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Application of Numerical Method in Assessing the Variations in Pile Group Efficiency under Different Circumstances

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ABSTRACT

Rapid urbanization creates a demand to expand the cities where using pile foundation became a recurrent practice. To ensure sustainability of projects pile load tests are important but may not be always feasible in terms of costing, on-site constrains etc. In this circumstance numerical analysis is a good alternate to estimate precise pile load capacity rather than conventional conservative approaches. This research illustrates the pile group efficiency fluctuation due to pile diameter, spacing, pile number and orientation in prescribed sandy soils. Using the conventional method the individual pile capacities are calculated for a constant depth with variable diameters and soil profiles. For simulating the piles, geometric models of sandy soils with sufficient boundaries are generated in PLAXIS 3D FOUNDATION software where the parameters of pile and soil components are considered as per predetermined values from reliable references. The analysis results have thoroughly been scrutinized by plotting several graphs at different aspects. The outcomes indicate that the conventional pile spacing i.e. 2.5D to 3.5D has an insignificant effect on pile group efficiency, irrespective to pile diameter and soil type. It also exhibits that the increment of pile number significantly decreases pile group efficiency for diameters of 600mm, 800mm, 1000mm and 1200mm in sandy soils. With a few exceptions as the diameter of the pile increases, the group efficiency decreases. The arrangement of piles in group has minor impact on pile group efficiency which enhances onsite flexibility. It is expected that these outcomes will facilitate the practicing engineers for efficient solutions.

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1. Introduction

Pile Foundations are the deep foundations which are basically formed by long, slender and columnar elements. They are typically made from strong materials such as concrete or steel or sometimes timber and driven into the ground to act as a steady support and transfer load of the structure at desired depth. These types of foundations are mainly preferred when the surface soil is weak and cannot support the structure load or when the structure has very high concentrated loads like water tank, high rise structure, transmission tower, chimney, stacks etc.

Structures on single pile are very rarely found. Usually, minimum of three piles are placed under a column or a foundation base to avoid alignment problems and inadvertent eccentricities. The capacity of group pile is less than the sum of the individual ones. If spacing is large enough, the effect of superposition is less, or perhaps it is totally eliminated. However, large spacing requires relatively large and thick concrete cap. So arrangement of group piles is essential and important.

A lot of works on group pile has been done previously related to settlement of pile, load bearing capacity variation etc. For instance, the settlement behavior of group pile in layered soils has been presented by nonlinear analysis. The analysis was executed along a confined soil zone which was disturbed soil [1]. Group piles can be subjected to tension or pullout force, axial force or vertical loading, lateral loading etc. The settlement analysis of group pile subjected to vertical loading was done previously by using nonlinear analysis. The predicted results from theoretical method were compared with experimented results and found to be quite satisfactory [2]. A research showed that under axial loading the settlement of compressible group pile is 2.5 times more than the rigid friction group pile [3]. Not only under axial load but also under lateral load, pile's behaviors are studied numerically in clayey slope using PLAXIS code. On the basis of the analysis, piles' capacities in lateral loading on sloping ground are generated in a non-dimensional design chart [4]. Apart from clayey soil, another research was worked on the elastic settlement of group pile that rested on nonhomogeneous rock. Several charts of elastic settlements were generated in order to select proper pile diameter, length that would restrain the pile settlement to an allowable limit [5]. Group piles' behavior varies from soil to soil i.e. sandy soil, cohesive soil etc. The behavior of group pile as well as single pile in saturated and unsaturated cohesion less soil has been previously investigated where it showed a significant change in load bearing capacity due to matric suction [6]. Here the term 'matric suction' denotes a pressure that a dry soil imposes on its adjacent soils in order to balance the moisture content in it. Besides group piles, single pile's behavior are also analyzed in many researches. For instance, a research showed if any tunnel affects a laterally loaded single pile then its initial capacity can be increased gradually before tunneling by increasing the strength and stiffness parameters of the soil [7]. Apart from these, researches were also carried on piled raft foundation. Such as, a research work was executed where several analysis on piled raft foundation were run by different software and compared with real pile load test data. Hence the results showed a considerable similarity among them [8].

So, many researches on group piles on various aspects are performed already, but this research work focuses on the efficiency variations of group piles with varying specifications. Usually the load bearing capacity of group pile is less than the summation of individual pile's bearing capacity, thus the efficiency of an individual in group is less than initial calculation. Several works related to efficiency of group piles are also performed previously. Like, the group pile efficiency in pullout force was analyzed using boundary integral technique where the output showed that the reduction in efficiency depended on pile spacing, length to diameter ratio, pile-soil interface depth etc. [9]. Some other efficiencies of group pile are predicted by Artificial Neural Network (ANN), a computing system that exerts simulations in a way similar to human brain functioning process. Under axial loading, the efficiencies of group pile installed in sandy soils are worked out by neural artificial network before [10]. Apart from ANN method, semi-empirical method was also used to determine or predict the capacity of group pile under pullout force in sandy soils. The predictions of uplift capacities of piles under various specifications were compared with model test results and found to be satisfactory [11]. In continuation with these studies, the research paper presented here has some similarities as in pile spacing, length, pile-depth etc. But Madhav and Shanker focus on pullout or uplift force instead of vertical load in the papers [9,11]. Researches were also gone through in soft clay soil under lateral load. A study used the *P*-multipliers to analyze the effect of spacing of piles and stiffness of the clay soil. The results showed that the *P*-multipliers increase if the stiffness of the clay and the spacing of pile are increased along the load direction; it also found no pile-soil interaction for 7D spacing [12]. But this presented paper here limits the research up to 3.5D spacing and sandy soils. Similarly, another research was run on multilayered cohesionless soil where pile group under lateral load was investigated both experimentally and numerically and the comparison between them ended up in an insignificant difference [13]. Apart from regular circular piles, some other experiments have gone through XCC piles (a special 'X' cross-section shape pile that creates greater area for side surface rather than conventional circular pile), slender piles etc. For instance, an experiment finds that the stability of a composite foundation can be increased by XCC pile as it has lower neutral point and less susceptibility towards traffic load [14]. Another study analyzed that in terms of very slender column, the L_{cr} (critical slenderness) varies from 65 to 200 corresponding to pile diameter of 0.06 to 0.18m [15].

The last three decades have witnessed a tremendous growth in the numerical method. For this, it is possible to obtain more realistic and satisfactory efficiencies of the group piles design to make it more economical. So many works are already found on this numerical method applied on group pile. For instance, the relationship between load and displacement of group piles under vertical loading was generated using numerical analysis for various pile layouts [16]. Another experiment generalized the behavior pattern of axially loaded group pile when it faces lateral cyclic loading. To perform this analysis a hybrid boundary element technique was used [17]. In numerical modeling many software are used nowadays. Like, ABAQUS, a finite element software, has been used to find out how much operative a perimeter group pile (with no inner piles) can be rather than conventional grid pattern. The outcome exhibits that conventional grid patterns of pile are less efficient than perimeter group piles [18]. But the presented research paper here is related to the conventional grid patterns of group pile only. Apart from vertical loading, numerical modeling has also been used in assessment of group pile behavior under lateral loading. A research computed the bending moment and deflection of pile under lateral cyclic loading by ABAQUS and the results were compared with previous reported field cases. The comparison results illustrated that three dimensional numerical analysis imposes good effect on modeling of complex soil-pile system [19]. Soil condition affects the behavior of pile. Thus many researches were performed under clayey and sandy soils. An experimental study was gone through in Iraq where the behavior of regular and finned pile foundation was examined in layered sandy soils [20]. This experiment has gone through layered sandy soils as like as our experiment. Another experiment enumerated the uplift execution pattern of granular pile anchors in expansive soil and it found the elevation of its uplift capacity with increasing pile length and diameter [21]. Beside those software, some other popular ones like ANSYS (a 3D design software that facilitates modeling of products with inimitable scales) has been used in many numerical modeling. A numerical analysis was performed by ANSYS to observe the effect of building frame on group pile under axial loading in cohesion less soil [22]. Among the numerical analysis software, Plaxis 3D Foundation software is used in this research paper for obtaining more precise and prominent results and can overcome the drawbacks of the conventional approaches. Another tremendous numerical analysis was executed through Plaxis 3D for the settlement modeling of raft foundation where the outcome indicates that the thickness of raft footing has an insignificant effect on the predicted settlement [23]. In this presented research paper various soil models are introduced in the program to simulate different geotechnical complexities for instance the elastic behaviors, anisotropy, hardening, creep, etc. Mohr-Coulomb soil model is used in this numerical analysis and Hardening soil model is considered to check the authenticity of the results.

The Mohr-Coulomb model [24–26] is a linear elastic and perfectly plastic soil model that is used to analyze soil behaviors in elastic zones. Hooke's law of isotropic elasticity is followed in the linear elastic part of the model and the perfectly plastic part is constructed on the Mohr-Coulomb failure criterion. The model requires the following material properties: cohesion, friction angle, dilatancy angle, unit weight, permeability and modulus of elasticity, which are well known to most geotechnical engineers and can be obtained from basic tests on soil samples. Both effective and undrained parameters can be considered depending upon the drainage type of the model.

The Hardening Soil model [27] an elasto-plastic model that can compute an acceptable collapse load in the plastic range. Plasticity theory, soil dilatancy is included in this model. A volumetric cap yield surface is been launched which has a different shape than other soft soil models. Two different types of hardening (shear hardening and compression hardening) are considered in the model. Permanent strains because of primary deviatoric loading are modeled by shear hardening and compression hardening handles the plastic strain due to compression loading and isotropic loading [28]. Soil Stiffness in this model is stress-dependent, which makes this model unique and reliable than the others. Three stiffness parameters, primary shear stiffness E_{50}^{ref}, primary compression stiffness E_{oed}^{ref} and unloading-reloading stiffness E_{ur}^{ref} and a stress dependency power, m is considered along with cohesion, friction angle and dilatancy angle.

So, many researchers explored and analyzed regarding these group piles. But this research comprises the efficiency fluctuations with varying diameters of pile along with pile numbers in group action under several orientations. In field practice, the efficiency is being considered to some fixed values for all diameters, pile number and spacing under all soil conditions which is very conservative approach. In this context this research executed many more numerical modeling of various diameter piles i.e. 600mm, 800mm, 1000mm, 1200mm (D_{600}, D_{800}, D_{1000}, D_{1200}) with several spacing like 2.5D, 3D, 3.5D etc. in three different sandy soils to observe their efficiency pattern and values. Different orientations in group of six piles are also numerically analyzed here. For precise observation, many group piles like two piles, three pile, four piles, five piles, six piles (P_2, P_3, P_4, P_5, P_6) etc. are numerically modeled by PLAXIS 3D FOUNDATION v1.6. After obtaining all the efficiencies for several specifications and parameters, those are thoroughly analyzed at various aspects to find out whether more precise and economic efficiency can be considered in field rather than conservative values.

2. Methodology

In this research conventional method for bored pile is applied to calculate theoretical bearing capacity of pile in sandy soils. Representative three different states of sandy soils have been chosen with varying parameters from several references [29,30]. All the piles capacity is calculated for a constant depth with variable diameters and soil profiles. For simulating the piles, geometric model of soils with relevant boundary conditions are generated in PLAXIS 3D using Mohr Coulomb model. The parameters of the soil layers are considered according to the predetermined rational values from references [29,30]. The piles are then modeled as confined by soil with pile cap having sufficient thickness against failure. The calculated loads from theoretical bearing capacity are applied on the pile group and analyzed for maximum vertical settlements. On the basis of serviceable settlements, the capacity of those piles are determined as well as the efficiency. After categorization of efficiencies for different diameters, spacing and orientations, the results are thoroughly analyzed, compared, grafted in various aspects to find out the behavior patterns of piles under group action. Later on, to justify the result a comparison between Mohr Coulomb and Hardening Soil model has been demonstrated using same pile specification.

2.1. Soil parameters

Three different sandy soil profiles are considered as shown in Fig. 1a. The layers express the overall soil's sate from loose to dense. S_1 soil denotes comparatively weak soil as loose soil governs. S_2 soil depicts comparatively better soil than S_1 as medium and dense soil are well prominent. And S_3 soil is stronger soil than other two samples, as dense soil governs. The soil parameters i.e. angle of internal friction, modulus of elasticity, unit weight, SPT-N value, cohesion, Poisson's ratio etc. for loose, medium dense and dense condition are selected rationally from several references as listed in Table 1.

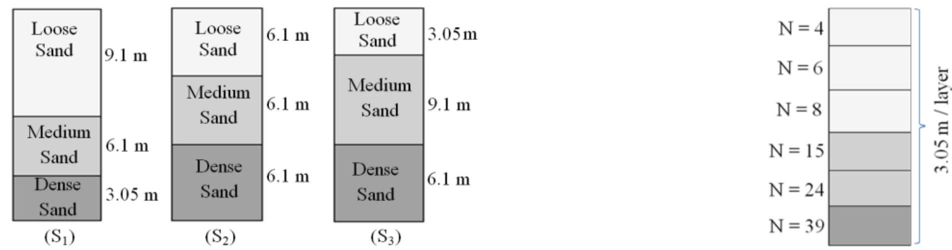


Fig. 1. Sandy soil samples; **(a)** Several multilayered sandy soils with varying density **(b)** Soil S_1 profile for SPT-N value.

Table 1
Soil parameters of different states of sand layers [Mohr Coulomb Model].

Soil parameters	Loose Sand	Medium Sand	Dense Sand	Reference
Unit weight, γ	15.55 KN/m^3	17 KN/m^3	18.22 KN/m^3	[29]
Angle of internal friction, ϕ	28°	34°	41°	[30]
SPT-N value	6	23	50	[30]
Modulus of elasticity, E	14364 KN/m^2	23940 KN/m^2	47880 KN/m^2	[30]
Poisson's ratio, ν	0.2	0.25	0.3	[31]
Cohesion, c	5 KN/m^2	5 KN/m^2	5 KN/m^2	Chosen a small amount for better result recommended by PLAXIS

2.2. Bearing capacity calculation of bored pile

For bored pile, the bearing capacity is summation of end bearing and frictional resistance. The pile capacities for different parameters and soil profiles are calculated thoroughly.
The sample calculation of single pile of diameter 1000mm (D_{1000}) in soil S_1 has been shown in Table 2.

Table 2
Bearing capacity calculation of D_{1000} single pile in soil S_1.

Description	Notation	Equation	Reference
Ultimate bearing capacity	Q_u	$Qu = QF + QE$	[32]
Frictional resistance	Q_F	$QF = 0.67\overline{N} * Af$	
End bearing	Q_E	$QE = 14N * (Db/D) * Ac$	
Soil type : S_1			
Pile type : Single pile of D_{1000}			

N	D_b (m)	D (m)	$Ac = \pi * D2/4$ (m^2)	$\overline{N}$	$Af = \pi * D * Db$ (m^2)	Q_E (KN)	Q_F (KN)	Q_u (KN)
39	3.05	1	0.7854	4+6+8+15+24+39=96	9.58188	1307.93	616.31	1924

Notations:
N = value of SPT-N at the tip
A_c = the cross-sectional area of pile tip
A_f = effective surface area of the pile in contact with the soil
D_b = the depth penetrated by the pile into the hard bearing stratum
$\overline{N}$ = average of uncorrected N-values along the considered length of the pile

The SPT-N values for the layers of soil S_1 are chosen 4, 6, 8, 15, 24 and 39 serially from top (surface) to bottom (up to required depth) at every 3.05m interval [Fig. 1b]. These values are picked up from Table 3.

Table 3
SPT-N values for different states of sandy soils [30].

States of Sandy soil	SPT-N value
Very loose	<4
Loose	4 - 10
Medium	10 - 30
Dense	30 - 50
Very Dense	> 50

So, using these values, the bearing capacity of a D_{1000} diameter bored pile penetrated up to the 'dense sand' of soil S_1 is found to be 1924 KN (approximately) from Table 2.
Similarly the bearing capacity of rest other diameters i.e. D_{600}, D_{800}, D_{1200} single pile have been calculated under three different soils [Table 6 under Article 3.0].

Now to illustrate efficiency determination, P_2 pile of D_{600} in Soil type S_1 penetrating a depth of 15.24 meter (50 feet) below the ground level has been considered here. Approaching through the conventional method, the capacity of P_1 of D_{600} has been found to be 1154 KN [Table 6]. Considering this load as 100%, additional three loads of 75%, 125% and 150% of 1154 KN have been picked up. Later on, these four different loads have been applied on that single pile designed in "Plaxis 3D Foundation" to find four different settlements. Those applied percent loads are being varied time to time as per necessity in order to find settlements below and above the allowable 20mm settlement [33]. These obtained values of settlements against their respective loads in soil S_1 are arranged along with the capacity at 20mm settlement in Table 7a under Article 3.0.

Using the values of settlement against their respective loads, a graph has been plotted to generate a regression equation of $y = 23.105x + 826.05$ with the value of R^2 as 0.95 which justifies the regression line to be considered as a well fitted line with representative outcomes.

Using this line or regression equation, the load against 20mm settlement has been obtained as 1288 KN.

$y = (23.105x + 826.05)\,KN$; ['x' in millimeter and 'y' in KN]
$y = (23.105 * 20 + 826.05)\text{ KN} = 1288.15\text{ KN} \approx 1288\text{ KN}$; So the capacity of this pile is 1288 KN.
In similar way the capacity of group of two piles are calculated in different three spacing i.e. 2.5D, 3D, 3.5D [Table 7b under Article 3.0].Then the capacity is divided by 2 to find the capacity of each pile individually in group action. This load is then divided by the load of single pile to find the efficiency of the group of two piles [Table 7b under Article 3.0].

In order to justify the results, a Group of 2 piles (P_2) of D_{600} in Soil S_1 has been modeled to find the efficiencies using Hardening Soil (HS) model which is compared with back-to-back efficiencies found in Table 7b using Mohr Coulomb Model. The following soil parameters shown in Table 4 are considered while using Hardening Soil Model,

Table 4
Soil parameters of different states of sand layers [Hardening Soil Model].

Soil parameters	Loose Sand	Medium Sand	Dense Sand	Reference
Unit weight, γ	15.55 KN/m^3	17 KN/m^3	18.22 KN/m^3	[29]
Angle of internal friction, ϕ	28^o	34^o	41^o	[30]
K_0^{NC} (=1-sin ϕ)	0.531	0.441	0.344	
Secant modulus 50% strength, $E_{50}{}^{ref}$	14364 KN/m^2	23940 KN/m^2	47880 KN/m^2	[34]
Oedometric modulus, $E_{oed}{}^{ref}$	14364 KN/m^2	23940 KN/m^2	47880 KN/m^2	[34]
Unloading-reloading modulus, Eur_{ref} (=3 $E_{50}{}^{ref}$)	43092 KN/m^2	71820 KN/m^2	143640 KN/m^2	[34]
Poisson's ratio, ν	0.2	0.25	0.3	[31]
Cohesion, c	5 KN/m^2	5 KN/m^2	5 KN/m^2	Chosen a small amount for better result recommended by PLAXIS

2.3. Numerical modeling parameters

Group of several piles (P_2, P_3, P_4, P_5, P_6) have been geometrically modeled in Plaxis with various diameters and spacings in three states of sandy soils. Water table has been considered far below the tip of the pile to avoid the effect of water on to the pile efficiency as the system is under static load with no dynamic load. As an example, a group of six piles of D_{1000} in regular orientation [Fig. 2] under soil S_1 has been illustrated with working steps using the software PLAXIS. The piles are at a spacing of 3D to follow the regular practices.

Required specifications of group of six piles in regular orientations are listed in Table 5.

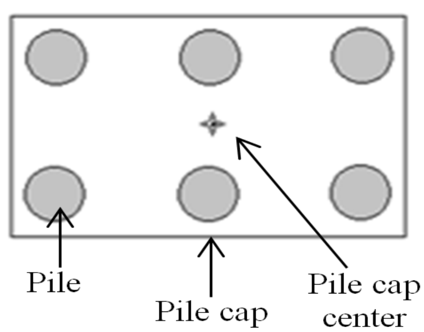


Fig. 2. Regular orientation of group of six piles at 3D spacing.

Table 5
Specifications of group of six piles (P_6) of D_{1000} in soil S_1.

Description	Notation	Value
Pile length	L	15.24 m (50 feet)
Concrete dry density	γ	24 KN/m^3
Young's modulus of steel	E	30x10^6 KN/m^2
Poisson's ratio	ν	0.2
Load on the center of pile cap	P	1924*6=11544 KN
Pile spacing	S	3D=3*1= 3 m
Pile cap depth	D	1.17 m

2.4. Stages of numerical modeling

Step 1- Defining soil properties and parameters: The soil layers i.e. loose layer, medium dense layer, dense layer etc. are generated with several color in 'Soil & Interfaces' sets. Also pile interface is incorporated along with them. As an example the parameters of S_1 soil i.e. the Modulus of elasticity of loose layer 14364 KN/m^2, Poisson's ratio 0.2, cohesion 5.0, angle of internal friction 28 etc. are introduced into them from Table 1 to 'Parameter' window of 'loose' layer. Other layers' parameter values are also presented similarly in their respective 'Parameter' windows along with pile's specifications.

Step 2- Defining work planes and placing the piles with pile cap: Work planes are introduced for the defining of pile, pile cap and soil interface position at different level of depth. At the top 0.3m work plane is kept for excavation depth and the subsequent depth 0.3m to 1.58m depth from ground level is kept for pile cap. These depths are being varied with the thickness of pile cap for different diameter of piles. Then a regular orientation of six piles is generated.

Step 3- Generating 2D mesh and 3D mesh: After placing the pile orientation set up, 2D mesh are created where the pile orientation are noticed in small triangular blocks along with surrounding soil. After updating this 2D mesh, 3D mesh is also generated where the full soil block is visible with loose, medium and dense layers.

Step 4- Defining interfaces in all work planes and application of Load on group pile center: Before application of desired load, several construction phases are introduced i.e. initial phase, piling, excavation, pile cap construction and finally load has been applied on it. For each phase, the work plane interfaces are different. That's why the interphases are specified for several construction phases in 'calculation' segment. Then the prescribed external load has been applied on pile cap by selecting the cap loading center.

Step 5- Running the analysis and finding the vertical displacement: After applying the load on the loading center, the analysis has been run. A moderate number of stages by which the construction load will gradually impose on the pile is specified in the software for reliable as well as precise values. After completion of the analysis the maximum vertical displacement of group pile is shown in output window.

In similar ways, all other diameter piles of other pile-groups have been modeled and analyzed to find their settlements. Hence, the bearing capacities of those group piles are calculated using these settlements against their respective loads on the basis of 20mm as allowable settlement [28]. To find out the capacity of each pile in that group, the capacity is divided by six and checked against the bearing capacity of single pile (P_1) of D_{1000} in soil S_1 obtained by similar process mentioned all along. Thus the efficiency variations among them are also obtained.

3. Results and discussion

The efficiencies of group piles under different spacing, diameters and orientations are numerically analyzed by PLAXIS 3D FOUNDATION under different sandy soils with layers having varying densities. For each specified type of single pile the ultimate capacity has been analyzed [Table 6] which is benchmarked for the determination of efficiency of group piles of that type.

Table 6
Bearing capacity of single pile of varying diameters in three types of soil.

Single pile (P_1)				
Pile Diameter		**Bearing capacity of the pile (KN)**		
(mm)	**Notation**	**Soil S_1**	**Soil S_2**	**`Soil S_3**
600	D_{600}	1154	2094	2262
800	D_{800}	1539	2793	3016
1000	D_{1000}	1924	3491	3770
1200	D_{1200}	2308	4189	4523

As an instance, the settlements found for P_1 pile of D_{600} in soil [Table 7a] against their respective loads have been plotted in graph as shown in Fig. 3. Later on, as discussed in Methodology the capacity of this pile has been found 1288 KN from the regression equation.

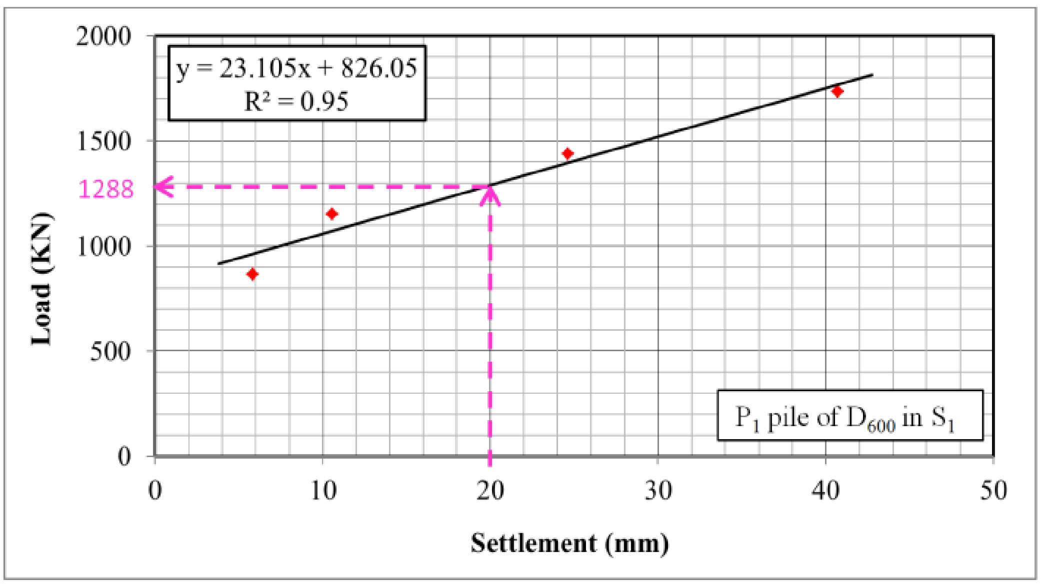


Fig. 3. Single pile of diameter 600mm in soil S_1.

Table 7a
Settlements of D_{600} single pile under different loads to find capacity. [Mohr Coulomb Model].

Soil S_1			**Capacity at 20mm settlement (KN)**
% load of conventional method	**Load (KN)**	**Settlement (mm)**	
75	866	5.81	1288
100	1154	10.55	
125	1442	24.64	
150	1731	40.75	

In similar way, Table 7b here shows capacity determination for group of two pile which has already been discussed in Methodology segment.

Table 7b

Settlement of group of two piles of D_{600} under different loads to find efficiency. [Mohr Coulomb Model].

Soil type:S_1					Capacity of each pile at 20mm settlement (KN)			Efficiency (%)		
Group of 2 piles, P_2 (D_{600})										
% load of conventional method	Load (KN)	Settlement (mm)								
		2.5D	3D	3.5D	2.5D	3D	3.5D	2.5D	3D	3.5D
50	1154	5.03	4.93	4.91	1192	1200	1225	92	93	95
75	1731	7.47	7.38	7.38						
100	2308	13.15	13.36	13.21						
125	2885	30.23	29.79	28.41						

Using the soil parameters shown in Table 4, the pile efficiencies found by Hardening Soil Model are tabulated below in Table 8a & Table 8b to compare with Mohr Coulomb Model.

Table 8a

Settlements of D_{600} single pile under different loads to find capacity. [Hardening Soil Model].

Soil S_1			Capacity at 20mm settlement (KN)
% load of conventional method	Load (KN)	Settlement (mm)	
100	1154	5.67	2132
150	1731	10.05	
175	2020	16.5	
200	2308	24.64	

Table 8b

Settlement of P_2 piles of D_{600} under different loads to find efficiency. [Hardening Soil Model].

Soil type:S_1					Capacity of each pile at 20mm settlement (KN)			Efficiency (%)		
Group of 2 piles, P_2 (D_{600})										
% load of conventional method	Load (KN)	Settlement (mm)								
		2.5D	3D	3.5D	2.5D	3D	3.5D	2.5D	3D	3.5D
100	2308	7.05	7.03	7.09	1980	1979	1895	93	93	89
150	3462	12.82	12.52	12.94						
175	4039	20.21	20.13	22.08						
200	4270	24.11	24.26	26.58						

All the varying efficiencies under varying spacing, diameters and orientations in three states of sandy soils have been plotted in suitable graphs and charts to depict various possible analogical behavior patterns of group piles. All these extended results and effects are discussed in the proceedings.

3.1. Effect of pile spacing in efficiency

The general procedure prescribed in methodology has been followed to find the efficiencies of P_2, P_3, P_4, P_5, P_6 piles of D_{600}, D_{800}, D_{1000}, D_{1200} in different pile spacing i.e. 2.5D, 3D, 3.5D under three different soil types i.e. S_1, S_2, S_3. As an example the efficiencies of D_{600} within soil S_1, S_2 and S_3 has been summarized in Table 9 and demonstrated in Fig. 4. As illustrated in Fig. 4, pile spacing has minor effect on the efficiency. Rest of the piles i.e. D_{800}, D_{1000}, D_{1200} under group action of P_2, P_3, P_4, P_5, P_6 for S_1, S_2, S_3 show similar behavior [Table 10].

Table 9
Group pile efficiencies of D_{600} at different pile spacing under three soil types.

Soil type	Pile spacing	Efficiency (%)				
		2 piles	3 piles	4 piles	5 piles	6 piles
S_1	2.5D	92	87	85	82	80
	3D	93	90	86	83	81
	3.5D	95	93	88	84	82
S_2	2.5D	95	92	91	90	87
	3D	94	94	90	90	88
	3.5D	95	95	92	91	88
S_3	2.5D	97	94	93	92	91
	3D	96	96	93	92	91
	3.5D	97	97	95	94	92

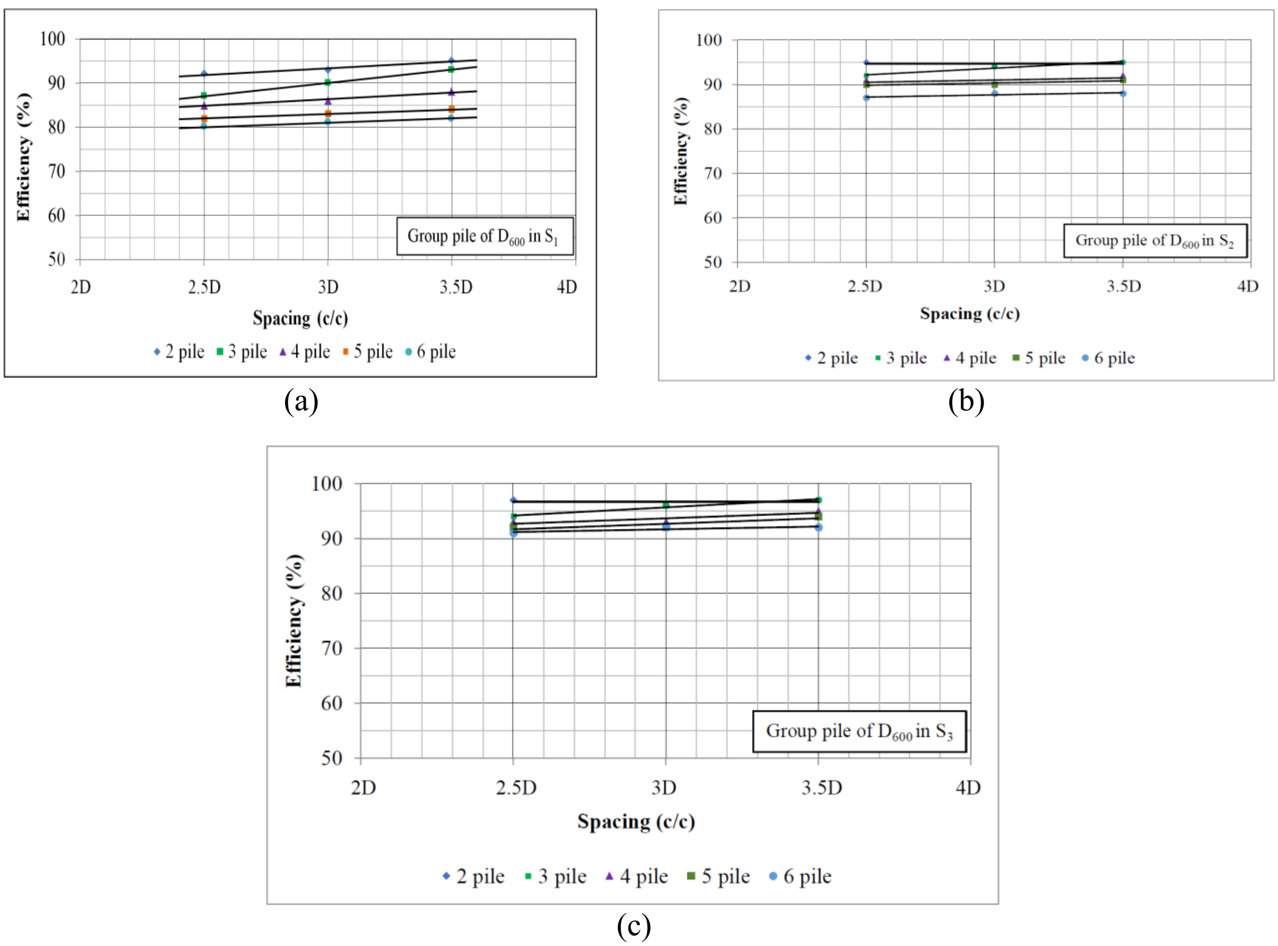


Fig. 4. Efficiency of group piles under different pile spacing in **(a)** soil S_1 **(b)** soil S_2 and **(c)** soil S_3.

Table 10
Group pile efficiencies of D_{800}, D_{1000}, D_{1200} at different spacing under three soil types.

Pile Diameter (mm)	Soil type	Pile spacing	Efficiency (%)				
			2 piles	3 piles	4 piles	5 piles	6 piles
800	S_1	2.5D	96	90	85	80	78
		3D	94	91	88	80	80
		3.5D	95	95	89	81	81
	S_2	2.5D	95	92	89	86	85
		3D	94	92	91	88	87
		3.5D	95	94	91	89	88
	S_3	2.5D	95	92	89	87	85
		3D	94	93	90	87	87
		3.5D	95	94	91	90	88
1000	S_1	2.5D	99	92	86	80	76
		3D	97	95	88	81	78
		3.5D	99	97	89	82	82
	S_2	2.5D	97	91	87	85	82
		3D	94	93	88	86	84
		3.5D	97	94	90	87	86
	S_3	2.5D	98	92	89	86	83
		3D	94	94	90	87	85
		3.5D	98	95	92	88	87
1200	S_1	2.5D	99	90	83	75	72
		3D	98	92	85	76	74
		3.5D	97	93	85	76	71
	S_2	2.5D	96	90	86	81	78
		3D	96	92	88	83	81
		3.5D	97	94	89	84	82
	S_3	2.5D	96	90	87	82	79
		3D	97	93	89	83	81
		3.5D	98	94	90	85	82

The analysis results depicted in this article indicate that the regular pile spacing i.e. 2.5D, 3D, 3.5D has insignificant effect on pile efficiency as the graphs [Fig. 4] show almost horizontal straight lines. So it can be recommended that as the regular pile spacing has insignificant effect on pile efficiency, the spacing may be selected based on construction method or other on-site requirements.

3.2. Effect of pile number and diameter in efficiency

A standard practice of 3D spacing has been considered for the rest of the analysis work as the spacing shows insignificant effect on group efficiency. Fig. 5 and Fig. 6 are the graphical representation of Table 11. From Fig. 5 it can be observed that efficiency mildly decreases with the increase in pile number in the group for a specific diameter and soil condition. For instance in Fig. 5a, 600mm diameter pile that is confined in soil type S_1 has efficiencies of 93%, 90%, 86%, 84%, 80% for pile group of P_2, P_3, P_4, P_5, P_6 respectively. Similarly these values are 94%, 93%, 91%, 89%, 88% in soil S_2 and 96%, 95%, 94%, 92%, 91% for soil S_3. Other diameter piles as in Fig 5b, 5c and 5d also show identical demotion of efficiency with increasing pile number.

Table 11
Efficiency of group piles at different diameters in different types of soil.

Pile diameter (mm)	Efficiency (%) with increasing Diameter (at spacing 3D)														
	2 Pile			3 Pile			4 Pile			5 Pile			6 Pile		
	S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3
600	93	94	96	90	94	96	86	90	93	83	90	92	81	88	91
800	94	94	94	91	92	93	88	91	90	80	88	87	80	87	87
1000	97	94	94	95	93	94	88	88	90	81	86	87	78	84	85
1200	98	96	97	92	92	93	85	88	89	76	83	83	74	81	81

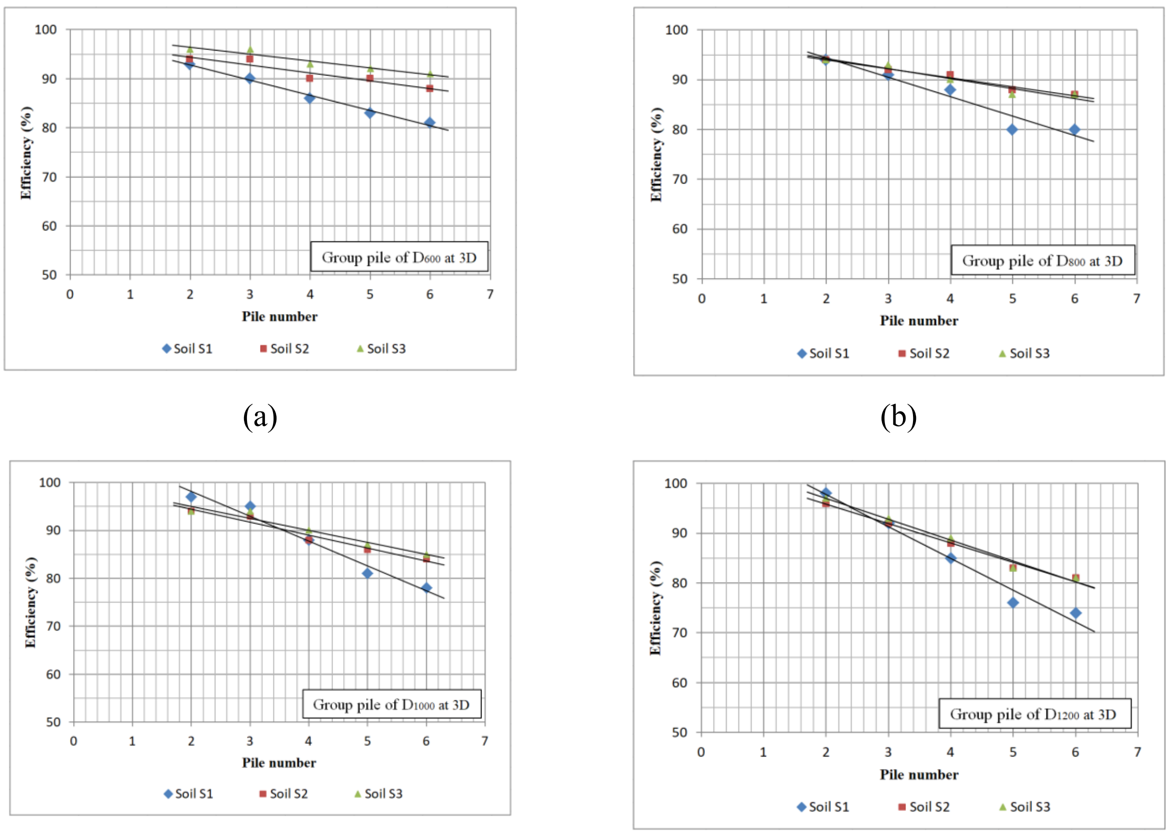
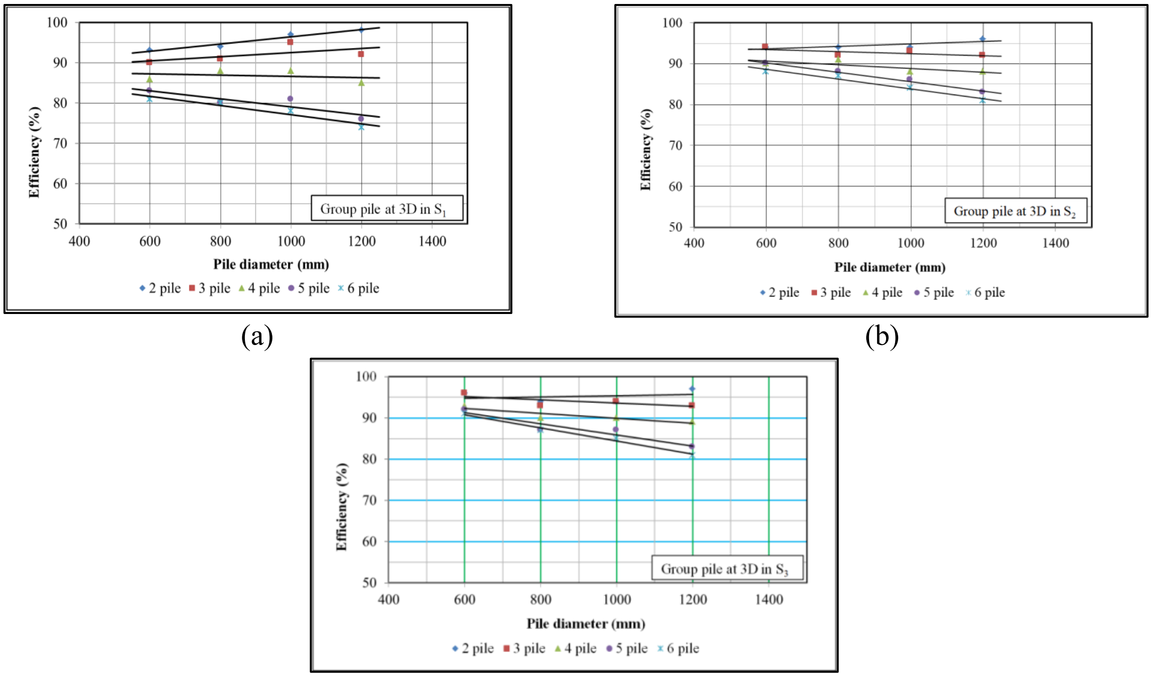


Fig. 5. Variation of group pile efficiency with different pile numbers of **(a)** diameter 600mm, **(b)** diameter 800mm **(c)** diameter 1000mm and **(d)** diameter 1200mm.

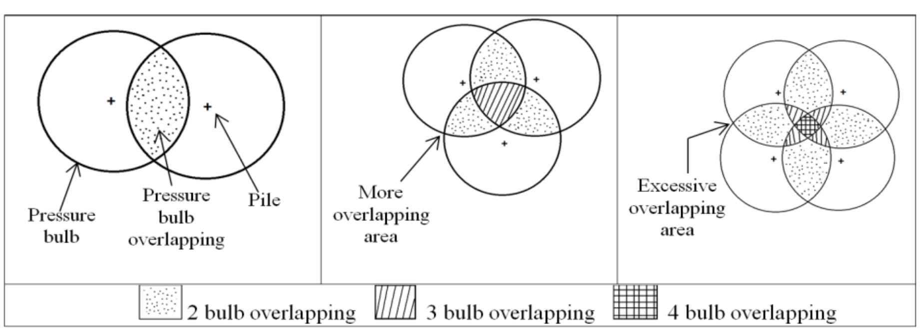
It is also observed from Fig. 6 that, the pile group efficiency decreases as the individual pile diameter increases except for the pile group of two and three pile in comparatively weak soil (S_1), Fig. 6a. As the soil became dense and strong (S_2 and S_3) the efficiency of the pile group with less pile number also shows a decreasing pattern, Fig. 6b and Fig. 6c. The pile group P_3 varies its efficiency for diameter 600mm to 1200mm, from 90% to 94%, from 94% to 92% and from 95% to 93% under the soil type S_1, S_2 and S_3 respectively. Pile groups of higher number of piles i.e. P_4, P_5, P_6 show even more decrease of group efficiency with the increment of pile diameter as shown in Fig. 6.



(c)

Fig. 6. Group pile efficiency with different diameters under **(a)** soil type S_1, **(b)** soil type S_2 and **(c)** soil type S_3.

So, in this article it shows more decrease in group efficiency with the increment of pile diameter. These phenomena may happen due to the overlapping of pressure bulbs generated in pile groups, Fig. 7. The intersecting of pressure bulbs may enhance some of the soil properties e.g. unit weight, friction between soil particles and soil pile interface but decrease the pile capacity as calculated individually. Observing the diagrams in Fig. 7 it can be considered that as the number of piles increases, the total overlapped area of the pressure diagram also increased which leads to the reduction of pile capacity. P_4 pile group has more overlapping area than P_3 pile group with four overlapping pressure bulbs. So P_4 pile group shows even less efficiency than P_3 pile group [Fig 6] for specific diameter and soil type. Besides, as the diameter of individual pile increased the surrounding area encumbered with pressure bulb also increased and in a continuation with that the total overlapped area of the pressure diagram also increased. This leads to the consequence of decrement in efficiency with a higher diameter of pile.



(a) (b) (c)

Fig. 7. Pressure bulb overlapping of **(a)** P_2 piles **(b)** P_3 piles **(c)** P_4 piles.

3.3 Effect of orientation in efficiency

Because of the obtained methodology and mode of construction, a specific number of piles needed to be placed at various orientations. Two possible orientations of 6 piles i.e. regular and triangular patterns have been selected for this study. Related data incorporating these two patterns are arranged in Table 12 and graphically presented in Fig. 8.

Table 12
Efficiency of group of 6 piles in two orientations.

Efficiency in Different Orientations of P_6 at 3D spacing						
Pile Diameter (mm)	**Efficiency (%) in Regular Pattern**			**Efficiency (%) in Triangular Pattern**		
	S_1	**S_2**	**S_3**	**S_1**	**S_2**	**S_3**
600	81	88	91	80	89	91
800	80	87	87	79	87	88
1000	78	84	85	76	84	85
1200	74	81	81	70	80	81

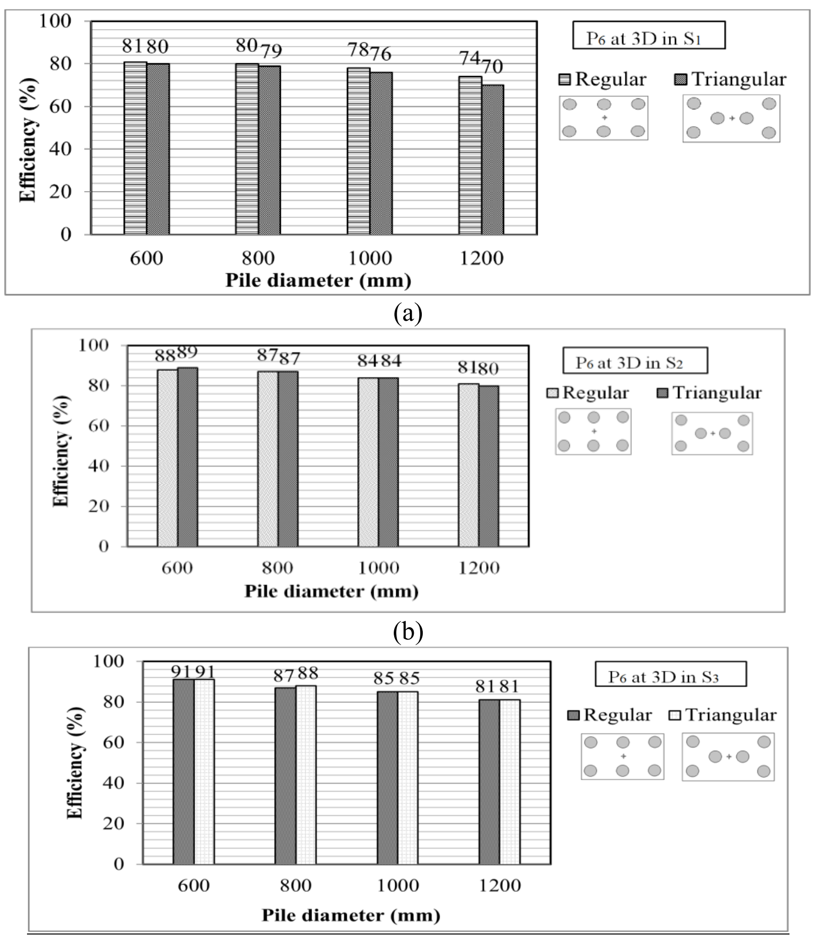


Fig. 8. Group efficiency of six piles in two orientations under

(a) soil S_1 **(b)** soil S_2 and **(c)** soil S_3.

Fig. 8 shows that the efficiency variation between regular and triangular patterns of six piles (P_6) is insignificant for other parameters i.e. pile diameter and soil type etc. Pile capacity under group action is dominated by preceding circumstances. So practitioners may choose any pile orientation of a specific spacing as per on-site requirements and sustainable design where efficiency variation may be overlooked.

3.4. Possible consideration of efficiencies in group piles

Conventionally the group capacity of bored pile in sandy soil is considered as 2/3 (66%) to 3/4 (75%) of the summation of individual pile capacities [32]. It is difficult for small to medium size projects to perform pile load tests for counting a precise and rational pile capacity. In these circumstances numerical analysis is a good alternate for more defined values of piles' capacity.

From the values of efficiencies in Table 11, it's clearly observed that using 66% to 75% efficiency for all types of pile groups irrespective of soil condition, pile diameter, number of piles etc. is not an economic practice. Rather more precise efficiency can be considered from numerical analysis. For instance, in soil S_2 the efficiency of group of two (P_2) pile of D_{600} is 94%. But in regular practice it would be considered 75% or less which is very uneconomical. Other efficiency values of D_{800}, D_{1000} and D_{1200} also show higher values rather than conventional conservative values.

4. Conclusion

In this research, several concrete group piles have been numerically analyzed by PLAXIS 3D FOUNDATION in three different states of sandy soil in order to find the efficiencies of group piles and to check them with conventional conservative efficiency considerations.

After approaching through various analyses over test results, the following outcomes have been sorted

a) Pile spacing has insignificant effect on group pile efficiency irrespective of pile diameter and soil type. As summarized in Table 9 and Table 10, the efficiencies of pile group on average vary from 1% to 3% for 2.5D to 3.5D pile spacing.

b) As the number of pile in a pile group increases for a specific diameter and soil condition, the pile group efficiency decreases. From Table 11 and Fig. 5, for D_{800} pile group the efficiencies decrease around 12% ~ 16% as pile number increases from P_2 to P_6 for several specified soil types. The other diameter pile groups also follow the similar trend.

c) In a comparatively weak soil (loose sand to medium dense sand) the pile groups of lower number of piles e.g. P_2 and $P_{3,}$ exhibit increment in group efficiency as the diameter of pile increases. For other cases, as the diameter of pile increases group efficiency decreases.

d) The orientation of piles in a pile group has insignificant effect on pile group efficiency for a specific spacing. As shown in Table 12, the efficiency variation in between regular and triangular orientation of six piles (P_6) is on average 0% to 1% for specified diameters, spacing and soil types.

e) Engineers may consider more precise, reliable as well as cost-effective values for pile group efficiencies through numerical analysis rather than a conventional approach.

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Declaration of interests

The authors declare that they have no known competing for financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

All data, models, and code generated or used during the study appear in the submitted article.

Reference

[1] Lee KM, Xiao ZR. A simplified nonlinear approach for pile group settlement analysis in multilayered soils. Can Geotech J 2001;38:1063–80. https://doi.org/10.1139/t01-034.

[2] Cairo R, Conte E. Settlement analysis of pile groups in layered soils. Can Geotech J 2006;43:788–801. https://doi.org/10.1139/t06-038.

[3] Singh V, Lal SK. Analytical Method for Settlement of Axially Loaded Compressible Pile. Indian Geotech J 2012;42:75–86. https://doi.org/10.1007/s40098-012-0008-4.

[4] Sivapriya S V., Gandhi SR. Experimental and Numerical Study on Pile Behaviour Under Lateral Load in Clayey Slope. Indian Geotech J 2013;43:105–14. https://doi.org/10.1007/s40098-012-0037-z.

[5] Eid HT, Shehada AA. Estimating the Elastic Settlement of Piled Foundations on Rock. Int J Geomech 2015;15:04014059. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000376.

[6] Al-Khazaali M, Vanapalli SK. Experimental Investigation of Single Model Pile and Pile Group Behavior in Saturated and Unsaturated Sand. J Geotech Geoenvironmental Eng 2019;145:04019112. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002176.

[7] Vali R, Saberian M, Beygi M, Porhoseini R, Abbaspour M. Numerical Analysis of Laterally Loaded Single-Pile Behavior Affected by Urban Metro Tunnel. Indian Geotech J 2020;50:410–25. https://doi.org/10.1007/s40098-019-00375-5.

[8] Abdolrezayi A, Khayat N. Comparative Three-Dimensional Finite Element Analysis of Piled Raft Foundations. Comput Eng Phys Model 2021;4:19–36.

[9] Madhav MR. Efficiency of pile groups in tension. Can Geotech J 1987;24:149–53. https://doi.org/10.1139/t87-014.

[10] Hanna AM, Morcous G, Helmy M. Efficiency of pile groups installed in cohesionless soil using artificial neural networks. Can Geotech J 2004;41:1241–9. https://doi.org/10.1139/t04-050.

[11] Shanker K, Basudhar PK, Patra NR. Uplift Capacity of Pile Groups Embedded in Sands: Predictions and Performance. Soils Found 2006;46:605–12. https://doi.org/10.3208/sandf.46.605.

[12] Taghavi A, Muraleetharan KK. Analysis of Laterally Loaded Pile Groups in Improved Soft Clay. Int J Geomech 2017;17:04016098. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000795.

[13] Chawhan BS, Quadri SS. Experimental and Numerical Investigations of Laterally Loaded Pile Group in Multilayered Cohesionless soil. Comput Eng Phys Model 2018;1:28–45.

[14] Yin F, Zhou H, Liu H, Chu J. Experimental and Numerical Analysis of XCC Pile-Geogrid Foundation for Existing Expressway Under Traffic Load. Int J Civ Eng 2018;16:1371–88. https://doi.org/10.1007/s40999-017-0267-7.

[15] Gatto MPA, Montrasio L. Analysis of the Behaviour of Very Slender Piles: Focus on the Ultimate Load. Int J Civ Eng 2021;19:145–53. https://doi.org/10.1007/s40999-020-00547-y.

[16] Comodromos EM, Anagnostopoulos CT, Georgiadis MK. Numerical assessment of axial pile group response based on load test. Comput Geotech 2003;30:505–15. https://doi.org/10.1016/S0266-352X(03)00017-X.

[17] Küçükarslan S, Banerjee PK. Behavior of axially loaded pile group under lateral cyclic loading. Eng Struct 2003;25:303–11. https://doi.org/10.1016/S0141-0296(02)00152-9.

[18] Rose AV, Taylor RN, El Naggar MH. Numerical modelling of perimeter pile groups in clay. Can Geotech J 2013;50:250–8. https://doi.org/10.1139/cgj-2012-0194.

[19] Banerjee S, Shirole ON. Numerical Analysis of Piles Under Cyclic Lateral Load. Indian Geotech J 2014;44:436–48. https://doi.org/10.1007/s40098-013-0092-0.

[20] Albusoda BS, Al-Saadi AF, Jasim AF. An experimental study and numerical modeling of laterally loaded regular and finned pile foundations in sandy soils. Comput Geotech 2018;102:102–10. https://doi.org/10.1016/j.compgeo.2018.06.007.

[21] Abhishek, Sharma RK. A Numerical Study of Granular Pile Anchors Subjected to Uplift Forces in Expansive Soils Using PLAXIS 3D. Indian Geotech J 2019;49:304–13. https://doi.org/10.1007/s40098-018-0333-3.

[22] Koteswara VRP, Padavala H, Chennarapu H. Experimental and Numerical Investigation of Pile Group With and Without Building Frame Subjected to Axial Load. Indian Geotech J 2020;50:473–84. https://doi.org/10.1007/s40098-019-00383-5.

[23] Bunyamin S, Aghayan S. Settlement Modelling of Raft Footing Founded on Oferekpe/Abakaliki Shale in South East Region of Nigeria. Comput Eng Phys Model 2018;1:68–82.

[24] Smith IM, Griffiths DV, Margetts L. Programming the finite element method. John Wiley & Sons; 1982.

[25] Koiter WT. General theorems for elastic plastic solids. Prog Solid Mech 1960:167–221.

[26] Van Langen H, Vermeer PA. Automatic step size correction for non-associated plasticity problems. Int J Numer Methods Eng 1990;29:579–98. https://doi.org/10.1002/nme.1620290308.

[27] Schanz T, Vermeer PA, Bonnier PG. The hardening soil model: formulation and verification. Beyond 2000 Comput. Geotech., Routledge; 2019, p. 281–96.

[28] Rahman SMS. Modelling deep mixing on the passive side of a deep excavation in soft soil-A pilot study to evaluate the effect of lime-cement columns on the passive side of excavation in soft soil 2020.

[29] Fang H-Y. Foundation engineering handbook. Springer Science & Business Media; 1974.

[30] Teng WC. Foundation Design, First Edition, India. 1981.

[31] Table from das, 1994, 12 December 2019 n.d.

[32] Arora KR. Soil Mechanics and Foundation Engineering, Sixth Edition, Standard Publishers Distributors, Delhi-110006 n.d.

[33] Bangladesh National Building Code (BNBC) 2006.

[34] United States Army Corps of Engineers (USACE) EM 111O-1-1904.