shallow foundation is unsuitable are being constructed under pile foundation which enables the loads to be transferred to the deeper stratum while maintaining the settlement within the permissible limits.

The history of pile foundations dates back centuries, with evidence of their use in ancient structures such as the Roman bridges. The use of piles is man's oldest method of overcoming the difficulties of foundation on soft soil [1]. Early pile systems were simple, wooden piles driven into the ground. Over time, the construction methods, materials, and design techniques evolved, leading to the development of modern pile foundation systems. This section traces the historical evolution of pile foundations, highlighting key milestones and innovations that have shaped their current state.

A pile can be referred as a slender structural member of timber, steel or concrete that is used to transmit loads to a deeper stratum in the soil mass either through skin friction along the shaft or by end bearing at its tip or both. However, a lateral load is transferred by means of a horizontal subgrade reaction developed at the upper part of the pile. Piles are usually constructed in Nepal by excavating a hole in the ground, placing the reinforcements and then filling it with concrete. Such type of pile is bored cast in-situ pile.

Pile foundations are recommended to be used in the following situations:

- The soil conditions at the surface is poor leading to weak ground conditions.
- When the structure is required to resist lateral loads along with horizontal loads.
- When the structures are subjected to uplift as in offshore structures.
- In bridge abutments and piers where there is a threat of scouring.
- To control the settlements when the structures are to be built up in an expansive or collapsible soil.
- To reduce differential settlements in a structure whose plan is irregular relative to its outline and load distribution.

Piles are seldom used as single piles but rather employed as groups to transfer the load of the structure to the underlying soil. Pile groups are used when the loads imposed by the superstructure are too high for a single pile to support or when the soil conditions are such that individual piles may not be adequate. Here are some key points about pile groups:

i) Load Distribution: The primary purpose of a pile group is to distribute the structural loads from the superstructure evenly to a group of piles. By doing so, the pile group reduces the pressure on the underlying soil and prevents excessive settlement.

ii) Types of Pile Groups: There are different configurations of pile groups, including square, rectangular, circular, and irregular shapes. The choice of pile group layout depends on factors such as the building's design, load distribution, and soil conditions.

iii) Pile Caps: Pile groups are often supported by a reinforced concrete cap or pile cap. The pile cap acts as a rigid foundation slab that sits on top of the piles and transfers the load from the superstructure to the individual piles within the group.

iv) Design Considerations: The design of pile groups involves considerations such as the magnitude and distribution of the loads, the type and properties of the piles, the soil characteristics, and the spacing between the piles. Engineers use various methods and software tools to design effective and efficient pile groups.

v) Settlement Control: One of the key advantages of pile groups is their ability to control settlement. By distributing the load over multiple piles and a larger area of soil, pile groups help limit differential settlement, which can cause structural damage.

vi) Cost and Efficiency: Pile groups can be more cost-effective than using a larger number of individual piles because they reduce the number of pile caps and simplify construction.

Pile foundation consists of a number of piles together in a group with a proper spacing and arrangement. However, during the construction of piles, the test is conducted only on a single pile which actually does not represent the working of a pile group. Also, the Chure region of Nepal consists of alternate layers of sandstone and claystone along with small quantity of silt. Most of the researches that have been conducted in a pile group are conducted in a homogeneous soil consisting of either cohesive or cohesionless soils which does not represent the actual site conditions of Nepal. For the safe and economic design of pile foundation, it is important to understand the influence of various design parameters in the actual soil conditions. Therefore, an analysis based on numerical modelling is done to understand the influence of pile spacing in the behaviour of a pile group for the given site conditions.

The area of study is the Somnath Khola major bridge in Narayanghat-Butwal Road Project. The bridge site is located at a chainage of 90+770.

2. Literature Review

In recent times, numerous past studies have been conducted to examine and comprehend the behaviors of individual piles, groups of piles, and pile raft foundations when subjected to vertical and lateral loads. Additionally, these studies have focused on evaluating their performance under static and seismic conditions.

O'Neill (1983) found that in loose sand, the efficiency of a pile group in compression is always greater than 1, and the highest efficiency occurs when the center-to-center pile spacing is 2 times the pile diameter. The efficiency of a pile group also increases with the number of piles in the group. In dense sand, the efficiency of a pile group can be either greater or less than 1, but it is generally greater than 1. O'Neill attributed the lower efficiency in dense sand to dilatancy, which is a phenomenon that occurs when sand grains are sheared and expand. This expansion can reduce the effective stress on the piles, which can lead to a lower efficiency [2].

Comodromos et al. (2003) performed a retrospective analysis of a pile load test to explore the connection between pile arrangement and load settlement dynamics within various pile group layouts. Their findings indicated that decreasing the spacing between piles led to heightened interaction between them, resulting in reduced individual pile stiffness [3].

Mandolini et al. (2005) investigated the response of pile groups under vertical loads, encompassing settlement, load distribution, and bearing capacity. This examination was conducted through the monitoring of real-world structures and experimental models. The researchers concluded that traditional foundation design methods, commonly employed in practice, were inadequate and required revision for accurate design purposes [4].

Engin et al. (2008) conducted a comprehensive study involving single piles and pile group foundations using an embedded pile row. Their investigations demonstrated parallels between the behavior observed in the field test data and the behavior displayed during compression and pullout tests. The influence of pile spacing was identified as a significant factor affecting the load-displacement curve of the pile group, with greater spacing corresponding to an increased load-bearing capacity for the same level of settlement [5].

Lebeau (2008) utilized numerical modeling of a volume pile to assess the impact of skin friction distribution on the behavior of a pile raft foundation. By comparing load-displacement curves from the volume pile and a pile raft foundation simulated under axisymmetric conditions, it was evident that the two curves exhibited reasonable similarity [6]. Moreover, the behavior of a pile group foundation under conditions of soil movement induced by excavation was explored.

Choudhury et al. (2008) analyzed a 4-pile group connected to a pile cap with varying degrees of rigidity using centrifuge model tests. Their conclusions highlighted that a rigid pile cap led to the development of a maximum negative bending moment at the pile head, which exceeded that observed in a flexible cap scenario. Furthermore, the pile group with a flexible cap exhibited greater pile head deflection compared to an analogous group with a rigid cap [7].

Comodromos et al. (2009) undertook an optimization process for a bridge foundation design, integrating experimental data and non-linear 3D analysis. The investigation included the analysis of load distribution concerning settlement and pile length for 2×2 and 3×3 pile group configurations . [8]

Chore et al. (2012) introduced a simplified finite element model to conduct a parametric examination of a pile group subjected to lateral loads. This study encompassed variables like pile spacing, pile diameter, number of piles, and pile arrangement. Notably, their proposed model exhibited reasonable agreement with the results from a 3D finite element analysis. In their work, Chore et al. (2012) utilized the finite element method to conduct a parametric investigation involving two sets of piles experiencing lateral loads. The analysis incorporated the nonlinear behavior of the soil [9].

Sawant and Ladhane (2012) carried out parametric investigations involving pile spacing, pile count, diverse pile arrangements, and soil modulus. They employed a three-dimensional finite element analysis to scrutinize the dynamic response of a pile group [10]. Similarly, they also explored solutions for laterally loaded piles through both three-dimensional finite element analyses and a closed-form expression utilizing the modulus of a subgrade reaction approach. Their study considered various combinations of soil and pile characteristics.

Chore and Siddiqui (2013) utilized the finite element method to analyze a piled raft foundation. Their investigation delved into parametric studies involving soil modulus, raft thickness, and distinct load patterns [11].

Chore (2014) and Dode et al. (2014) harnessed the three-dimensional finite element method to explore the behavior of a single-story building frame situated atop a pile foundation within cohesive soil. They conducted parametric studies regarding variables like pile count, pile diameter, and pile spacing, examining their influence on superstructure responses [12].

Doran and Seckin (2014) investigated the lateral load-carrying capacity of a designed wharf structure, taking into account soil-pile interaction effects under varying soil conditions [13].

In recent times, Fattah et al. (2015) undertook an experimental study focused on comprehending the behavior of a piled raft system across different sandy soil types. Meanwhile, Wu et al. (2015) developed an analytical solution utilizing a nonlinear softening model to elucidate the load transfer mechanism of a singly axially loaded pile [14]. The efficacy of this analytical solution was confirmed through pile load testing.

3. Methodology

This section deals with the materials and the methodology followed to carry out the present study. This study involves the study of pile group behavior by using commercial finite element software Plaxis 3D Version V21. The analysis is carried out from the soil data of the major river bridge along the Narayanghat-Butwal road project. The following are the steps taken to carry out the study:

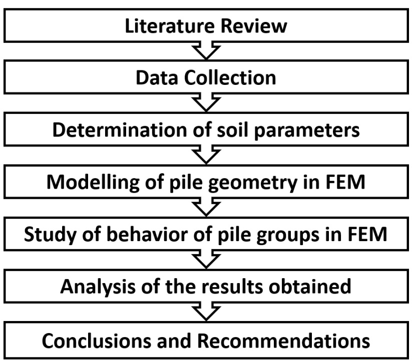

Figure 1: Methodology Flowchart

3.1 Data collection

The data for this work is collected through field investigation and from the laboratory test results of that site.The laboratory tests that were conducted includes natural moisture content, bulk density test, specific gravity test, grain size analysis, Atterberg limits test, direct shear test and unconfined compression test. The soil parameters were then obtained based on the results of these tests.

3.2 Modelling of Pile Geometry

The modelling of the pile geometry was done in a finite element software, Plaxis-3D V21. For the analysis of the model, Mohr-Coulomb model was used as material model. The parameters of the soil required by PLAXIS-3D to carry out calculations based on this model are Young's Modulus of soil, Poisson's ratio of soil, angle of internal friction of soil, cohesion of soil, Dilatancy angle of soil. The model dimensions were chosen such that the models' length, width and depth were 80m, 80m and 50m respectively. It was chosen in the manner so as to optimize the computation time as larger size of the model will increase in calculation time.

After defining the project properties, soil stratigraphy has to be defined. It was done by creating a borehole, adding and assigning respective materials and levels for different soil layers. The ground water table is at the ground surface. The next step is defining the soil and structural elements. The soil layers are defined based on the information obtained from the laboratory test results. The pile is modelled as an embedded beam and the pile cap is modelled as a plate element. The details of the input properties are given in table below.

Table 1: Input Properties of Soil

Layer	Depth (m)	c (kN/m^2)	phi	γ_{sat} (KN/m^3)
1	0-9	65	0	18.1
2	9-12	3.5	33	18.2
3	12-13.5	80	0	18.1
4	13.5-16.5	3.5	33	18.2
5	16.5-18	80	0	18.1
6	Above 18	3	30	18.3

Table 2: Properties of Embedded Beam

γ (KN/m^3)	E (KN/m^2)	L (m)	Dia (m)	v
7	30,000,000	16.5	1	0.15

Table 3: Properties of plate element

γ (KN/m^3)	E (kN/m^2)	Depth (m)	v
25	30,000,000	1.5	0.15

In table 2, the value of unit weight is taken as 7kN/m3 only because this FEM software requires the unit weight of embedded beam to be input after deducting the unit weight of soil mass.

The pile group is modelled as a 3×3 pile group such that there is a gap of 0.1m between the pile cap and the ground level. It is done so that the structure is modelled as a pile group rather than as a pile raft. If the pile cap contacts the ground surface, then there will be transfer of load from the pile cap to the soil beneath leading the pile group to behave as a pile raft. This modelling was preferred so that there will be no transfer of load to the underlying soil via the pile cap and the applied load will be transferred only to the piles in the group from the pile cap.

The boundary conditions are taken such that the bottom boundary is fully fixed, vertical boundaries are horizontally fixed and the top boundary is free.

Then, the mesh is generated in so that there is a balance between accuracy and calculation time. Generating mesh using a very fine mess option provides better accuracy in the result. However, the computation time increases greatly with the increase in fineness of the mesh. So, fine mesh option was selected to generate the mesh and obtain reasonable accuracy for our current study.

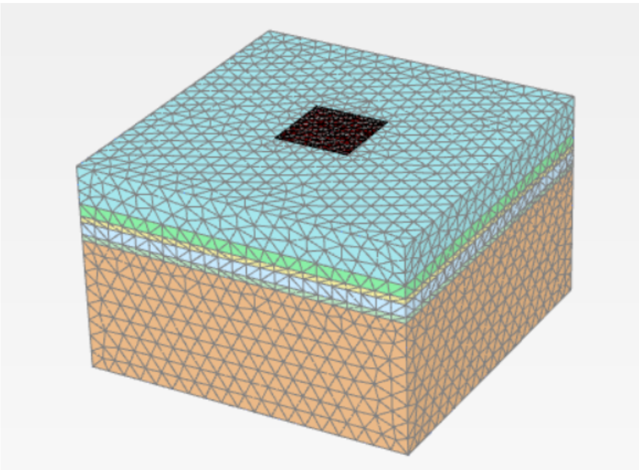

Figure 2: Generated Mesh

The numerical calculation was done from the staged construction tab in the finite element software, Plaxis-3D. In each stage, the soil and structures tab were activated as per the requirement. The first calculation phase was defined automatically as a calculation of the initial stress field for the geometry by the Ko procedure. After initial phase, subsequent calculation phases were defined manually by activating the respective geometry and structure.

To study about the load distribution pattern, a point load of 18000kN was applied at the center of the pile cap. The study was conducted by varying the spacing of the piles in the group and the results of the calculations were obtained from the output program after the calculations were completed.

4. Results

Load is transferred from the pile cap to the group of piles and from the piles to the surrounding soil by skin friction and point bearing at the pile toe. The distribution of the applied load was studied from the output of the numerical modelling. Axial load transfer plots were plotted (for a 3×3 pile group) to determine the effect of spacing on the load distribution pattern for spacing of 3d, 4d, 6d and 8d, where 'd 'refers to the diameter of pile in the group. The axial load transfer behaviour in the corner pile, center pile and the middle pile (pile between the corner piles) have been considered due to the symmetricity of the case. The following figures will help us to understand the load transfer behaviour in piles considering the effect of spacing.

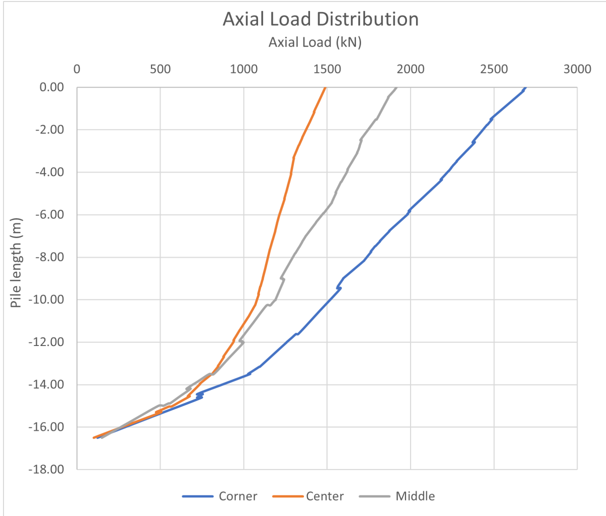

Figure 3: Axial Load Distribution curve for a spacing of 3d

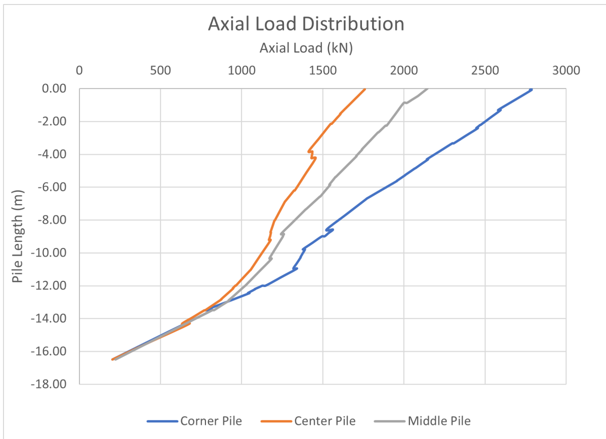

Figure 4: Axial Load Distribution curve for a spacing of 4d

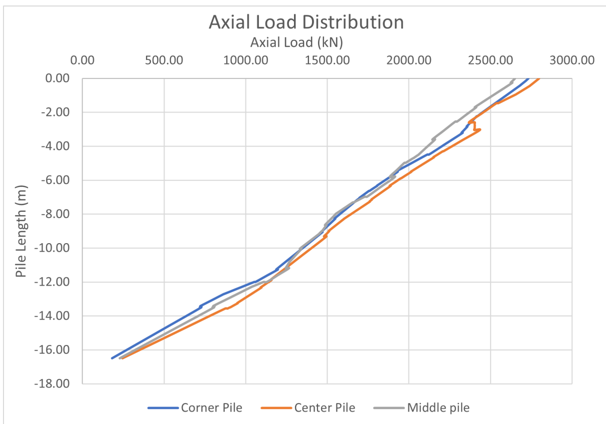

Figure 5: Axial Load Distribution curve for a spacing of 6d

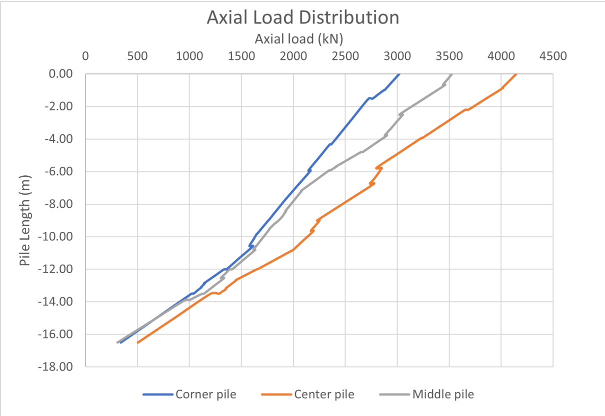

Figure 6: Axial Load Distribution curve for a spacing of 8d

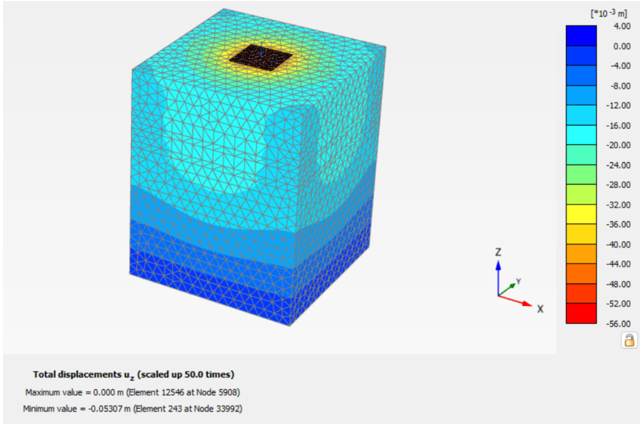

Figure 8: Settlement for a spacing of 4d

It can be seen that for smaller spacing the corner piles carries more load than the center piles (Figure-2). With the increase in spacing, the central pile starts to carry more load than the corner piles. At a spacing of 6d, the load distribution in corner and center pile are almost equal as can be seen in figure-4. For the spacing of 8d, the center pile gets more loaded than the corner pile as in figure-5. The increment in spacing leads to increment in the load to be carried by the center pile while there will be decrement in the load to be carried by the corner pile. Also, it is clear that the axial load decays along the length of the pile.

A study about the settlement of the pile group accounting for the effect of spacing was also done. The following table shows the settlement obtained from the output of finite element modelling for aforementioned spacings.

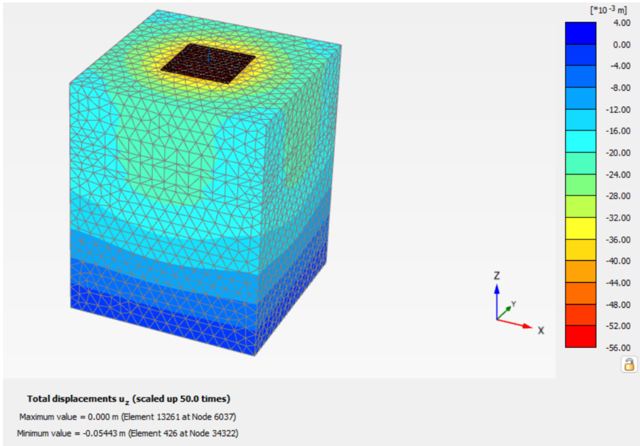

Figure 9: Settlement for a spacing of 6d

Table 4: Settlement obtained for the corresponding spacing

Spacing	Settlement (m)
3d	32
4d	56
6d	54
8d	50

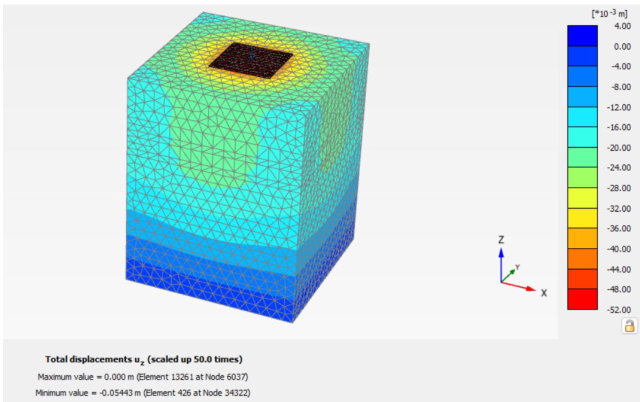

Figure 10: Settlement for a spacing of 8d

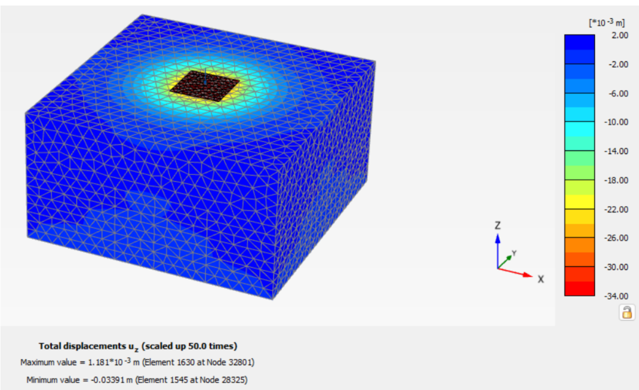

Figure 7: Settlement for a spacing of 3d

It was observed that by increasing the spacing of the piles, the settlement of the pile group first increases up to a spacing of 4d and then it goes on decreasing slightly up to 8d spacing.

5. Conclusion and Recommendation

The load distribution settlement behaviour of a 3×3 pile group for different spacings are analyzed in this paper using Plaxis 3D finite element software. All the geotechnical parameters are assigned with the most realistic values as all the input datas of soil mass were obtained from the laboratory test results. Currently, mostly used type of foundation for a bridge in Nepal is the pile foundation. Hence, the study of pile groups is important for the proper design and construction of pile foundations. The following conclusions were drawn from this study:

i) The corner piles carry a larger proportion of the appiled load than the center pile for smaller spacings. However, as the spacing is increased the proportion of the load carried by the center pile increases.

ii) The load distribution between the piles were almost equal for a spacing of 6d. Increasing the spacing of piles after 6d will increase in the load carried by the center pile as compared to the corner piles.

iii) The least settlement was observed for the spacing of 3d and it increased at a spacing of 4d. The settlement decreases very gradually with increasing spacing after the spacing of 4d.

iv) From the point of view of settlement of pile groups, a spacing of 3d can be considered the optimum spacing for pile groups for this study area.

This paper encompasses the study of 3×3 pile group considering the effect of spacings. Similar studies can be done in the future considering other related parameters as well, and covering wide range of soil conditions.

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