BEHAVIOUR OF PILE GROUPS UNDER LATERAL LOADS

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BEHAVIUOR OF PILE GROUPS UNDER LATERAL LOADS

submitted by **ANIL ERCAN** in partial fulfillment of the requirements for the degree of **Master of Science in Civil Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen ____________________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Güney Özcebe ____________________
Head of Department, **Civil Engineering**

Prof Dr. Orhan Erol ____________________

Supervisor, **Civil Engineering Dept., METU**

Examining Committee Members:

Prof. Dr. Erdal Çokça ____________________
Civil Engineering Dept., METU

Prof. Dr. Orhan Erol ____________________
Civil Engineering Dept., METU

Prof. Dr. Kemal Önder Çetin ____________________
Civil Engineering Dept., METU

Asst. Prof. Dr. Nejan Huvaj Sarıhan ____________________
Civil Engineering Dept., METU

Dr. Özgür Kuruoğlu ____________________
Yüksel Proje

Date: 28.04.2010

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name : ANIL ERCAN

Signature :

ABSTRACT

BEHAVIOUR OF PILE GROUPS UNDER LATERAL LOADS

Ercan, Anıl

M.S., Department of Civil Engineering

Supervisor: Prof Dr. Orhan Erol

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To investigate the lateral load distribution of each pile in a pile group, the bending moment distribution along the pile and the lateral group displacements with respect to pile location in the group, pile spacing, pile diameter and soil stiffness three dimensional finite element analysis were performed on 4x4 pile groups in clay. Different Elatic Modulus values, pile spacings, pile diameters and lateral load levels used in this study. In the analysis PLAXIS 3D Foundation geotechnical finite element package was used. It is found that, lateral load distribution among the piles was mainly a function of row location in the group independent from pile spacing. For a given load the leading row piles carried the greatest load. However, the trailing row piles carried almost the same loads. For a given load, bending moment values of the leading row piles were greater than the trailing row piles. On the other hand, as the spacing increased group displacements and individual pile loads decreased under the same applied load. However, this behavior was seen more clearly in the first and the second row piles. For the third and the fourth row piles, pile spacing became a less significant factor affecting the load distribution. It is also found that, pile diameter and soil stiffness are not significant factors on lateral load distribution as row location and pile spacing.

Keywords: Piles; Pile Groups; Pile Spacing; Finite Element

ÖZ

KAZIK GRUPLARININ YANAL YÜKLER ALTINDAKİ DAVRANIŞI

Ercan, Anıl

Yüksek Lisans, İnşaat Mühendisliği Bölümü

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Nisan 2010, 123 sayfa

Araştırma konusu kil içerisindeki 4x4 kare kazık grupları için, verilen yanal yükler altında kazıklardaki yük, moment dağılımlarının ve grup deplasmanlarının kazıkların grup içerisindeki yerleşimi, kazık ara mesafesi, kazık çapı ve zemin rijitliğine bağlı olarak nasıl etkilendiği amacına yöneliktir. Analizler; farklı deformasyon modül değerleri, kazık aralıkları, kazık çapları ve yanal yük değerleri kullanılarak, sonlu elemanlar yöntemi ile 3 boyutlu olarak gerçekleştirilmiştir. Analizlerde "PLAXIS 3D Foundation" sonlu elemanlar programı kullanılmıştır. Yapılan çalışmalar sonucunda, yanal yük dağılımının büyük oranda kazıkların grup içerisindeki yerleşimine bağlı olduğu görülmüştür. Kazıkların sıra içerisindeki yerleşiminin ise yük dağılımını daha az etkilediği gözlemlenmiştir. Aynı yanal yük altında ilk sıra kazıkların diğerlerine orana daha fazla yük taşıdığı, fakat ikinci, üçüncü ve dördüncü sıra kazıkların taşıdıkları yüklerin ise birbirlerine çok yakın oldukları görülmüştür. Her bir kazık için kazık boyunca moment dağılımları incelenmiştir ve yük dağılımlarıyla benzer şekilde ilk sıra kazıkların eğilme moment değerlerinin diğer sıra kazıklara oranla daha yüksek olduğu görülmüştür. Bunun yanında, kazık aralıkları arttıkça kazık gruplarında meydana gelen deplasmanların ve kazıkların taşıdıkları yüklerin azaldığı gözlemlenmiştir. Fakat bu davranışın ilk iki sıra kazık için daha belirgin olduğu sonucuna ulaşılmıştır. Bunların yanı sıra, kazık çapındaki ve zemin deformasyon modülündeki değişimin, kazıklar arası yük dağılımda daha az etkili olduğu gözlemlenmiştir.

Anahtar Kelimeler: Kazıklar; Kazık Grupları; Kazık Aralığı; Sonlu Elemanlar

To My Family...

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CHAPTER 1

INTRODUCTION

1.1 Theoretical Background

Many structures need deep foundations in order to utilize the bearing capacity of deeper and stronger soil layers. Group piles are one particular type of deep foundations most widely-used for high structures. In addition to the vertical loads that must be carried by the piles, lateral loads may be present and must be considered in design. These lateral loads can be caused by a variety of sources such as earthquakes, high winds, wave action, ship impact, liquefaction, and slope failure.

With respect to their use in practice, piles under lateral loads are termed active piles or passive piles. An active pile is loaded principally at its top in supporting a superstructure such as a brigde. However, a passive pile is loaded principally along its length due to earth pressure, such as piles used as a retaining wall in a moving slope.

The nature of the loading and the kind of soil around the pile, are major factors in determining the response of an isolated single pile and the pile groups. According to active loading at the pile head, four types can be identified: static loading, cyclic loading, sustained loading and dynamic loading. Besides, passive loadings can occur along the pile length due to moving soil, when a pile is used as an anchor.

The curve in Figure 1.1 illustrates the case for a particular value of z where a static loading is applied to a pile. Although this type of loading is encountered seldom in practice, static curves are very useful since:

1- Analytical procedures can be used to develop expressions to correlate with some portions of the curves,

2- The curves serve as a baseline for demonstrating the effects of other types of loading, and

3- The curves can be used for sustained loading for some clays and sands. (Reese and Impe; Single Piles and Pile Groups under Lateral Loading; 2001)

Piles are most widely used in groups as shown in Figure 1.2. The models that are used for the group piles should reply to two problems:

1- The group efficiency of closely-spaced piles that are loaded laterally

2- Load distribution of individual piles in a group.

In the first case the forces are transmitted through the soil, however, in the second case the forces are transmitted by the pile cap. In widely spaced pile groups the pile-soil-pile interaction is inconsiderable and a solution is made in order to reveal lateral load to each of the piles in the group.

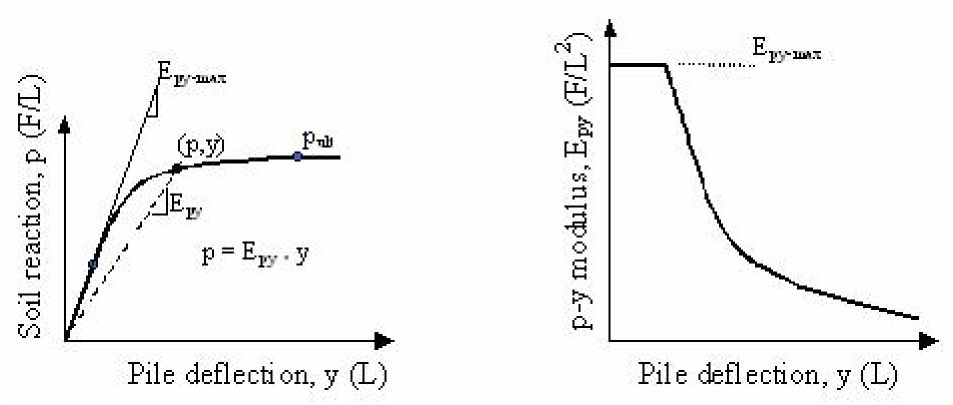


Figure 1.1 Typical p-y curve and resulting soil modulus

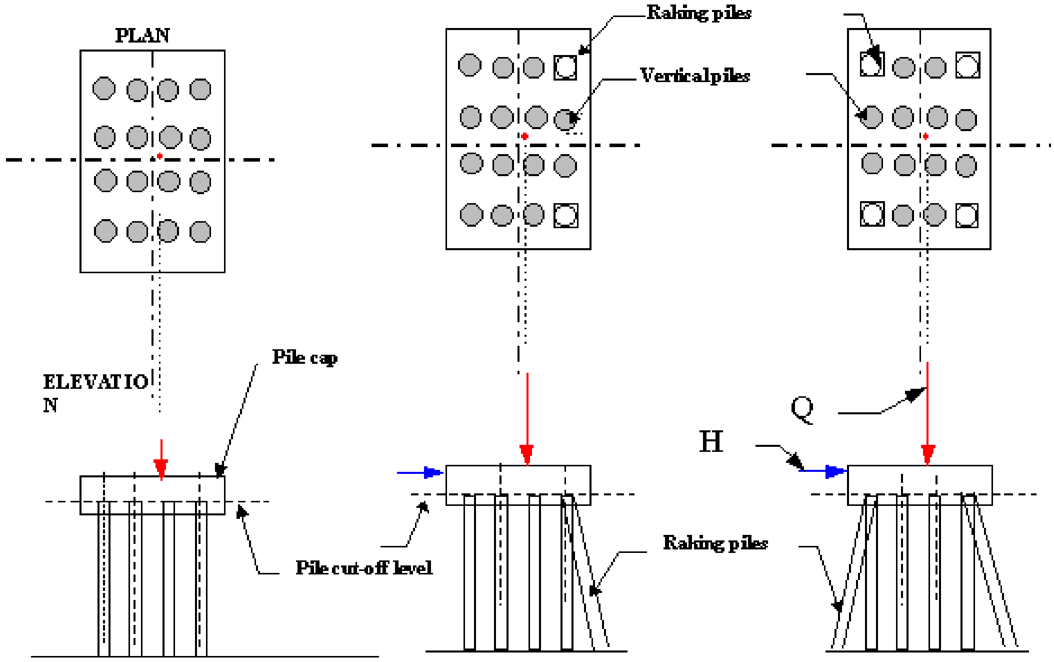


Figure 1.2 Basic formation of pile groups

1.2 Research Objective

The aim of the study is to explore the effect of pile spacing, soil stiffness and the load level on the load distribution of each pile in a pile group, bending moment along the pile and the group displacements of the 4x4 pile groups in clay. A numerical study on these factors using finite element analysis on different cases of pile groups have been performed.

1.3 Scope of the Study

Following this introduction,

Chapter 2 presents an extensive literature review on the laterally loaded pile groups. Full-scale and small-scale tests are illustrated first and then numerical solutions are discussed.

Chapter 3 gives details of the numerical modeling. It defines the assumed pile group arrangement and the pile and pile cap properties. Soil profile and soil parameters are defined. Then, details regarding finite element model are given. The chapter is concluded by presenting the material properties and construction stages used in the analysis.

Chapter 4 includes the discussion of the results. For the static lateral loading, effect of pile spacing on load distribution of each pile in a pile group is discussed and FEM results are illustrated graphically

Chapter 5 presents major research findings and conclusions.

CHAPTER 2

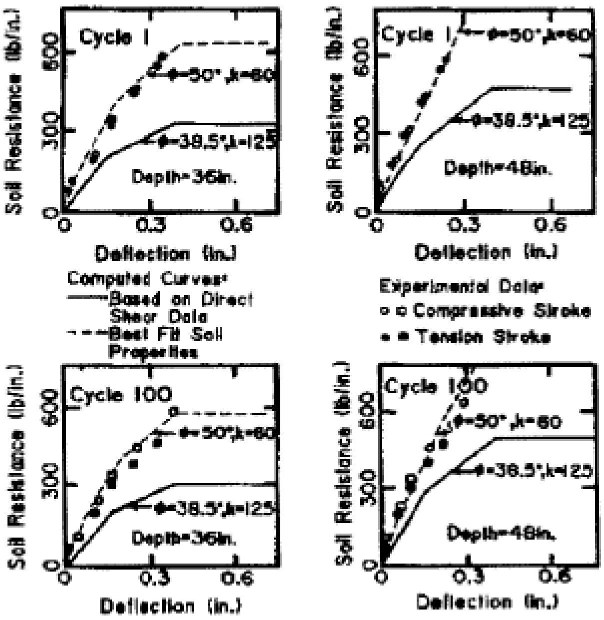
LITERATURE REVIEW

2.1 Introduction

In literature, there are number of studies which deal with the laterally loaded pile groups. These studies generally consist of two basic types, namely load tests (full-scale and model tests) and numeraical solutions. Tests have been performed since 1920's and provide a body of information concerning laterally loaded pile groups. Full-scale tests are generally believed to provide the most accurate results but, are rare due to the high costs. Therefore, many studies are available concerning centrifuge and model testing. Evaluation of laterally loaded pile groups has also been performed using numerical models. In many studies, the results of the computer analyses that were performed using finite element approach, were compared with the limited full-scale tests results. Most of these computer analyses were performed in 3D Finite Elemet Programs, rather than 2D modelling. In this chapter, results of previous research in these areas will be discussed and summarized.

2.2 Full-Scale Tests

A study was carried out by Brown et al. (1988) in order to determine lateral load behaviour of pile group in sand. In their study, a full-scale test was conducted on a 3x3 pile group in medium sand underlain by very stiff clay. The relative density of sand (D_r) is determined as 50%. Tests were performed



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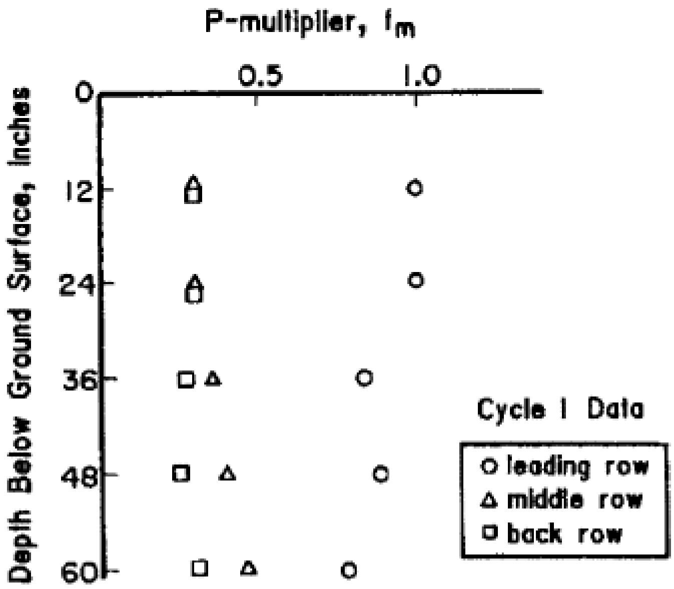


(b)

Figure 2.1 (a) Comparison of experimental and computed p-y curves for a single pile (b) experimental p-multipliers (f_m) vs. depth (Brown et al., 1988) on nine closed-ended steel pipe piles that have 273mm of outer diameter and 9.27mm of wall thickness. The pile group was spaced at 3D on centers. Both pile group and a single isolated pile were subjected to two-way cyclic lateral loading.

Brown et al. (1988) concluded that the pile group “was observed to deflect significantly more than the isolated single pile when loaded to similar average load per pile.” Moreover, the row position had an effect on the efficiency of the individual piles. The front row (leading row) piles exhibited stiffer responses than the trailing rows (second and third row). However, no pattern was observed of the pile position within a given row. The “shadowing” effect was more considerable in sand compared to the clay as was mentioned in Brown et al. (1987). However, when piles were under two-way cyclic loading, group effects were still significant in sand, unlike the reduced significance of “shadowing” with cyclic loading that was observed in clay.

The p-y curves were generated and typical p-y curves generated for single pile are shown in Figure 2.1a. Moreover, p-multipliers concept was introduced and this curve modified to group pile p-y curve for different depths and the results are presented in Figure 2.1 b. As a result, Brown et al. (1988) suggested p-multiplier values for the front, middle and back rows 0.8, 0.4 and 0.3 respectively.

Another study was conducted by Rollins et al. (1998) in order to investigate the lateral load behaviour of pile groups in clay. Full-scale tests were performed on a 3x3 pile group spaced at 2.82D with a pinned-head connection in soft to medium-stiff clays overlaying dense sand. Moreover, in order to provide a comparison, a single pile test was performed. For the tests, closed-end steel pipe piles with an inner diameter of 0.305m and 9.5mm wall thickness were chosen.

Rollins et al. (1998) concluded that, pile group deflection turned out to be more than two times the single pile deflection for the same load level. In order to provide a match between computed and measured results, the p-multipliers method approach was used. As a result, Rollins et al. (1998) suggested p-multiplier values for the front, middle and back rows 0.6, 0.38 and 0.43 respectively.

Rollins et al. (2006) conducted another study to investigate group interaction effects with respect to the pile spacing on laterally loaded pile groups. In order to evaluate the behaviour, full-scale cyclic lateral load tests were performed on 3x5, 3x4 and 3x3 pile groups in stiff clay with 3.3D, 4.4D and 5.65D pile spacing respectively, as shown in Figure 2.2. The soil profile generally consists of stiff clay layers with sand layers that were in a medium compact density state (D_r=60%), to a depth of 5m. These soils were underlain by sensitive clay, silty clay and sand layers. Similar to the other studies, lateral load tests were performed on single piles in order to provide comparison to the pile group test results. For the tests, closed-end steel pipe piles with an outer diameter of 0.324m and 9.0mm wall thickness were chosen.

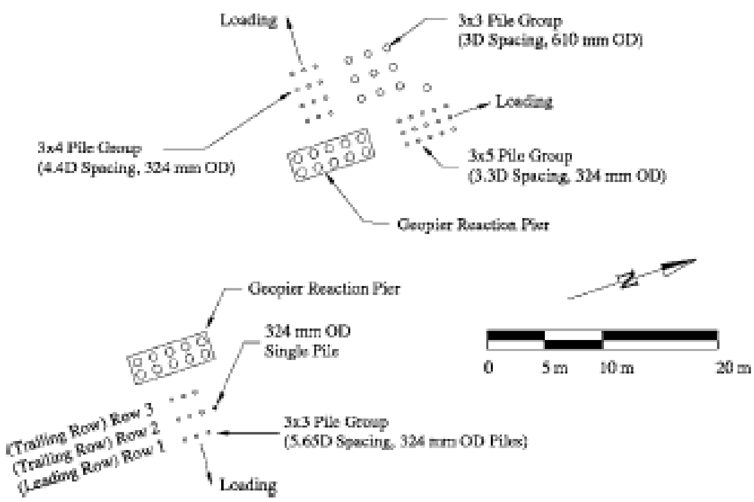
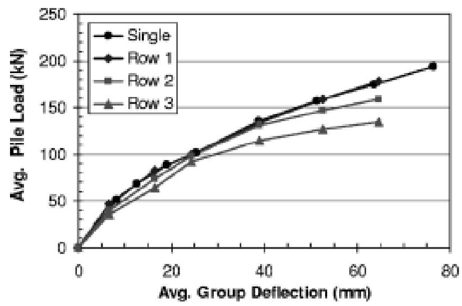


Figure 2.2 Layout of single piles and pile groups (Rollins et al., 2006)



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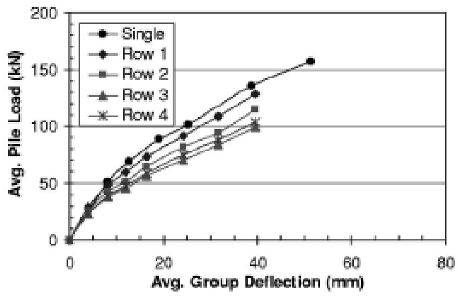

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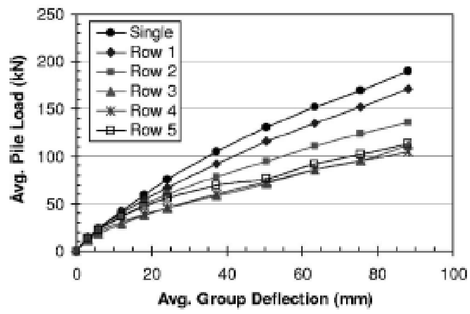


(c)

Figure 2.3 Average pile load-deflection curves for each rowin: (a) 3x3 pile group at 5.65D spacing; (b) 3x4 pile group at 4.4D pile spacing; (c) 3x5 pile group at 3.3D pile spacing compared with the single pile test curve (Rollins et al., 2006)

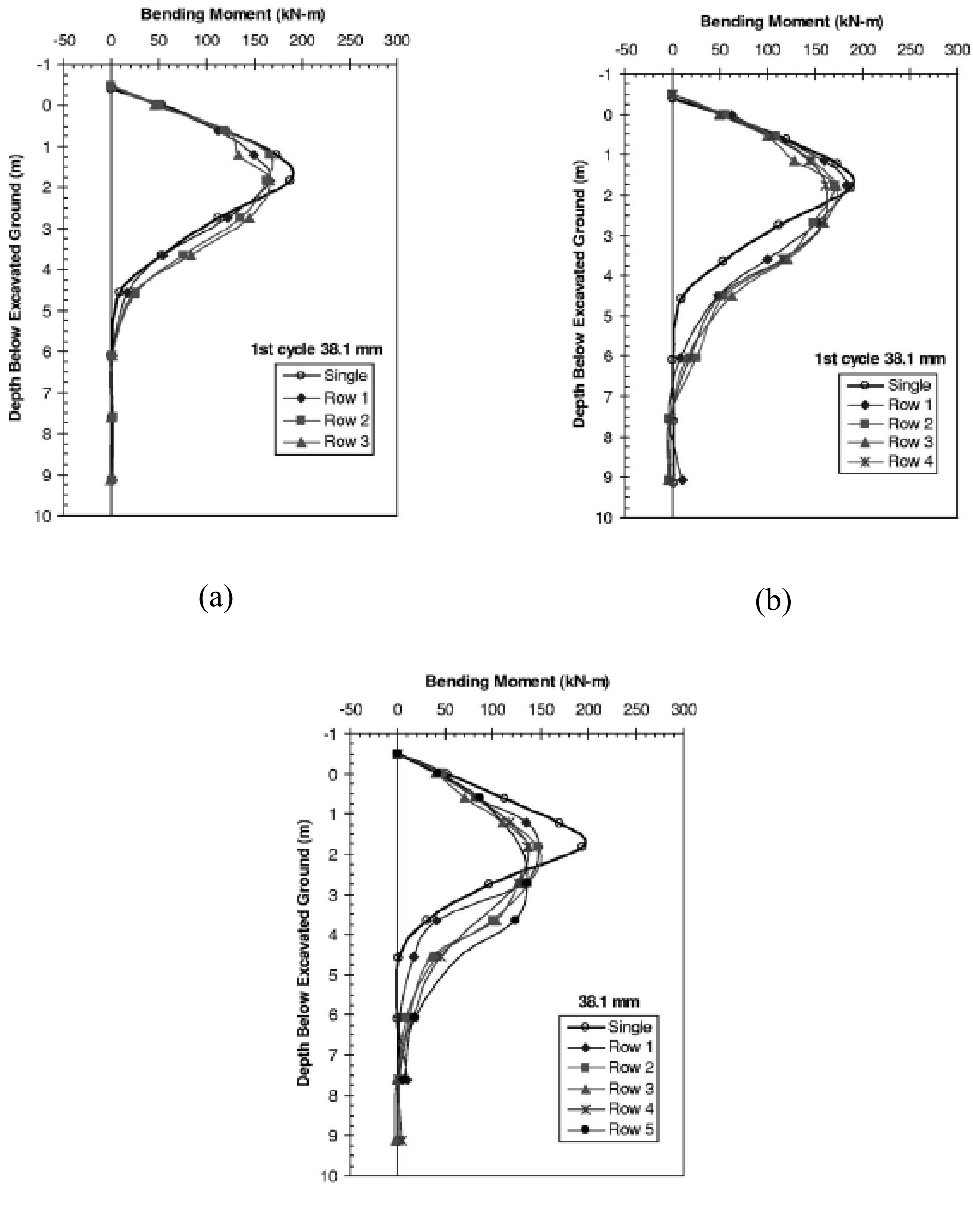
Rollins et al. (2006) concluded that, lateral load resistance was a function of pile spacing. While decreasing the pile spacing from 5.65D to 3.3D, group interaction effects became progressively more important. Furthermore, as it can be seen from Figure 2.3, the leading row (1st row) piles in the group carried the greatest load, while the trailing row piles (second, third, fourth and fifth row piles), carried smaller loads for the same displacement level. For these pile groups driven in clay, row location within the group had more significant effect on the lateral resistance than the location within a row. Figure 2.4 illustrates the bending moment distribution for each row piles and it is concluded that, for the same load level, the maximum moment in the trailing row piles were greater than in the leading row piles, due to the group interaction effects.

2.3 Small-Scale Tests

Small-scale tests generally consist of two types. These are the ones which utilized a centrifuge and those that did not. The first section will discuss centrifuge model tests and their results, and second section will discuss the other small-scale tests results.

2.3.1 Centrifuge Testing

Centrifuge test is one of the most widely-used methods of conducting a model test. The basic theory behind centrifuge modeling is “similitude” as well as “increased gravitational forces” (Gerber, 2003). Ilyas et al. (2004) shows a sketch of the model setup as shown in Figure 2.5. During the test, a model is accelerated about an axis until the inertial forces reach to the gravitational forces experienced by the prototype. The reduced cost of the test and the ability to repeat tests with different parameters for comparison, are the major advantages of this test. However, the difficulty in scaling is the major disadvantage of this small-scale method (Gerber, 2003).



(a) (b)

(c)

Figure 2.4 Average pile load-deflection curves for each rowin: (a) 3x3 pile group at 5.65D spacing; (b) 3x4 pile group at 4.4D pile spacing; (c) 3x5 pile group at 3.3D pile spacing compared with the single pile test curve (Rollins et al., 2006)

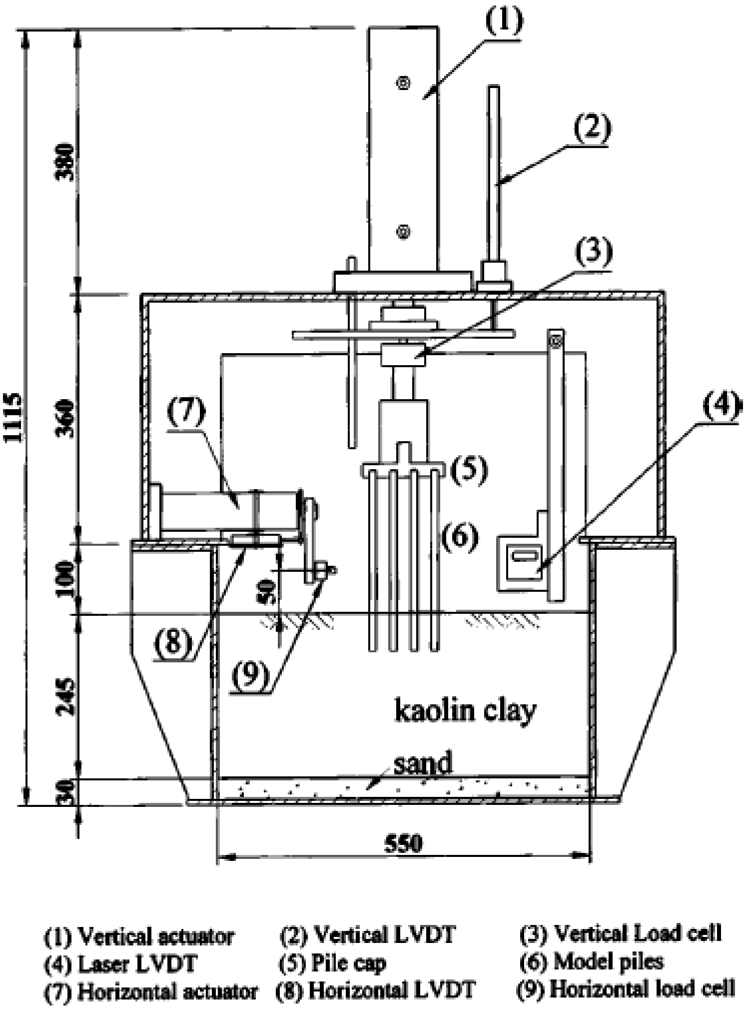


Figure 2.5 Sketch of the Model Setup

(Ilyas et al., 2006)

A study was carried out by Barton (1984) in order to determine the response of pile groups to lateral loading in the centrifuge. In tests, piles having diameters that ranged from 9.5mm to 16mm that corresponds to prototype diameters from 0.95m to 1.60m were used. During the tests, centrifugal acceleration varied from 30g to 120g. Tests were conducted on both single piles and pile groups of two, three and six piles with spacing of 2D, 4D and 8D.

In order to determine the group effects, interaction factors proposed by Poulos (1971) were used in the analysis. The research was aimed mainly to evaluate the accuracy of the elastic methods of analysis and determine the necessity of non-linear analysis on model pile group response.

Barton (1984) concluded that the elastic method actually under-estimates pile group interactions at a very close spacing. However, at a larger spacing this method over-estimates the interaction factors. This shows that, soil non-linearity has a significant affect on the strain field around a laterally loaded pile even at small strains. Barton (1984), also concluded that the "experimentally derived factors for pairs of piles can be superimposed to give a good prediction of the overall interaction factors for larger groups of piles."

Another study was carried out by McVay et al. (1998) in order to evaluate the behaviour of laterally loaded pile groups in sand. Tests were conducted on 3x3 and 7x3 pile groups with 3D pile spacing. Moreover, single piles were tested in order to provide comparison.

McVay et al. (1998) used p-multipliers method in order to predict the lateral load behaviour of pile group. McVay et al. (1998) concluded that group response and p-multiplier approach is independent of soil density, but mainly a function of group geometry and row position. Table 2.1 shows the p-multipliers suggested by McVay et al (1998) for each row.

Table 2.1 Relations Suggested p-multipliers for laterally loaded pile groups (McVay et al., 1998)

Row position (1)	Three rows (2)	Four rows (3)	Five rows (4)	Six rows (5)	Seven rows (6)
Lead row	0.8	0.8	0.8	0.8	0.8
Second row	0.4	0.4	0.4	0.4	0.4
Third row	0.3	0.3	0.3	0.3	0.3
Fourth row	—	0.3	0.2	0.2	0.2
Fifth row	—	—	0.3	0.2	0.2
Sixth row	—	—	—	0.3	0.2
Seventh row	—	—	—	—	0.3

Lateral load tests were performed in centrifuge in order to determine the group effects by Remaud et al. (1998). Tests were conducted on a free-headed model two-pile groups arranged at pile spacings of 2D and 6D. AU4G aluminium hollow piles having 18mm outer diameter, 1.5mm wall thickness and 380mm length were used during tests. These dimensions correspond to prototype piles having 720mm outer diameter, 60mm wall thickness and 15.20m length. The soil profile generally consists of Fontainebleau sand with a unit-weight of 16.3kN/m^3.

Remaud et al. (1998) developed p-y curves using the bending moment profiles. When the pile groups having different pile spacings were compared, group effect was seen more clearly at the pile group having 2D spacing. The group resistance decreased 20% for 2D spacing, however, pile group with 6D spacing showed 5% resistance decrease. Moreover, at 2D spacing, the p-y curve on the trailing pile was 50% of a single pile reaction but this value was reached to 93% for 6D spacing. On the other hand, the bending moments of the front row pile was almost the same with the isolated single pile.

Much of the centrifuge model studies on laterally loaded pile groups were conducted with soil profile consist of sand layers. Ilyas et al. (2004) is one of the relatively few studies on laterally loaded pile groups in clay. Centrifuge model tests were performed both in normally consolidated and overconsolidated kaolin clay. The piles were arranged symmetrically and the groups consist of 2, 2x2, 2x3, 3x3, and 4x4 piles with 3^{Δ} and 5^{Δ} ($^{\Delta}$= pile width) spacing. In tests, hollow aluminium square tube piles having 12mm width and 260mm length were used. These model piles correspond to the prototype piles having 840mm width and 18.20m length. All the tests were performed at 70g on the National University Singapore Geotechnical Centrifuge.

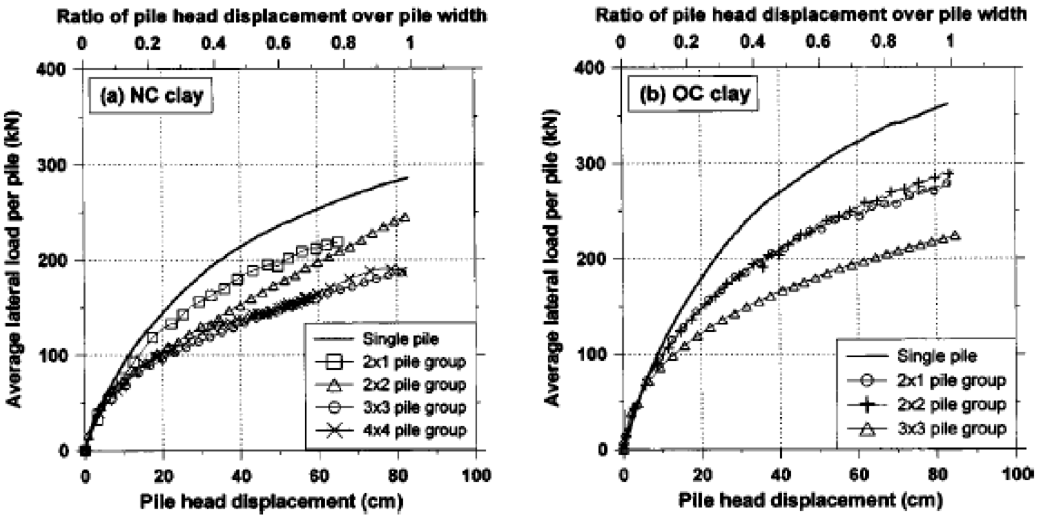
Ilyas et al. (2004) concluded that, while increasing the number of piles in group, the average lateral load per pile decreased. As Figure 2.6 illustrates clearly, for piles installed in overconsolidated clay, the reduction of group effect was less clear than for piles installed in normally consolidated clay. Furthermore, for pile groups having 3^{Δ} centre-centre pile spacing installed both in normally consolidated clay and overconsolidated clay, group effect decreased as the number of piles increased. However, for larger spasings (5^{Δ}), group effect became recessive.

Ilyas et al. (2004) also concluded that, the “shadowing” effect was occured on lead piles over trailin piles and this effect increased as the number of piles in group increased. Thus, higher lateral loads were carried by the lead row piles. When the average load per pile was compared among the piles within a row, the centre piles carried much less load and bending moment than the outer piles.

2.3.2 Other Model Tests

A study was conducted by Cox et al. (1984) in order to determine the behaviour of laterally loaded pile groups in very soft clay. Tests were performed on both single piles and group piles to provide a comparison. The pile groups consist of three and five piles with a clear spacing of 0.5D, 1D, 2D, 3D and 5D. Piles were arranged both in side-by-side and in-line configuration. In side-by-side configuration, loading was perpendicular to the line of the piles. However, in in-line configuration, loading was parallel to the line of piles. For the tests, steel pipe piles having a wall-thickness of 0.71mm were chosen and the soil was inorganic clay of high plasticity (PI = 40).

Cox et al. (1984) concluded that 2D or 3D clear pile spacing was enough to produce resistance to match that of a single pile in side-by-side configuration. For the in-line configuration, the load distribution depended on the pile group horizontal displacement and the group efficiency decreased with the increase of number of in-line piles from three to five. About 5D and 6D clear spacing was enough to 100% group efficiency as illustrated in Figure 2.7..



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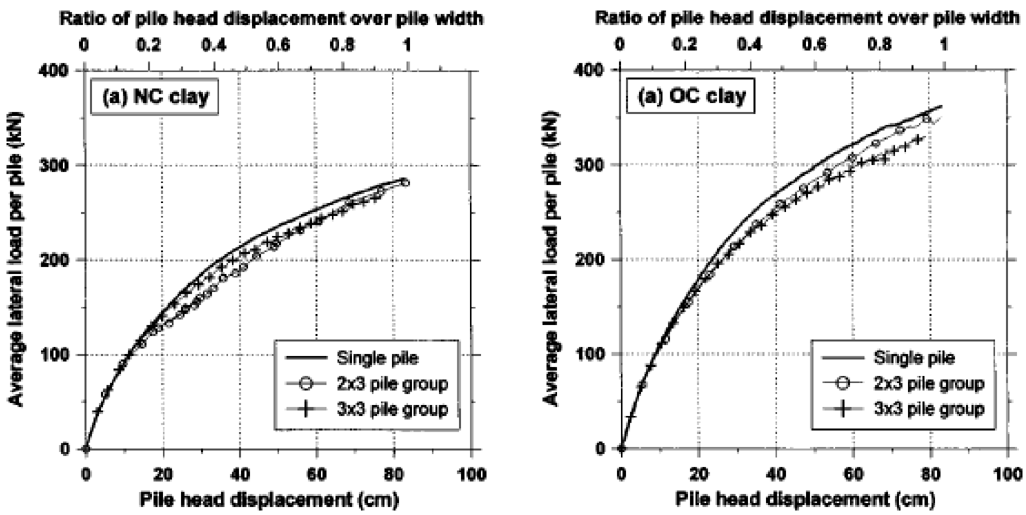


(b)

Figure 2.6 Average lateral load-pile displacement response (a) for pile groups with 3^{Δ} spacing (b) for pile groups with 5^{Δ} spacing ($^{\Delta}$= pile width) (Ilyas et al.,2004)

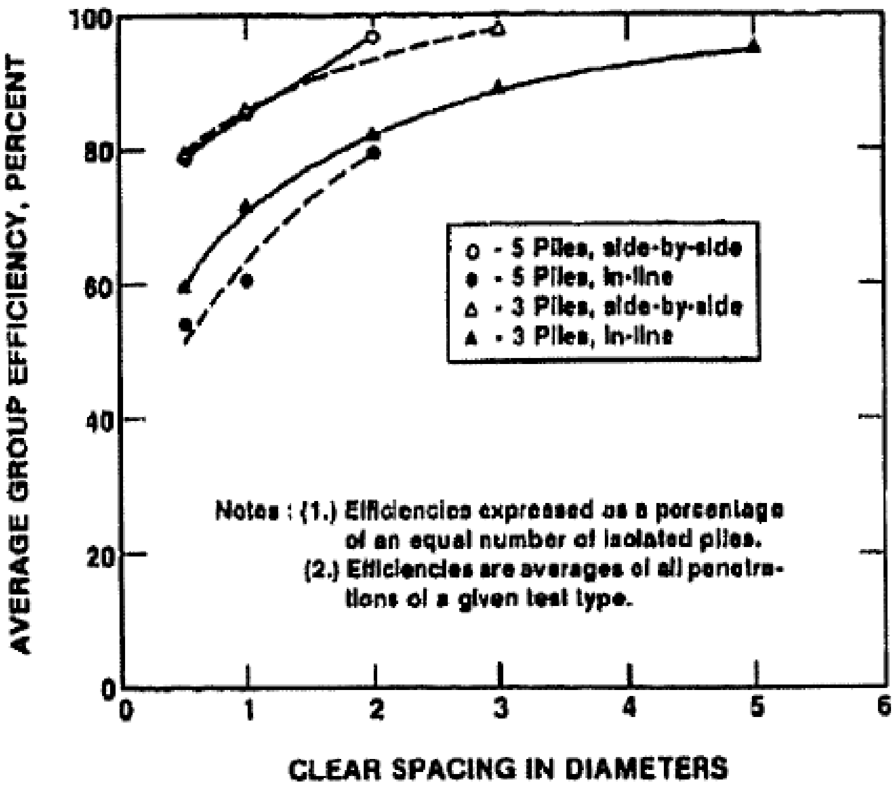


Figure 2.7 Measured group efficiencies versus clear spacing for both in-line and side-by-side configurations (Cox et al., 1984)

Another study was conducted by Rao et al. (1998) in order to determine the influence of rigidity on laterally loaded pile groups in marine clay. In tests, marine clay deposits of India that had a PI of 30 were used. As Rao et al. (1998) suggested that pile-fixity condition is closer to a free-headed configuration, the piles were fixed to a pile cap which was a thin aluminum plate. In tests, aluminum and mild steel pipe piles with different diameters and embedment ratios (L/D) were used. 1x2, 2x3 and 1x4 pile groups were loaded both in series and in parallel. In series loading, the groups were loaded parallel to the pile line. However, in parallel loading, the groups were loaded perpendicular to the pile line.

In this study finite element method (FEM) analysis was also used for comparison. The piles were defined as shear beams, and the pile cap or aluminum plate was defined as a thin plate that connected the pile heads. The results were compared as shown in Figure 2.8.

Rao et al. (1998) concluded that pile groups of short and rigid piles showed greater resistance when loaded in parallel than in series, which means that strength of the soil was more effective on the rigid pile deflection. However, pile groups of long and flexible piles showed greater resistance when loaded in series, which means that pile strength was more effective.

Patra and Pise (2001) conducted a study on ultimate lateral resistance of pile groups in sand. In this study both single piles and group piles of 2x1, 3x1, 2x2, and 3x2 configurations with 3D to 6D pile spacings were tested. Aluminum alloy pipes having an outer diameter of 19mm and a wall thickness of 0.81mm were used as model piles. Length to diameter ratios of the piles were equal to 12 and 38. The soil profile generally consisted of dry Ennore sand from Chennai, India. In this study soil-pile friction angle was another variable. The tests were repeated for $\delta = 20°$ and $\delta = 31°$.

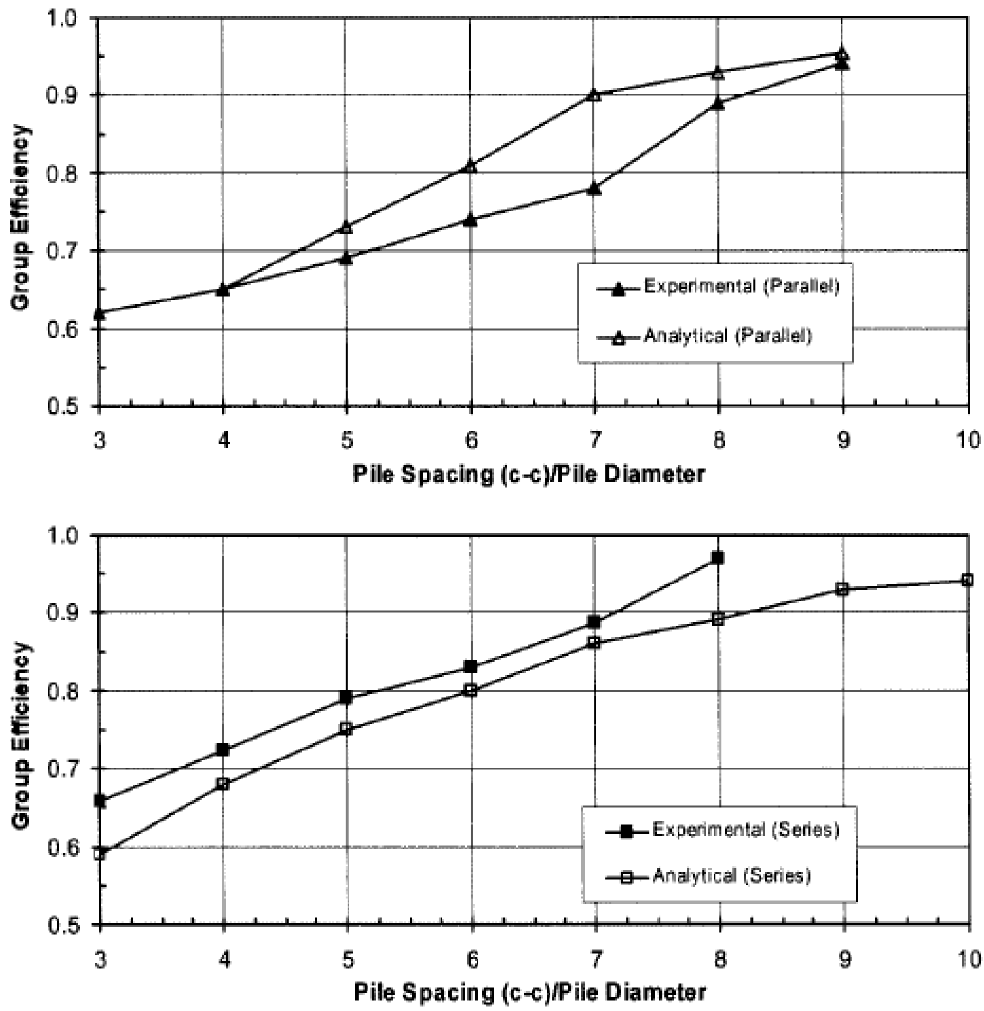


Figure 2.8 Comparison of group efficiencies for series and parallel loading configurations (Rao et al., 1998)

Approaches developed by Meyerhof et al. (1981), and Prasad and Chari (1999) were used to compare the experimental results and observations of Patra and Pise (2001). The predicted values of the ultimate lateral resistance for single and group piles are presented in Table 2.2 and Table 2.3 with the values observed by Meyerhof et al. (1981), and Prasad and Chari (1999). The results observed by Patra and Pise (2001) were in close agrrement with the values predicted by Meyerhof et al. (1981), and Prasad and Chari (1999). As shown in Table 2.2, Meyerhof et al. (1981) and Prasad and Chari (1999) underestimates the single pile capacity. However, as shown in Table 2.3, Meyerhof et al. (1981) overestimates the group capacity.

2.4 Numerical Solutions

A study was conducted by Bransby and Springman (1995) in order to evaluate the short-term behaviour of group piles when subjected to lateral loading occurred by deformation of a clay layer under an adjacent surcharge load as shown in Figure 2.9, using three dimensional finite element analysis. The objective of the analysis was to search on the pile-clay interaction behaviour.

The geometry modelled in this study was the same geometry modelled in centrifuge tests performed by Bransby (1995) in order to provide a comparison. As illustrated in Figure 2.10, the pile group consisted of two infinitely long rows. Piles having 1.27m diameter and 19m length, were embedded in a 6m layer of clay overlying dense sand. There was a 5m distance between the rows and the piles were at a center-center spacing of 6.67m along the row. The pile cap had a 9m of width and 1m of thickness and it was considered to be rigid. Over the clay layer, there was a 1m layer of sand that applied a uniform surcharge of 17kPa. However, the increasing uniform vertical surcharge load was applied 1m away from the pile cap to the surface.

Table 2.2 Comparison of Ultimate Lateral Resistance of Single Pile
(Patra and Pise, 2001)

Single pile	Meyerhof et al.'s approach (1981) (N)	Prasad and Chari's approach (1999) (N)	Writers' approach (N)	Writers' observed values (N)
$^{\Lambda}/_{\delta}$ = 12	28.4	25.4	42.3 (δ = 20°) 57.8 (δ = 31°)	40 (δ = 20°) 50 (δ = 31°)

Table 2.3 Comparison of Ultimate Lateral Resistance of 2x2 Pile Groups
(Patra and Pise, 2001)

2 × 2 pile group, δ = 31°	Spacing	Meyerhof et al.'s approach (1981) (N)	Writers' approach (N)	Writers' observed values (N)
$^{\Lambda}/_{\delta}$ = 12	3^{δ}	173.8	130	150
	4.5^{δ}	259.3	140	170
	6^{δ}	350	150	200
$^{\Lambda}/_{\delta}$ = 38	3^{δ}	611.6	600	600
	4.5^{δ}	912	634	700
	6^{δ}	1,223.2	668	800

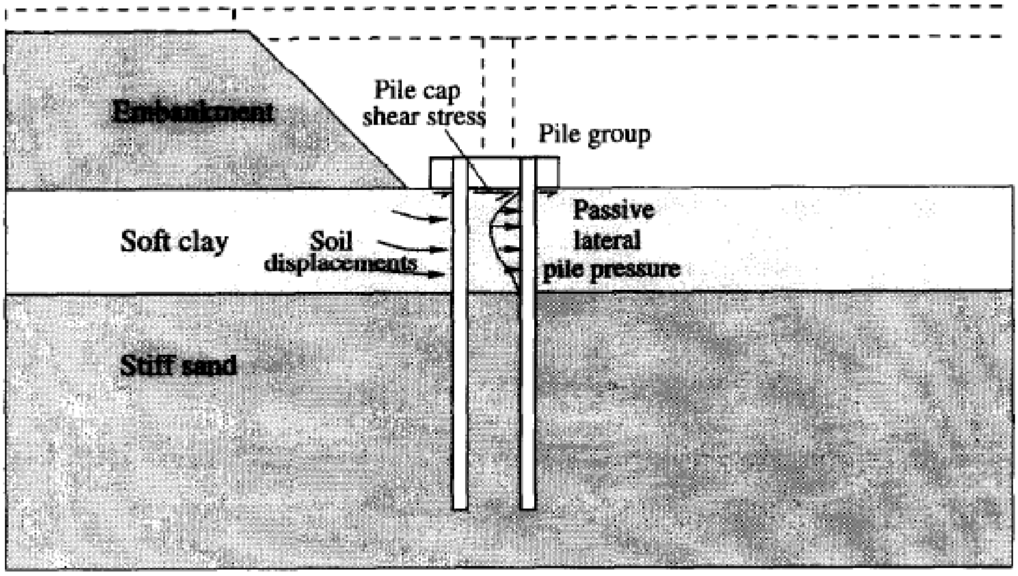


Figure 2.9 Surcharge loading adjacent to a pile group
(Bransby and Springman, 1995)

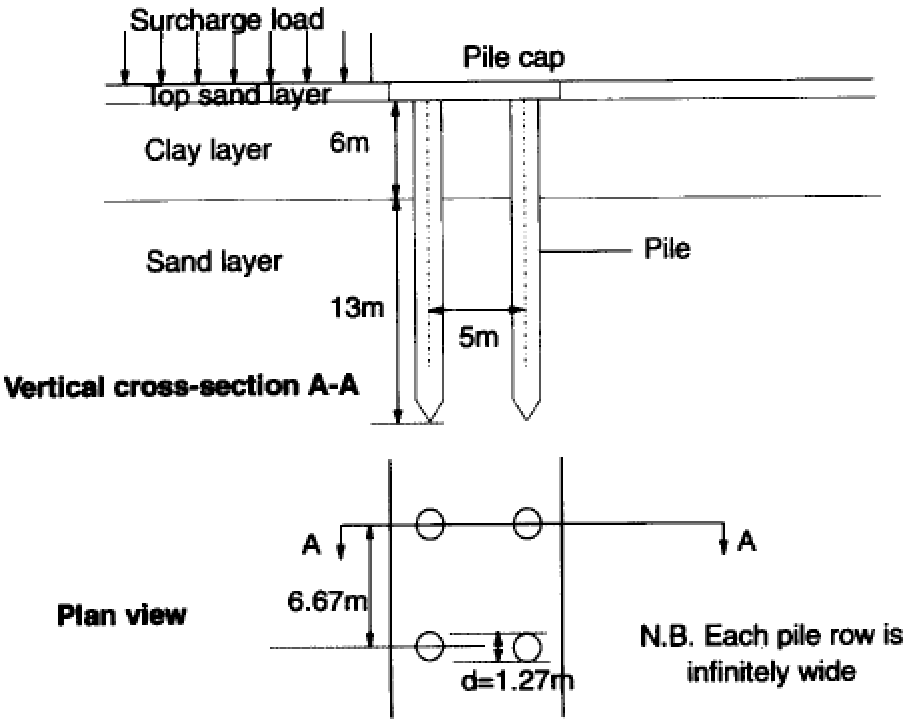


Figure 2.10 Geometry of the model (Bransby and Springman, 1995)

The analysis were performed by using the finite element program 3D CRISP. The geometry was modelled with the same dimensions of prototype model in centrifuge test and the boundries were determined same with the centrifuge strongbox size. The piles were modelled with the linear elastic elements with the stiffness of E_p = 40GPa. In the analysis all piles were modelled as fully adhesive because of the nonavailability of the interface elements in 3D. However, the results of the analyses were not affected by this assumption since gapping would have not occurred with interface elements, too. While determining the soil layers, pile installation effects were ignored. The sand layer was modelled by using "Mohr-Coulomb" model and the clay layer was modelled by using the "Hysteretic Cam Clay" model.

Bransby and Springman (1995) concluded that, finite element analysis results were in close agreement with the results obtained from the centrifuge tests. Bending moment profiles were of the same shape with the test data and the magnitudes were close enough. Thus, Bransby and Springman (1995) suggested that, modelling the laterally loaded piles and pile groups using 3D finite element method is very useful both in design and to understand the soil and system behaviour.

Another study was conducted on predicting the lateral response of the laterally loaded piles by Zhang, McVay and Lai (1999) by using the numerical code FLPIER. Single piles and 3x3 to 7x3 pile groups that are founded in both loose and medium dense sands were modelled. The p-multiplier factors suggested by McVay et al. (1998) for laterally loaded pile groups with multiple pile rows were used to provide a comparison.

The geometry modelled in this study was the same geometry modelled in centrifuge tests performed by McVay et al. (1998). The model piles were aluminum square piles having a width of 9.5mm and a length of 304.8mm. they were located at 3D spacing from one another. The layout for the single piles and 4x3 pile groups were shown in Figure 2.11. The soil properties were determined through a back-analysis procedure based on single pile test results. Subgrade reaction for the loose sand and the medium dense sand were back-calculated as 1.357MN/m^3 and 2.714MN/m^3 respectively.

Zhang, McVay and Lai (1999) concluded that, as expected, the largest bending moments were developed in the leading row piles, whereas those in the trailing row piles were smaller (Figure 2.12). Same behaviour was seen in the shear distribution pattern. In addition, moments in the outer piles within a row were larger than that in the interior piles. These predicted values were in close agreement with the values obtained from the experiment results. Maximum bending moment values did not differ much with the variation of the group size. Zhang, McVay and Lai (1999) also concluded that shear and moment distribution on group piles were independent of group size but a function of pile position within the group. The finite element program FLPIER proved to be considerable for laterally loaded pile group analysis and predicted the response of the single piles and large pile groups in close agreement with the centrifuge tests.

As mentioned before, Rollins et al. (2006) conducted full-scale cyclic lateral load tests to investigate group interaction effects with respect to the pile spacing on laterally loaded pile groups. Using the results from these full-scale load tests, computer analyses were performed in order to back-calculate p-multipliers. Load tests were performed on single piles and 3x5, 3x4 and 3x3 pile groups in stiff clay with 3.3D, 4.4D and 5.65D pile spacing respectively. The soil profile generally consists of stiff clay layers with sand layers that were in a medium compact density state (D_r=60%), to a depth of 5m. In computer analyses same geometry and was modelled.

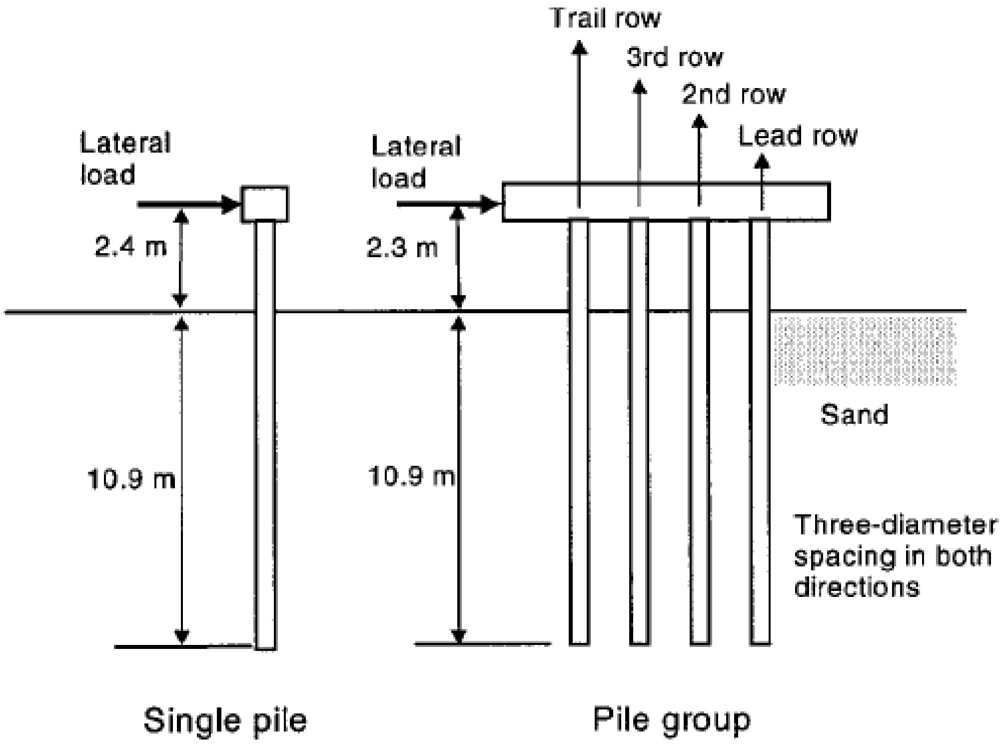
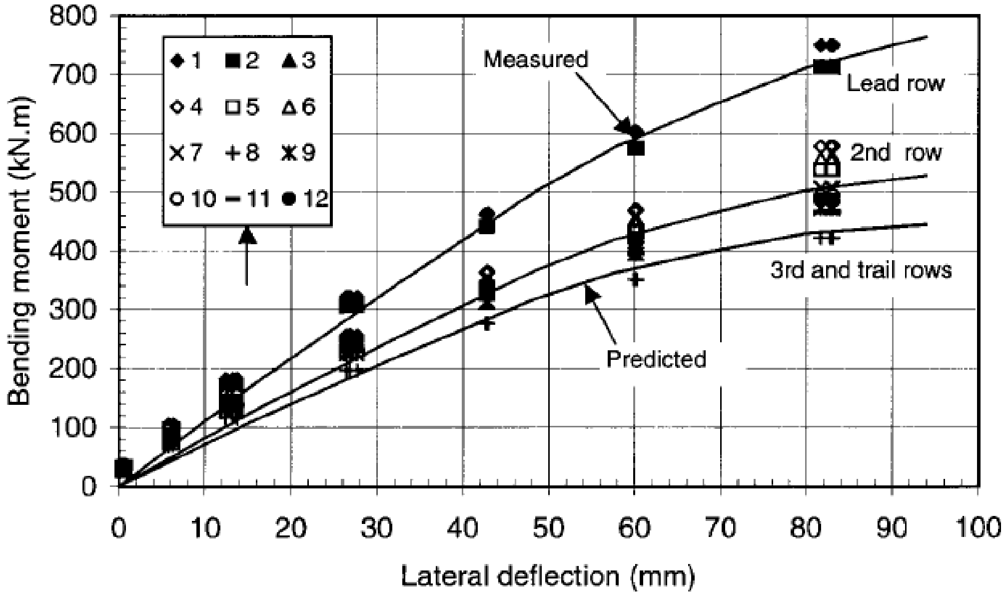
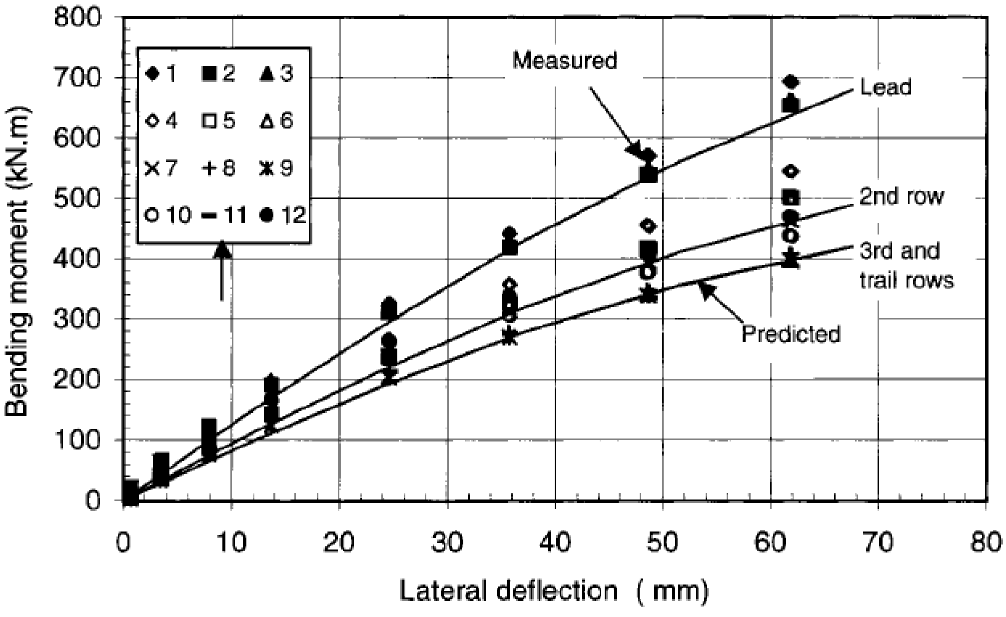


Figure 2.11 Layouts of single piles and pile groups
(Zhang, McVay and Lai, 1999)



(a)



(b)

Figure 2.12 Measured and predicted maximum bending moments in individual piles of 4x3 pile group (a) in loose sand (b) in medium dense sand (Zhang, McVay and Lai, 1999)

By using the same soil profile and properties described previously, single piles were analysed first in order to obtain the possible match between the measured and computer response. While performing computer analyses, some changes in soil properties were permitted to improve the match accuracy. For the group pile analyses, these soil properties were held constant and only the variations in p-multipliers 75were used to obtain the possible match between the measured and computed pile group response. For the computer analyses of single piles, computer programs LPILE that uses the finite difference approach and FLPIER that uses the finite element approach were used. For the pile group analysis, computer program GROUP was used in order to back-calculate the p-multiplier values.

Rollins et al. (2006) concluded that p-multipliers obtained from the back-analyses increased with the increase of pile spacing from 3.3D to 5.65D. As illustrated in Figure 2.13, extrapolation of the results showed that group efficiency can be ignored for spacings greater than about 6.5D for leading piles and about 7.5D for trailin row piles. Load versus deflection, maximum moment versus load, bending moment versus depth graphs were drawn for each row in pile groups computed using GROUP and FLPIER. The results were generally in close agreement with the full-scale test results. However, as shown in Figure 2.14 both programs underestimated the bending moments at depths below the maximum value.

Another study was performed by Kahyaoglu et al. (2009) using 3D finite element analysis to investigate the behaviour of single piles and a group of free-head piles subjected lateral soil movement. A number of numerical analysis were performed in order to figure out the force acting on passive piles with different pile spacing. Effect of pile spacing and the internal friction angle of the moving soil were determined by this parametric study. In order to verify the accuracy of numerical analysis, existing experimental test results evaluating the soil arching effect were re-examined.

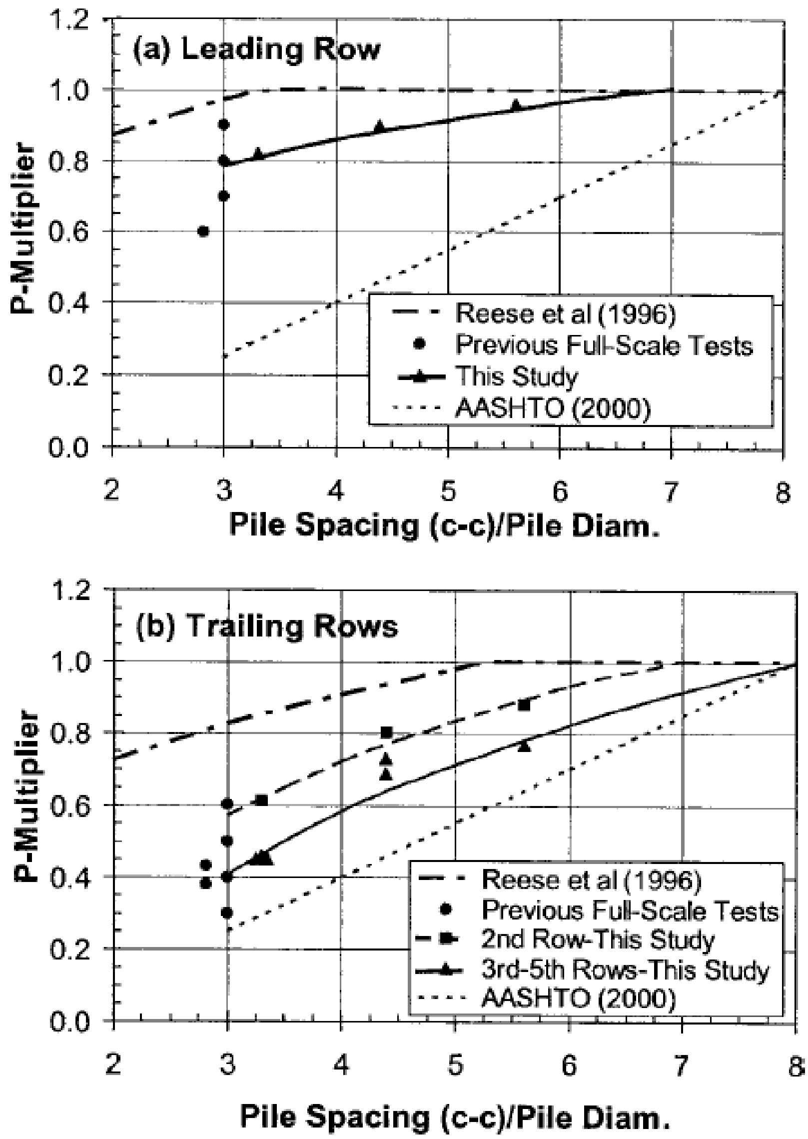


Figure 2.13 Back-calculated p-multipliers for: (a) leading row; (b) trailing row piles from this study and previous full-scale load tests along with recommended design curves (Rollins et al., 2006)

For the analysis, the finite element analysis program PLAXIS 3D Foundation was used. In Figure 2.15 both the plan view of model simulation and soil, structure element simulation were shown. In models a wide range pile spacing ranging from 2D to 8D was determined.

Kahyaoglu et al. (2009) concluded that results of the analysis performed using PLAXIS 3D Foundation and the experiments were in close agreement. As the pile spacing getting larger, the loads acting on the piles increased. However, for the pile spacing larger than 8D, each pile behaved like an isolated single pile without arching effect. The computer analysis results also showed that as the pile spacing increased the residual load acting on the soil mass between piles increased. In other words, for smaller pile spacings a small amount of load acting on the soil between the piles was transferred to the piles. The soil with higher internal friction angle developed stronger arching thus, more loads transferred to the piles and less displacements occurred.

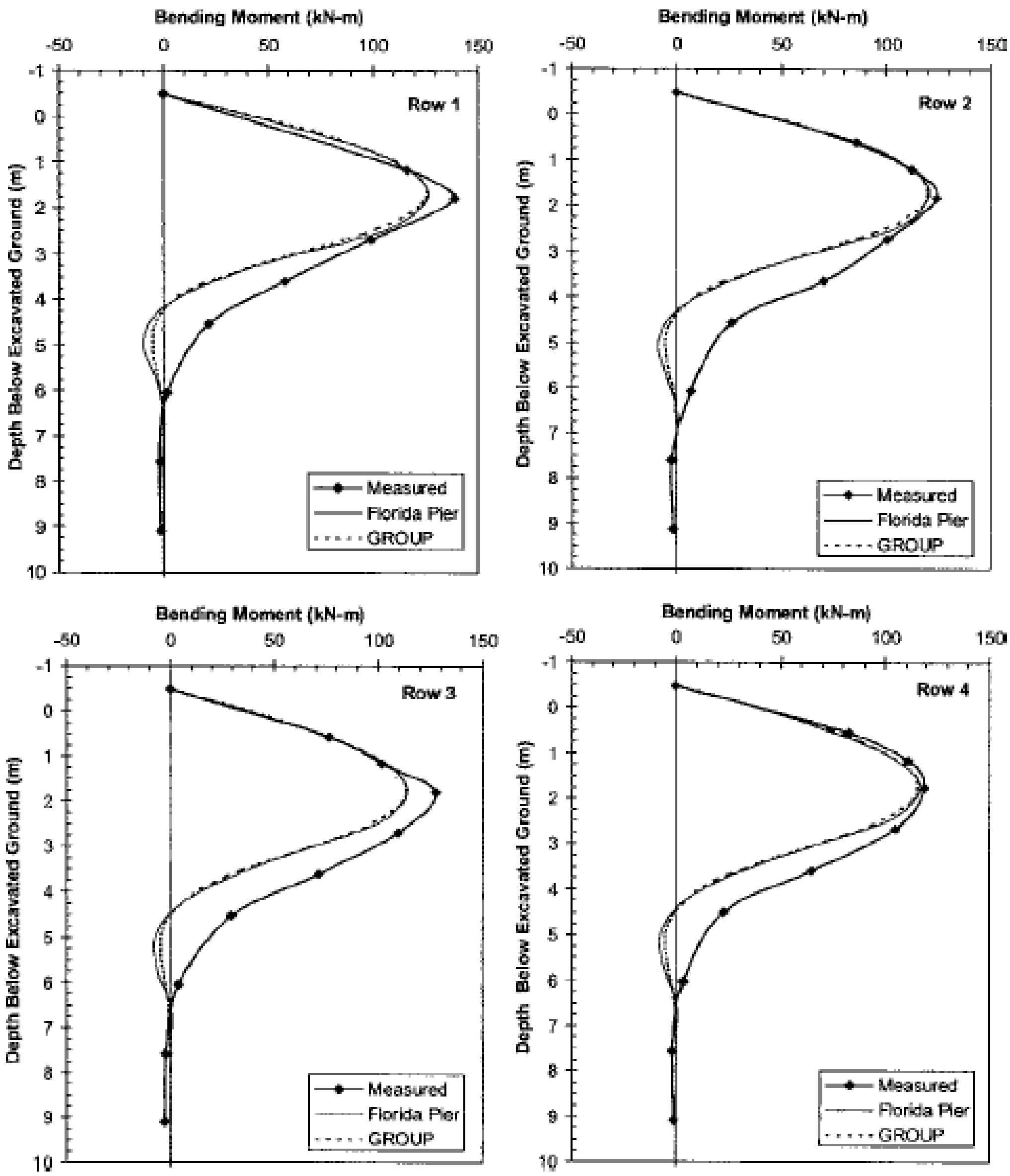


Figure 2.14 Measured bending moment versus depth curves for each row of 3x4 pile group at deflection of 25mm in comparison to curves computed using GROUP and FLPIER with p-multipliers developed during this study (Rollins et al., 2006)

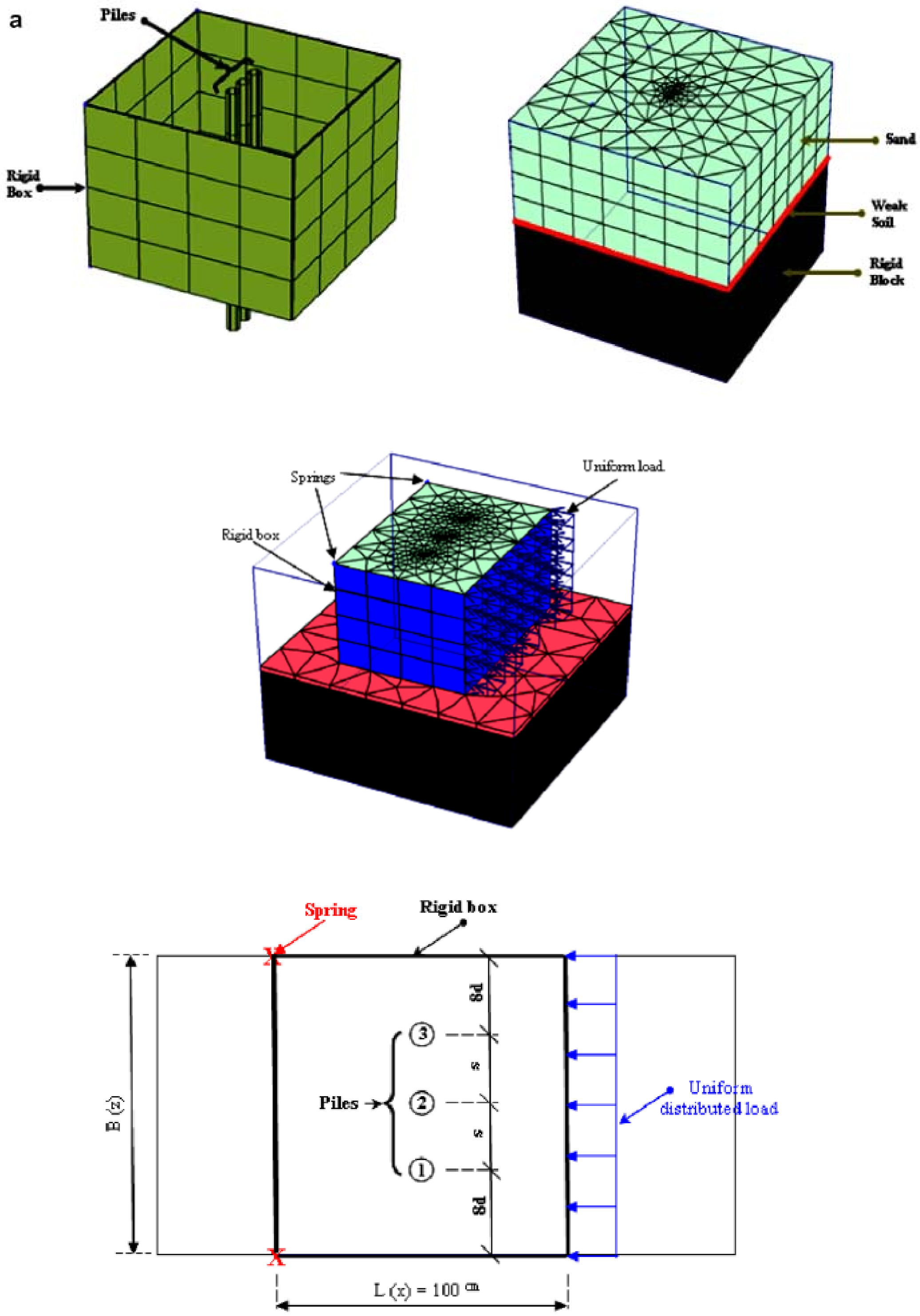


Figure 2.15 Soil and structure finite element simulation and plan view of model simulation (Kahyaoglu et al., 2009)

CHAPTER 3

NUMERICAL MODELLING

3.1 Introduction

This study is focused on the assessment of the effects of pile spacing, pile diameter and soil stiffness on lateral load distribution of each pile in a pile group and bending moment distribution along the pile. A parametric study was carried out for this purpose. Numerical analysis performed as a part of this parametric study were carried out by Plaxis 3D Foundation geotechnical finite element package which is specifically preferred for advanced analysis for piles and pile-raft foundations. In the following paragraphs a short review of this program is given.

Plaxis 3D Foundation program consists of four basic components, namely Input, Calculation, Output and Curves. In the Input program the boundary conditions, problem geometry with appropriate material properties are defined. The problem geometry is the representation of a real three-dimensional problem and it is defined by work-planes and boreholes. The model includes an idealized soil profile, structural objects, construction stages and loading. The model should be large enough so that the boundaries do not influence the results. Boreholes are points in the geometry model that define the idealized soil layers and the groundwater table at that point. Multiple boreholes are used to define the variable soil profile of the project. During 3D mesh generation soil layers are interpolated between the boreholes so that the boundaries between the soil layers coincide with the boundaries of the elements. Work-planes are horizontal planes with different y-coordinates that show the top-view of the model geometry. They are used to draw, activate and deactivate the structural elements and loads. Each work-plane holds the same geometry lines but vertical distance between them may vary. Within work-planes, points, lines and clusters are used to describe a 2D geometry model.

After creating the 2D geometry model in a work-plane, a 2D is automatically generated based on the composition of the clusters and lines in 2D geometry model. 2D finite element mesh is composed of 6-nodes triangles. However, the 3D finite element mesh is the extension of 2D mesh into the third dimension and it is generated after generating 2D mesh. The 2D mesh generation in the program is fully automatic while 3D mesh generation is semi automatic. Mesh dimensions should be appropriately defined, to prevent the effects of boundary conditions. The 2D mesh should be constructed before proceeding to the 3D mesh extension. Typical 2-D and 3-D meshes used in this study are presented in Figure 3.1 and 3.2, respectively. To increase the accuracy, mesh width used in the pile group was decreased. The mesh element size can be adjusted by using a general mesh size varying from very coarse to very fine and also by using line, cluster and point refinements. Very fines meshes should be avoided in order to reduce the number of elements, thus to reduce the memory consumption and calculation time. The program does not allow entering a new structural element or a new soil cluster after the mesh is generated. If a new element or cluster is added to the geometry model, the mesh generation should be repeated with the new input.

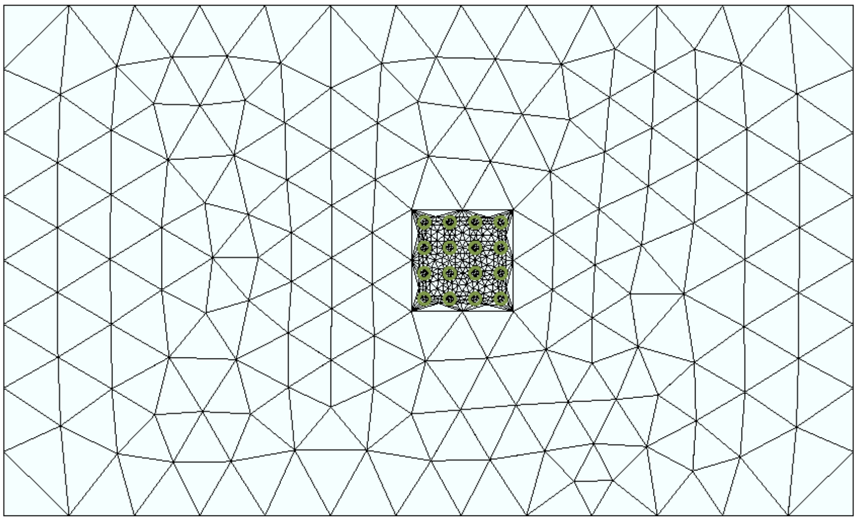


Figure 3.1 Mesh dimensions of the cross section of a typical 3D FE model

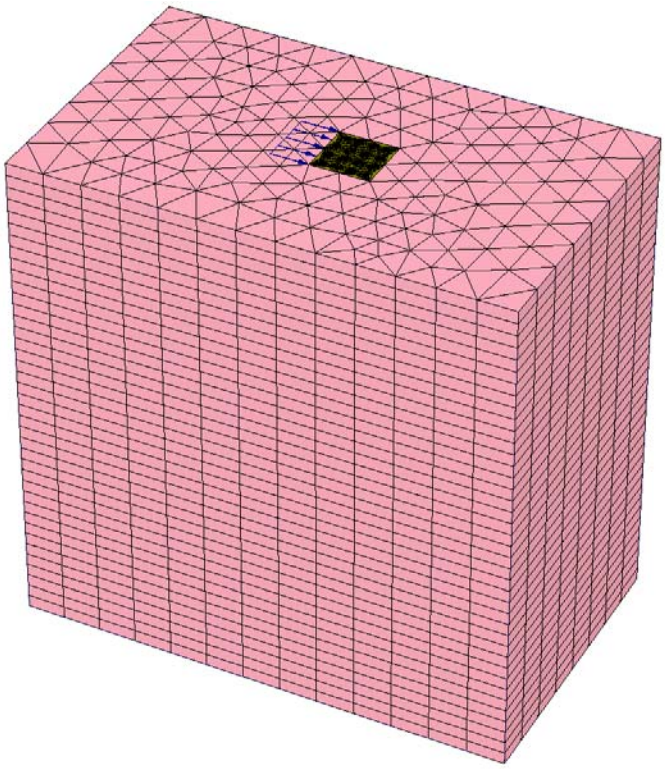


Figure 3.2 Mesh dimensions of a typical 3D FE model

3D finite elemet mesh is composed of elements, nodes and stress points. While generating the mesh, the geometry is divided into 15-node wedge elements. As mentioned before, these elements are composed of the 6-node triangles in x-z direction, as generated by 2D mesh generation. Moreover, 8-node quadrilateral faces are generated in y-direction. The soil and the interfaces can be modelled with different complexity levels. 6-node plate elements and 16-node interface elements are used to model the soil-structure interaction.

The wedge elements that are used during mesh generation consist of 15 nodes. Figure 3.3 illustrates the distribution of nodes over the elements. Joining elements are connected through their common nodes. During a finite element analysis, displacement values are calculated at the nodes and a specific node can be selected before calculation steps in order to generate the load-displacement curves. On the contrary, stresses and strains are calculated at individual stress points (Gaussian integration points) rather than at the nodes. A 15-node wedge element contains 6 stress points that shown in Figure 3.3. However, stress and strain values at stress points are extrapolated to the nodes for the output purposes.

At the bottom of the 3D finite element mesh, total fixities were used that restrain the movements in both horizontal and vertical directions. For upper part, 3D finite element mesh had no fixities. Besides, for right and left sides, roller supports were used in order to restrain only the horizontal movements and vertical displacements were left free.

After defining the model geometry and 3D mesh generation, initial stresses are applied by using either K_0-procedure or gravity loading. The calculation procedure can be performed automatically or manually. The initial stresses in the soil are affected by the weight of the soil and history of the soil formation. Stress state is characterized by vertical and horizontal stresses. Initial vertical stress depends on the weight of the soil and pore pressures; whereas initial horizontal stresses are related to the vertical stresses by the coefficient of lateral earth pressure at rest. This relation is provided by the K_0-procedure in this study.

In this study, it is assumed that the water table is at the ground surface and clay formations are fully saturated; hence, initial stresses should be calculated in terms of effective stresses. The relation between initial vertical and horizontal stresses is given in Equation 3.1 and the coefficient of lateral earth pressure at rest, K_0, for normally consolidated soils can be calculated by Jacky (1944) 's formula as given in Equation 3.2.

$$\sigma_h' = K_0 \sigma_v' \tag{3.1}$$

$$K_0 = 1 - \sin\phi' \tag{3.2}$$

The construction stages are defined by activating or deactivating the structural elements or soil clusters in the work-planes and a simulation of the construction process can be achieved. A construction period can also be specified for each construction stage but the soil material model should be selected as “Hardening Soil Model”.

The most important calculation type in Plaxis 3D Foundation is the staged construction. In every calculation step, the material properties, geometry of the model, loading condition and the ground water level can be redefined. During the calculations in each construction step, a multiplier that controls the staged construction process (ΣMstage) is increased from zero to the ultimate level that is generally 1.0. The constructions that are not completed fully can be modeled by using this feature. (Plaxis 3D Foundation Manual, 2004)

This chapter is devoted to introduce the details of constitutive models, material properties, and finite element modeling used in the performed parametric study.

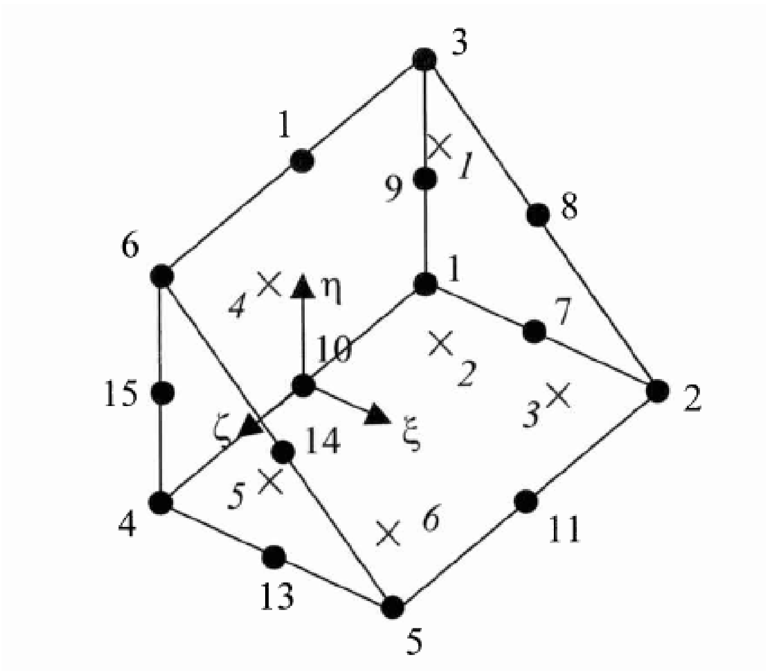


Figure 3.3 Distribution of Nodes and Stress Points in a 15-node Wedge Element (Plaxis 3D Foundation Manual, 2004)

3.2 Modeling Basics

3.2.1 Definition of the Parametric Study and Analyzed Pile Groups

This study was performed on a 4x4 pile groups with rows spaced at from 2D to 5D center-center in the direction of the loading as shown in Figure 3.4. As illustrated in Figure 3.4 the piles were classified in the group according to their row location and the location witihin the row. Leading row and trailing rows were defined according to the loading direction. Moreover piles were defined as outer and inner piles according to the location within the row. The purpose of the analysis was to determine the individual pile behaviour within the group. The load distribution of each pile and the bending moment distribution along the pile at this particular pile arrangement was defined for clays.

The parametric study considers the variations in pile spacing, soil stiffness, load level and pile diameter. The variables of the parametric study are listed in Table 3.1. A total of 24 different combinations were studied using the variables listed in Table 3.1.

For 3D numerical models, 4x4 pile group was used that shown in Figure 3.4. The piles were fixed with a pile cap that has a thickness of 0.80m. The 15m pile length was constant in all models. In order to determine the individual pile behaviour with respect to the pile diameter, analysis had been performed with two different pile diameters namely 0.80m and 0.50m. The pile spacing of 3D was found to be sufficient for the explanation of load distribution with respect to pile diameter. By increasing the applied force to observe the behavior of 0.80m pile diameter at 3D pile spacing in pile group, the loads acting on

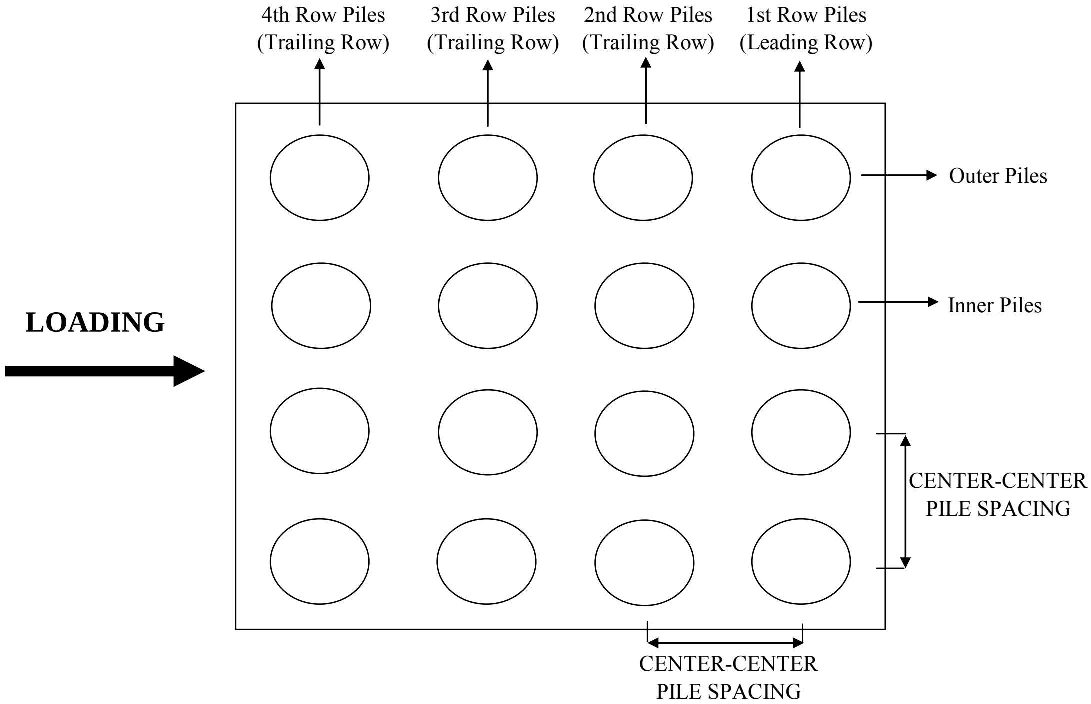


Figure 3.4 Typical pile group used in the parametric study

individual piles were calculated. A wide range of pile spacing ranging from 2D to 5D for the cases where the pile diameter was 0.50m had been investigated to evaluate the influence of pile spacing. By increasing the applied force to observe the behavior of 0.50m pile diameter, the loads acting on individual piles were calculated for each pile spacing configuration.

In addition to pile diameter, pile spacing and lateral load level, other variable in the parametric study was the soil stiffness. Analysis were performed on pile group having 3D pile spacing for both soft and moderately stiff clay .

Table 3.1 Variables of the parametric study

		Total Lateral Load Applied to the System (kN)	Center - Center Pile Spacing			
			2D	3D	4D	5D
D = 0.50m	E = 40000kPa	1600	✓	✓	✓	✓
		3200	✓	✓	✓	✓
		6400	✓	✓	✓	✓
		8000	✓	✓	✓	✓
		9600			✓	
		11200				✓
	E = 10000kPa	1600		✓		
		3200		✓		
		6400		✓		
		8000				
		9600				
		11200				
D = 0.80m	E = 40000kPa	1600		✓		
		3200		✓		
		6400		✓		
		8000				
		9600				
		11200				

3.3 Modeling Parameters

3.3.1 Clay Parameters

Soil elements were modeled using "Hardening Soil" Model. Hardening Soil model needs five input parameters, modulus of elasticity (E) and Poisson's ratio (ν) to define elastic soil response; friction angle (Φ) and cohesion (c) to define plastic response and angle of dilatancy (ψ). The parametric study was carried out for both soft clay and stiff clay layers. The parameters used in this study are presented in Table 3.2. The dilatancy of the clay is not taken into account in this study and full bond interface elements are used between soil and piles.

3.3.2 Pile and Raft Parameters

Piles and pile cap were modeled using a linear elastic material model and the corresponding material properties are given in Table 3.3.

Table 3.2 Material Ptoperties of Clay

Parameter	**Symbol**	**Soft Clay**	**Stiff Clay**	**Unit**
Type of Material Behaviour		Drained	Drained	-
Unit Weight	γ	19	19	kN/m^3
Poisson's Ratio	ν	0.30	0.30	-
Cohesion	c'	25	25	kN/m^2
Internal Friction Angle	Φ	28	28	°
Elastic modulus	E	10 000	40 000	kN/m^2
Dilatancy Angle	ψ	0	0	°

Table 3.3 Material Ptoperties of Pile and Pile Cap

Parameter	**Symbol**	**Pile**	**Pile Cap**	**Unit**
Type of Material Behaviour		Elastic	Elastic	-
Thickness	t	-	80	cm
Diameter	d	50	-	cm
Unit Weight	γ	24	24	kN/m^3
Elastic modulus	E	28 500 000	28 500 000	kN/m^2
Poisson's ratio	ν	0.15	0.15	-

3.3.3 Loading Conditions

For the numerical simulation of the laterally loaded pile groups, 3D finite element analysis had been performed at different load levels. These lateral loads were determined depending on the lateral load capacity of a fixed-head single pile in cohesive soil. The Broms' method is the most widely-used approach in practice. Thus, lateral load capacity of a single pile was calculated using this method.

In the active pile loading case, the horizontal force at the pile causes the pile deformation as shown in Figure 3.5. In this case, the mobilized earth pressure provides an increasing resisting pressure with the increasing of the pile deflection. On the other hand, "plastic hinges" can be occured on the critical sections of the deflected piles due to the bending moment values larger than the capacity. However, this behaviour is effected by the length of the pile and the head fixity condition that is shown in Figure 3.6. A short pile rotates about a point along its length. However, a long pile can not rotate and plastic hinges and cracks occur at critical points.

In Broms' approach it is assumed that ultimate resisting pressure is formed in an idealized one layer soil profile. This resisting pressure depends on the pile diameter (b) and undrained cohesion (c) of the soil. Broms (1964) eliminated the soil resistance for the top 1.5b of the pile because of the lower resistnce in that zone due to the pile deflection, below this level the pressure continues constantly as 9c as shown in Figure 3.7. In this study the piles were fixed against rotation at their top by a pile cap and the lateral load capacity of fixed head piles with a diameter of 0.50m and a length of 15m were calculated as follows.

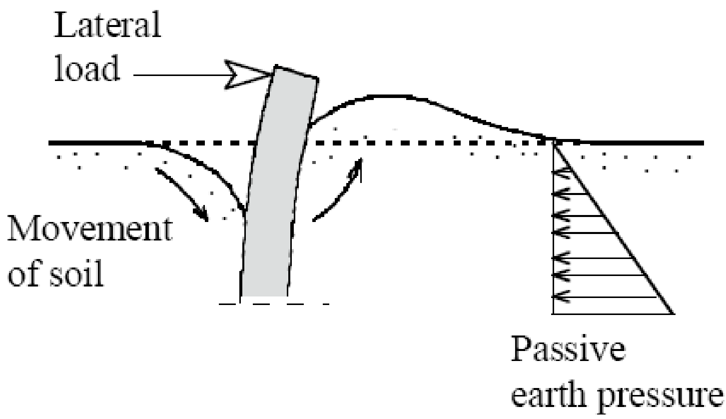


Figure 3.5 Shematic illustration of lateral loading of piles (Active-pile-loading) (Cubrinovski and Ishihara, 2007)

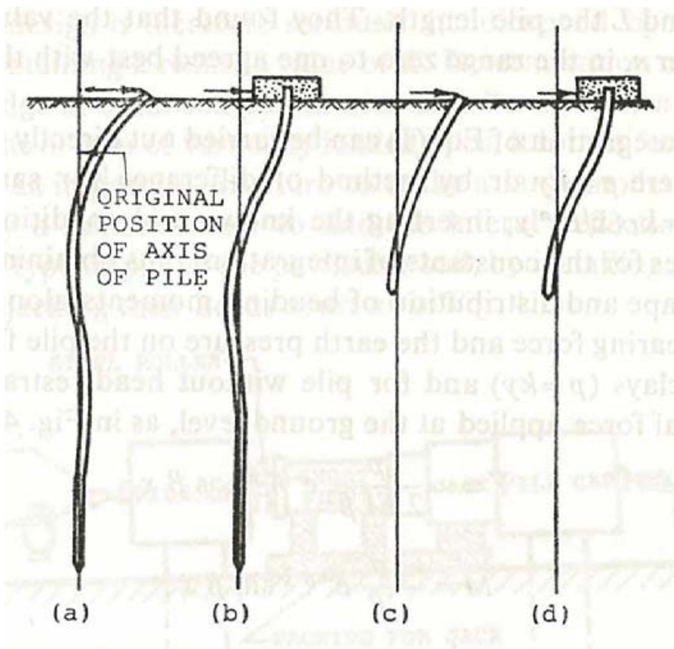


Figure 3.6 The deflected forms of long and short piles subjected to horizontal force at ground level; (a) a long pile with no head restraint; (b) a long pile with a cap permitting no rotation of the head; (c) a short pile with no head restraint; (d) a short pile with a cap permitting no rotation of the head (Mohan, 1988)

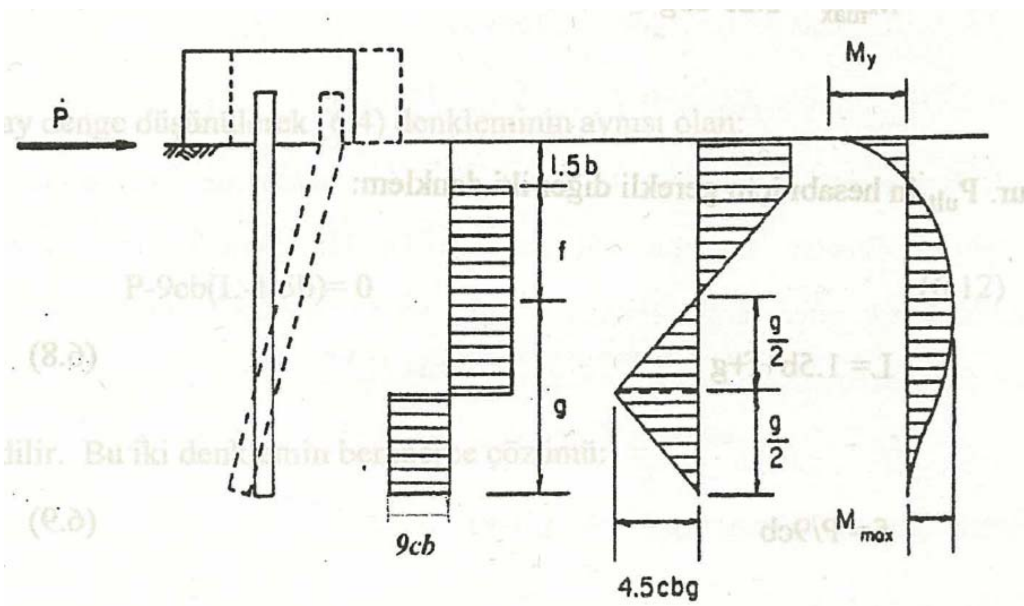


Figure 3.7 Shear and Bending Moment distribution along a fixed head pile (Broms, 1964a)

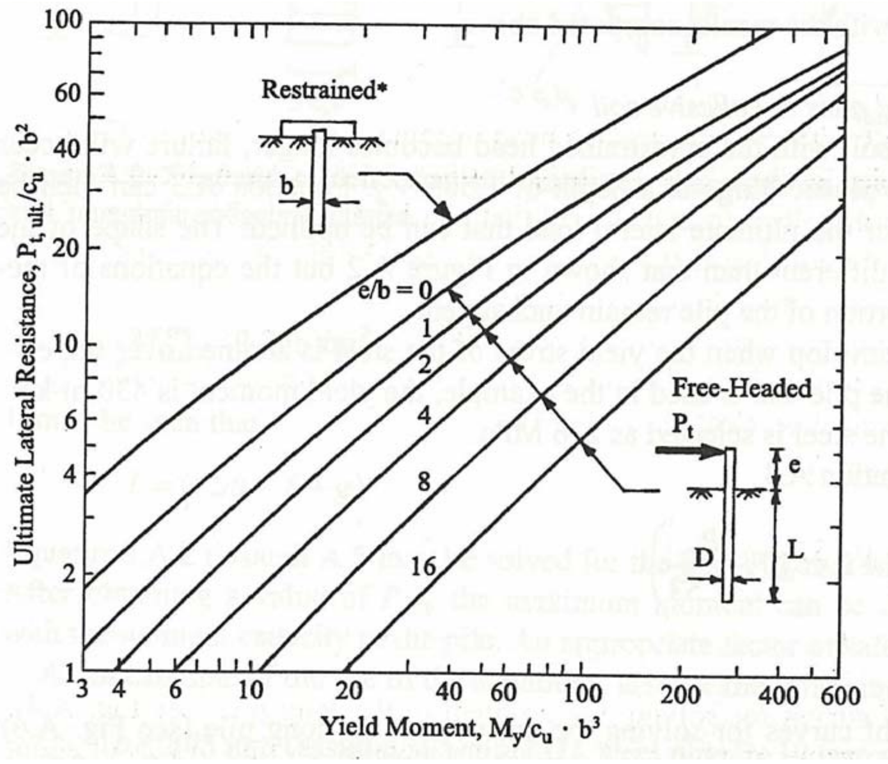


Figure 3.8 Curves for design of long piles under lateral load in cohesive soil (Broms, 1964a)

As mentioned before, short piles rotate without bending and reaches the ultimate resisting pressure. Considering this behaviour, an equlibrium can be written as follows and ultimate resisting force (P) can be calculated.

$$P = 9 \times c \times b \times (L - 1.5 \times b) \tag{3.3}$$

For a particular pile length the behaviour does not change. However, as the pile length increses plastic hinges will be developed. At a particular pile length a plastic hinge is developed at the pile head, and this length is termed as "intermediate length". For this condition, the point where the maximum bending moment (bending moment capacity of the pile) occurs, can be calculated from the following equations.

$$M_{max} = P \times (1.5 \times b + 0.5 \times f) - M_y \tag{3.4}$$

$$M_{max} = 2.25 \times c \times b \times g^2 \tag{3.5}$$

For the calculation of ultimate resisting force following two equations are also needed.

$$L = 1.5 \times b + f + g \tag{3.6}$$

$$f = \frac{P}{9 \times c \times b} \tag{3.7}$$

On the other hand, as the pile becomes longer, second plastic hinge is developed at a critical point along the pile. This type of pile can be termed as "long pile". For this condition "$M_{max} = M_y$" equilibrium can be wriiten and P can be calculated from the following equation.

$$P = \frac{2M_y}{(1.5 \times b + 0.5 \times f)} \text{ (same as Equation 3.4)} \tag{3.8}$$

With these equtions, Broms presented a set of curves for solving the long pile problem that shown in Figure 3.8. Entering the curve the value of M_y/cb^3, P value can be determined easily. However, first the pile length should be determined. In order to determine pile length whether long or short, the intermediate length should be calculated first, and this value can be found from the following equation with Equation 3.3.

$$P = \frac{M_y}{(0.5 \times L + 0.75 \times b)} \qquad (3.9)$$

For the piles that were modeled in 3D finite element analysis, the lateral load capacity was determined by following the procedure above. First, the bending moment capacity of a bored pile having a diameter of 0.50m was calculated. The interaction diagram shown in Figure 3.9 was used in order to determine theis value. The axial load applied to the piles were assumed zero. Moreover, the longitudinal reinforcement ratio was assumed about 4% as Turkish Standards (TS500) suggested for coloumns. Thus, the moment capacity was determined as 400kNm.

The parameters that were used in calculating the lateral load capacity of the model piles are summarized below.

b = 0.50m

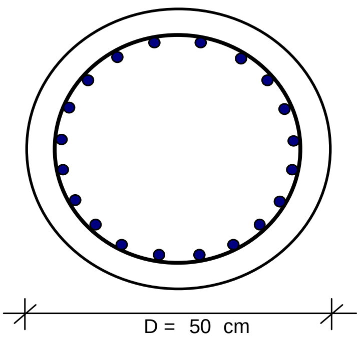
L = 15.00m

c = 100kPa

M_y = 400kNm

INTERACTION DIAGRAM

ϕ 50	*12*	*Φ 28*



Material :

Concrete	:	C	20	f_{cd} =	133	kg/cm²
Reinforcement	:	St	420	f_{yd} =	3652	kg/cm²

Pile Diameter	=	**50** **cm**
Reinforcement Diameter	=	Φ ***28***
Number of Reinforcement	=	**12**
Concrete Cover	=	**5** **cm**
Percentage of Reinforcement	=	***% 3.76***

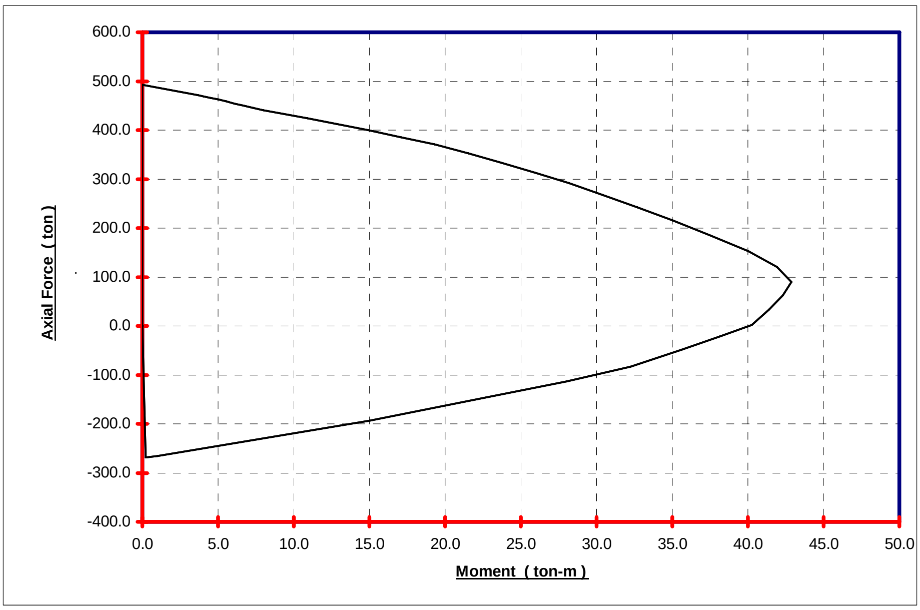


Figure 3.9 Interaction diagram use in determining the bending moment capacity of a single pile with a diameter of 0.50m

First, the pile length, where the pile goes from short pile mode of behaviour to intermediate pile mode of behaviour, was calculated using the Equations 3.3 and 3.9. By solving these equations together, this value was found as 1.50m which is smaller than the model pile length. Thus, a second pile length, where the pile goes from intermediate pile mode of behaviour to long pile mode of behaviour, was calculated using the Equations 3.4, 3.5, 3.6 and 3.7. By solving these equations together, this value was found as 4.00m which is also smaller than the model pile length. Thus, the ultimate resistance force was determined as 600kN using the curves for design of long piles suggested by Broms (1964).

In 3D finite element analysis, lateral loads were determined based on the lateral load capacity of a single pile. Thus, the load applied to the pile groups varied from 100kN/pile up to 700kN/pile.

CHAPTER 4

DISCUSSION OF THE RESULTS

This chapter presents of the results of the parametric study. A detailed discussion on the role of important factors on lateral behavior of piles; such as row location and pile location within a row, pile spacing, pile diameter, and soil stiffness are also presented.

4.1 Effect of Row Location and Pile Location within a Row

The lateral load distribution among the individual piles and rows is a primary concern, in order to understand group effects and various other behavioral characteristics of pile groups. Here, the variation of the individual pile load among the rows and within the row will be discussed.

Lateral load analysis for the pile groups were performed using computer program Plaxis 3D Foundation and the load distribution was determined for each row and for each pile within the row. The lateral load carried by the piles was found to be a function of both row location and location within a row. Table 4.1 presents the load distribution of pile groups with respect to row location and pile location within the row for each pile group with different pile spacings.

Table 4.1 Load Distribution of Pile Groups with respect to Row Location and the Location Within the Row for each Pile Group with different Pile Spacing (D = 0.50m, L = 15m, E = 40Mpa)

1st ROW PILES	**Individual Pile Load (kN) in Group having 2D Pile Spacing**		**Individual Pile Load (kN) in Group having 3D Pile Spacing**		**Individual Pile Load (kN) in Group having 4D Pile Spacing**		**Individual Pile Load (kN) in Group having 5D Pile Spacing**	
Total Load Applied to the System (kN)	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**
1600	138	107	114	93	79	69	60	53
3200	370	247	278	227	181	161	142	125
6400	800	496	604	500	479	428	396	359
8000	1030	619	770	632	620	555	514	467
9600	x	x	x	x	775	690	x	x
11200	x	x	x	x	x	x	780	720

2nd ROW PILES	**Individual Pile Load (kN) in Group having 2D Pile Spacing**		**Individual Pile Load (kN) in Group having 3D Pile Spacing**		**Individual Pile Load (kN) in Group having 4D Pile Spacing**		**Individual Pile Load (kN) in Group having 5D Pile Spacing**	
Total Load Applied to the System (kN)	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**
1600	88	63	82	63	61	50	47	38
3200	188	141	177	139	131	110	112	94
6400	377	299	350	288	320	273	292	256
8000	466	388	434	368	395	340	368	322
9600	x	x	x	x	475	412	x	x
11200	x	x	x	x	x	x	521	463

3rd ROW PILES	Individual Pile Load (kN) in Group having 2D Pile Spacing		Individual Pile Load (kN) in Group having 3D Pile Spacing		Individual Pile Load (kN) in Group having 4D Pile Spacing		Individual Pile Load (kN) in Group having 5D Pile Spacing	
Total Load Applied to the System (kN)	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**
1600	83	58	75	58	60	48	45	36
3200	160	117	163	125	122	98	109	90
6400	312	242	311	243	296	245	277	241
8000	385	308	378	305	359	300	346	300
9600	x	x	x	x	423	354	x	x
11200	x	x	x	x	x	x	480	422

4th ROW PILES	Individual Pile Load (kN) in Group having 2D Pile Spacing		Individual Pile Load (kN) in Group having 3D Pile Spacing		Individual Pile Load (kN) in Group having 4D Pile Spacing		Individual Pile Load (kN) in Group having 5D Pile Spacing	
Total Load Applied to the System (kN)	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**
1600	104	73	87	69	69	57	52	44
3200	172	128	169	137	143	120	119	100
6400	296	240	314	260	299	265	288	254
8000	354	295	370	320	360	324	353	313
9600	x	x	x	x	426	383	x	x
11200	x	x	x	x	x	x	478	432

Table 4.2 Load Distribution Coefficient of Individual Piles with respect to Row Location and the Location Within the Row for different Pile Spacings (D = 0.50m, L = 15m, E = 40Mpa)

1st ROW PILES	Individual Pile Load / Average Pile Load (2D Pile Spacing)		Individual Pile Load / Average Pile Load (3D Pile Spacing)		Individual Pile Load / Average Pile Load (4D Pile Spacing)		Individual Pile Load / Average Pile Load (5D Pile Spacing)	
Average Pile Load (kN)	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**
100	1.38	1.07	1.14	0.93	0.79	0.69	0.60	0.53
200	1.85	1.24	1.39	1.14	0.91	0.81	0.71	0.63
400	2.00	1.24	1.51	1.25	1.20	1.07	0.99	0.90
500	2.06	1.24	1.54	1.26	1.24	1.11	1.03	0.93
600	x	x	x	x	1.29	1.15	x	x
700	x	x	x	x	x	x	1.11	1.03

2nd ROW PILES	Individual Pile Load / Average Pile Load (2D Pile Spacing)		Individual Pile Load / Average Pile Load (3D Pile Spacing)		Individual Pile Load / Average Pile Load (4D Pile Spacing)		Individual Pile Load / Average Pile Load (5D Pile Spacing)	
Average Pile Load (kN)	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**
100	0.88	0.63	0.82	0.63	0.61	0.50	0.47	0.38
200	0.94	0.71	0.89	0.70	0.66	0.55	0.56	0.47
400	0.94	0.75	0.88	0.72	0.80	0.68	0.73	0.64
500	0.93	0.78	0.87	0.74	0.79	0.68	0.74	0.64
600	x	x	x	x	0.79	0.69	x	x
700	x	x	x	x	x	x	0.74	0.66

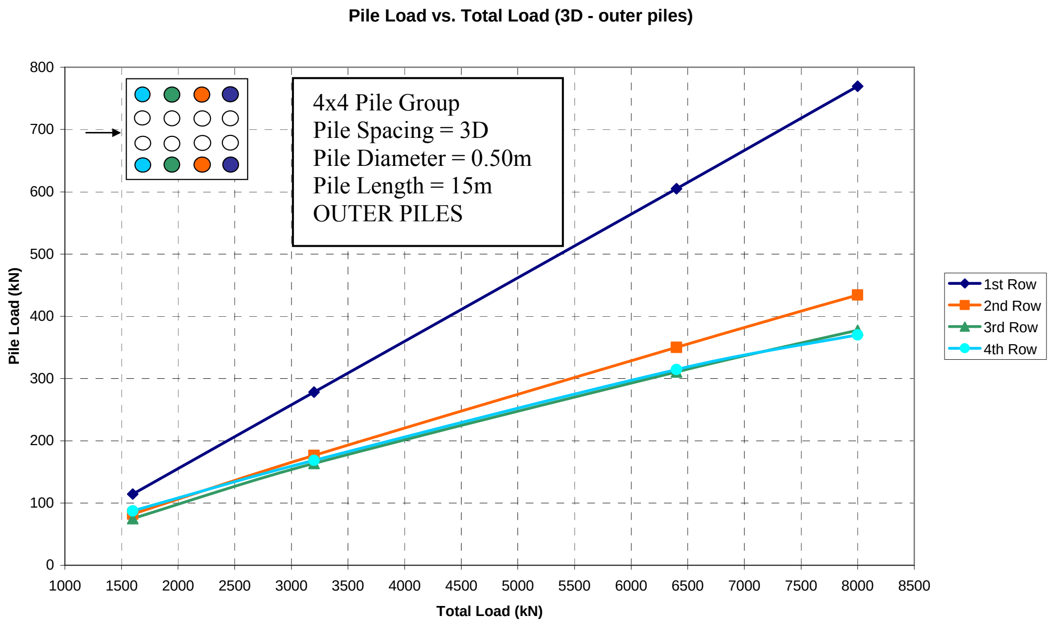
3rd ROW PILES	Individual Pile Load / Average Pile Load (2D Pile Spacing)		Individual Pile Load / Average Pile Load (3D Pile Spacing)		Individual Pile Load / Average Pile Load (4D Pile Spacing)		Individual Pile Load / Average Pile Load (5D Pile Spacing)	
Average Pile Load (kN)	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**
100	0.83	0.58	0.75	0.58	0.60	0.48	0.45	0.36
200	0.80	0.59	0.82	0.63	0.61	0.49	0.55	0.45
400	0.78	0.61	0.78	0.61	0.74	0.61	0.69	0.60
500	0.77	0.62	0.76	0.61	0.72	0.60	0.69	0.60
600	x	x	x	x	0.71	0.59	x	x
700	x	x	x	x	x	x	0.69	0.60

4th ROW PILES	Individual Pile Load / Average Pile Load (2D Pile Spacing)		Individual Pile Load / Average Pile Load (3D Pile Spacing)		Individual Pile Load / Average Pile Load (4D Pile Spacing)		Individual Pile Load / Average Pile Load (5D Pile Spacing)	
Average Pile Load (kN)	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**	**Outer Piles**	**Inner Piles**
100	1.04	0.73	0.87	0.69	0.69	0.57	0.52	0.44
200	0.86	0.64	0.85	0.69	0.72	0.60	0.60	0.50
400	0.74	0.60	0.79	0.65	0.75	0.66	0.72	0.64
500	0.71	0.59	0.74	0.64	0.72	0.65	0.71	0.63
600	x	x	x	x	0.71	0.64	x	x
700	x	x	x	x	x	x	0.68	0.62

As it was illustrated in Figure 3.4, the rows were defined as the leading row and the trailing rows in the loading direction and piles were defined as outer and inner piles according to their location within the row. Figure 4.1, illustrates the summary of load distribution presented in Table 4.1 as a representative case.

As expected based on the elastic theory, the piles located on the edges of a row carry more load than the inner piles for an applied load. Moreover, the front row piles (leading row piles) carried the greatest load while the second row piles carried succesively smaller loads under the same load applied. However, the third and the fourt row piles carried about the same load. In fact, the fourth row piles carried slightly higher loads than the third row piles.

Table 4.2 summarizes the load distribution among individual piles with a coefficient of pile load for each pile in pile groups with different pile spacings. These coefficients were calculated by dividing individual pile load calculated from computer analysis with the assumed average pile load applied in the analysis. Using Table 4.2 it is concluded that lateral load developed in outer piles is about 1.25 times the load developed in inner piles. Moreover, although this coefficient reaches to 1.5 or 2 for the leading row piles, coefficient of trailing row piles decreases to 0.55 and 0.65 in some cases.



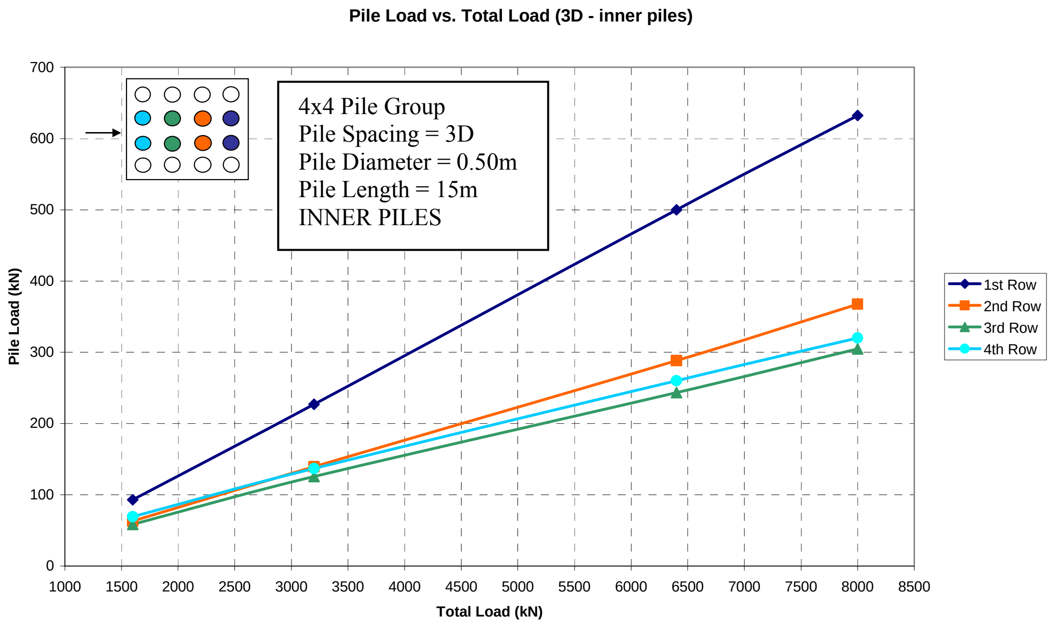
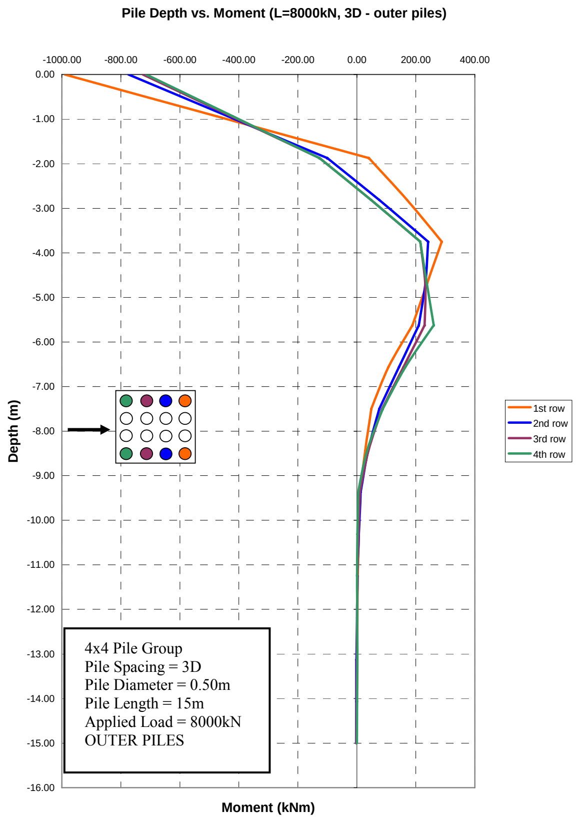


Figure 4.1 Load Distribution with respect to row location for outer and inner piles under same load applied (Pile Group with 3D pile spacing)



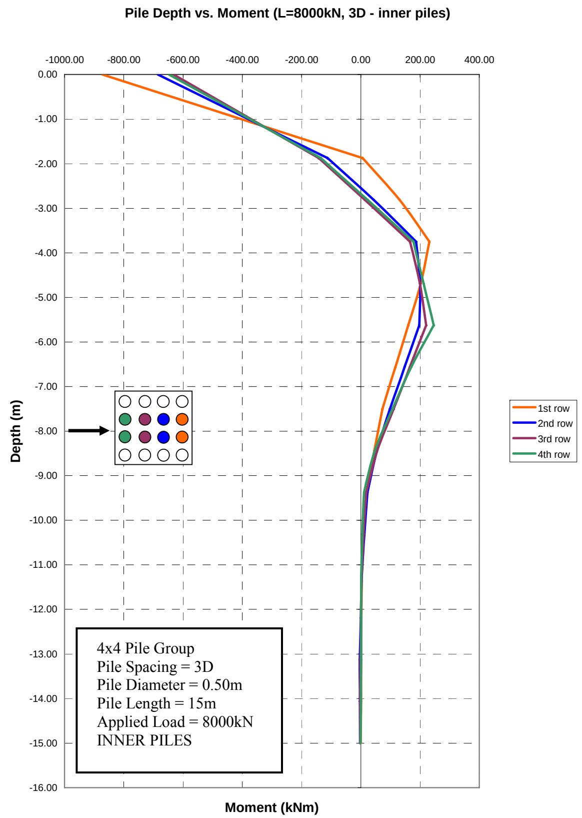


Figure 4.2 Bending Moment vs. Depth Curves with respect to Row Location for Outer and Inner Piles under same load (Pile Group with 3D Pile Spacing, 8000kN total Load applied)

Bending moment versus depth curves are also shown with respect to row location and pile location within the row in Figure 4.2 as a representative case. Since all the piles were fixed to a pile cap, maximum moment occurred at pile head as support moment. Parallel to the load distribution among piles, the piles located on the edge of a row develop greater bending moment than the inner piles under the same applied load. Lead row piles develop the maximum bending moment while the trailing row piles develop somewhat smaller moments under the same applied load. However, at greater depths lead row piles develop less moment than the trailing row piles.

4.2 Effect of Pile Spacing

The alternative pile spacings used in this study have been introduced in Section 3.2.1. The load displacement curves of different pile spacings for pile groups composed of 0.50m diameter and 15m long piles in stiff clay is presented in Figure 4.3. Under the same lateral load applied, pile groups with 2D pile spacing resulted in the largest lateral deflections, whereas pile groups with 5D pile spacing resulted in the lowest lateral deflections. Pile groups with 3D and 4D pile spacings on the other hand, produced intermediate levels of deflection as expected. Lateral deflection distribution along length of piles under 8000kN total load applied is also presented in Figure 4.4. as an illustrative case. In addition to the maximum displacement values of the pile groups with respect to the pile spacing, in Figure 4.4, zero deflection point can be determined.

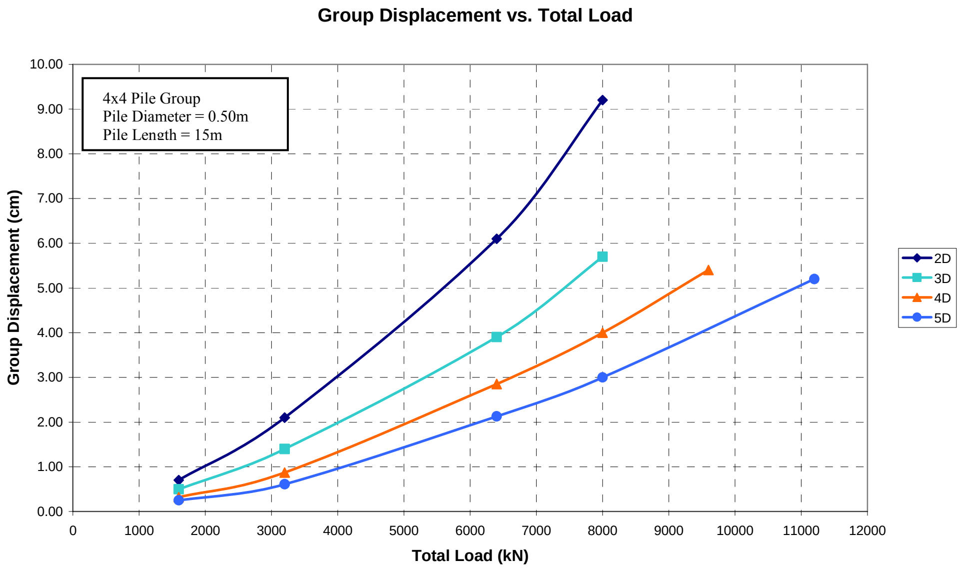


Figure 4.3 Total Load vs. Group Displacement for different pile spacings

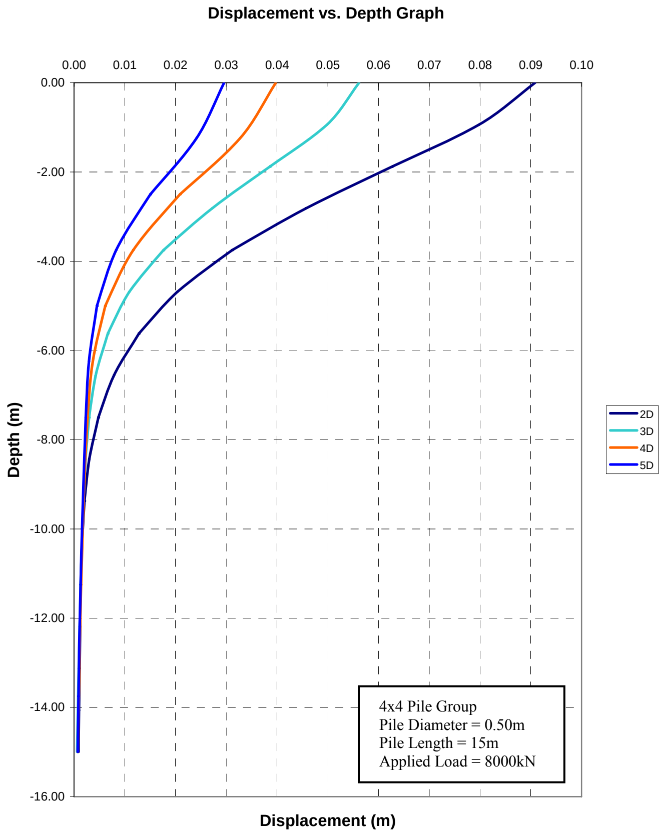
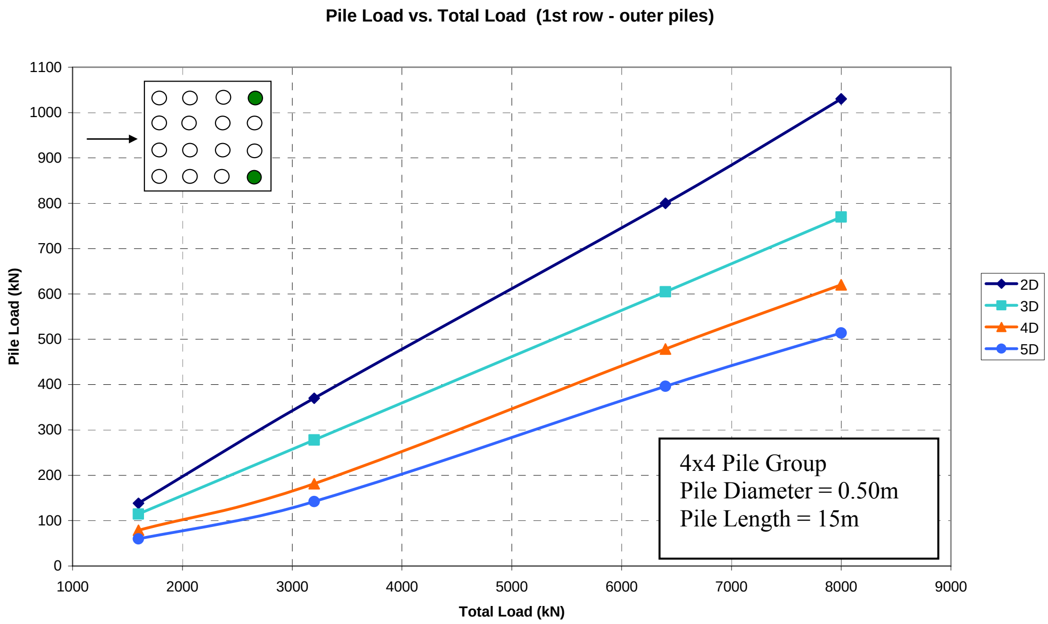


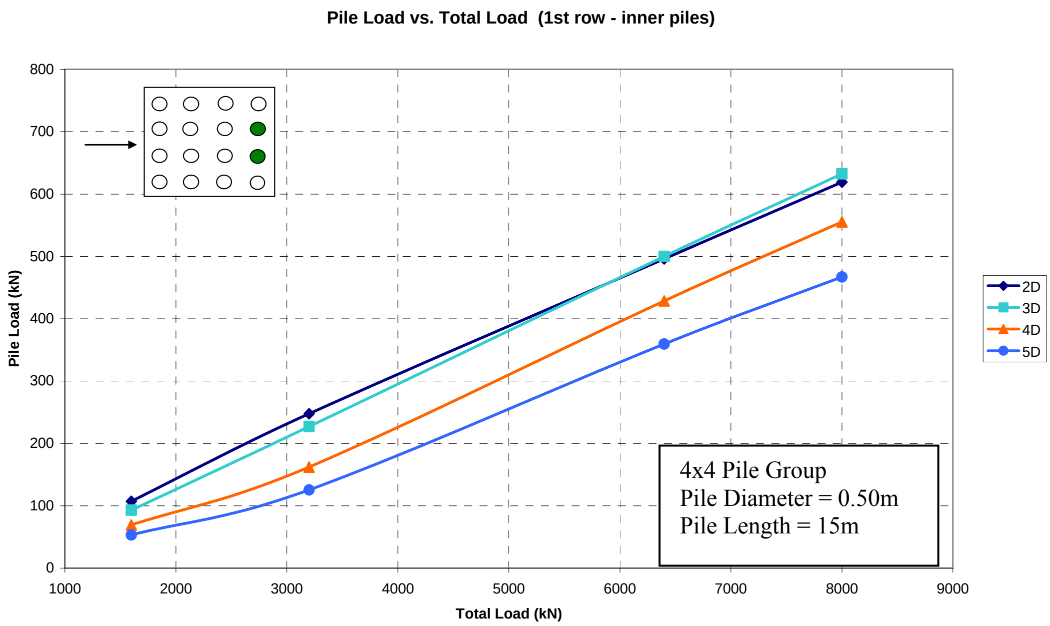
Figure 4.4 Lateral Deflection Distribution along Length of Piles under 8000kN

The lateral load capacity of a single pile was described in Section 3.3. Lateral load capacity of a 0.50m diameter pile was calculated as 600kN. In Figure 4.4 the lateral deflection of an individual pile is presented under a total load of 8000kN which means 500kN/pile. In other words, the results for this case is presented under a load of 85% of its ultimate lateral load capacity. Using both Figure 4.3 and 4.4, the increment of lateral deflection can be estimated for a 4x4 pile group depending on pile spacing. These figures reveal that lateral deflection increased considerably as pile spacing decreased from 5D to 2D. In this study, it is observed that for a 4x4 pile group under the same load, when pile spacing decreases from 5D to 4D, maximum lateral deflection of the group increases about 33%. However, this increment of deflection is calculated larger when pile spacing decreases from 4D to 3D and from 3D to 2D, namely 37.5% and 64% respectively. Moreover, lateral deflection of individual piles in pile groups with larger pile spacing reaches to zero at greater depths as expected. In this study deflections become nearly zero between 7 m and 9 m depths from the ground surface.

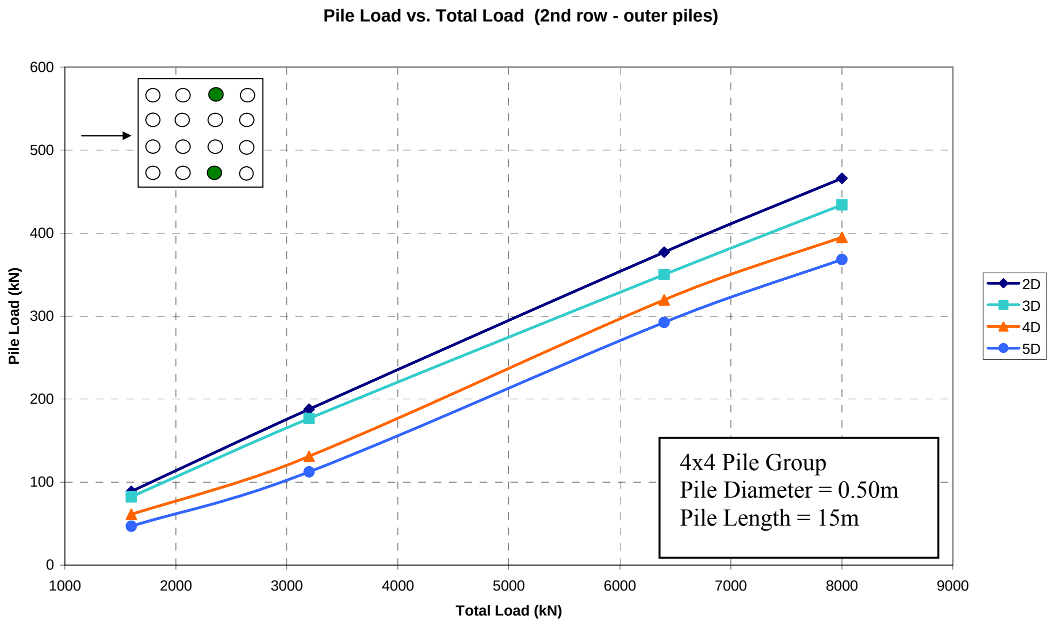
In this study, it is observed that pile spacing affects lateral load distribution in pile groups significantly. In order to estimate the pile group behaviour, total load versus pile load plots are shown in Figure 4.5 for each pile in the group. Based on the variation of pile spacing, it can be concluded that as pile spacing increases, pile load decreases. However, this type of behaviour can be seen more clearly in the first and the second row piles. For the third and the fourth row piles, pile spacing becomes a less significant factor affecting the load distribution in a pile group.


Pile Load vs. Total Load (1st row - outer piles)
Pile Load (kN)
Total Load (kN)
1100
1000
900
800
700
600
500
400
300
200
100
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
2D
3D
4D
5D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m

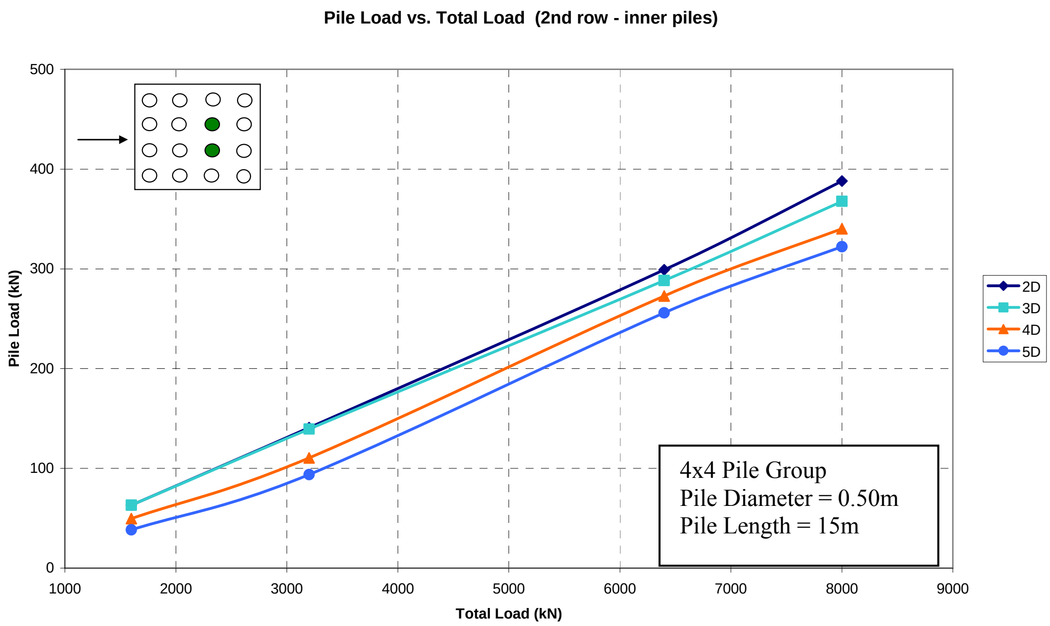
(a)


Pile Load vs. Total Load (1st row - inner piles)
Pile Load (kN)
Total Load (kN)
800
700
600
500
400
300
200
100
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
2D
3D
4D
5D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m

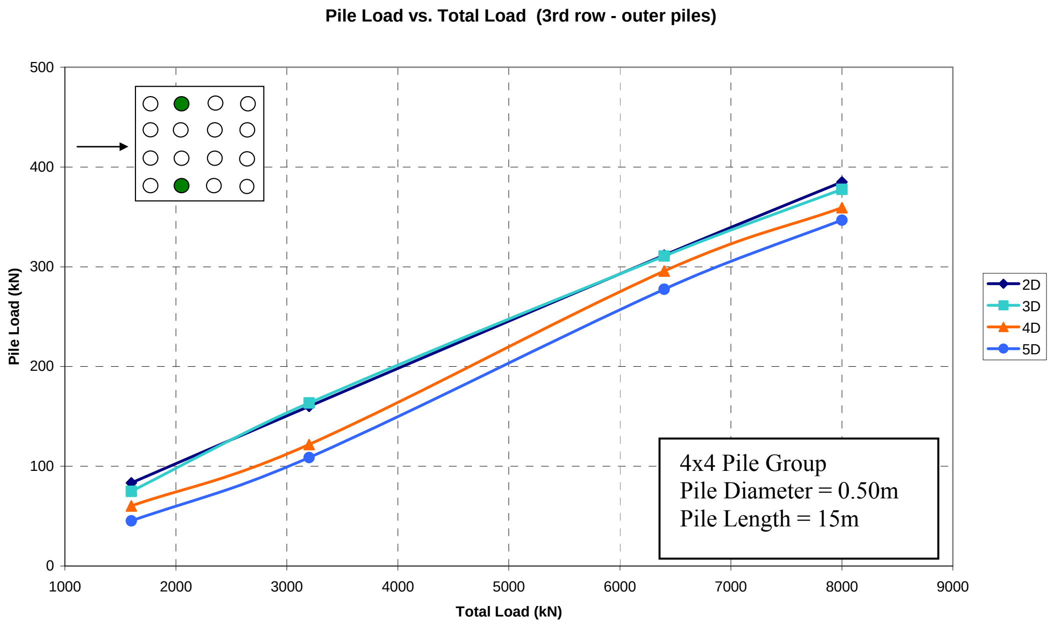
(b)


Pile Load vs. Total Load (2nd row - outer piles)
Pile Load (kN)
Total Load (kN)
2D
3D
4D
5D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m

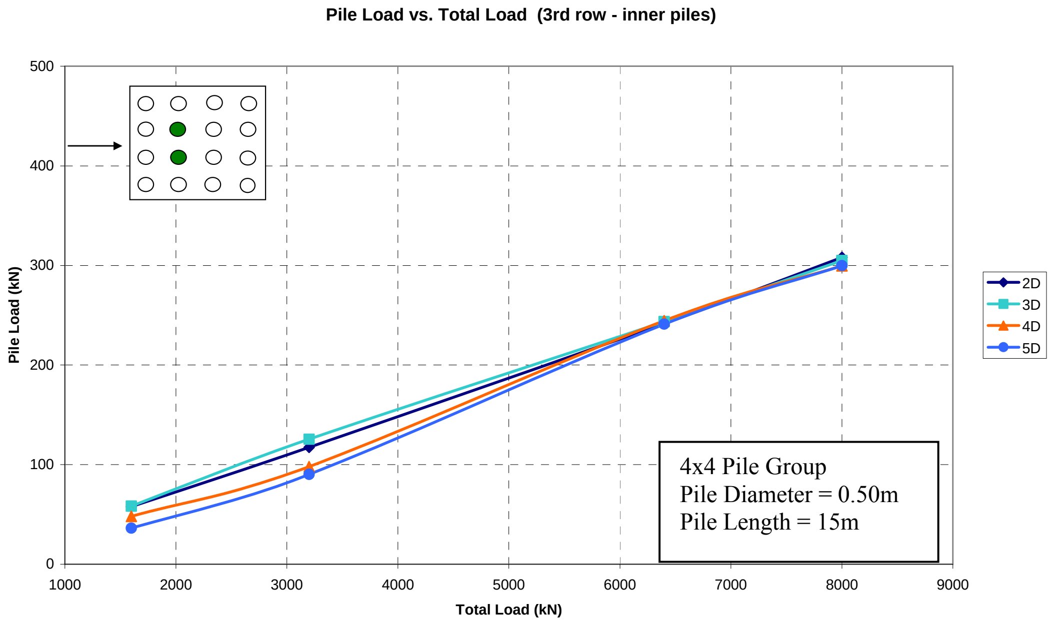
(c)


Pile Load vs. Total Load (2nd row - inner piles)
Pile Load (kN)
Total Load (kN)
2D
3D
4D
5D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m

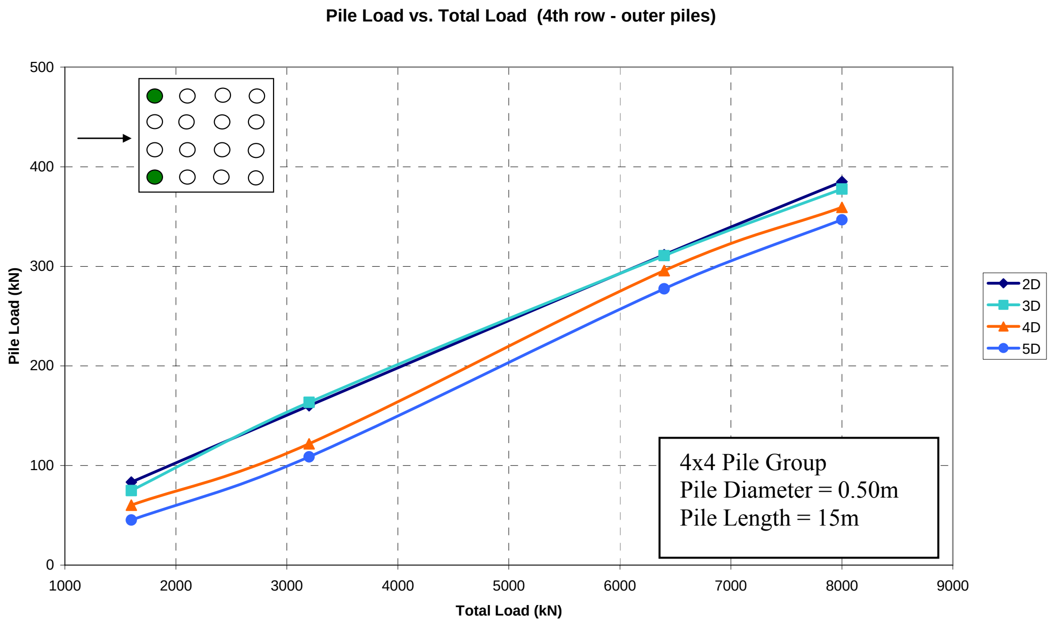
(d)


Pile Load vs. Total Load (3rd row - outer piles)
Pile Load (kN)
Total Load (kN)
500
400
300
200
100
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
2D
3D
4D
5D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m

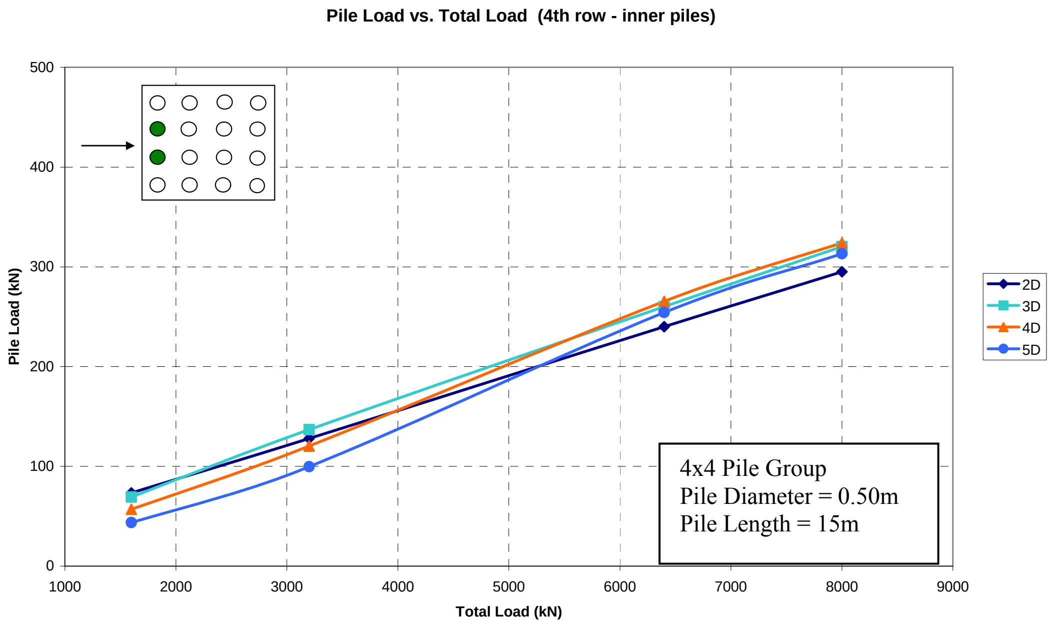
(e)


Pile Load vs. Total Load (3rd row - inner piles)
Pile Load (kN)
Total Load (kN)
500
400
300
200
100
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
2D
3D
4D
5D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m

(f)



(g)



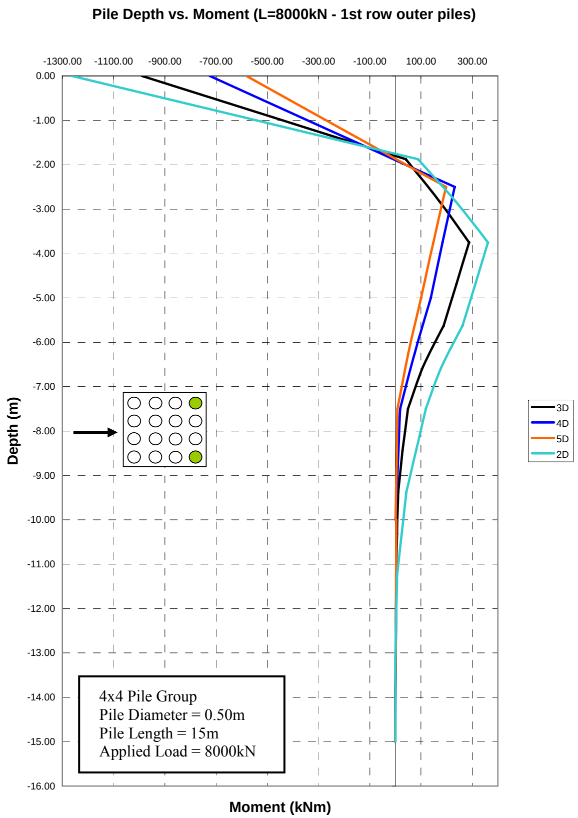
(h)

Figure 4.5 Total Load vs. Pile Load Curves with respect to Pile Spacing for each Pile

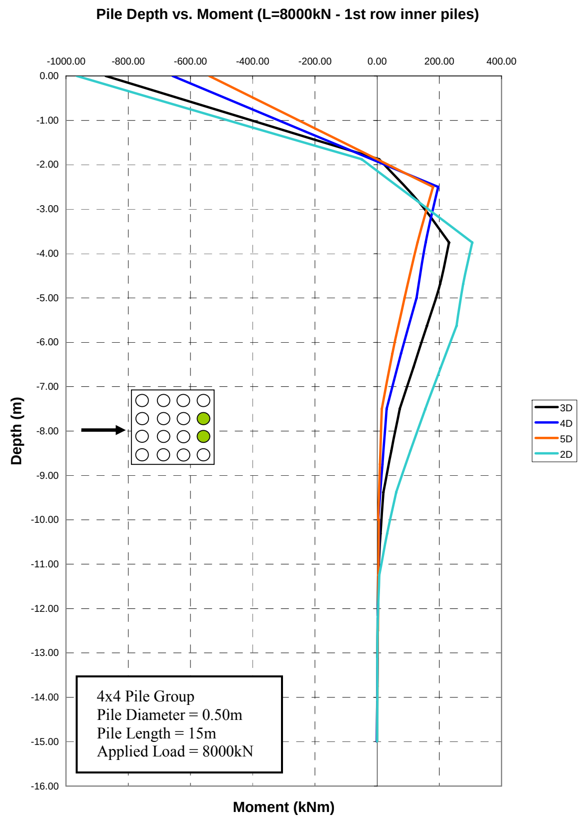
Bending moment versus depth curves are also shown with respect to pile spacing under 8000kN load applied in Figure 4.6 as a representative case. Curves are shown for each pile in the group. Since all the piles were fixed with a pile cap, maximum moment occurred at pile head as support moment as mentioned in previous sections. Parallel to the load distribution among piles, it can be concluded that as pile spacing increases, maximum bending moment occurred decreases under the same load applied. However, in case of bending moment, the variation due to pile spacing can be clearly observed in all piles and rows.

Using the tables and figures shown, the piles were reclassified as shown in Figure 4.7. In this classification, the load and bending moment of each pile were considered rather than the row location. Pile group behaviour determined from this study, was close enough to the classification of DIN 4014. Thus, the same terminology with DIN 4014 is used while evaluating the load distribution. DIN 4014 determines the load distribution of pile groups in which all piles are subject to the same lateral head displacement as all piles do in this study.

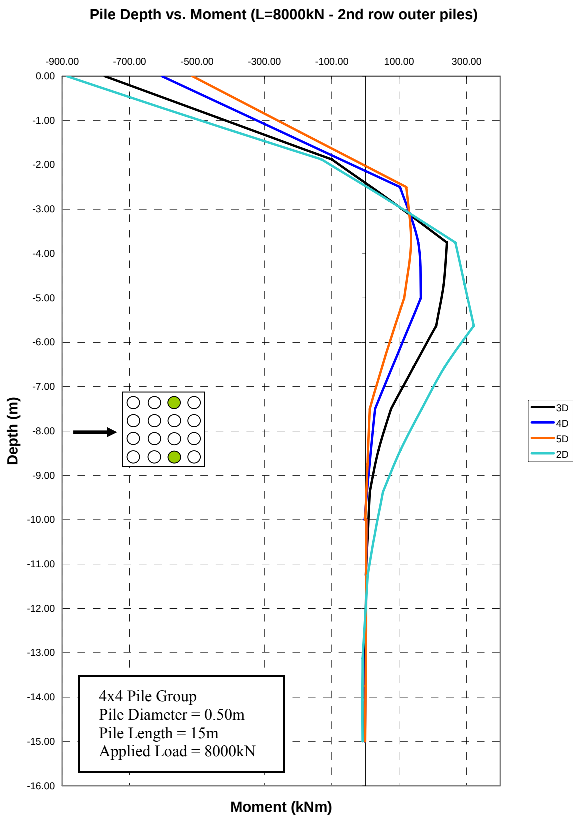
With this second classification of piles in pile groups, the pile load coefficients are recalculated for each pile spacing and shown in Table 4.3. Figure 4.8 illustares how the pile load coefficients are calculated as a representative case. The average values are taken into account while determining the pile load coefficients.


Pile Depth vs. Moment (L=8000kN - 1st row outer piles)
-1300.00
-1100.00
-900.00
-700.00
-500.00
-300.00
-100.00
100.00
300.00
Depth (m)
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 8000kN
Moment (kNm)

(a)

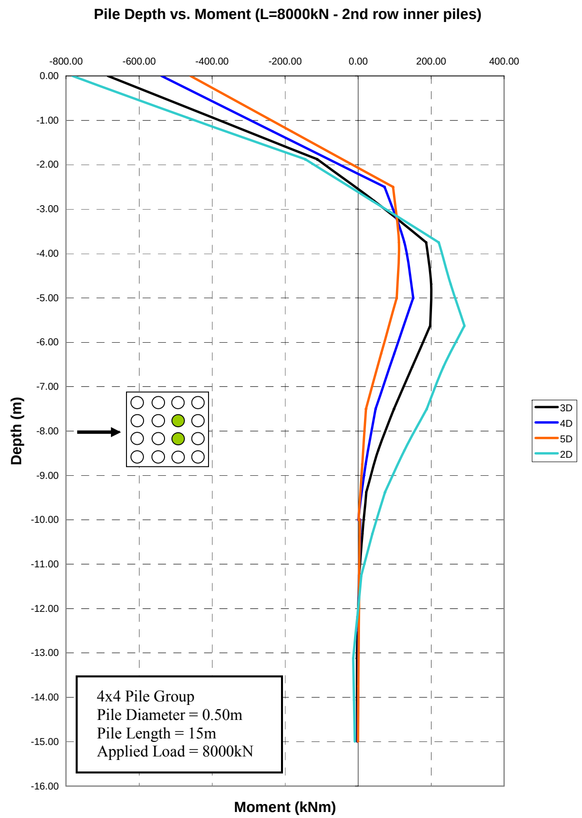

Pile Depth vs. Moment (L=8000kN - 1st row inner piles)
-1000.00
-800.00
-600.00
-400.00
-200.00
0.00
200.00
400.00
Depth (m)
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 8000kN
Moment (kNm)

(b)



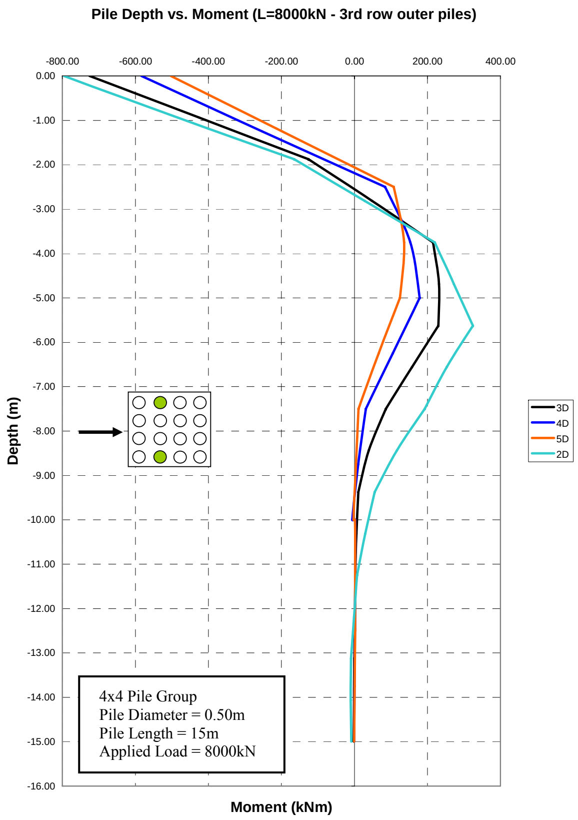
Pile Depth vs. Moment (L=8000kN - 2nd row outer piles)
-900.00
-700.00
-500.00
-300.00
-100.00
100.00
300.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 8000kN

(c)

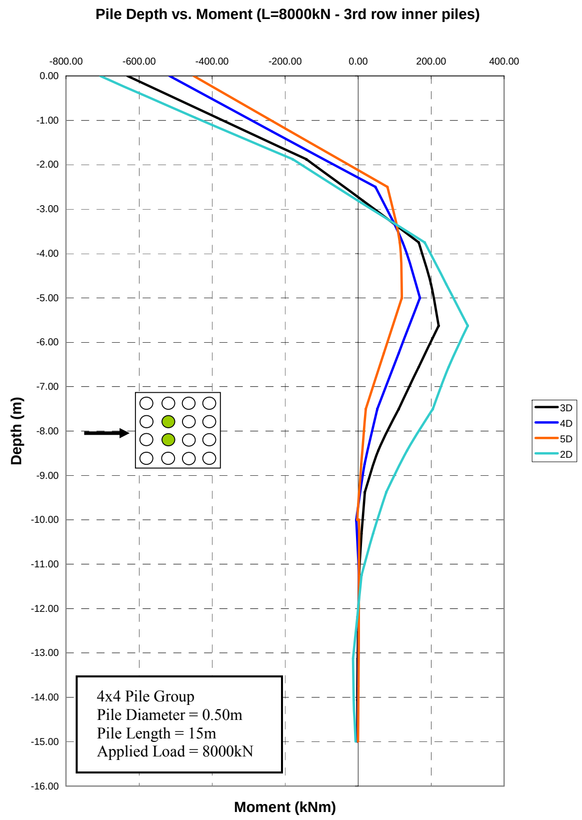


Pile Depth vs. Moment (L=8000kN - 2nd row inner piles)
-800.00
-600.00
-400.00
-200.00
0.00
200.00
400.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 8000kN

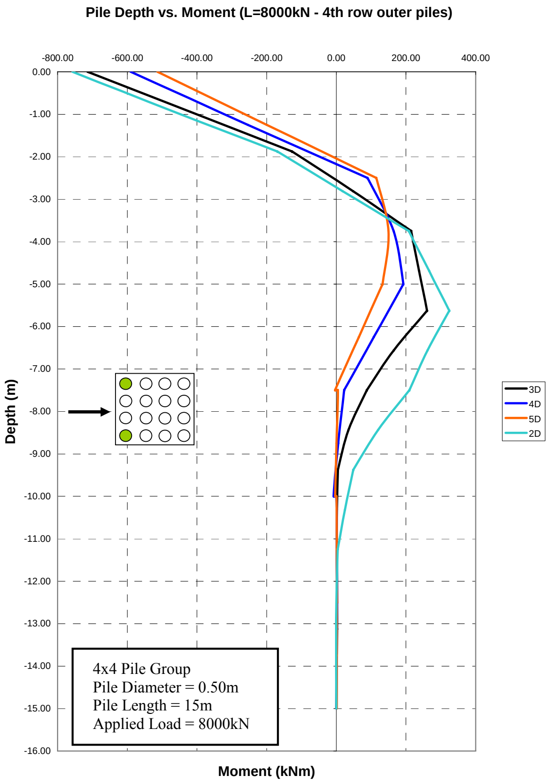
(d)


Pile Depth vs. Moment (L=8000kN - 3rd row outer piles)
-800.00
-600.00
-400.00
-200.00
0.00
200.00
400.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 8000kN

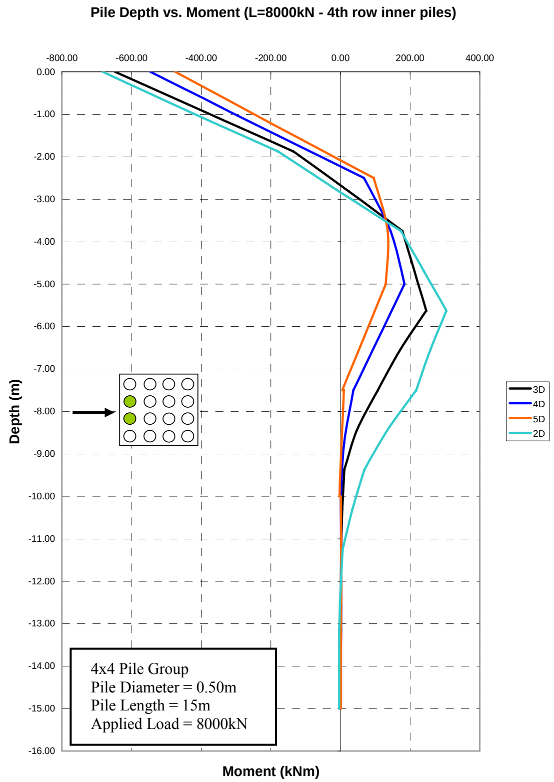
(e)


Pile Depth vs. Moment (L=8000kN - 3rd row inner piles)
-800.00
-600.00
-400.00
-200.00
0.00
200.00
400.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 8000kN

(f)



(g)



(h)

Figure 4.6 Bending Moment Distribution Along Pile with respect to Pile Spacing under 8000kN load applied

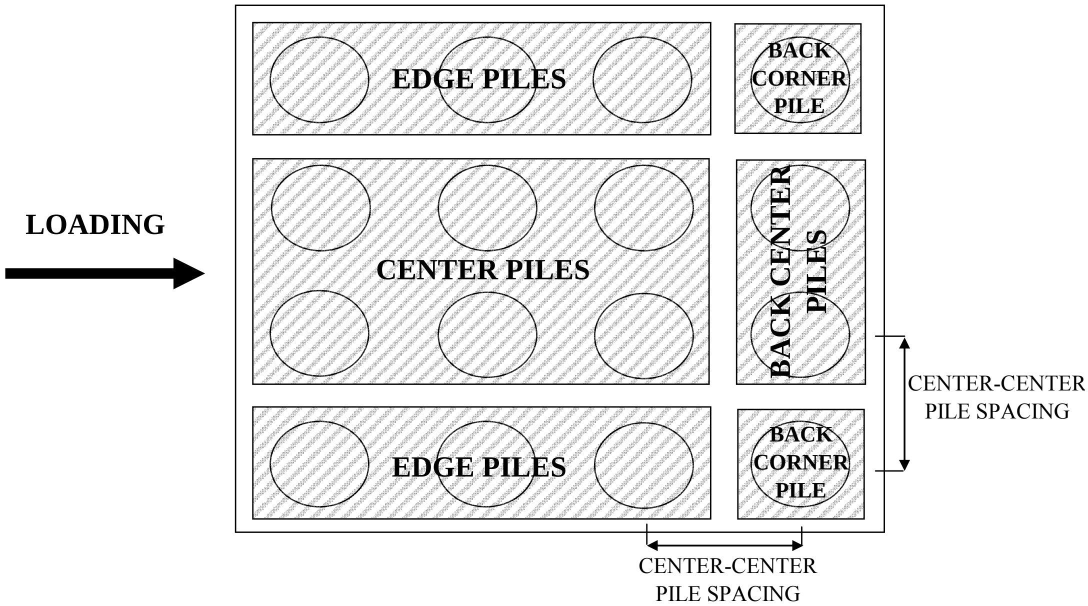


Figure 4.7 Pile Classification (DIN 4014)

Table 4.3 Load Distribution Coefficient of Individual Piles

2D Pile Spacing	Individual Pile Load / Average Pile Load			
Average Pile Load (kN)	**Back Corner Piles**	**Back Center Piles**	**Edge Piles**	**Center Piles**
100	1.38	1.07	0.92	0.65
200	1.85	1.24	0.87	0.64
400	2.00	1.24	0.82	0.65
500	2.06	1.24	0.80	0.66

3D Pile Spacing	Individual Pile Load / Average Pile Load			
Average Pile Load (kN)	Back Corner Piles	Back Center Piles	Edge Piles	Center Piles
100	1.14	0.93	0.81	0.63
200	1.39	1.14	0.85	0.67
400	1.51	1.25	0.81	0.66
500	1.54	1.26	0.79	0.66

4D Pile Spacing	Individual Pile Load / Average Pile Load			
Average Pile Load (kN)	Back Corner Piles	Back Center Piles	Edge Piles	Center Piles
100	0.79	0.69	0.63	0.52
200	0.91	0.81	0.66	0.55
400	1.20	1.07	0.76	0.65
500	1.24	1.11	0.74	0.64
600	1.29	1.15	0.74	0.64

5D Pile Spacing	Individual Pile Load / Average Pile Load			
Average Pile Load (kN)	Back Corner Piles	Back Center Piles	Edge Piles	Center Piles
100	0.60	0.53	0.48	0.39
200	0.71	0.63	0.57	0.47
400	0.99	0.90	0.71	0.63
500	1.03	0.93	0.71	0.62
700	1.11	1.03	0.70	0.63

From the results of the computer analysis, it can be concluded that the outer piles of the leading row carries the greatest lateral load and these piles are termed as back corner piles. Piles that carries significantly higher loads than the others are the inner piles of the leading row and these piles are termed as back center piles. When the the trailing row piles are examined, it is realized that location of the pile within the row is more important in regarding the load distribution, than the row location in the group. Thus, the outer piles of the trailing rows are termed as edge piles, whereas the inner piles of the trailing rows are termed as center piles as described in DIN 4014. In this study, the ratio of pile load obtained from the analysis and the average pile load applied is calculated for each pile in each pile group with different pile spacing for each load level and termed as the pile load coefficient. According to this classification, an average coefficient value is calculated and presented in Table 4.3. In order to illustrate the behaviour more clearly these values are also presented as curves in Figure 4.9.

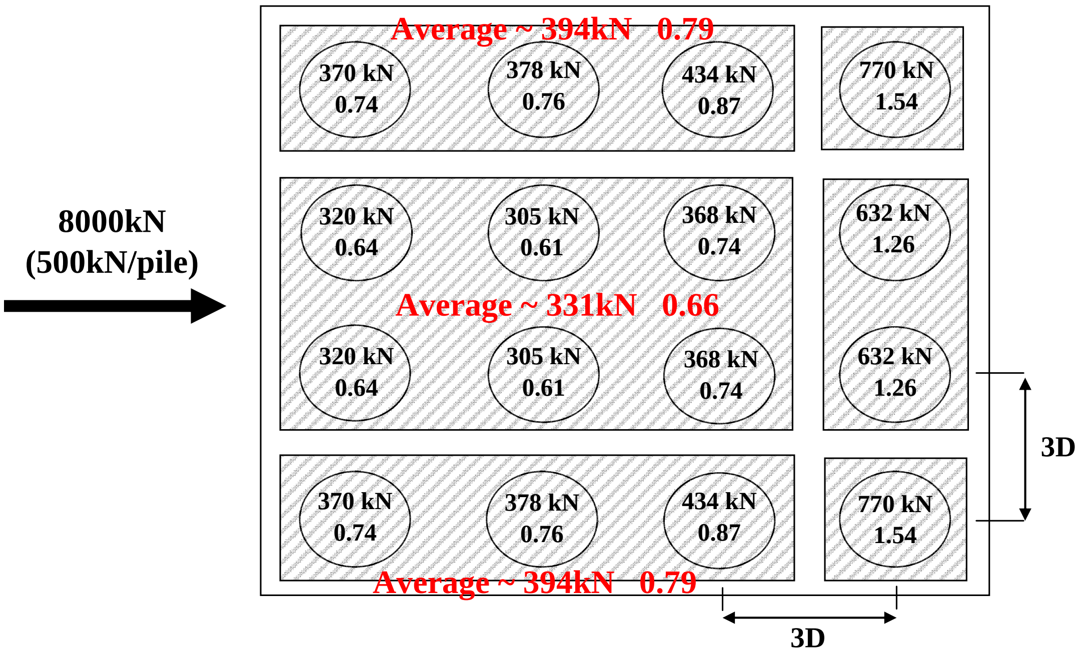
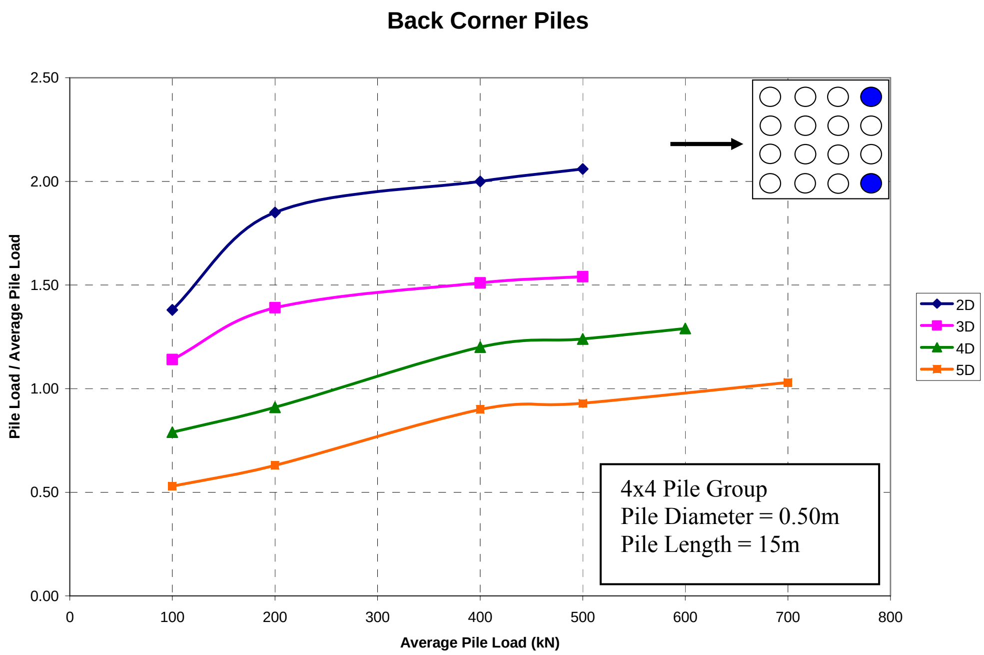
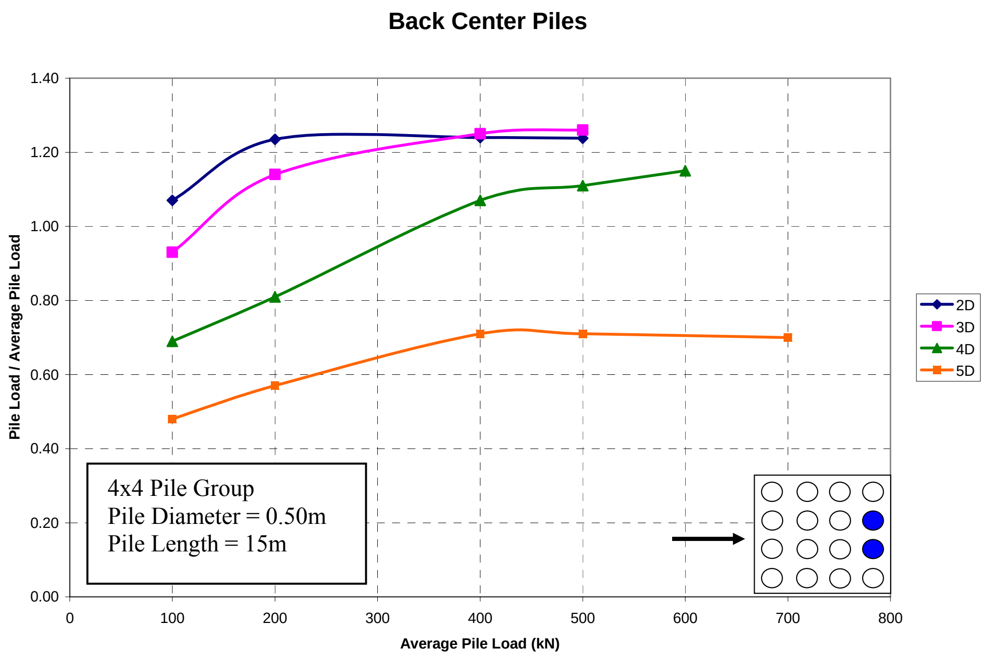


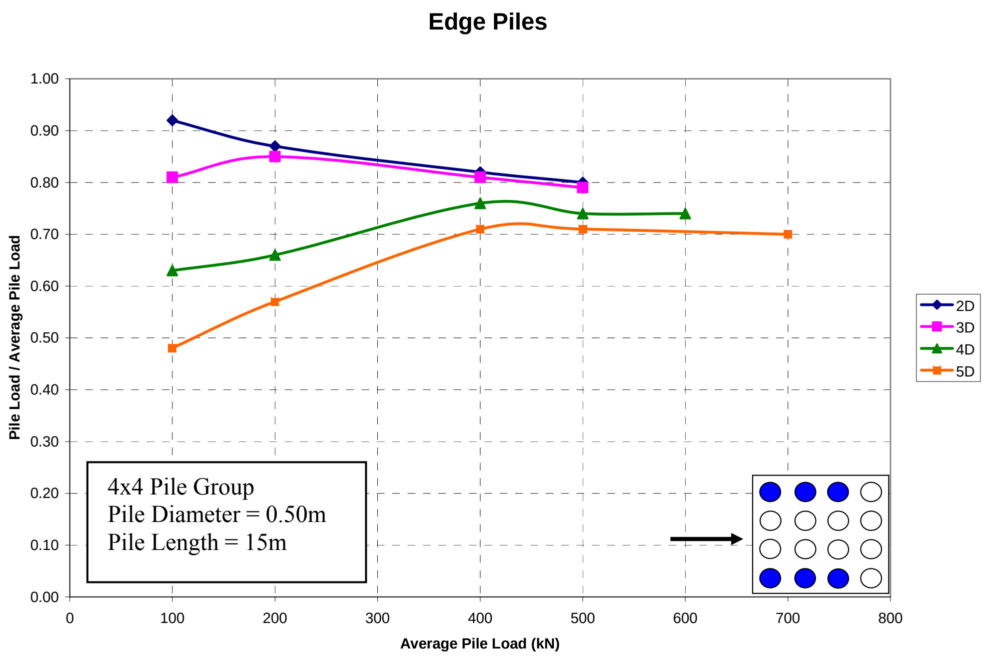
Figure 4.8 Pile Load Distribution in the group with 3D Pile Spacing and 8000kN load Applied


Back Corner Piles
Pile Load / Average Pile Load
Average Pile Load (kN)
2D
3D
4D
5D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m

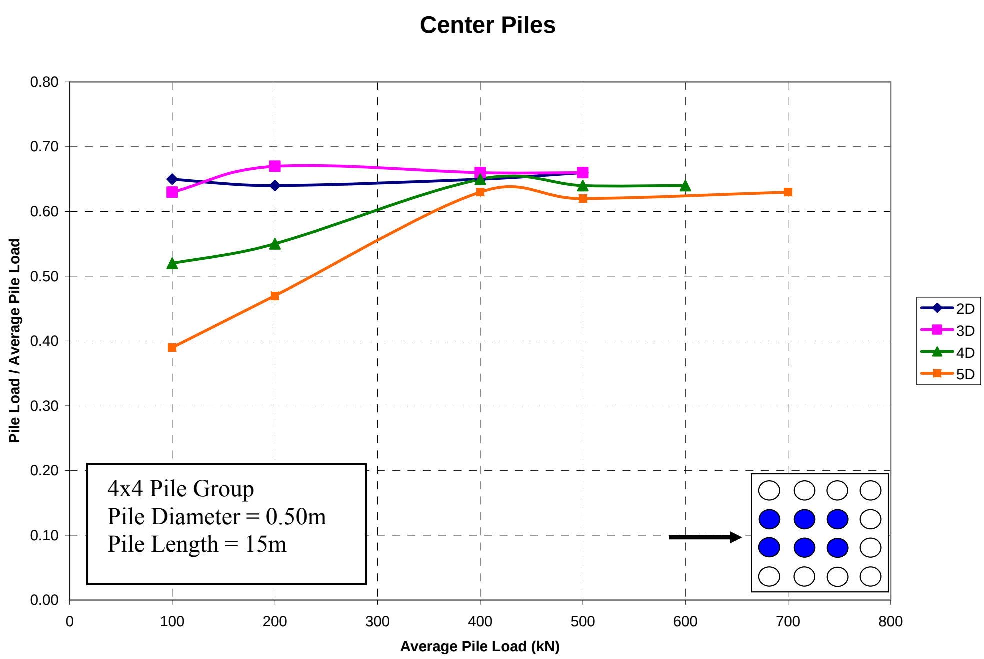
(a)


Back Center Piles
Pile Load / Average Pile Load
Average Pile Load (kN)
2D
3D
4D
5D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m

(b)



(c)



(d)

Figure 4.9 Average Pile Load vs. Pile Load Coefficient with respect to Pile Spacing

The lateral load distribution of the pile group was found to be a function of pile spacing and location of the pile in the group. For back corner piles it can be concluded that as pile spacing increases pile load coefficient value decreases for every pile spacing condition. However, as the applied load increases the coefficient tends to be constant. For the loads greater than 400kN/pile the coefficient can be taken as 2.00 for 2D pile spacing condition, 1.50 for 3D pile spacing condition, 1.25 for 4D pile spacing condition and 1.00 for 5D pile spacing condition.

For back center piles, almost the same group behaviour can be observed except for closely spaced pile group conditions. The pile load coefficients of both 2D pile spacing and 3D pile spacing groups coincide with each other. For the loads greater than 400kN/pile the coefficient can be taken as 1.25 for 2D and 3D pile spacing conditions, 1.10 for 4D pile spacing condition and 0.70 for 5D pile spacing condition.

For the edge piles, it can be concluded that, the pile load coefficient converges to 0.75 in all pile spacing conditions as the applied load increases. For the loads greater than 400kN/pile the coefficient can be taken as 0.75 for all pile spacing conditions. For center piles same group behaviour obtained with the edge piles except the value of converged pile load coefficient. For the loads greater than 400kN/pile the coefficient can be taken as 0.65 for all pile spacing conditions.

According to DIN4014 the lateral load on a single pile in a pile group can be calculated as follows:

$$\frac{H_i}{H_G} = \frac{\alpha_i}{\sum \alpha_i} \tag{4.1}$$

$$\alpha_i = \alpha_L \times \alpha_Q \tag{4.2}$$

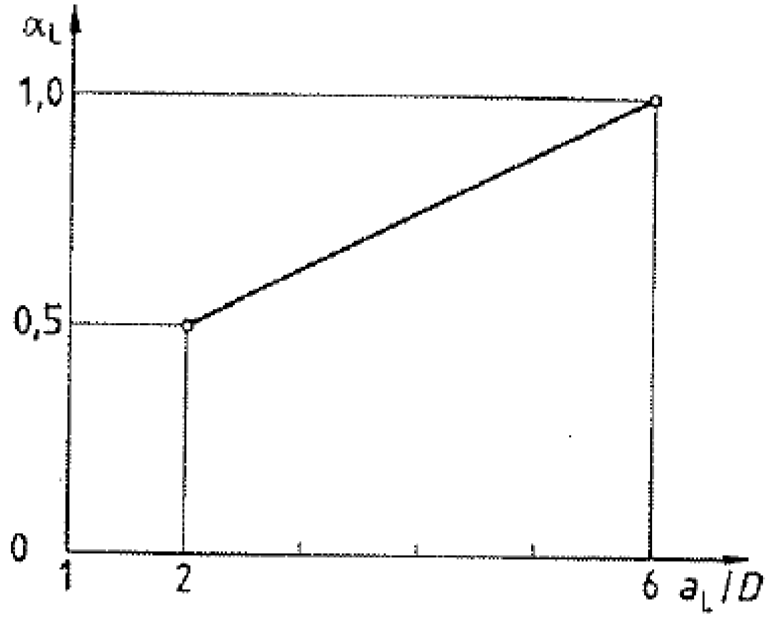
where; H_G is the total lateral load applied to the pile group, H_i is the single pile load, α_L and α_Q are the interaction factors that are a function of the pile spacing in the direction of loading and transverse to it respectively. These interaction factors are simply determined using Figure 4.10

For the comparison, pile load coefficients (PLC = pile load/average pile load) of a 4x4 pile group with 2D and 3D pile spacing are calculated according to DIN4014 and summarised below. Figure 4.11 show the results of this study and Figure 4.12 show the results reached using DIN4014 procedure.

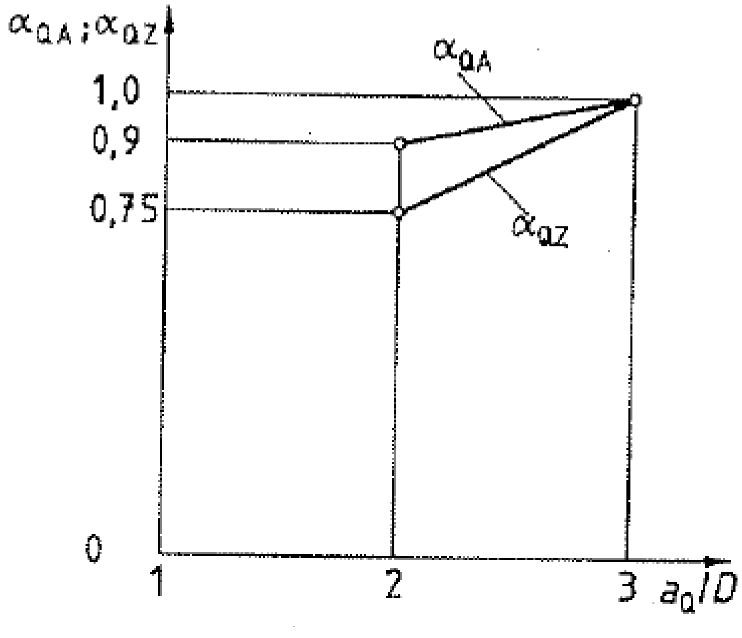
From these results, it can be concluded that the individual pile behaviour in a pile group determined from 3D finite element method is compatable with DIN4014. However, it is found that finite element analysis underestimate the back center and center pile coefficients. To conclude; the ratios of the pile load and the average pile load are close enough to use in practice.

4.3 Effect of Pile Diameter

Two different pile diameters, D=0.80m and D=0.50m, were used in these parametric study. For comparison pile spacing of the system is kept constant as 3D. The load displacement curves of different pile diameters for pile groups with 3D pile spacing in stiff clay is presented in Figure 4.13. It is observed that as pile diameter gets larger, group displacement decreases. Since the system gets stiffer with the increase of the pile diameter, the deflections decreased as expected.

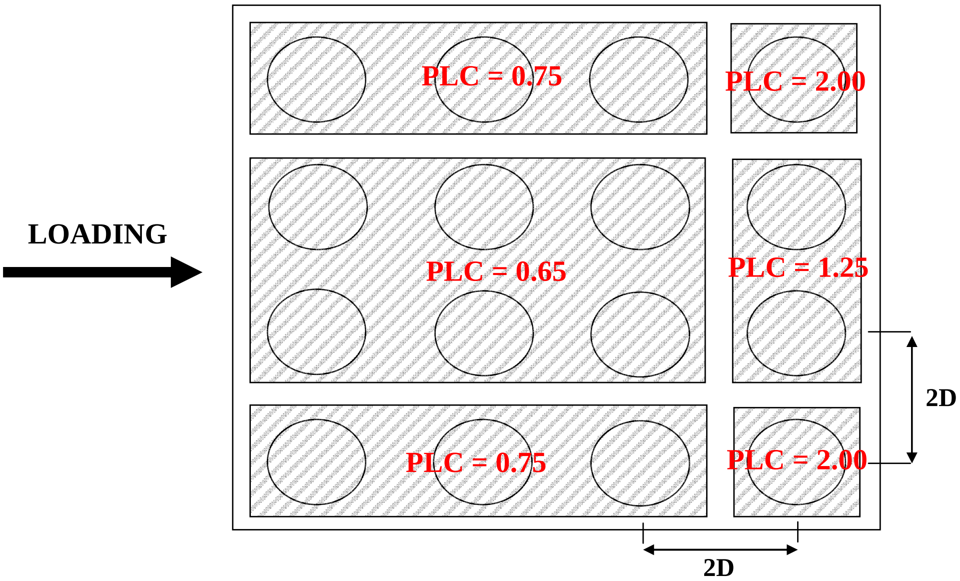


(a)



(b)

Figure 4.10 Interaction factors as a function of pile spacing



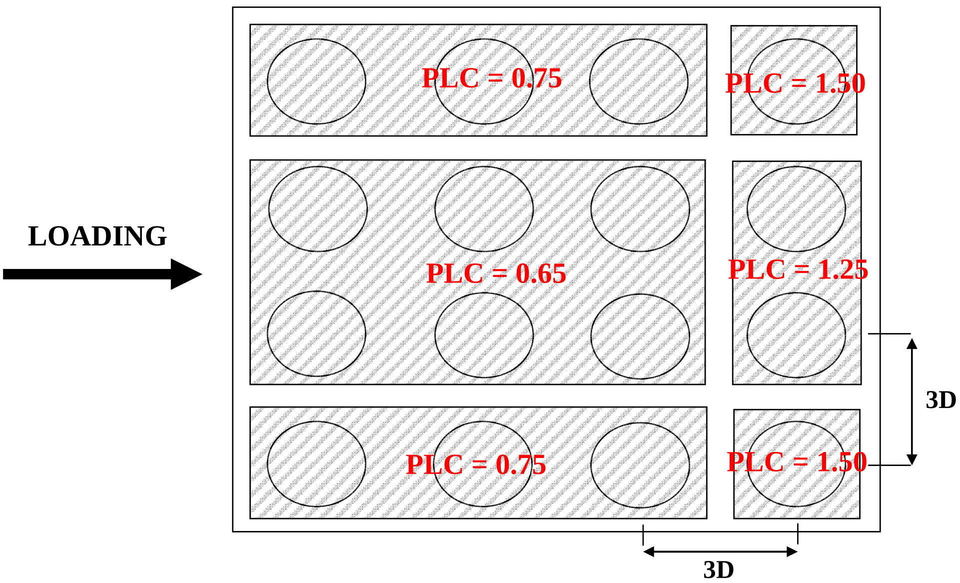
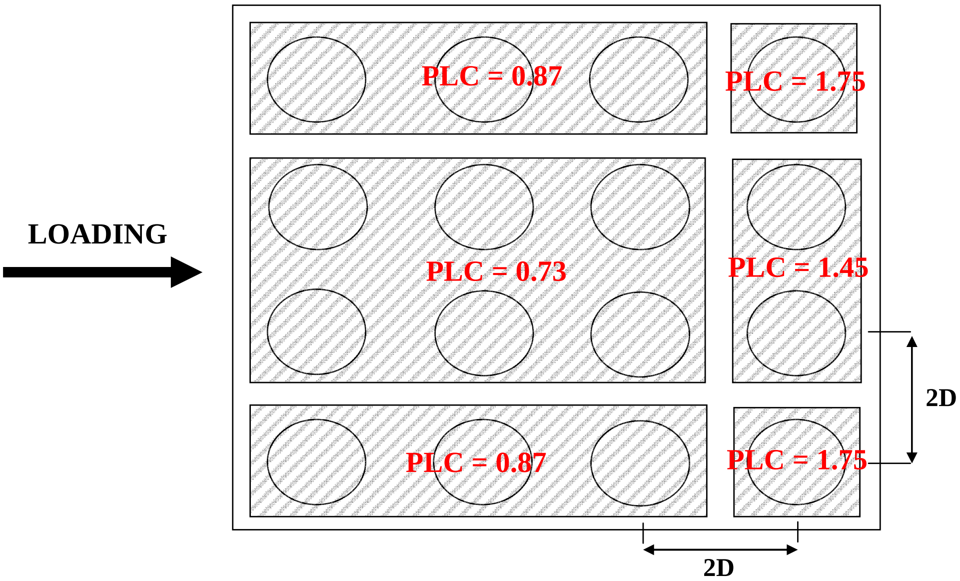


Figure 4.11 Pile Load Coefficient values (Finite Element Analysis)



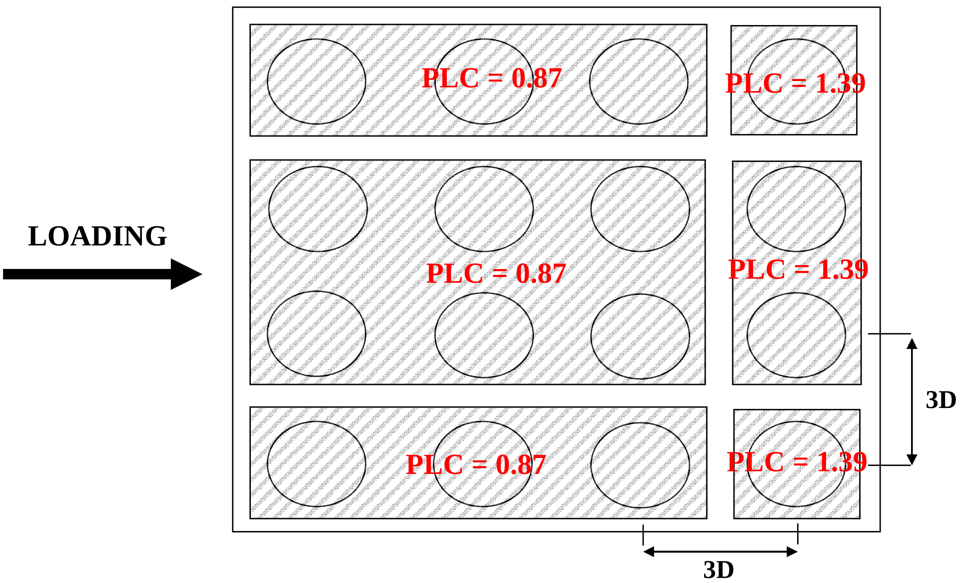


Figure 4.12 Pile Load Coefficient values (DIN4014)

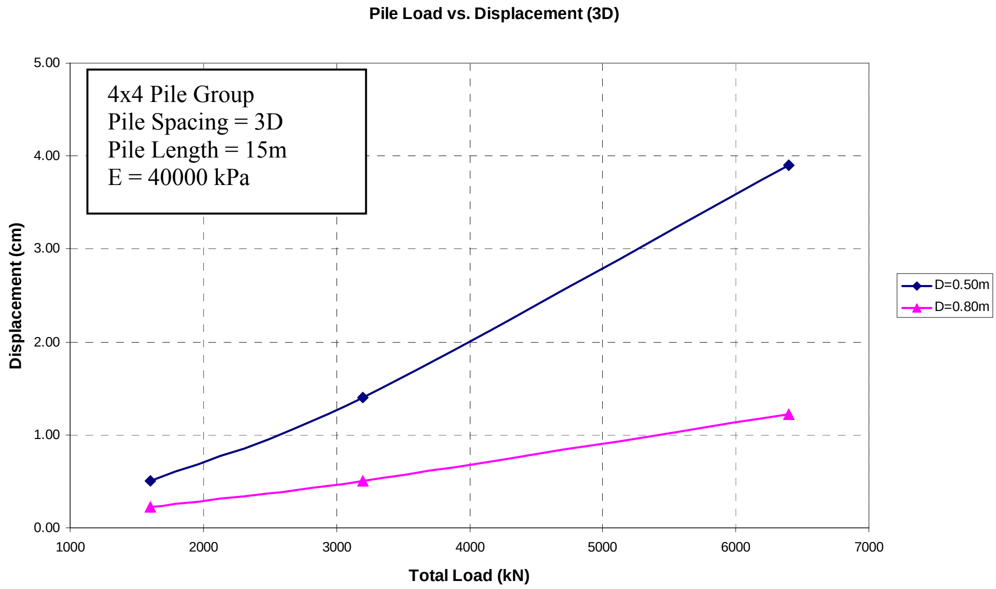
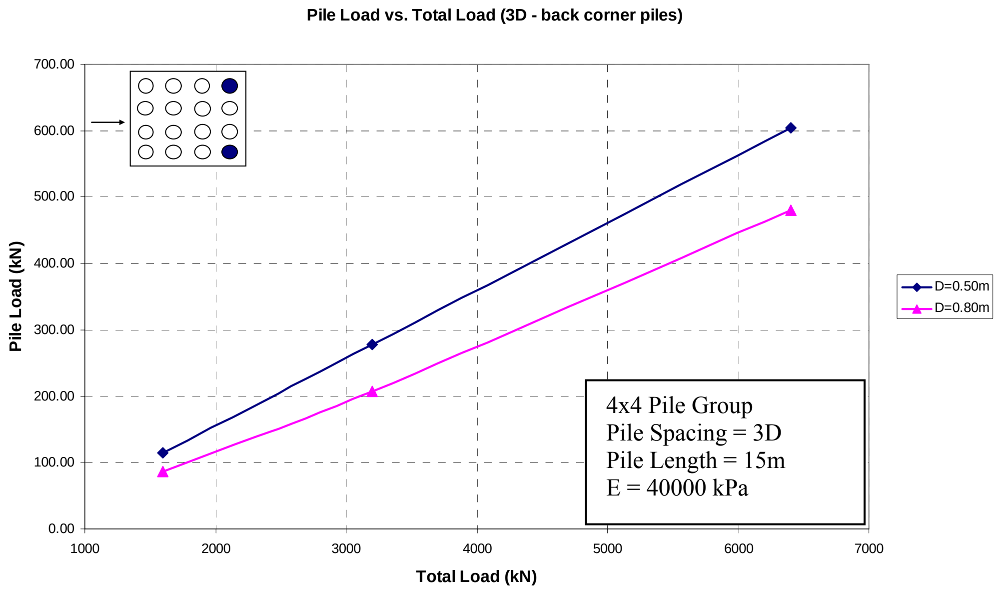


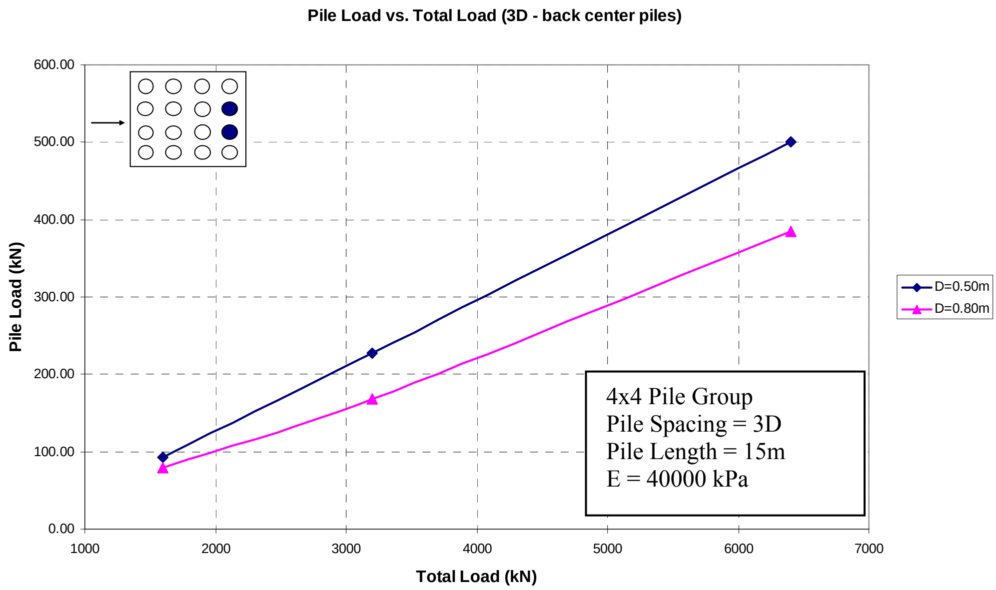
Figure 4.13 Total Load vs Displacement (Pile Spacing is 3D)

From the results of the analysis, it is concluded that, pile diameter is not a significant factor on lateral load distribution as row location and pile spacing. Figure 4.14 illustrates the effect of pile diameter on lateral load distribution of the pile group. For back corner and back center piles it can be concluded that, 0.50m diameter piles carry more load than 0.80m diameter piles. However, the difference between these loads is not as large as the difference occurred by change in pile spacing. In trailing row piles case, in other words, for the edge and the center piles, loads carried are quite close that in practice they can assumed to be the same. As a result, pile diameter has not an important effect on load distribution of pile groups.



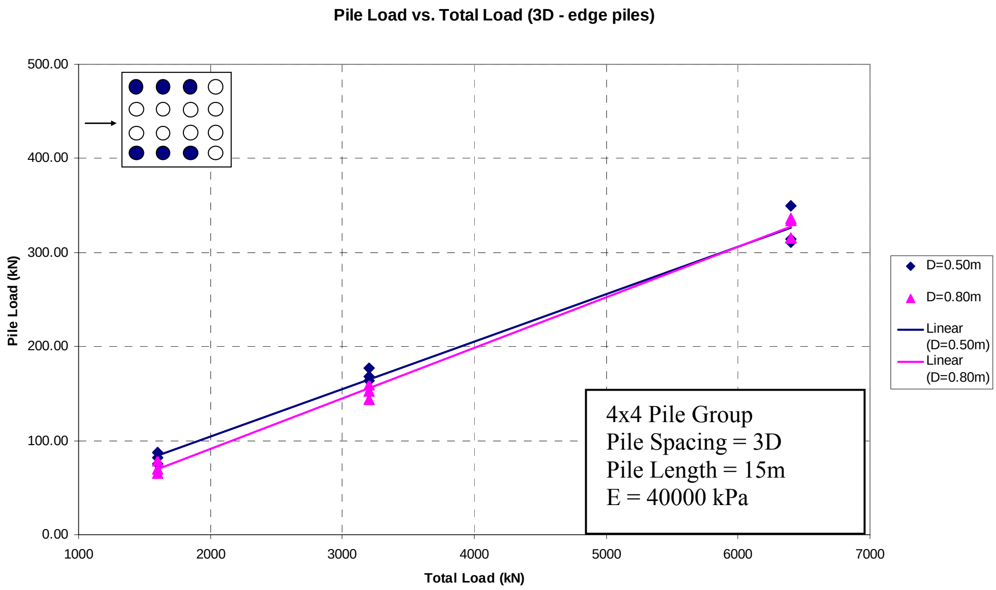
Pile Load vs. Total Load (3D - back corner piles)
Pile Load (kN)
Total Load (kN)
D=0.50m
D=0.80m
4x4 Pile Group
Pile Spacing = 3D
Pile Length = 15m
E = 40000 kPa

(a)

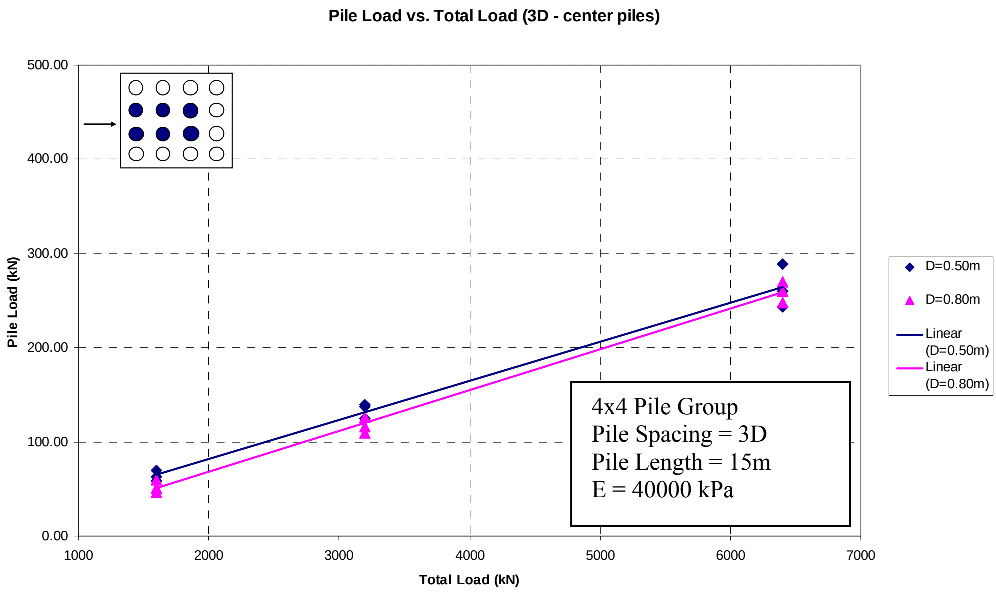


Pile Load vs. Total Load (3D - back center piles)
Pile Load (kN)
Total Load (kN)
D=0.50m
D=0.80m
4x4 Pile Group
Pile Spacing = 3D
Pile Length = 15m
E = 40000 kPa

(b)



(c)



(d)

Figure 4.14 Total Load vs Pile Load (Pile Spacing is 3D)

4.4 Effect of Soil Stiffness

In this study, the last variable is the elastic modulus (Young's Modulus, E) of the clay layer. For this part of the study, three different loads (1600kN, 3200kN, and 6400kN) have been applied to the pile group that has 3D, center to center pile spacing. In order to see the behaviour clearly, the system has been analysed with a clay layer that has a relatively low modulus of elasticity (10MPa). However, second set of analysis have been done with an average elastic modulus value of 40MPa.

As a result, two different graphs have been drawn. First graph shown in Figure 4.15 illustrates the change in deflection due to the modulus of elasticity. However, second graph (Figure 4.16) shows the relationship between the total load applied, and the lateral load distribution on individual piles. Thus, second graph has been drawn for both edge and intermediate piles of each row seperately.

Figure 4.15 concludes that, the pile group displacement in relatively softer clay, are larger then the displacements occurred in pile group in stiff clay layer as expected. However, when the load levels are considered, the difference between the displacement values gets larger as the load increases.

Figure 4.16 concludes that, elastic modulus of clay has less significant effect on load distribution of pile groups. As seen from the graphs below, the load carried by the individual piles does not differ with the variation of soil stiffness.

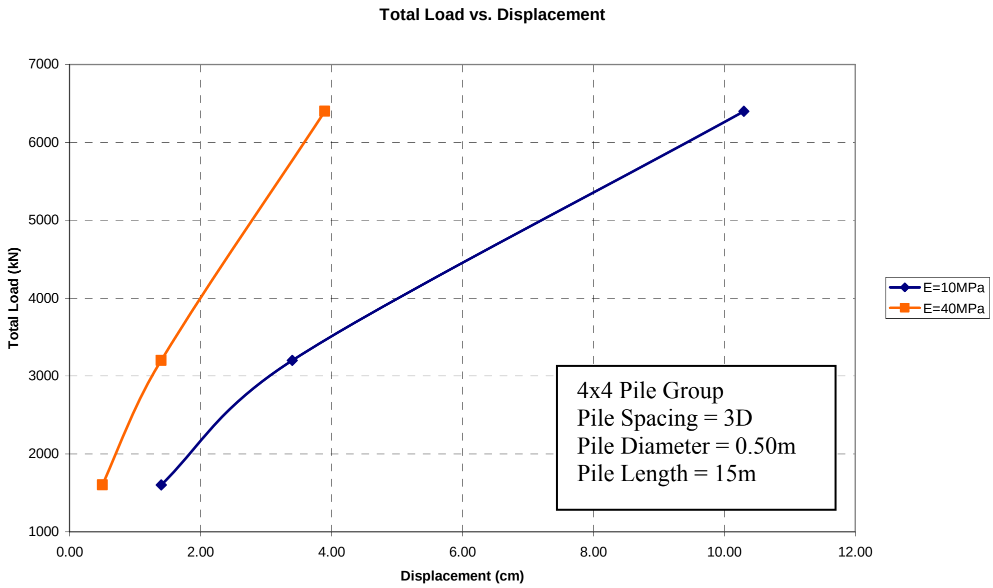
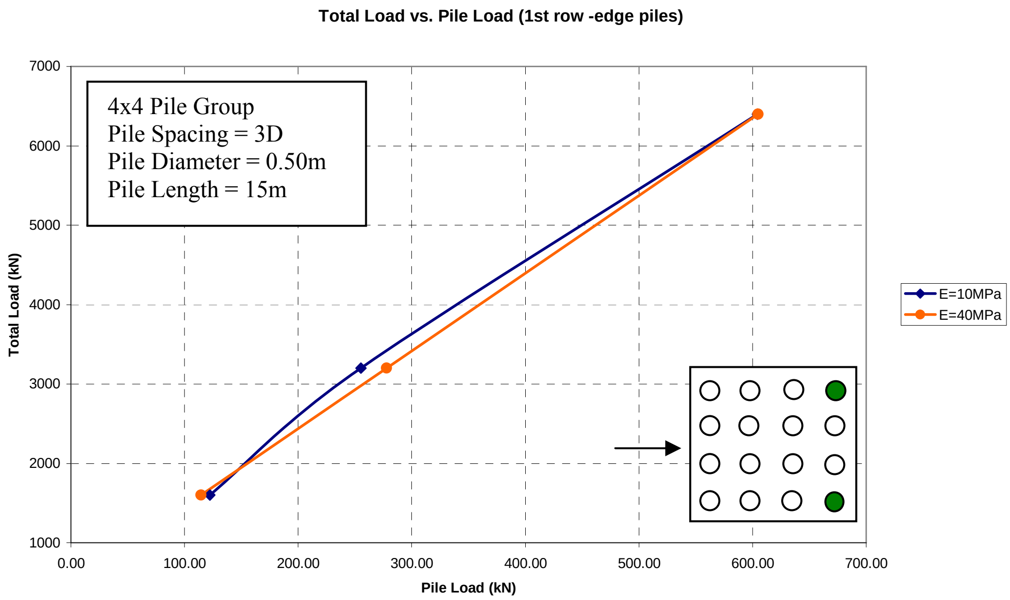
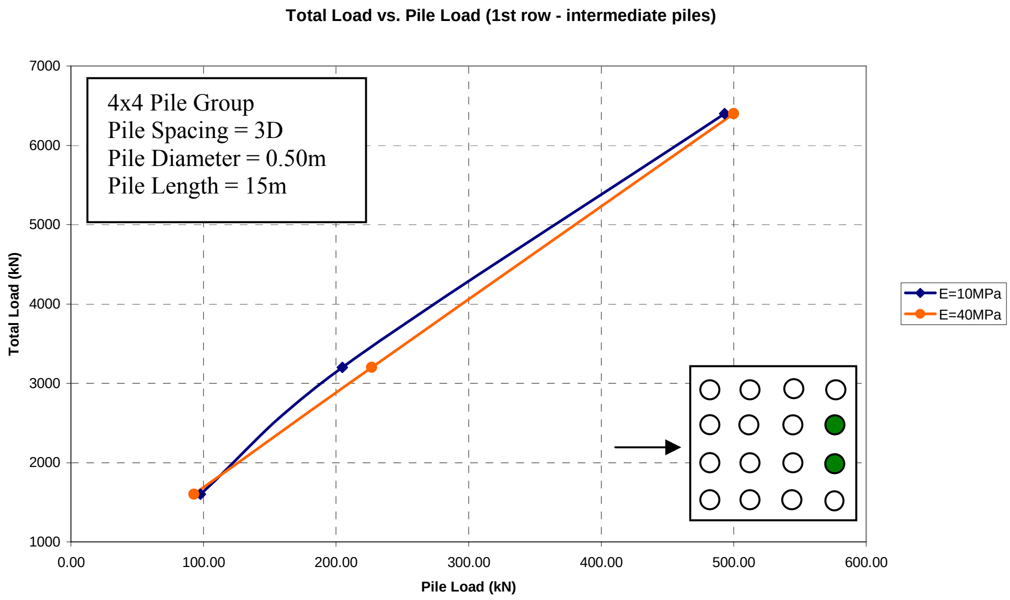


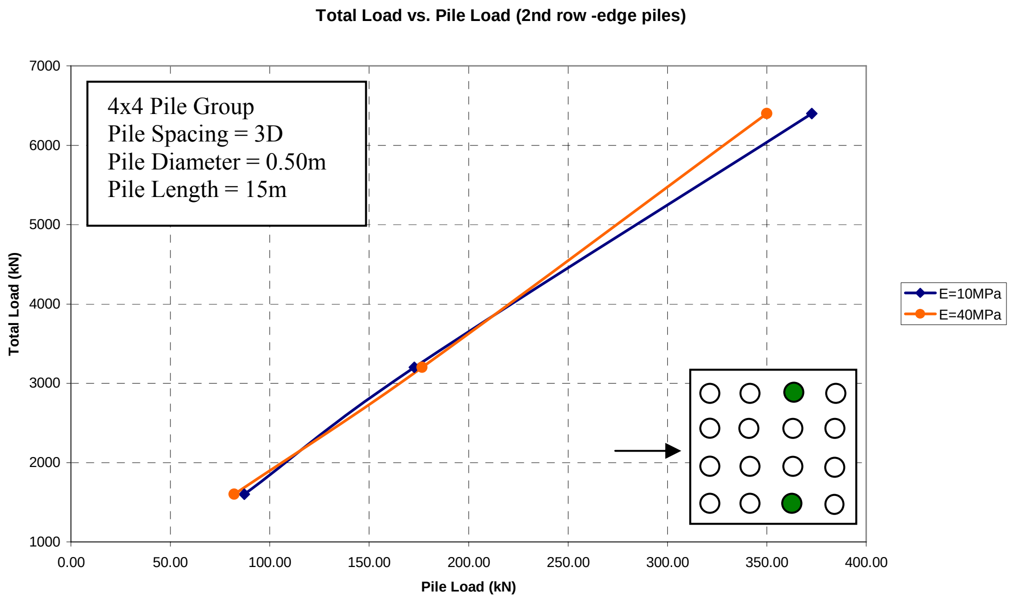
Figure 4.15 Displacement curves for two differenet soil stiffness (E=10Mpa, E=40MPa)



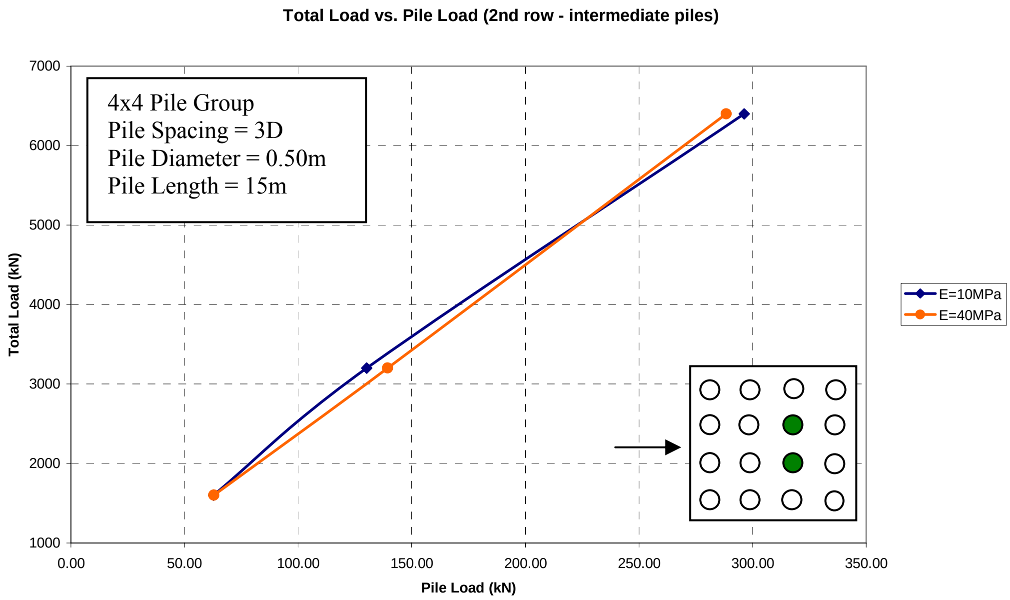
(a)


Total Load vs. Pile Load (1st row - intermediate piles)
4x4 Pile Group
Pile Spacing = 3D
Pile Diameter = 0.50m
Pile Length = 15m
Total Load (kN)
Pile Load (kN)
E=10MPa
E=40MPa
7000
6000
5000
4000
3000
2000
1000
0.00
100.00
200.00
300.00
400.00
500.00
600.00

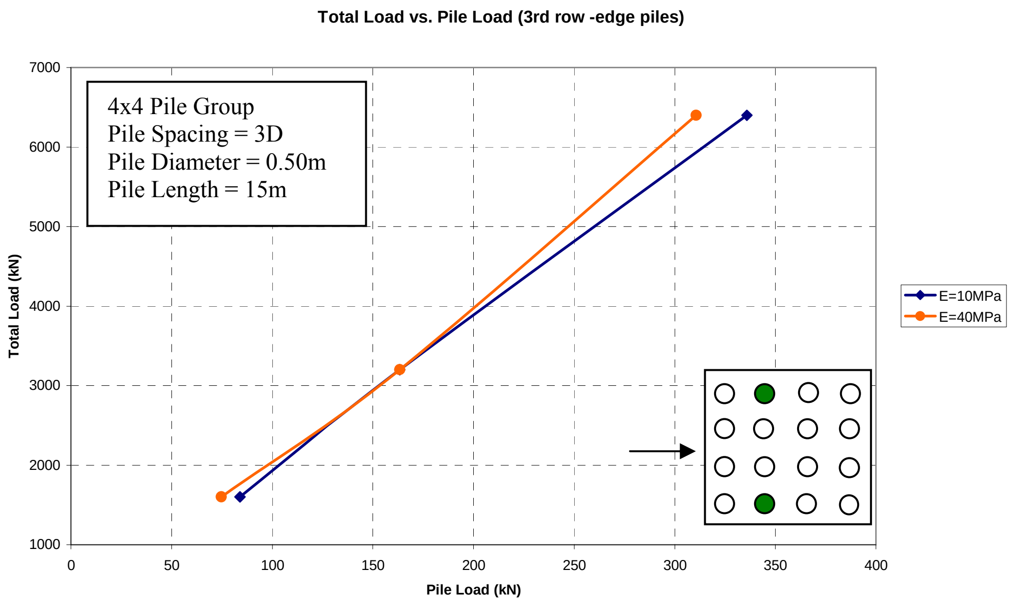
(b)


Total Load vs. Pile Load (2nd row -edge piles)
4x4 Pile Group
Pile Spacing = 3D
Pile Diameter = 0.50m
Pile Length = 15m
Total Load (kN)
Pile Load (kN)
E=10MPa
E=40MPa
7000
6000
5000
4000
3000
2000
1000
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400.00

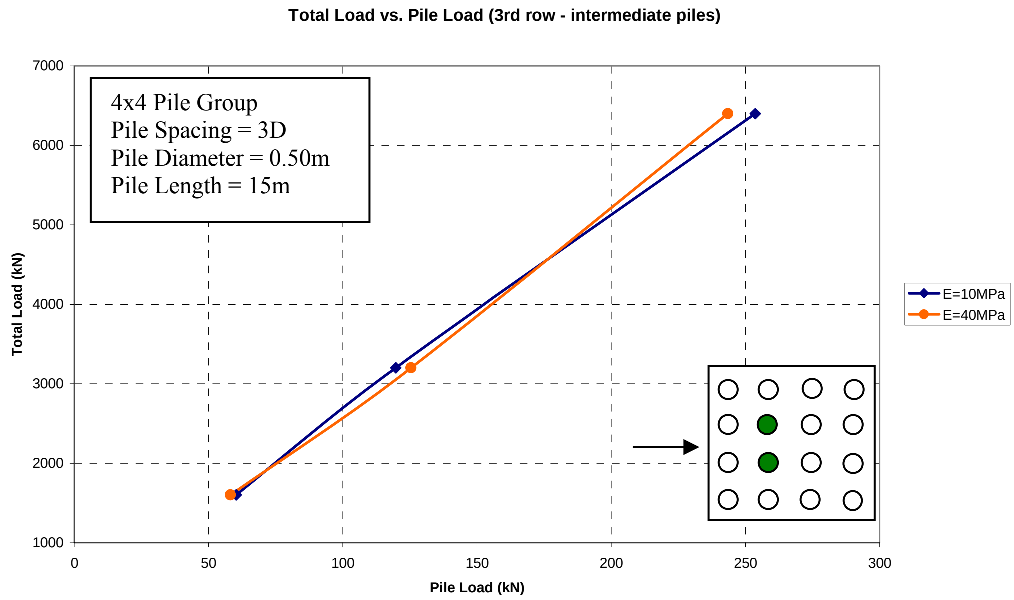
(c)


Total Load vs. Pile Load (2nd row - intermediate piles)
4x4 Pile Group
Pile Spacing = 3D
Pile Diameter = 0.50m
Pile Length = 15m
Total Load (kN)
Pile Load (kN)
E=10MPa
E=40MPa
7000
6000
5000
4000
3000
2000
1000
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00

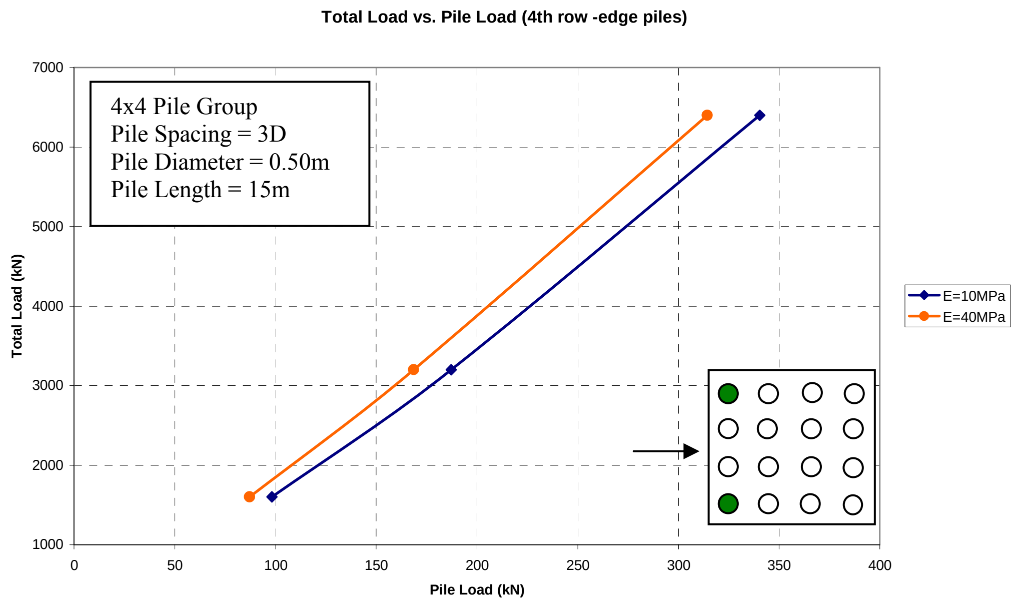
(d)


Total Load vs. Pile Load (3rd row -edge piles)
4x4 Pile Group
Pile Spacing = 3D
Pile Diameter = 0.50m
Pile Length = 15m
Total Load (kN)
Pile Load (kN)
E=10MPa
E=40MPa
7000
6000
5000
4000
3000
2000
1000
0
50
100
150
200
250
300
350
400

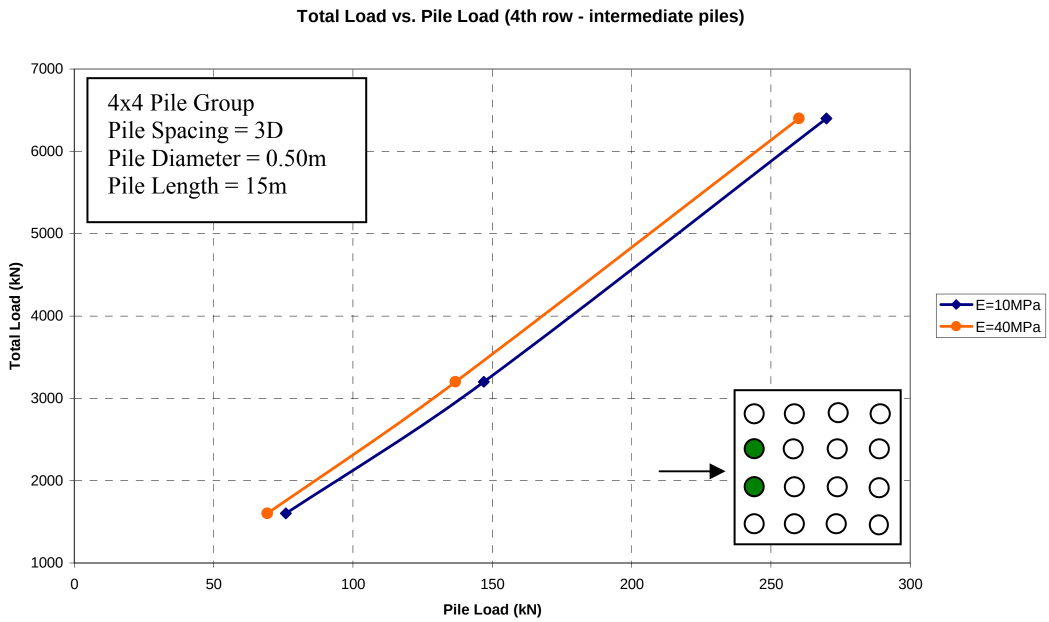
(e)


Total Load vs. Pile Load (3rd row - intermediate piles)
4x4 Pile Group
Pile Spacing = 3D
Pile Diameter = 0.50m
Pile Length = 15m
Total Load (kN)
Pile Load (kN)
E=10MPa
E=40MPa
7000
6000
5000
4000
3000
2000
1000
0
50
100
150
200
250
300

(f)


Total Load vs. Pile Load (4th row -edge piles)
4x4 Pile Group
Pile Spacing = 3D
Pile Diameter = 0.50m
Pile Length = 15m
Total Load (kN)
Pile Load (kN)
E=10MPa
E=40MPa
7000
6000
5000
4000
3000
2000
1000
0
50
100
150
200
250
300
350
400

(g)



(h)

Figure 4.16 Pile Load vs.Total Load Applied for two differenet soil stiffness (E=10Mpa, E=40MPa)

CHAPTER 5

CONCLUSIONS

A parametric study has been carried out to assess the effects of pile spacing, load level and the soil stiffness on load distribution od each pile in group and bending moment distribution along pile. For the numerical modeling of generic cases, Plaxis 3D Foundation Version 2 geotechnical finite element package is used. Effects of pile spacing and load level are presented.

The followings are the main conclusion of this study:

- As expected based on the elastic theory, the piles located on the edges of a row carry more load than the inner piles for an applied load. Moreover, the front row piles (leading row piles) carried the greatest load while the second row piles carried succesively smaller loads under the same load applied. However, the third and the fourth row piles carried about the same load. In fact, the fourth row piles carried slightly higher loads than the third row piles.
- Load developed in outer piles is about 1.25 times the load developed in inner piles. Moreover, although this coefficient reaches to 1.5 or 2 for the leading row piles, coefficient of trailing row piles decreases to 0.55 and 0.65 in some cases.

- The piles located on the edge of a row develop greater bending moment than the inner piles under the same applied load. Lead row piles develop the maximum bending moment while the trailing row piles develop somewhat smaller moments under the same applied load. However, at greater depths lead row piles develop less moment than the trailing row piles.

- Under the same load applied, pile groups with 2D pile spacing resulted in the largest deflections, whereas pile groups with 5D pile spacing resulted in the lowest deflections. Pile groups with 3D and 4D pile spacings on the other hand, produced intermediate levels of deflection as expected.

- Lateral deflection increased considerably as pile spacing decreased from 5D to 2D. In this study, it is observed that for a 4x4 pile group under the same load, when pile spacing decreases from 5D to 4D, maximum lateral deflection of the group increases about 33%. However, this increment of deflection is calculated larger when pile spacing decreases from 4D to 3D and from 3D to 2D, namely 37.5% and 64% respectively and the deflections become nearly zero between 7 m and 9 m depths from the ground surface.

- Pile spacing affects load distribution in pile groups significantly. As pile spacing increases, pile load decreases. However, this type of behaviour can be seen more clearly in the first and the second row piles. For the third and the fourth row piles, pile spacing becomes a less significant factor affecting the load distribution in a pile group.

- As pile spacing increases, maximum bending moment occurred decreases under the same load applied. However, in case of bending moment, the variation due to pile spacing can be clearly observed in all piles and rows.

- The outer piles of the leading row carries the greatest load and these piles are termed as back corner piles. Piles that carries significantly higher loads than the others are the inner piles of the leading row and these piles are termed as back center piles. The outer piles of the trailing rows are termed as edge piles, whereas the inner piles of the trailing rows are termed as center piles as described in DIN 4014.

- For the loads greater than 400kN/pile the pile load coefficient can be taken as 2.00 for 2D pile spacing condition, 1.50 for 3D pile spacing condition, 1.25 for 4D pile spacing condition and 1.00 for 5D pile spacing condition; for back corner piles.

- For the loads greater than 400kN/pile the pile load coefficient can be taken as 1.25 for 2D and 3D pile spacing conditions, 1.10 for 4D pile spacing condition and 0.70 for 5D pile spacing condition; for back center piles.

- For the edge piles, the pile load coefficient converges to 0.75 in all pile spacing conditions as the applied load increases.

- For center piles same group behaviour is obtained with the edge piles except the value of converged pile load coefficient. For the loads greater than 400kN/pile the coefficient can be taken as 0.65 for all pile spacing conditions.

- Pile diameter is not a significant factor on load distribution as row location and pile spacing.

- For back corner and back center piles it is concluded that, 0.50m diameter piles carry more load than 0.80m diameter piles. However, the difference between these loads is not as large as the difference occurred by change in pile spacing. In trailing row piles case, loads carried are quite close that, in practice they can assumed to be the same.

- Pile group displacement in relatively softer clay, are larger then the displacements occurred in pile group in stiff clay layer as expected. However, when the load levels are considered, the difference between the displacement values gets larger as the load increases.

- Elastic modulus of clay has less significant effect on load distribution of pile groups. The load carried by the individual piles does not differ with the variation of soil stiffness.

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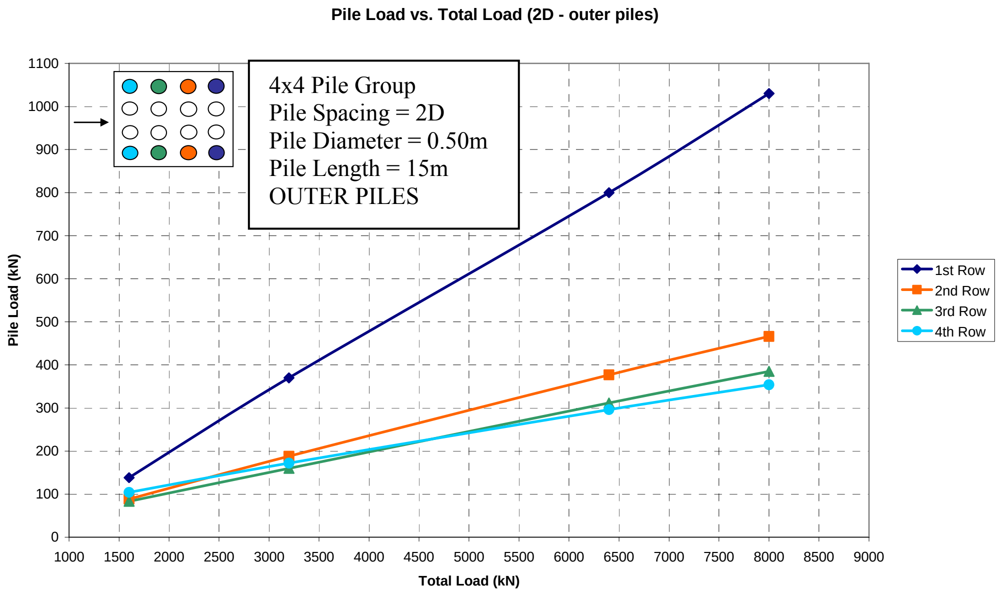
APPENDIX A



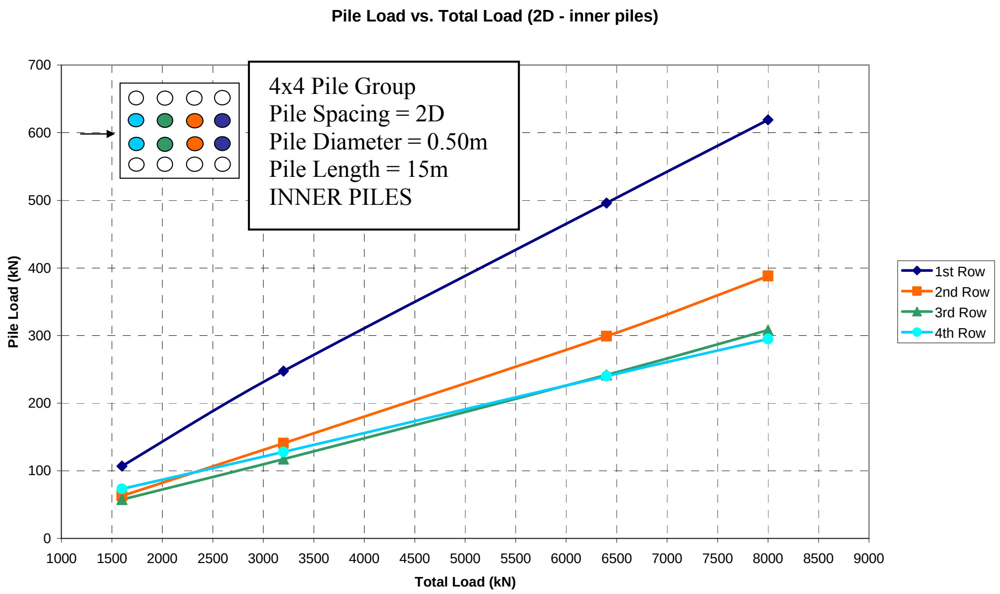
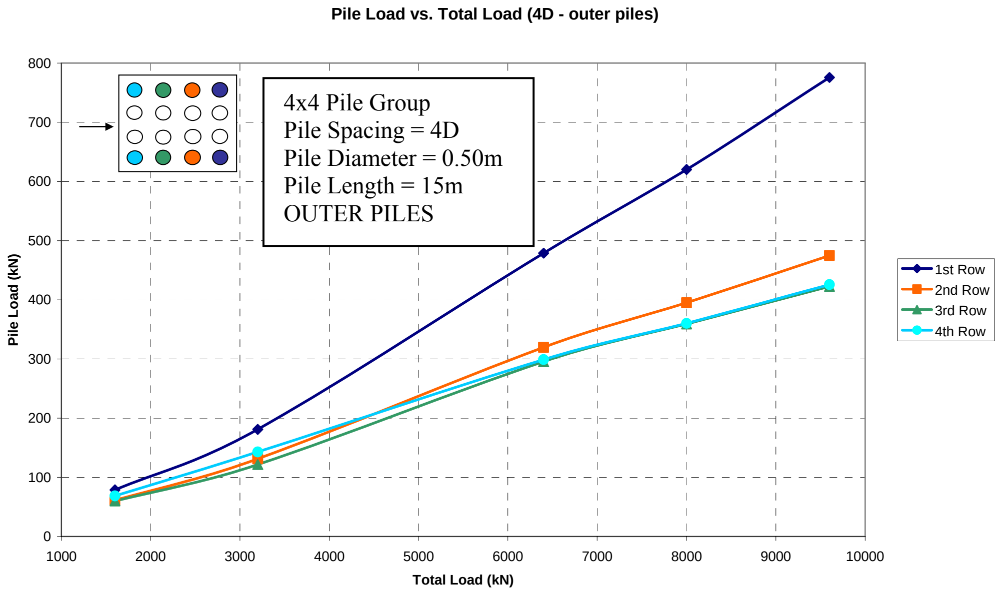


Figure A.1 Load Distribution with respect to row location for outer and inner piles under same load applied (Pile Group with 2D pile spacing)



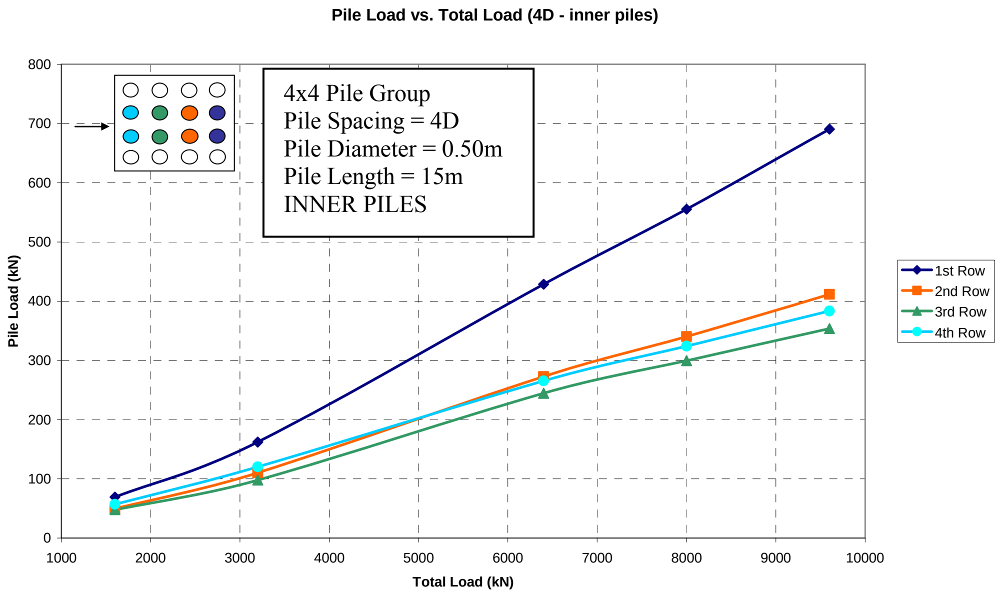
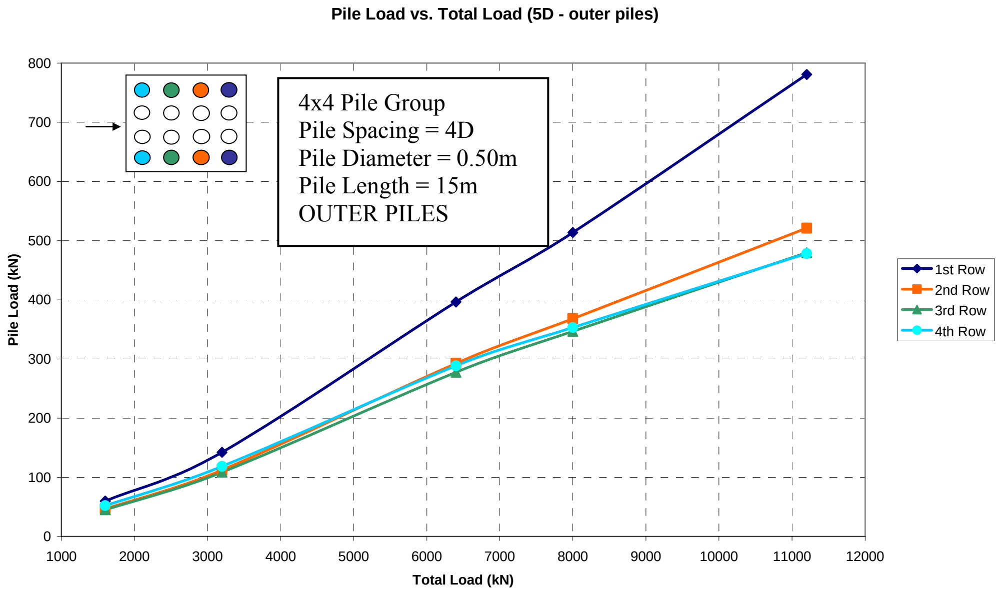


Figure A.2 Load Distribution with respect to row location for outer and inner piles under same load applied (Pile Group with 4D pile spacing)



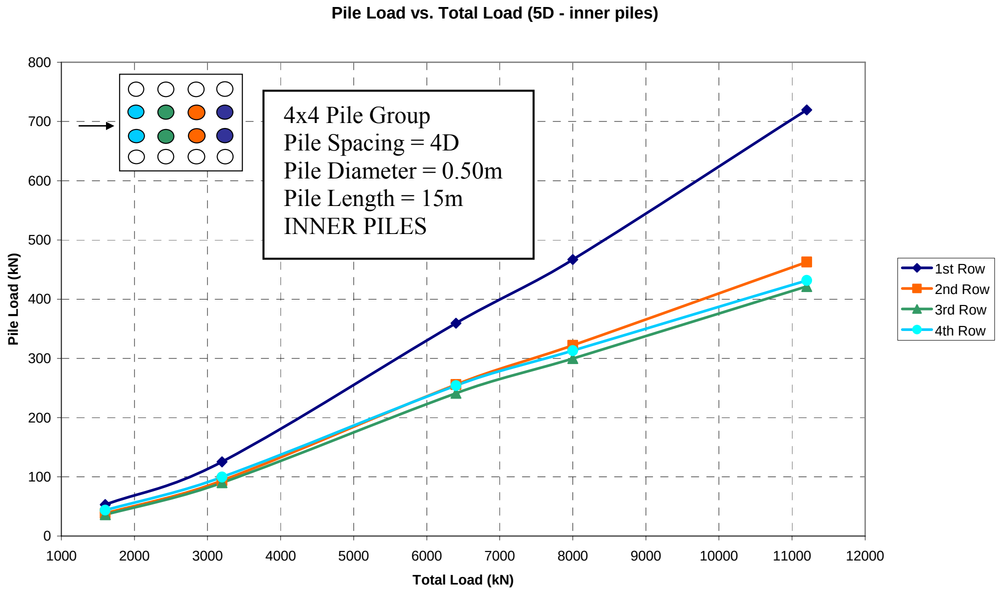
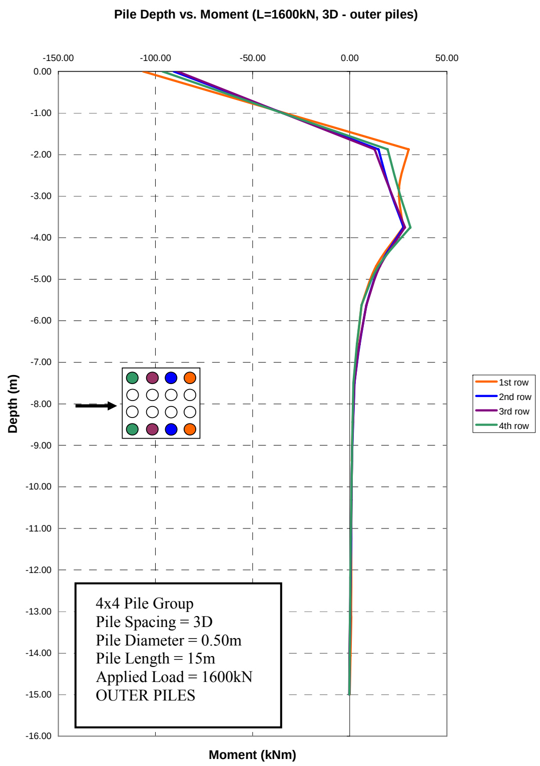


Figure A.3 Load Distribution with respect to row location for outer and inner piles under same load applied (Pile Group with 5D pile spacing)



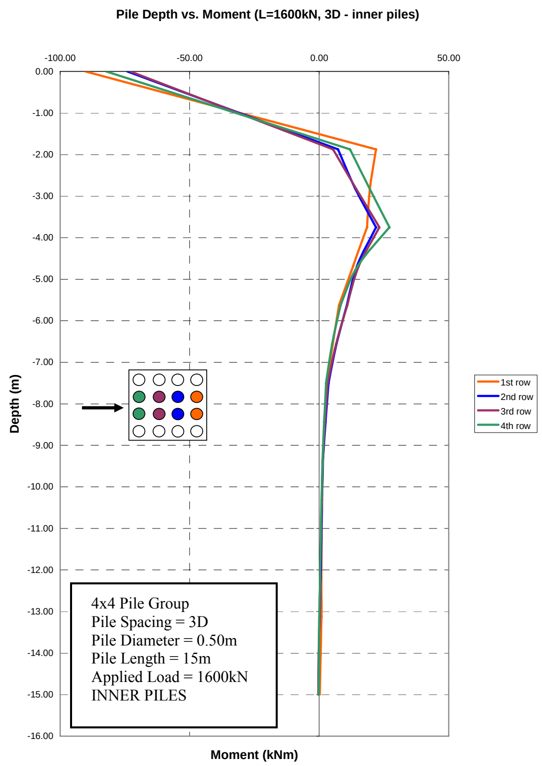
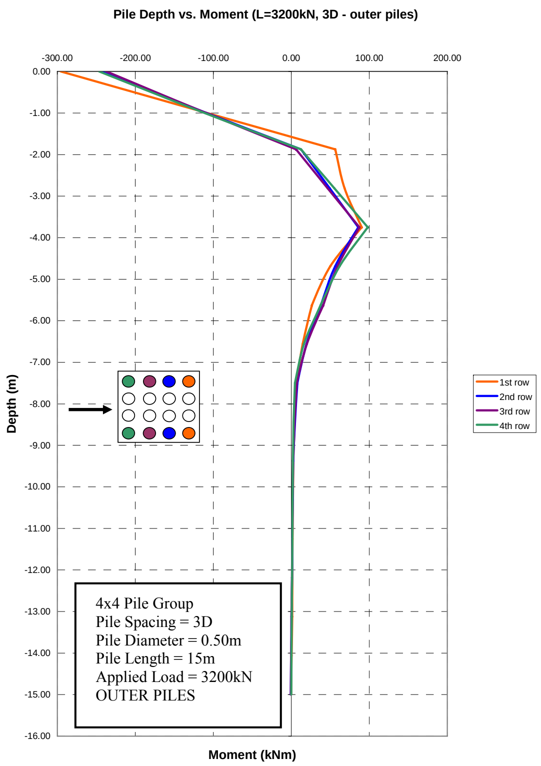


Figure A.4 Bending Moment vs. Depth Curves with respect to Row Location for Outer and Inner Piles under same load (Pile Group with 3D Pile Spacing, 1600kN total Load applied)



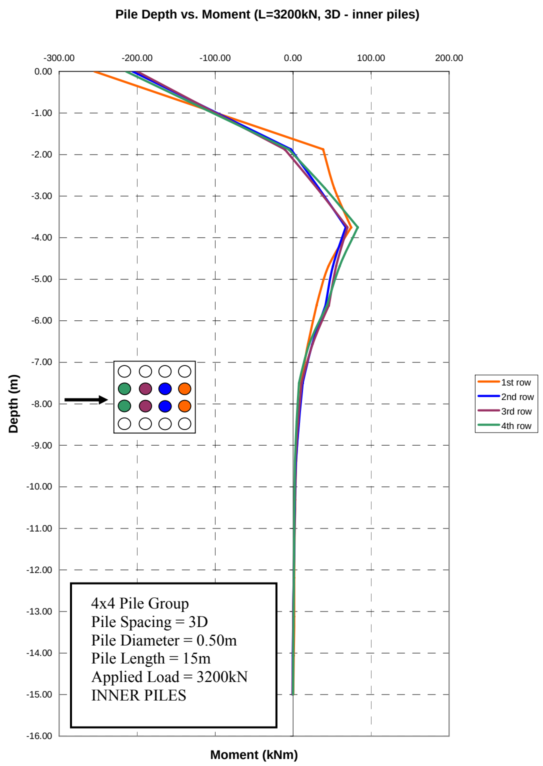
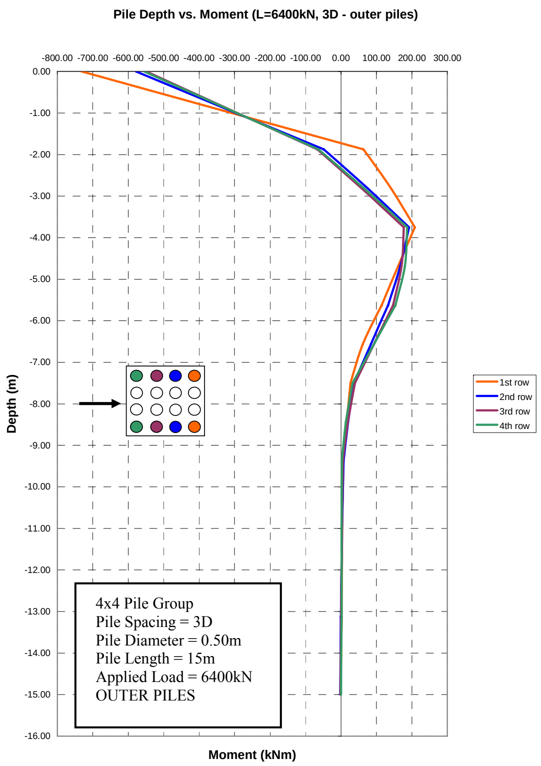


Figure A.5 Bending Moment vs. Depth Curves with respect to Row Location for Outer and Inner Piles under same load (Pile Group with 3D Pile Spacing, 3200kN total Load applied)



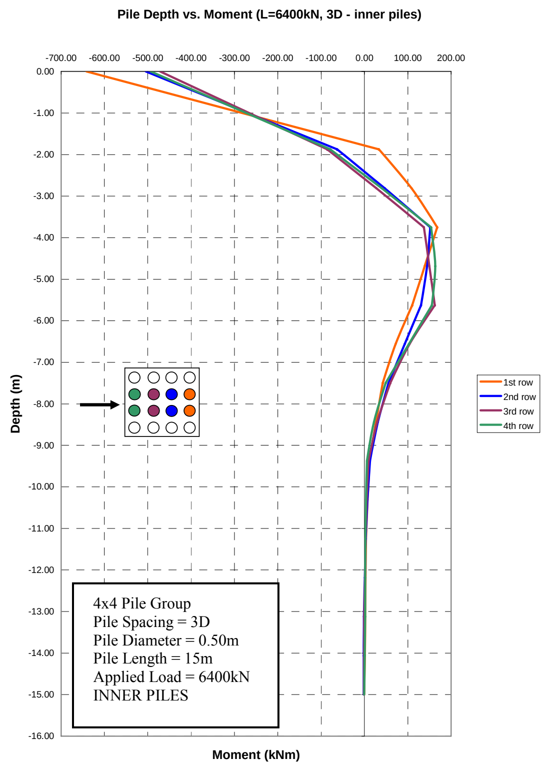
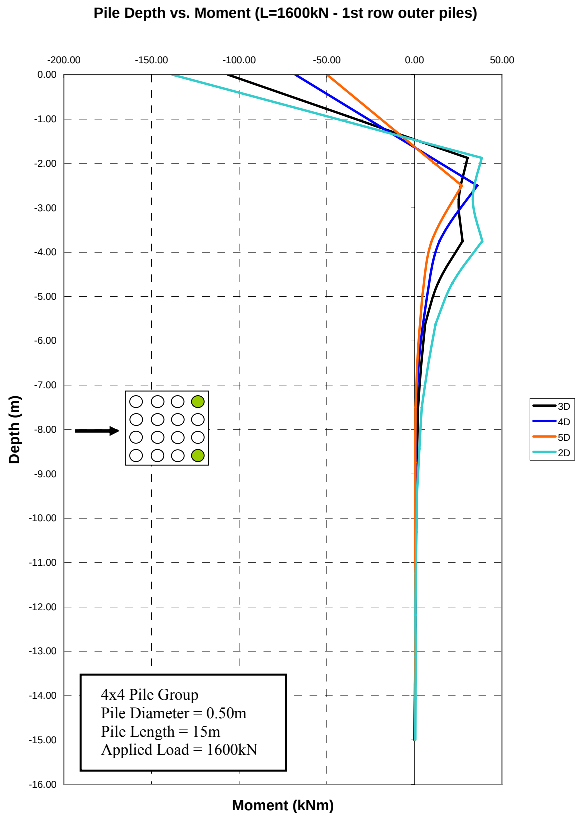
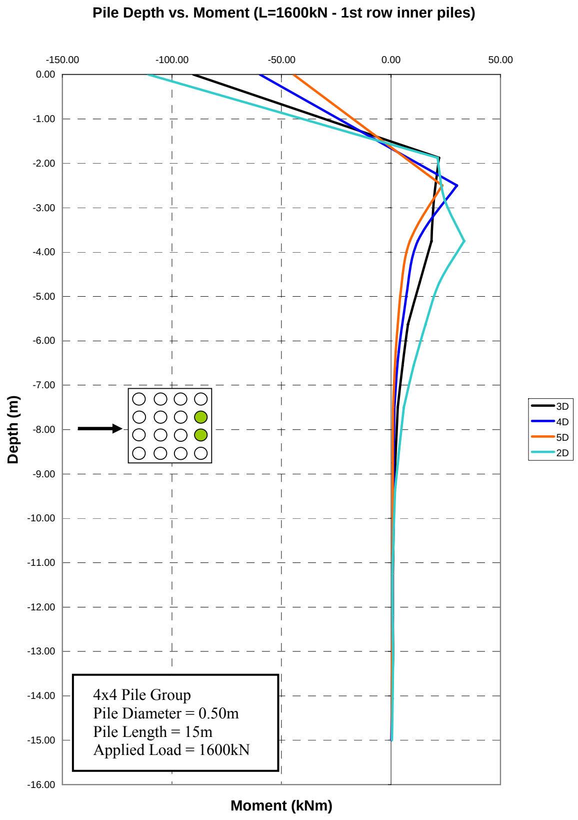


Figure A.6 Bending Moment vs. Depth Curves with respect to Row Location for Outer and Inner Piles under same load (Pile Group with 3D Pile Spacing, 6400kN total Load applied)


Pile Depth vs. Moment (L=1600kN - 1st row outer piles)
-200.00
-150.00
-100.00
-50.00
0.00
50.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 1600kN

(a)


Pile Depth vs. Moment (L=1600kN - 1st row inner piles)
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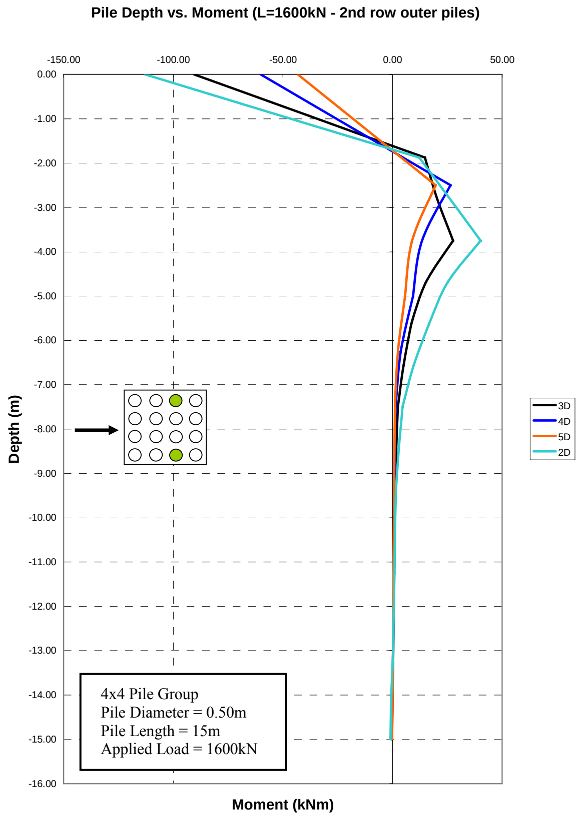
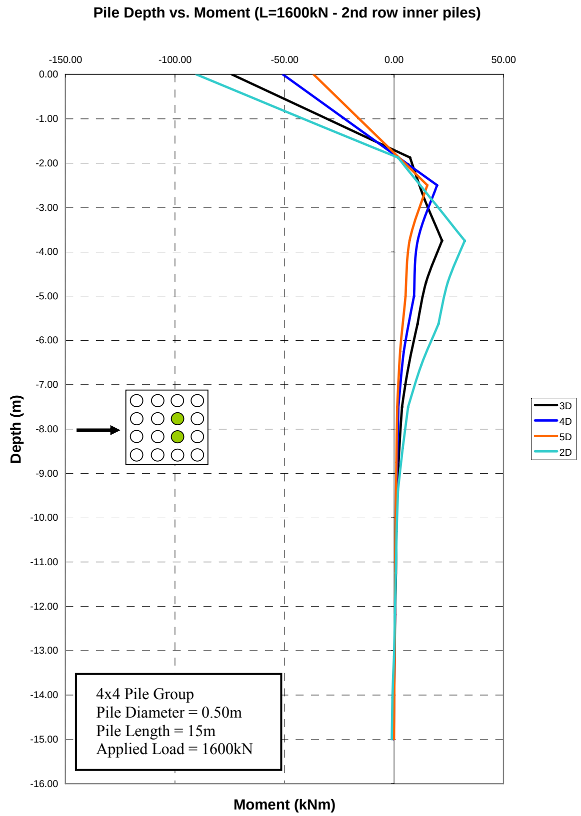
-100.00
-50.00
0.00
50.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 1600kN

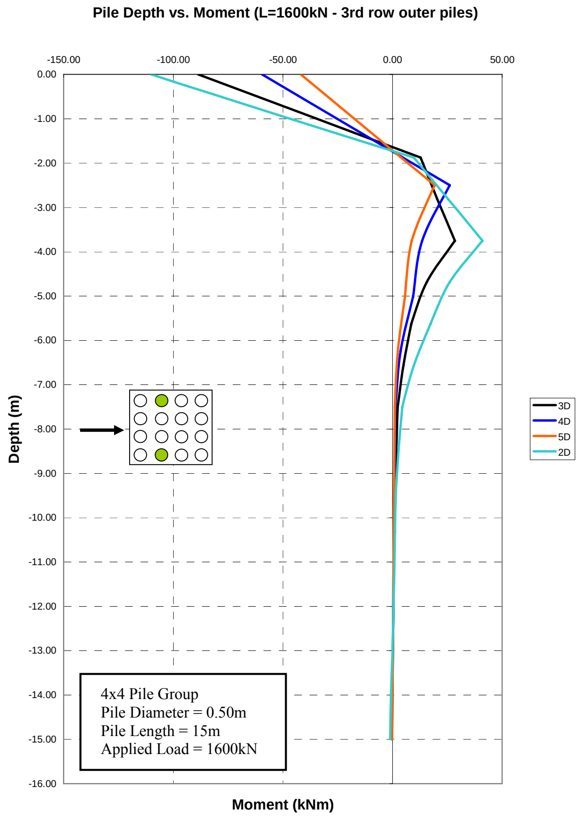
(b)


Pile Depth vs. Moment (L=1600kN - 2nd row outer piles)
-150.00
-100.00
-50.00
0.00
50.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 1600kN

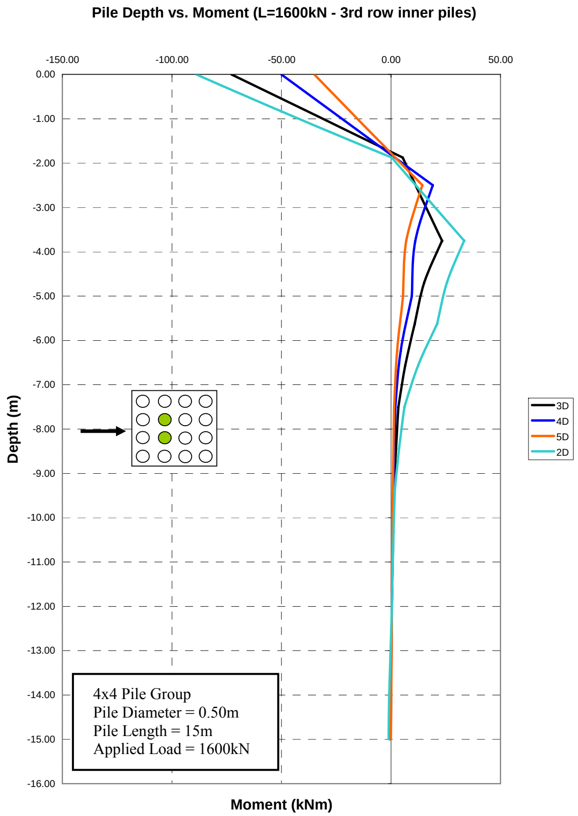
(c)


Pile Depth vs. Moment (L=1600kN - 2nd row inner piles)
-150.00
-100.00
-50.00
0.00
50.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 1600kN

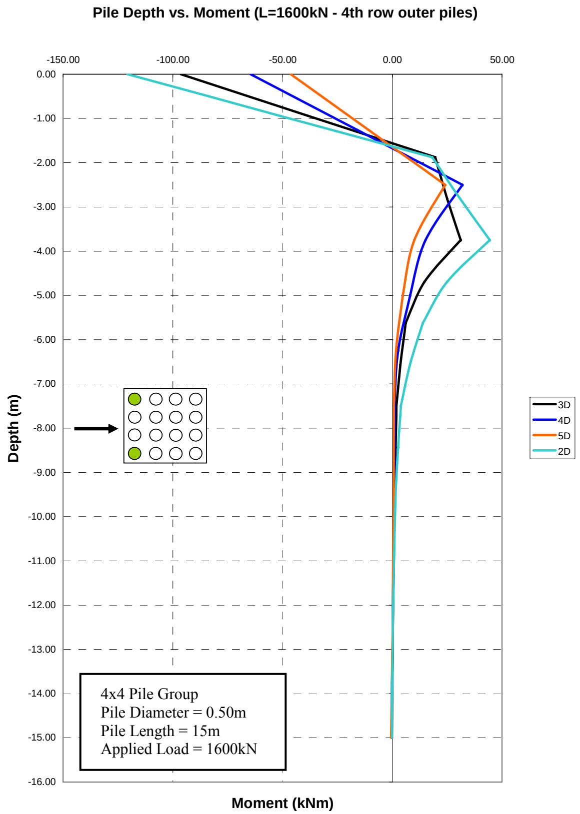
(d)


Pile Depth vs. Moment (L=1600kN - 3rd row outer piles)
-150.00
-100.00
-50.00
0.00
50.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 1600kN

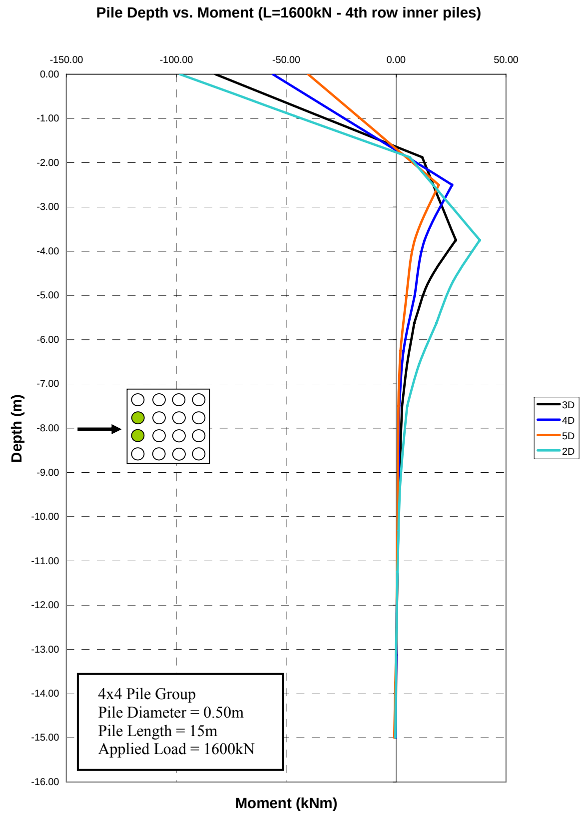
(e)


Pile Depth vs. Moment (L=1600kN - 3rd row inner piles)
-150.00
-100.00
-50.00
0.00
50.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 1600kN

(f)

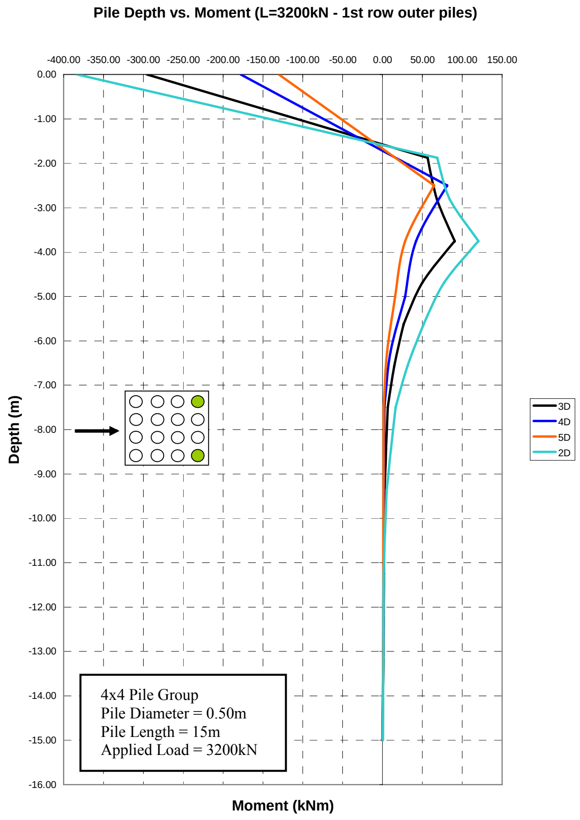


(g)

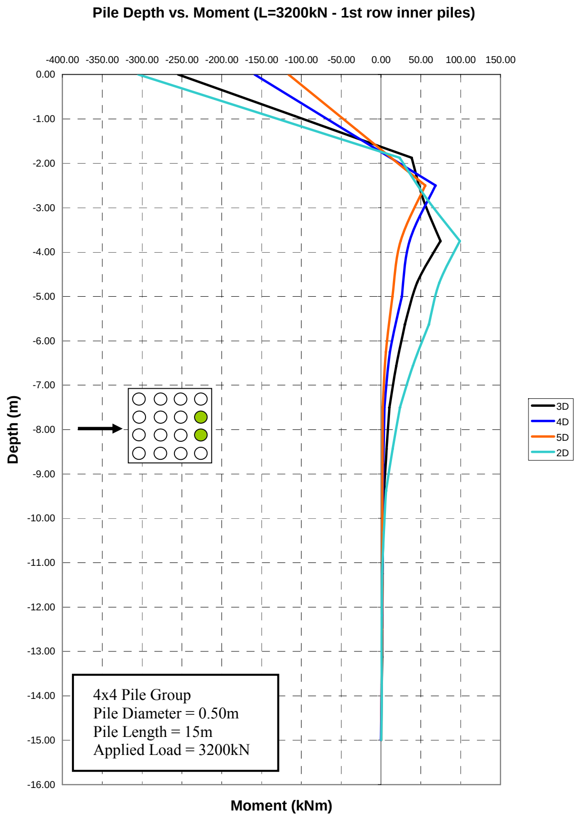


(h)

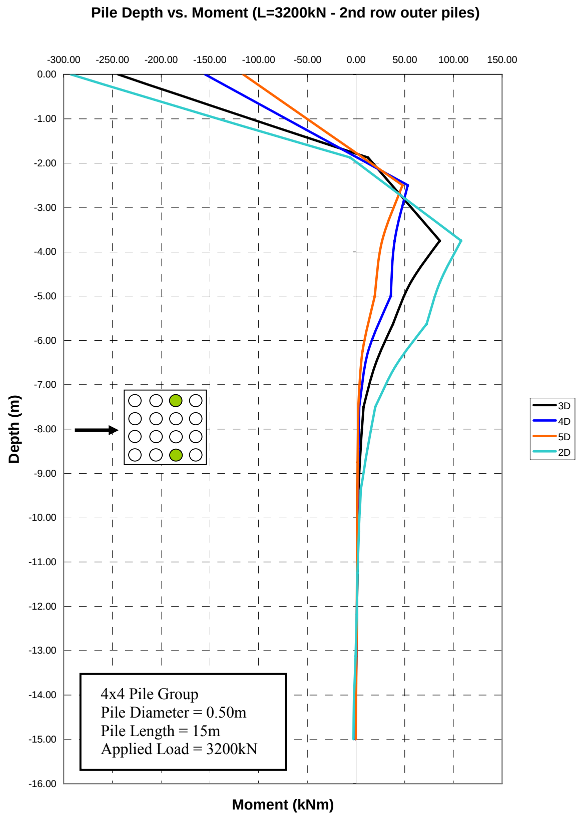
Figure A.7 Bending Moment Distribution Along Pile with respect to Pile Spacing under 1600kN load applied


Pile Depth vs. Moment (L=3200kN - 1st row outer piles)
Moment (kNm)
Depth (m)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 3200kN

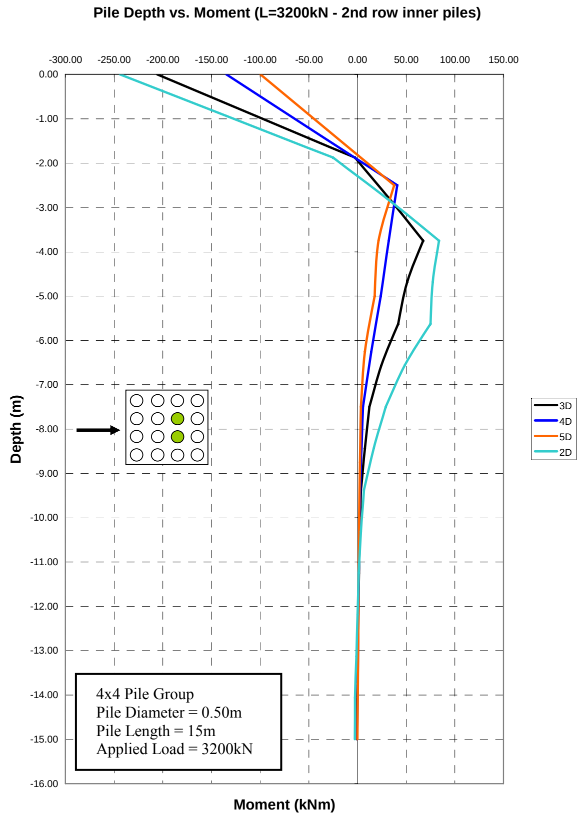
(a)


Pile Depth vs. Moment (L=3200kN - 1st row inner piles)
Moment (kNm)
Depth (m)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 3200kN

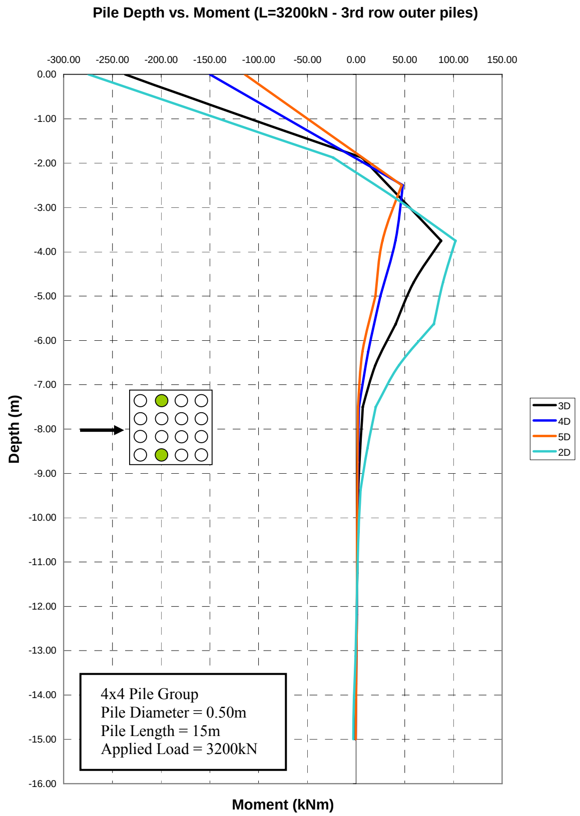
(b)


Pile Depth vs. Moment (L=3200kN - 2nd row outer piles)
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 3200kN

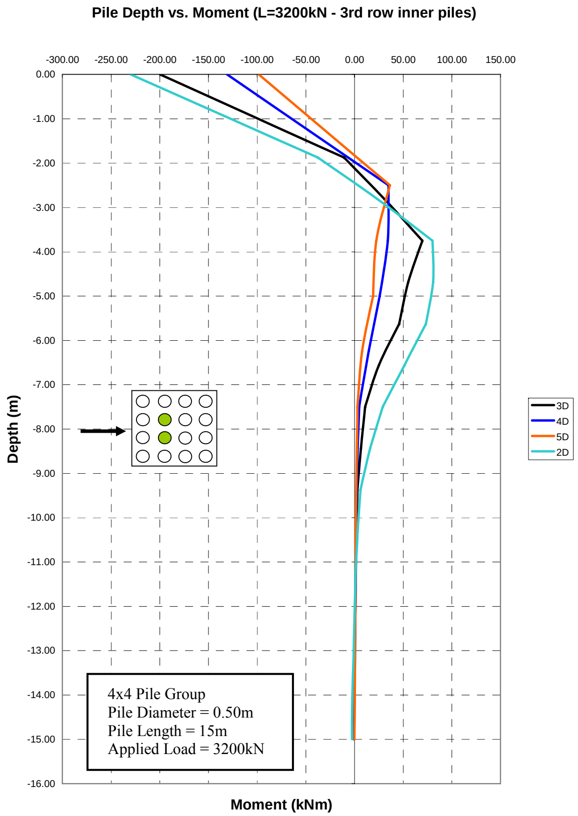
(c)


Pile Depth vs. Moment (L=3200kN - 2nd row inner piles)
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 3200kN

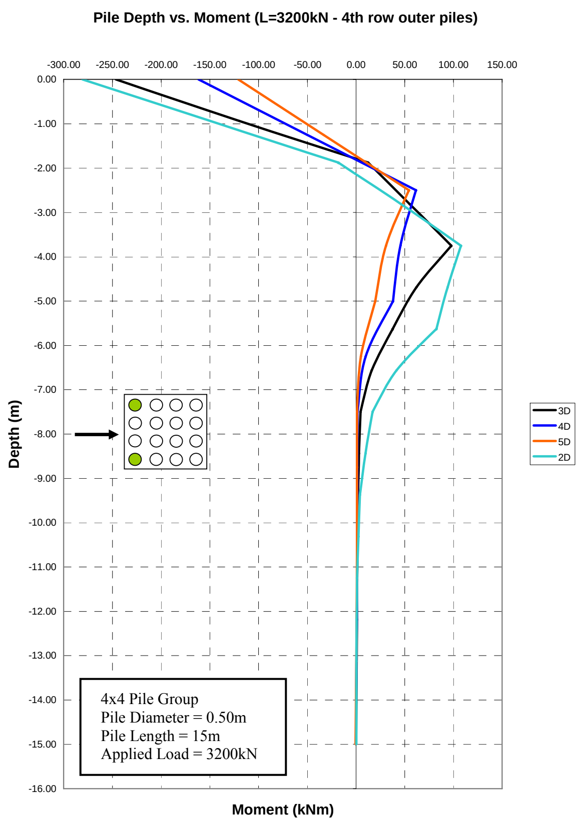
(d)


Pile Depth vs. Moment (L=3200kN - 3rd row outer piles)
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 3200kN

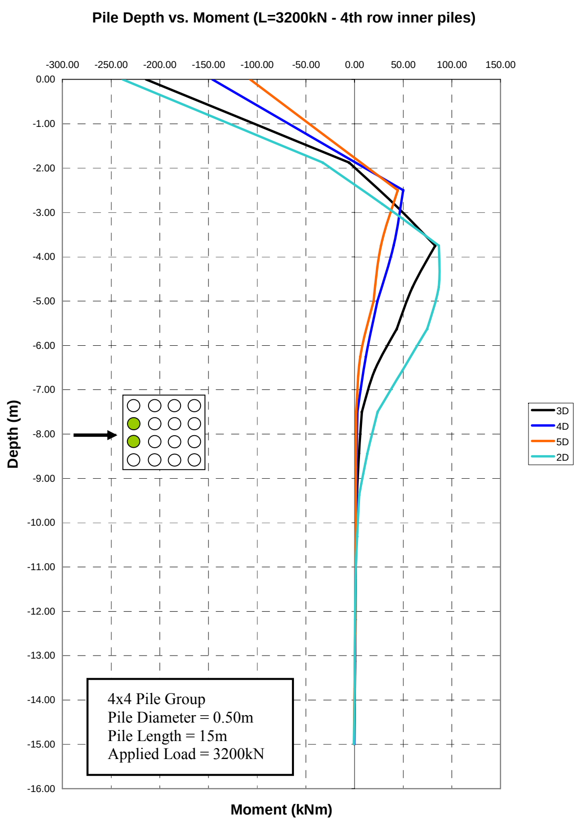
(e)


Pile Depth vs. Moment (L=3200kN - 3rd row inner piles)
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 3200kN

(f)

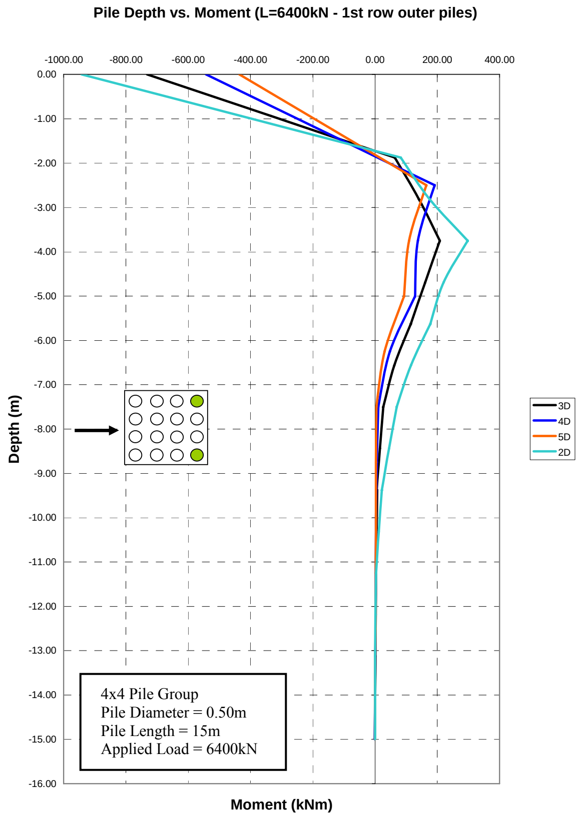


(g)

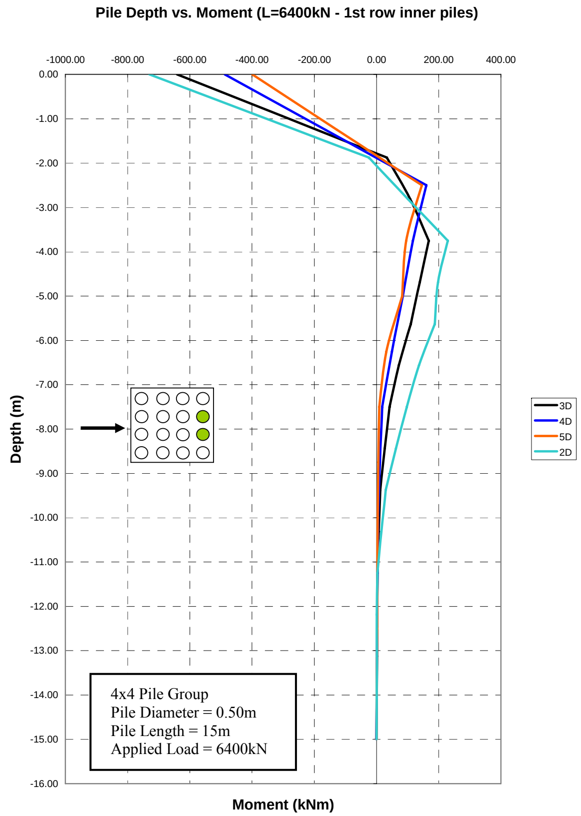


(h)

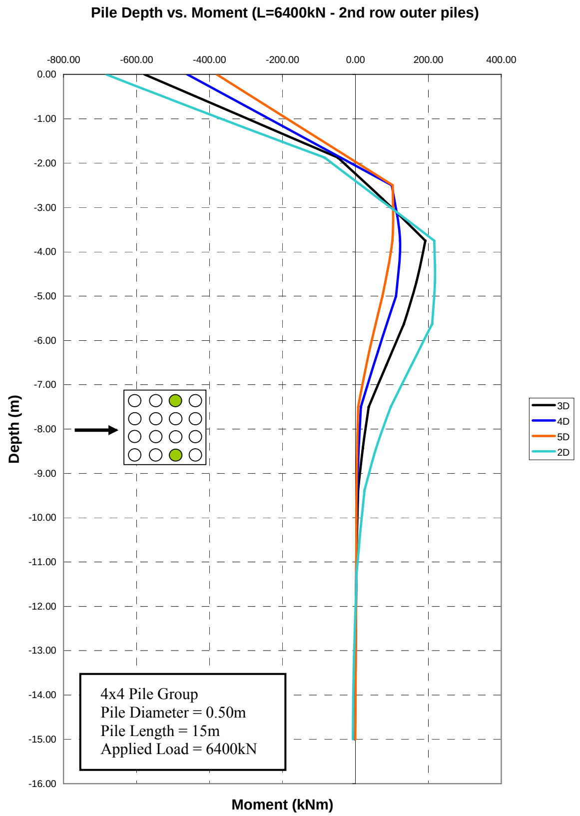
Figure A.8 Bending Moment Distribution Along Pile with respect to Pile Spacing under 3200kN load applied


Pile Depth vs. Moment (L=6400kN - 1st row outer piles)
-1000.00
-800.00
-600.00
-400.00
-200.00
0.00
200.00
400.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 6400kN

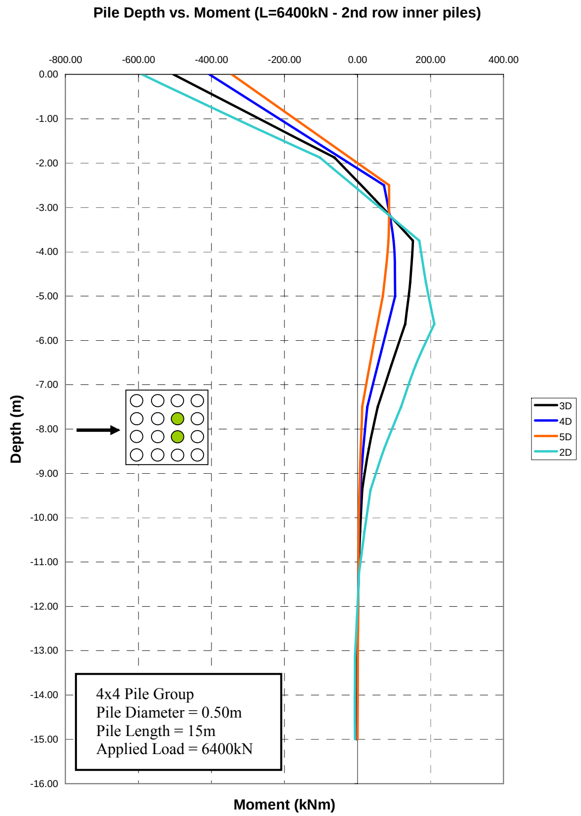
(a)


Pile Depth vs. Moment (L=6400kN - 1st row inner piles)
-1000.00
-800.00
-600.00
-400.00
-200.00
0.00
200.00
400.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 6400kN

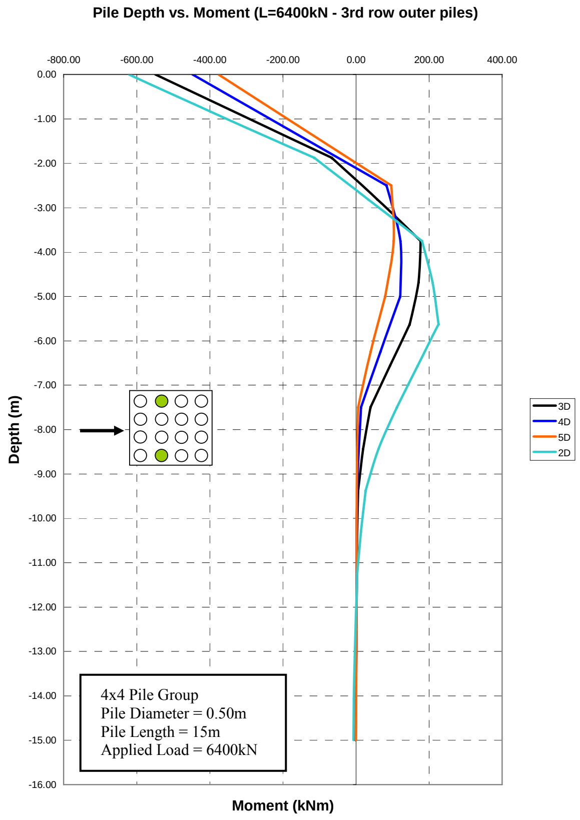
(b)


Pile Depth vs. Moment (L=6400kN - 2nd row outer piles)
-800.00
-600.00
-400.00
-200.00
0.00
200.00
400.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 6400kN

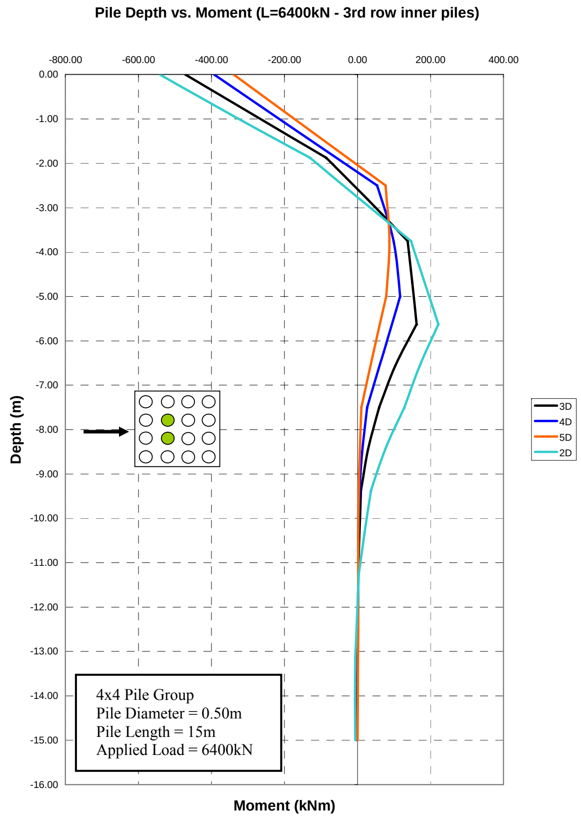
(c)


Pile Depth vs. Moment (L=6400kN - 2nd row inner piles)
-800.00
-600.00
-400.00
-200.00
0.00
200.00
400.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 6400kN

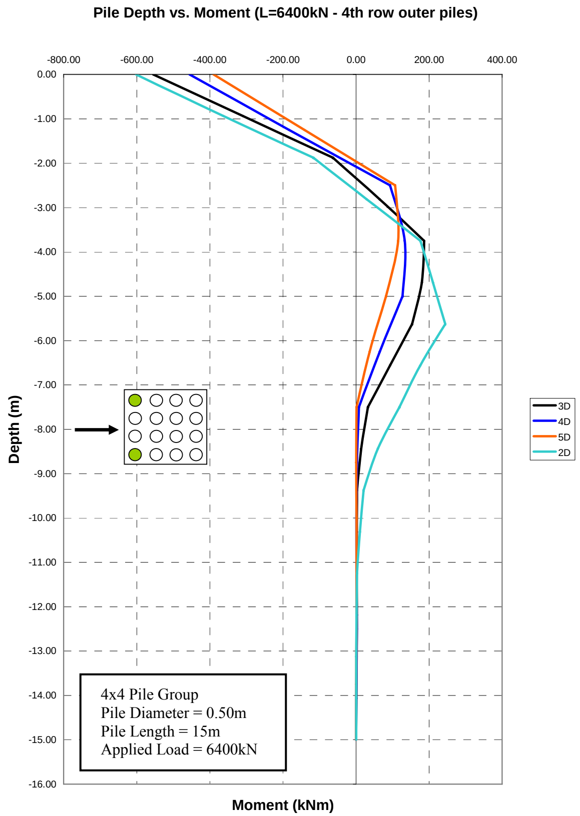
(d)


Pile Depth vs. Moment (L=6400kN - 3rd row outer piles)
-800.00
-600.00
-400.00
-200.00
0.00
200.00
400.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 6400kN

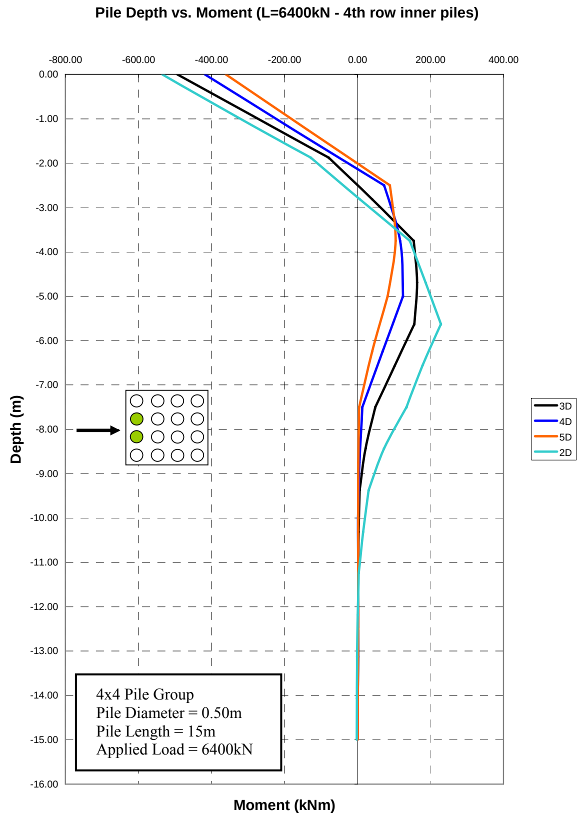
(e)


Pile Depth vs. Moment (L=6400kN - 3rd row inner piles)
-800.00
-600.00
-400.00
-200.00
0.00
200.00
400.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
-16.00
Depth (m)
Moment (kNm)
3D
4D
5D
2D
4x4 Pile Group
Pile Diameter = 0.50m
Pile Length = 15m
Applied Load = 6400kN

(f)



(g)



(h)

Figure A.9 Bending Moment Distribution Along Pile with respect to Pile Spacing under 6400kN load applied

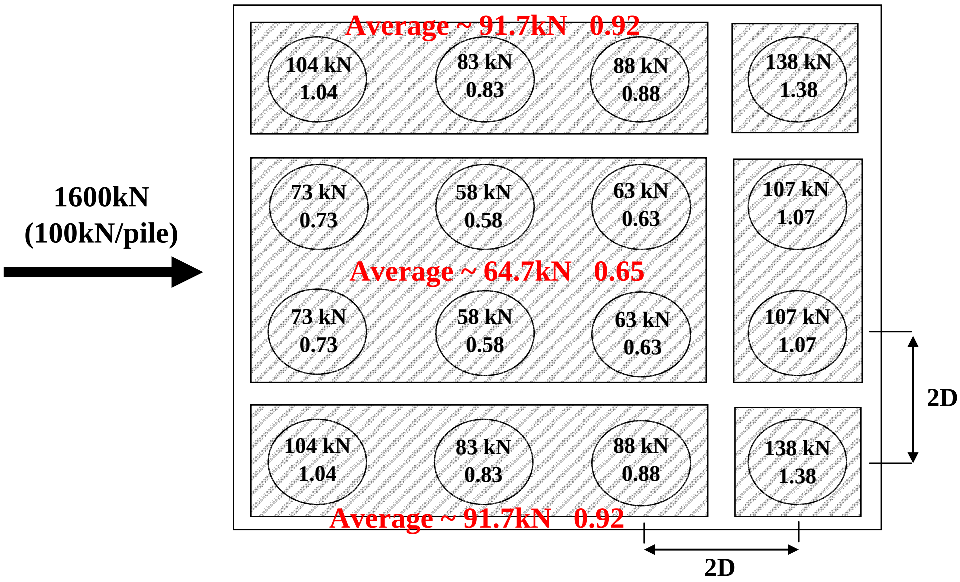


Figure A.10 Pile Load Distribution in the Group with 2D Pile Spacing and 1600kN load Applied

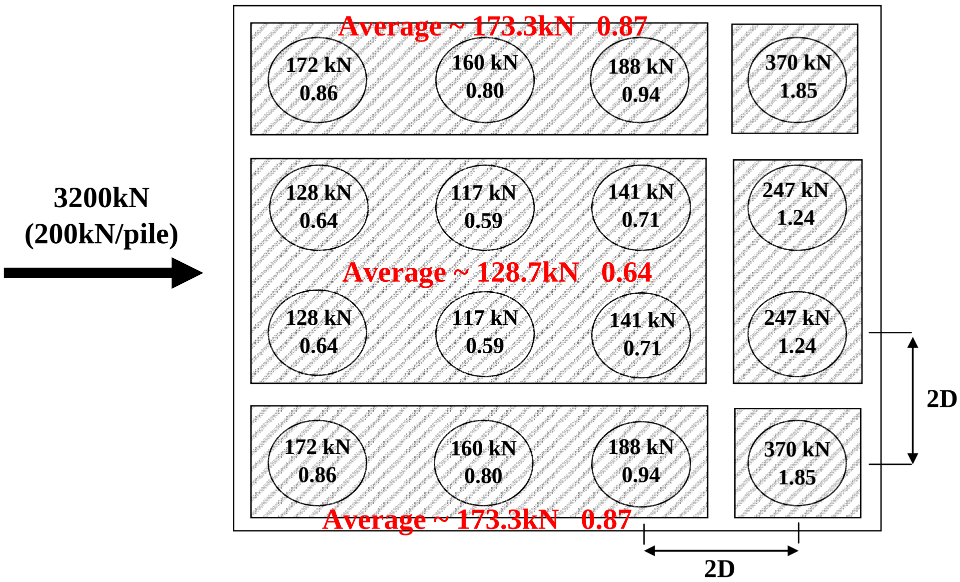


Figure A.11 Pile Load Distribution in the Group with 2D Pile Spacing and 3200kN load Applied

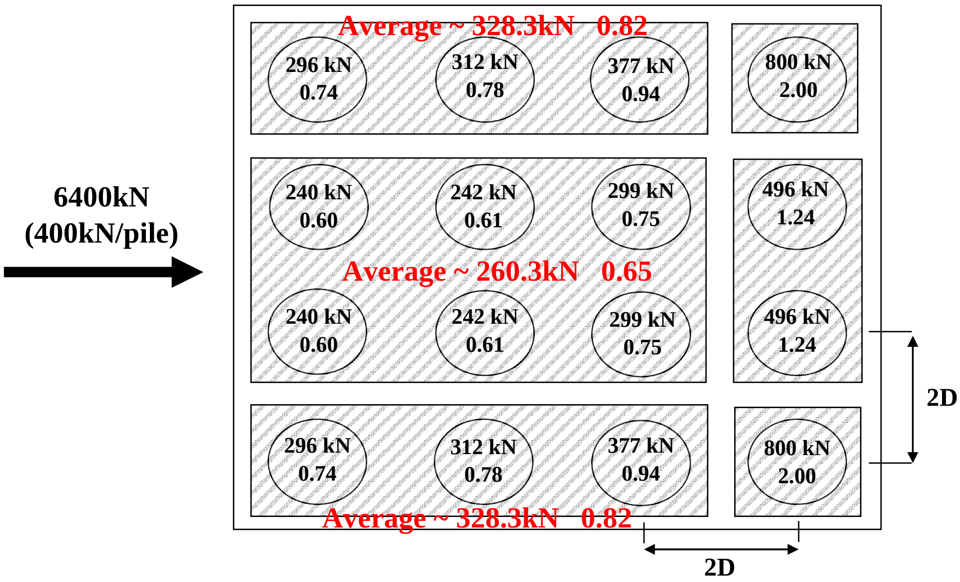


Figure A.12 Pile Load Distribution in the Group with 2D Pile Spacing and 6400kN load Applied

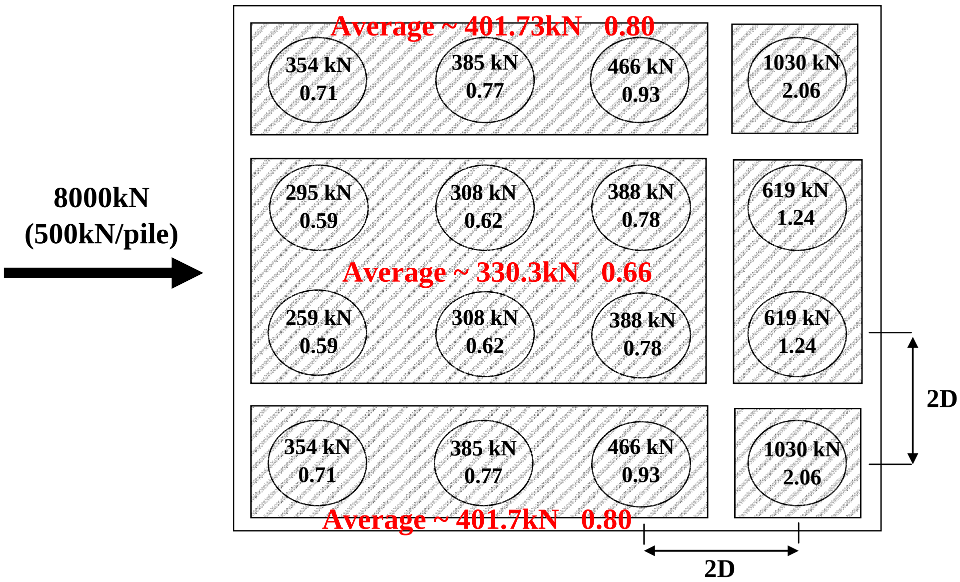


Figure A.13 Pile Load Distribution in the Group with 2D Pile Spacing and 8000kN load Applied

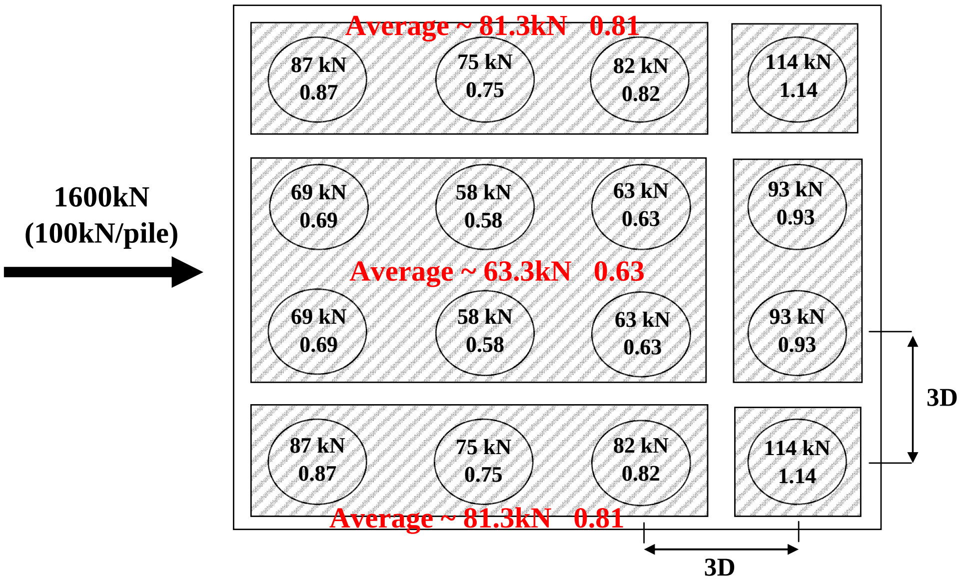


Figure A.14 Pile Load Distribution in the Group with 3D Pile Spacing and 1600kN load Applied

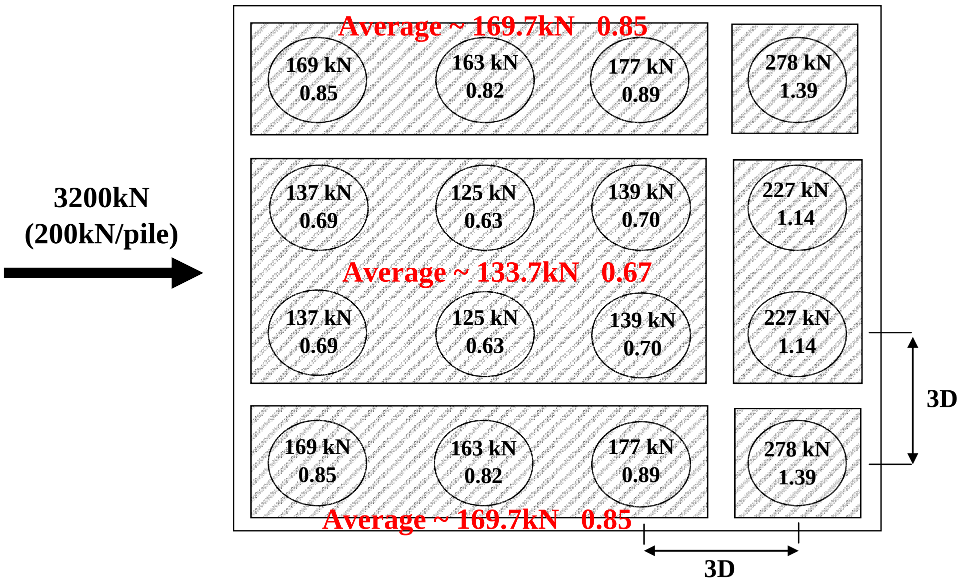


Figure A.15 Pile Load Distribution in the Group with 3D Pile Spacing and 3200kN load Applied

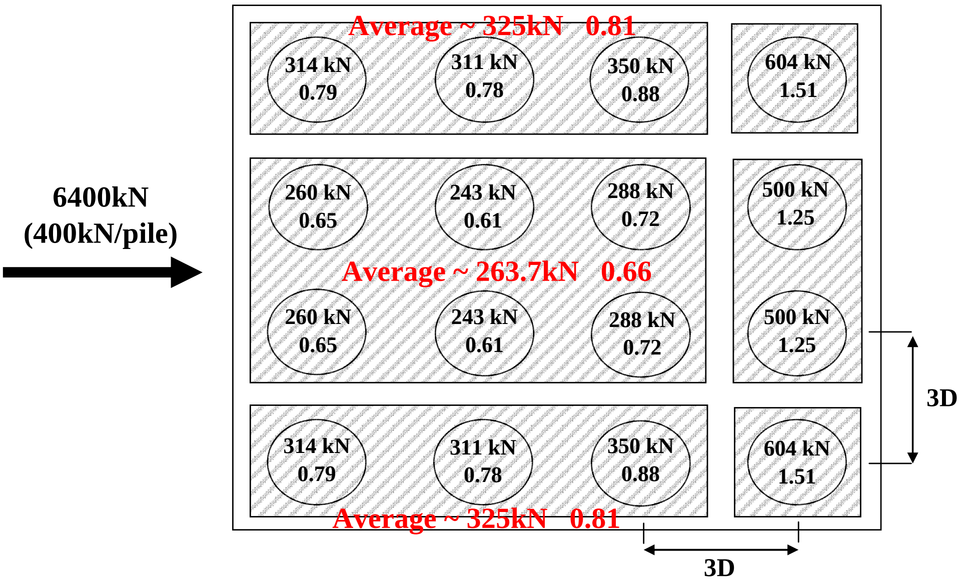


Figure A.16 Pile Load Distribution in the Group with 3D Pile Spacing and 6400kN load Applied

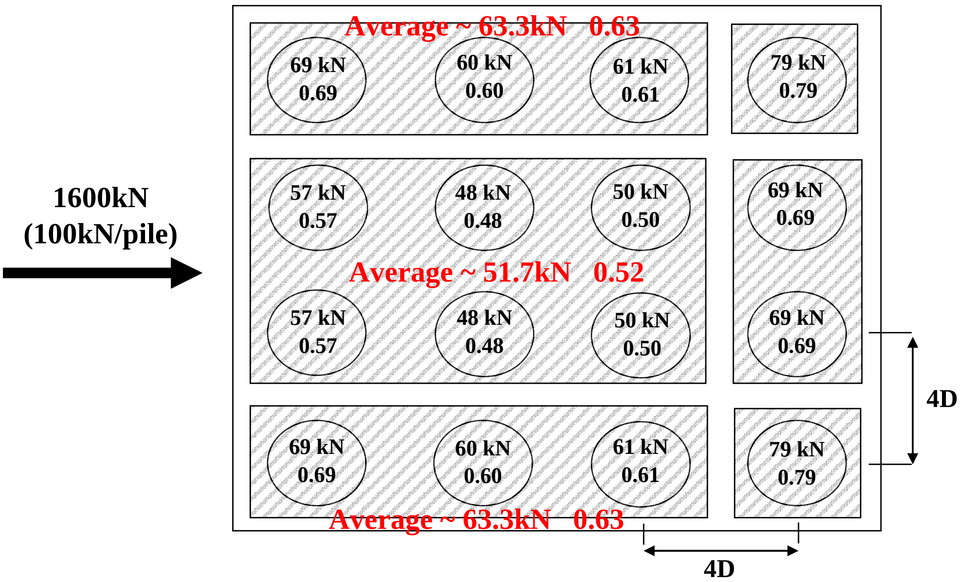


Figure A.17 Pile Load Distribution in the Group with 4D Pile Spacing and 1600kN load Applied

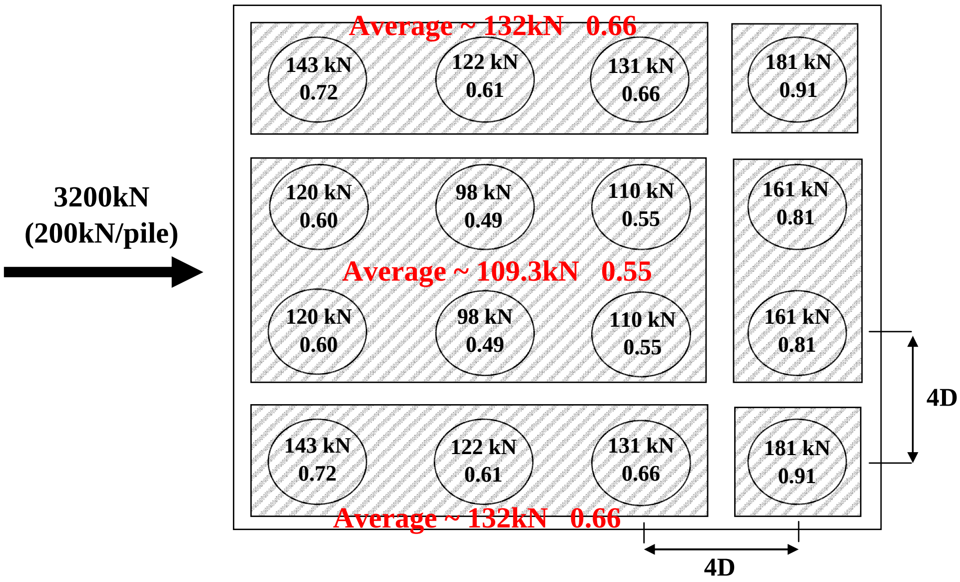


Figure A.18 Pile Load Distribution in the Group with 4D Pile Spacing and 3200kN load Applied

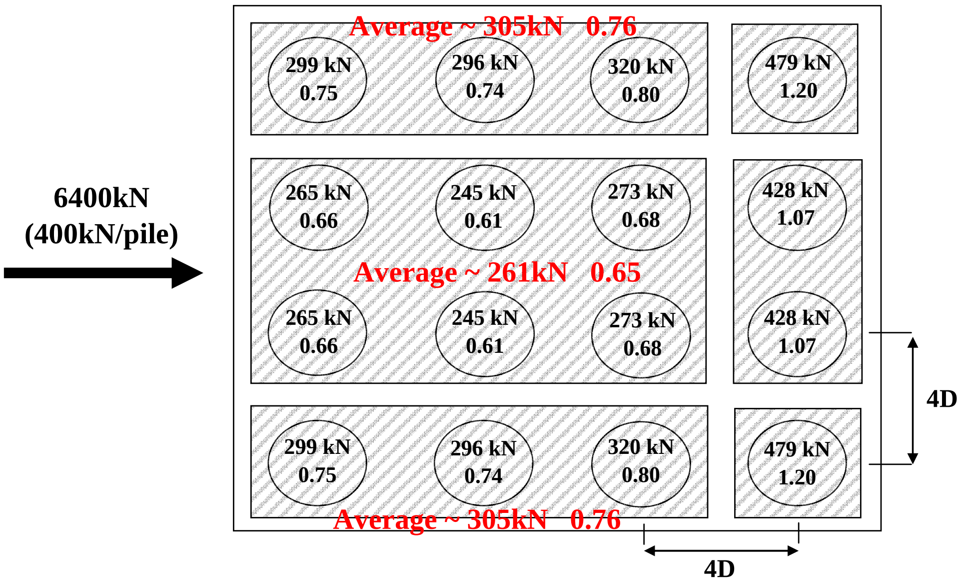


Figure A.19 Pile Load Distribution in the Group with 4D Pile Spacing and 6400kN load Applied

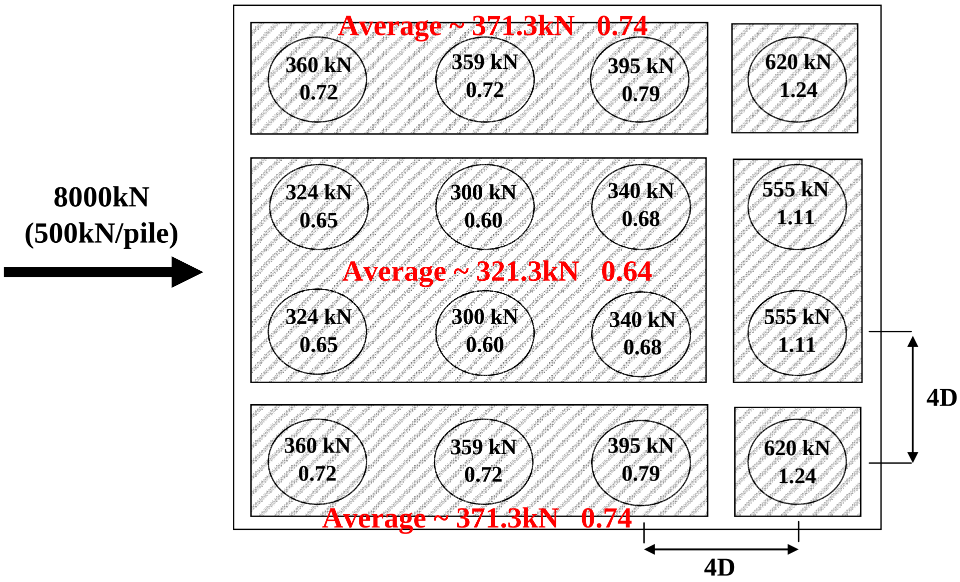


Figure A.20 Pile Load Distribution in the Group with 4D Pile Spacing and 8000kN load Applied

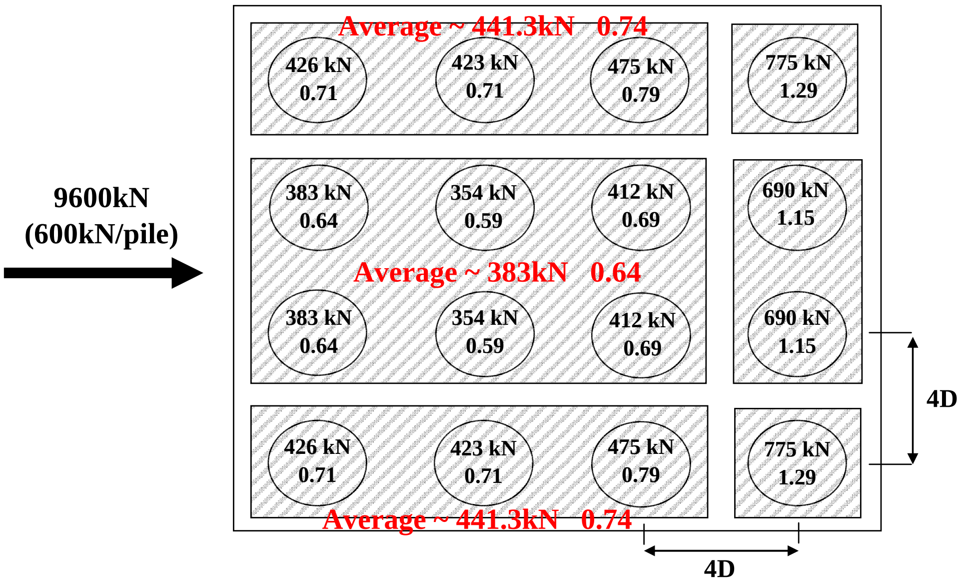


Figure A.21 Pile Load Distribution in the Group with 4D Pile Spacing and 9600kN load Applied

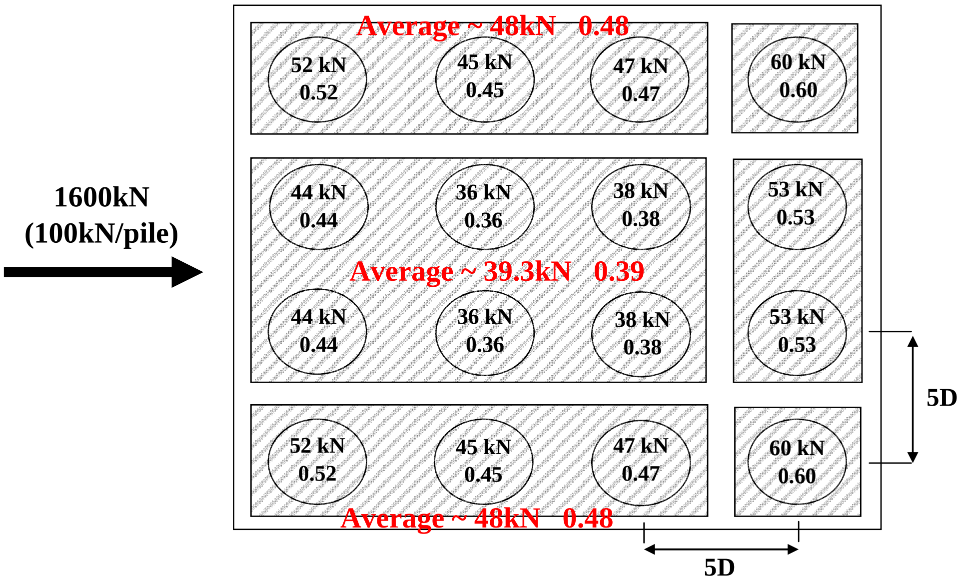


Figure A.22 Pile Load Distribution in the Group with 5D Pile Spacing and 1600kN load Applied

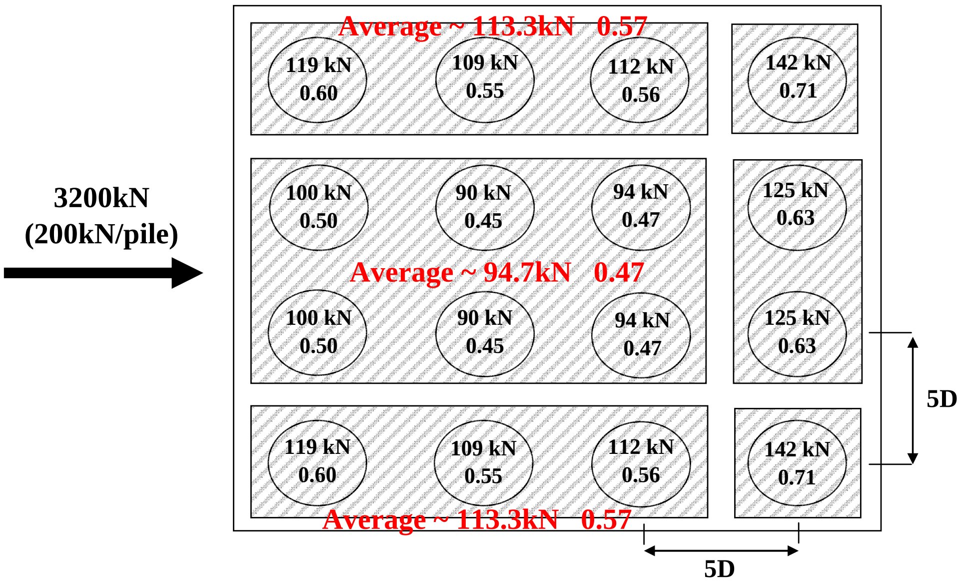


Figure A.23 Pile Load Distribution in the Group with 5D Pile Spacing and 3200kN load Applied

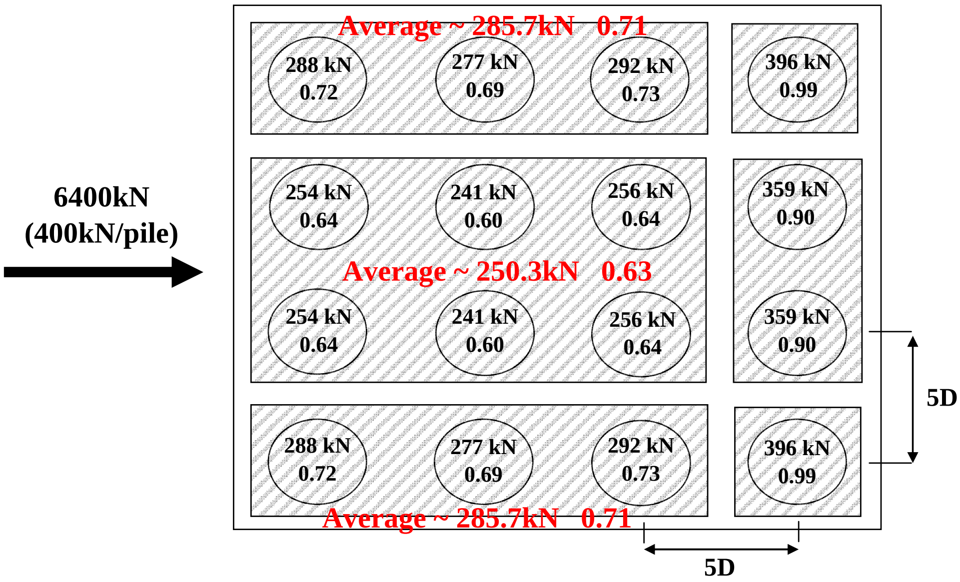


Figure A.24 Pile Load Distribution in the Group with 5D Pile Spacing and 6400kN load Applied

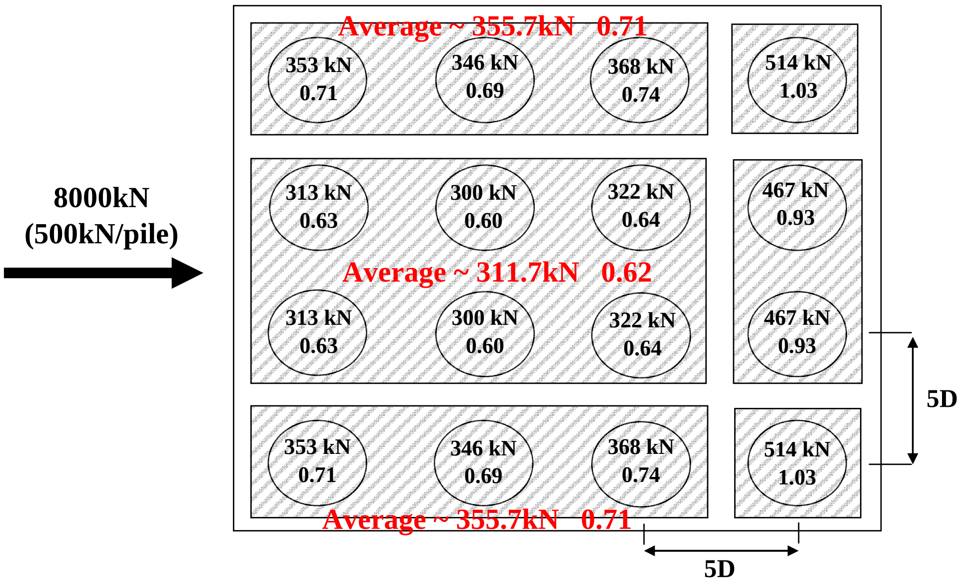


Figure A.25 Pile Load Distribution in the Group with 5D Pile Spacing and 8000kN load Applied

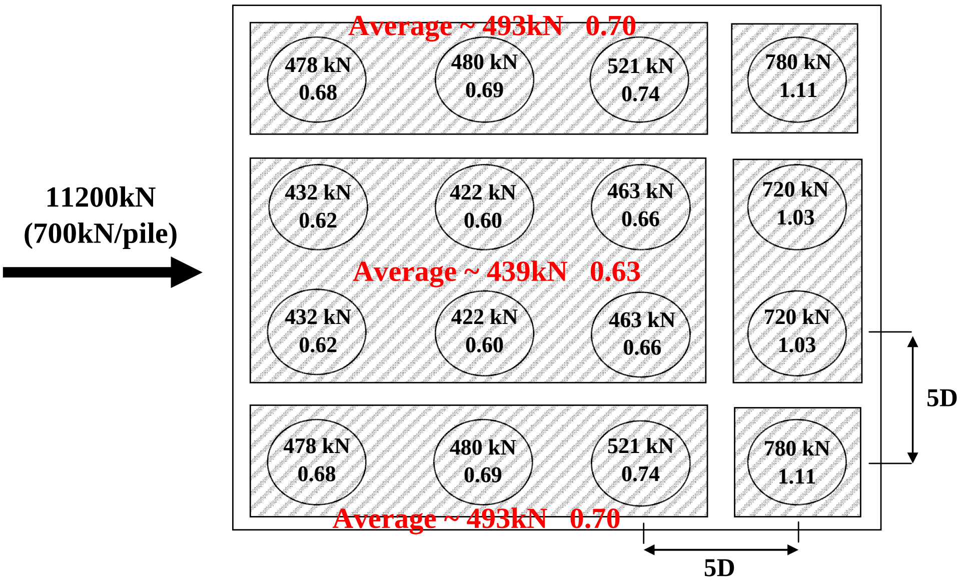


Figure A.26 Pile Load Distribution in the Group with 5D Pile Spacing and 11200kN load Applied