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Analysis of Laterally Loaded (2×2) square Pile groups Using Finite Element Method

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***Abstract*—The finite element method, along with an elastoplastic constitutive model, is used to investigate the response of laterally loaded single pile and (2×2) square pile groups in sand. Also, a real practical problem of an on-shore container yard in Um Qaser Port-Basra Province is solved. ABAQUS finite element program is used to analyze the behavior of single pile and (2×2) square pile groups. The pile and the soil around the pile are modeled by three-dimensional brick elements. The pile is modeled as a deformable body with linear elastic material properties, while the soil is modeled as an elasto-plastic Mohr-Columb model continuum material. The software is verified against field load-test measurements and its efficiency is assessed. Successful comparisons between the predicted and measured behaviors are obtained. The effect of pile-soil-pile interaction (group action) is investigated by studying the effect of pile spacing on the behavior (2×2) square pile groups. The lateral pressure distributions and the p-y curves are obtained and the p-multipliers are calculated for all piles. From the results it is found, p-multipliers are greater for the leading piles than the trailing piles up to a spacing of, approximately, five times pile diameter. They approach unity at a spacing of six times pile diameter and the group efficiency is increased with pile spacing and approaches (100%) at a spacing of seven times pile diameter.**

***Keywords*— Finite element, Laterally loaded pile groups, P-multipliers, p-y curves**

I. Introduction

Piles are columnar elements in a foundation which have the function of transferring load from the superstructure through weak compressible strata or through water, onto stiffer or more compact and less compressible soils or onto rock. They may be required to carry uplift loads when used to support tall structures subjected to overturning forces from winds or waves. Piles used in marine structures are subjected to lateral loads from the impact of berthing ships and from waves.

Combinations of vertical and horizontal loads are carried where piles are used to support retaining walls, bridge piers and abutments, and machinery foundations [1]. For proper functioning of such structures, two criteria must be satisfied: (1) a pile should be safe against ultimate failure; and (2) lateral displacement at working loads should be within the permissible limit. Several methods are available for predicting the ultimate lateral resistance of piles. However, these methods often produce significantly different ultimate resistance values.

The behavior of piles subjected to lateral loads is governed by the interaction between the pile and the soil. The behavior is affected by a non-linear, three dimensional soil-structure interaction. Pile properties (including pile stiffness and geometry), soil stress-strain behavior (including stiffness, shear strength, and volume change characteristics), and pile/soil interface properties play important roles in the response of piles. A fundamental study of the effect of the pile and soil properties on the pile and soil response of laterally loaded single piles would help to improve our understanding on this subject. In addition to the pile properties and soil behavior mentioned above, the response of piles in a laterally loaded pile group may also be affected by the interaction between individual piles. Individual piles in group may behave as isolated units if pile spacing is large enough or may interact with each other significantly if pile spacing is small. Understanding of the behavior of piles in a group subjected to lateral loads is needed for proper design of the foundation elements. However, pile load tests on laterally loaded pile groups in sand; indicate that group interaction results in a substantial reduction in the ultimate soil resistance relative to that of single piles [2]. Thus, an investigation of the behavior of piles in a group subjected to lateral loads, especially the influence of group interaction on soil resistance is conducted to provide a better understanding of the mechanism of pile-to-pile interactions.

Although piles in the leading row of a group may sometimes have loads versus deflection curves similar to that for a single pile, piles in trailing rows will exhibit significantly lower load versus displacement curves. Apparently, as closely spaced pile groups move laterally, the failure zone for individual piles overlap as shown in Fig.1. The tendency of a pile in a trailing row is to exhibit less lateral resistance because of the pile in front of it is commonly referred to as ‘‘shadowing’’. This shadowing effect becomes less significant as the spacing between piles increase and is relatively unimportant for spacing greater than about six pile diameter center-to-center based on model tests [3]. P-multiplier is employed to get simple relationship between piles in a group.

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In this study, the finite element method via ABAQUS program is utilized to analyze the behavior of single piles and pile groups, embedded into sandy deposits, and subjected to static lateral loads. The objectives of this study are to investigate the following:

1. The effects of pile spacing (2D, 3D, 4D, 5D, 6D, 7D), for (2×2) square pile groups on the p-multiplier values of the piles in the group.
2. The effects of pile spacing (2D, 3D, 4D, 5D, 6D, 7D), for (2×2) square pile groups on the group efficiencies.
3. The interface between soil and pile.
4. The nonlinear soil behavior, adopting Mohr-Coulomb yield criterion.

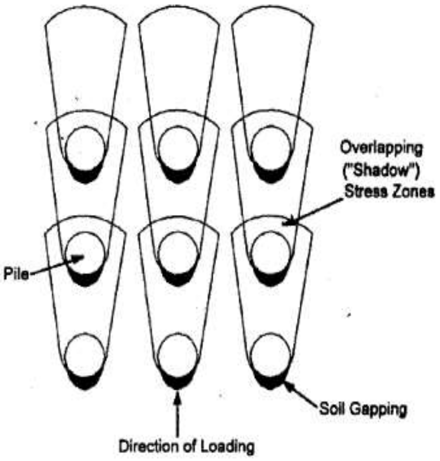


Figure 1. Schematic drawing illustrating reduction in load capacity in pile group due to overlapping of failure zone and gap formation behind piles [3].

II. Pile-Soil Contact Theory

1. Master-slave surface

Because Master-Slave contact algorithm is adopted in computer program that is used in the case of study, it is very convenient to simulate the pile-soil contact as long as the contact pairs are correctly set up between the piles and soil [4]. When determine the master and slave surfaces in computer program node-to surface discretization method and surface-to-surface discretization are available. In the node-to-surface discretization method, every node in the slave surface establishes contact relationship with the projective point in the master surface and every contact condition includes a slave-surface node and a relative master-surface node. The slave-surface node will not penetrate the master surface but the master-surface node can penetrate the slave surface. The surface-to-surface discretization method establishes relationship for the whole slave surface. The change shape of the master-slave surface is considered in the contact analysis. According to the reference Cao and shi, 2009 as cited by Can et.al., 2010 [5], to obtain the best numerical simulation results in some principles need that to be followed when we choose the maser-slave surface in the pile-soil contact analysis: (1) Select the lateral soil around piles as slave surface and the piles as master surface. (2) Assure that the mesh of lateral soil around piles is finer than that of piles. (3) Choose the more accurate Surface-to-surface discretization method if possible.

2. Contact model

The contact problem between pile and soil is highly nonlinear [6]. The elastic Coulomb friction model was adopted as the contact constructive model where friction coefficient (μ) and ultimate friction resistance (τ_{max}) were used to reflect the friction activity between the two surfaces. The relationship between the shear stress, slip displacement and normal stress in the contact surface is shown in the Fig. 2. The relationship between them is

$$\begin{cases} \tau = k\omega & \omega \leq \omega s \\ \tau = \mu Pn & \omega \geq \omega s \end{cases} \qquad (1)$$

Where μ is the friction coefficient between contact surface, τ is the shear stress, τ_{max} is the ultimate friction resistance that user defines, P_n is the normal stress, k is the shear stiffness, ω_s is the elastic ultimate slip displacement and ω is the slip displacement in the contact surface.

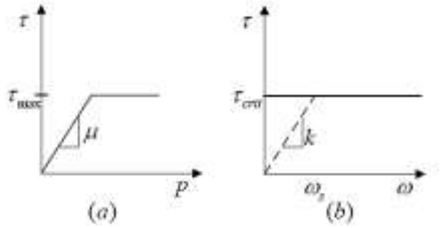


Figure 2. Elastic Coulomb friction model

The solid line in the Fig. 2b represent the ideal friction activity, where shear motion keeps zero until the drag force in the contact surface reaches the critical shear stress τ_{crit} = min (μP_n, τ_{max}). However the actual friction activity between pile and soil is not an ideal one. When slip displacement is less than ω_s this small-amount motion is allowed. The pile-soil shear stress is relevant to the friction coefficient, normal stress and the ultimate friction resistance user defines.

III. Adopted Strategy

A three-dimensional finite element mesh is used to discretize the soil domain around the pile diameter segment. The piles are modeled as a deformable body with linear elastic material properties, while the soil is modeled as a deformable body using elasto-plastic continuum material which deforms elastically by linear elasticity and plastically based on Mohr-Coulomb model. Due to the geometric symmetry, all analyses are performed on one-half of the model to reduce the time of computation. Boundary condition along the symmetric plane were assumed to be on rollers, which moves in the vertical plane, this plane was parallel to the direction of the applied horizontal load, and restraint in the direction perpendicular to the symmetric plane, and for the side and base of the soil mass.

The dimensions of soil mass should be established properly to reduce the effects of boundaries on the results.

The soil boundaries should be taken at distance range of (6-18) times pile diameter from outer pile edge [7]. In this work, the width or diameter of the soil mass is (30D) for single pile, in which, (D) is the pile diameter or pile width; and for pile group, the width of the soil mass is equal to [17D + (n-1)S], in which, (S) is piles spacing (center to center) and, (n) is the number of piles in that direction. The height of soil mass is (L+7.5D), in which, (L) is the length of the pile. A relatively fine mesh is used near the pile-soil interface, and becomes coarser farther from the pile. The 20-node quadratic brick element, with reduced integration is used to discretize both the pile and soil medium.

The interface between the pile and the soil was simulated by using penalty–type interface. This type of interface uses a stiffness (penalty) method that permits some relative motion of the surfaces (an“elastic slip”) when they should be sticking. While the surfaces are sticking, the magnitude of sliding is limited to this elastic slip [8].

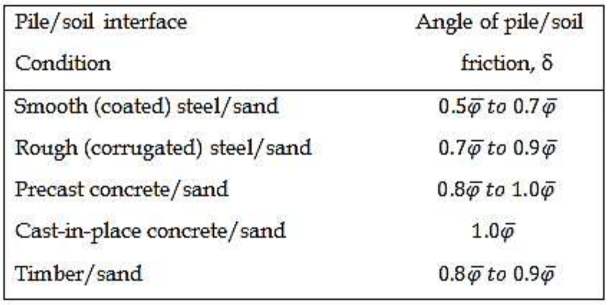
IV. Pile–Soil interaction

The interaction at the pile-soil surface can range from perfect contact, where no relative sliding between soil and pile occurs, to perfect sliding conditions where no friction develops along the shaft of the pile. The interface characteristics are dependent on the placement method of the pile. Piles that are impact driven (ID) tend to exhibit degrees of relative motion between the pile and the soil once the system is under load. On the other hand, cast-in-place (CIP) piles tend to have much less relative sliding than their (ID) counterpart. On this basis, the friction coefficient varies depending on the method of construction.

1. Frictional Parameters

Surface contact in ABAQUS requires the input of various parameters that govern the behavior of the two bodies in contact. Interaction tangential to the surface is governed by the coefficient value of, (μ). Determining an appropriate value of (μ) for the interaction of pile and soil was more difficult because the different materials of piles and soil types and method of construction. Table (1) can be used as guides. Friction factors are listed based on the type of soil, pile material and method of construction. As shown in the table (1), the angle of pile/soil friction, (δ) equals to the angle of internal friction in the case of cast-in-place concrete/sand.

TABLE 1 VALUSE OF THE ANGLE OF PILE TO SOIL FRICTION FOR VARIOUS INTERFACE CONDITIONS [9]



Pile/soil interface Condition	Angle of pile/soil friction, δ
Smooth (coated) steel/sand	0.5φ to 0.7φ
Rough (corrugated) steel/sand	0.7φ to 0.9φ
Precast concrete/sand	0.8φ to 1.0φ
Cast-in-place concrete/sand	1.0φ
Timber/sand	0.8φ to 0.9φ

V. VERIFICATION

The computer program is verified against real behavior through making comparisons between the computed and the measured results obtained from field tests. This comparison is presented in terms of the relationships between the applied lateral loads and corresponding pile head displacements.

A bored, cast in-site pile (0.203 m) in diameter and (2.89 m) long, embedded (2.4 m) into silty sand is tested under lateral loading [10]. The lateral load was applied at (0.49 m) above the ground line. The properties of the soil and the pile are listed in table (2). Fig. 3 compares the computed and the measured pile head responses. It appears that the model analysis and experimental result are fairly good matching.

TABLE 2 GEOTECHNICAL PROPERTIES OF THE SOIL AND PILE [10].

Parameter	Symbol	Unit	Soil	Pile
Unite weight	γ	kN/m^3	19	24
Young's modulus	E	kPa	3×10^4	25×10^5
Poisson's ratio	υ	------	0.3	0.16
Cohesion intercept	c	kPa	1	------
Friction angle	Ø	deg.	30	------
Dilation angle	ψ	deg.	25	------

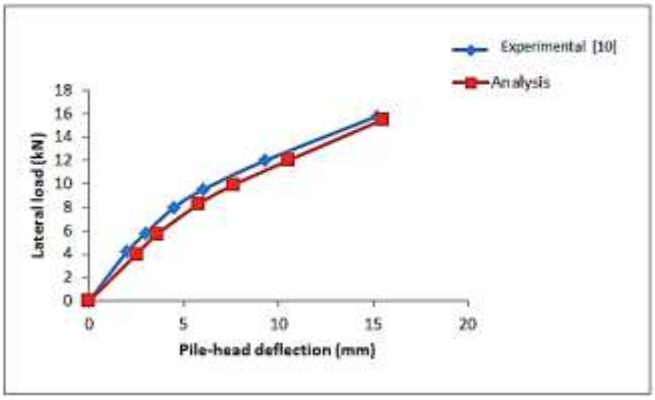


Figure 3. Comparison between experimental and result of program value of pile- head deflection for a bored pile partially penetrating silty sand

VI. RESULTS AND DISCUSSION

The case study is selected from a project at Um Qaser port, south of Basra province. A container yard is to be extended by utilizing steel pipe piles. Table (3) represents the properties of piles and the properties of in-situ soil profile are listed in tables (4a, 4b) [11]. It should be mentioned that, the values of elastic parameters are assigned by the researcher based on soil consistency and depending on selected references [12,13]. The loads associated with specified pile head displacements (6.35 mm, 12.7 mm) are used for predicting the p-multipliers whereas, the ultimate loads (defined by the points of intersections of initial and final tangents) are used for determining group efficiencies.

TABLE 3 STEEL PIPE PILE PARAMETERS

Properties	Values
Total pile length, m	18
Outer diameter, m	0.9144
Wall thickness, m	0.0127
Modulus of elasticity (Ep), kN/m^2	210×10^6
Poisson's ratio (υ)	0.3
Unit weight (γ), kg/m^3	7800

TABLE 4a SOIL PROPERTIES FOR UM QASER PORT [11].

Depth (m)	Type of Sandy Soil	*Ncorr.*	γ (kN/m^3)
0.0 – 3.0	Medium dense (above W.T)	34	20.1
3.0 – 4.5	Loose (above W.T)	7	18.3
4.5 – 6.0	Loose (below W.T)	10	8.5
6.0 – 8.68	Dense (below W.T)	50	9.61
8.68 – 11.36	Medium dense (below W.T)	26	10.2
11.36 – 14.0	Dense (below W.T)	50	9.61
14.0 – 23.5	Medium dense (below W.T)	15	10.2

TABLE 4b SOIL PROPERTIES FOR UM QASER PORT [11].

Depth (m)	Ø * (degree)	ψ (degree)	υ
0.0 – 3.0	33	20	0.30
3.0 – 4.5	28	20	0.25
4.5 – 6.0	31	20	0.25
6.0 – 8.68	37	25	0.33
8.68 – 11.36	32	20	0.30
11.36 – 14.0	35	25	0.33
14.0 – 23.5	33	20	0.30

$* \ \delta = 0.6\emptyset$

1. Laterally Loaded Single Piles

Single piles are analyzed with different head conditions; namely free-head (without cap) and fixed-head (with cap). The cap dimensions are (5m×5m×1m) and is located above ground to eliminate the action of pile-raft system. The properties of cap concrete are ($E=25\times10^3$ MPa, $\upsilon=0.16$, $\gamma=24$ kN/m^3).

It is observed from the load-deflection responses of Fig.4 that, the load required to produce a specified lateral displacement is larger for a fixed-head condition than its counterpart for a free-head condition; [(128 kN) and (201 kN)] compared to [(102 kN) and (144 kN)] for a pile head displacement of (6.35 mm) and (12.7 mm), respectively.

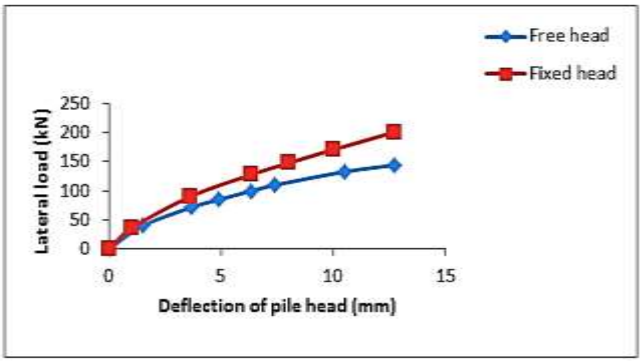


Figure 4. Load versus deflection of pile head for single piles

2. Pile Groups

The behavior of each pile within the group is compared to the fixed-head single pile response. In order to determine the p-multipliers, the ratios of pile resistance are computed for (6.35 mm and 12.7 mm) pile head displacements at three depths (1.5 m, 3 m, 4.5 m) from ground surface.

The values of group efficiency are calculated based on the ultimate loads determined from points of intersections of tangents to the load-displacement curves [14]. Therefore;

$$G_e = (H_{ult.})_g/[n\times(H_{ult})_s] \qquad (2)$$

Where,

G_e = group lateral efficiency,
$(H_{ult.})g$ = ultimate lateral capacity of a pile group,
$(H_{ult})s$ = ultimate lateral capacity of a single pile, and
n = number of piles in the group

3. LATERALLY LOADED (2×2) PILE GROUPS

A square group of four piles is analyzed repeatedly for different values of spacing. A typical section of the pile group is shown in Fig.5. For the pile spacing (S=2D), Fig.6 and Fig.7 show the horizontal soil pressure along pile length for all piles at maximum deflections of (6.35 mm and 12.7 mm), respectively.

Fig.8, Fig.9 and Fig.10, show the p-y curves at various depths. It is noted that the soil resistance for a single pile is greater than the soil resistance for the piles in the group, which means that, the p-multipliers are less than unity. Table (5) lists the p-multiplier average values at different pile head displacements. Small values of the average p-multiplier are reported due to the shadowing effect. It can be realized that, the average values for piles are increase with the increase in spacing of piles.

Fig 11 and Fig 12 illustrates the prediction method of ultimate loads of fixed head single pile and (2×2) pile group with spacing (S=2D), respectively. From the point of intersection of two tangents to be (632 kN) for fixed head single pile and (1140 kN) for (2×2) pile group with spacing (S=2D). Table (6) lists the ultimate lateral loads and efficiencies of the pile groups at different spacings.

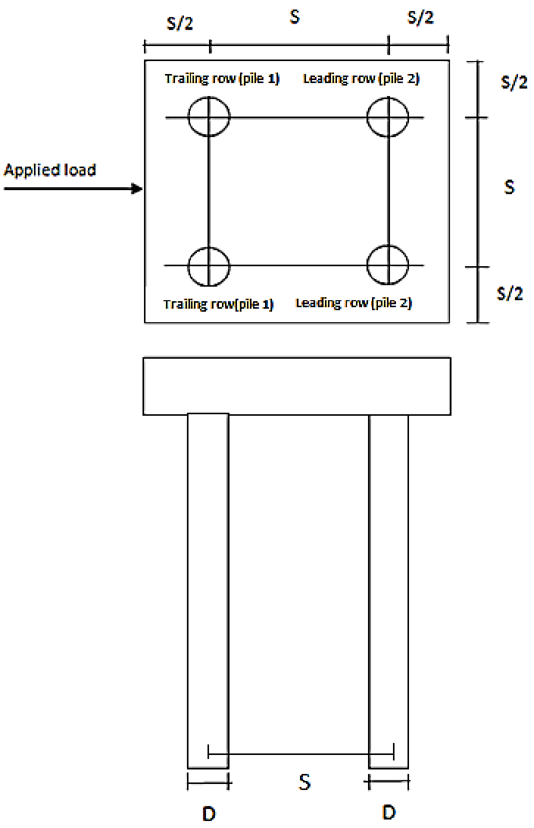


Figure 5. Typical section for the (2×2) pile group

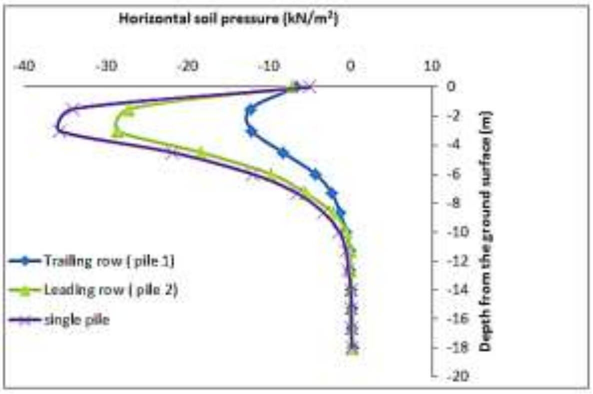


Figure 6. Horizontal soil pressure [(2×2) group, S=2D, max. displacement = 6.35 mm]

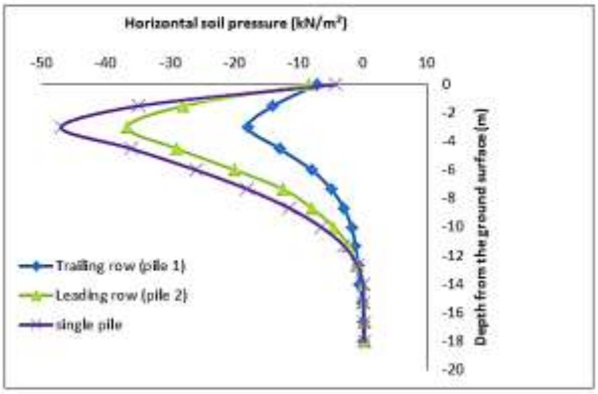


Figure 7. Horizontal soil pressure [(2×2) group, S=2D, max. displacement = 12.7 mm]

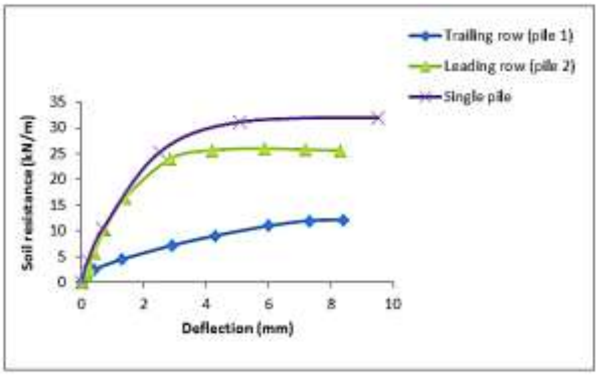


Figure 8. p-y curves [(2×2) group, S=2D, depth= 1.5 m]

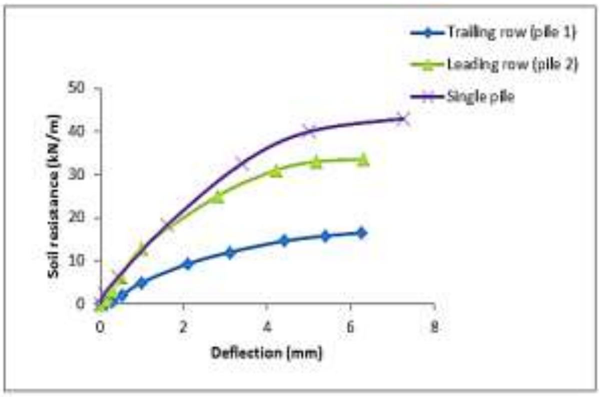


Figure 9. p-y curves [(2×2) group, S=2D, depth= 3.0 m]

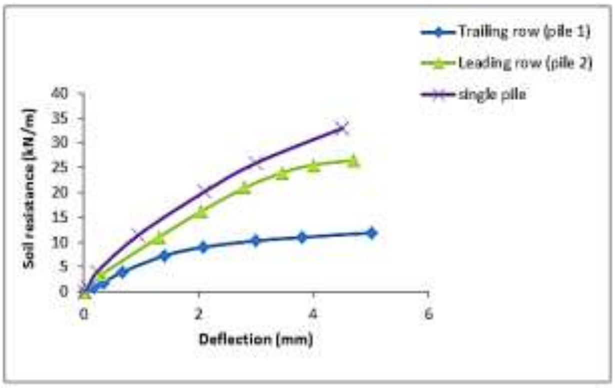


Figure 10. p-y curves [(2×2) group, S=7D, depth= 4.5 m]

TABLE 5 AVERAGE VALUES OF P-MULTIPLIERS FOR [(2×2) GROUP, MAXIMUM DEFLECTION = 6.35 mm, 12.7mm]

Spacing (S)	P-multiplier (average value)			
	Trailing row (pile 1)		Leading row (pile 2)	
	maximum deflection =6.35mm	maximum deflection =12.7mm	maximum deflection =6.35mm	maximum deflection =12.7mm
S=2D	0.36	0.37	0.81	0.79
S=3D	0.53	0.54	0.82	0.83
S=4D	0.64	0.64	0.86	0.85
S=5D	0.8	0.8	0.86	0.86
S=6D	0.93	0.92	1.01	0.99
S=7D	0.99	0.98	1.04	1.03

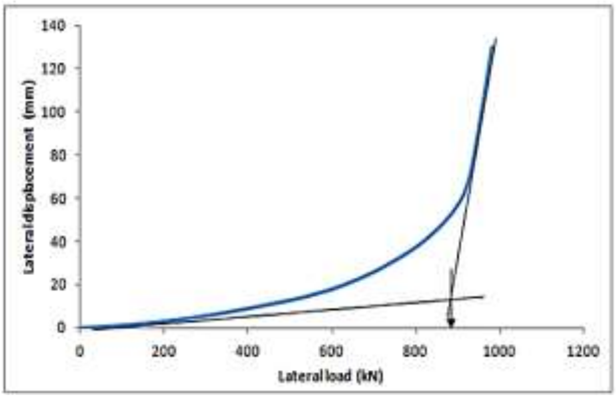


Figure 11. Load versus deflection for fixed head single pile

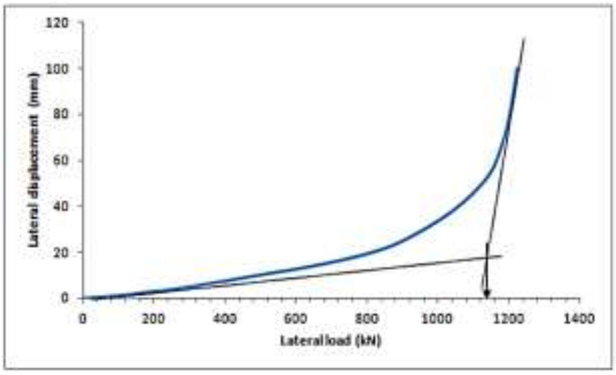


Figure 12. Load versus deflection [(2×2) group, S=2D]

TABLE 6 THEORETICAL EFFICIENCY OF THE (2x2) PILE GROUP AT DIFFERENT SPACINGS

Pile Spacing	Ultimate Lateral Load (kN)	Theoretical Efficiency (%)
S=2D	1140	45
S=3D	1440	57
S=4D	1650	65
S=5D	1860	74
S=6D	2100	83
S=7D	2460	97

VII. CONCLUSIONS

For the studied soil profile and pile properties in question, the following conclusions can be drawn:

1. The fixed-head single pile exhibits greater lateral resistance than that of free-head.
2. From the results of (2×2) square pile group;
   - a- The p-multipliers for the leading piles are greater than their counterparts for the trailing piles, up to spacing of, approximately, five times pile diameter. They approach unity at a spacing of six times pile diameter.
   - b- The predicted values at the two head displacements are almost equal.
3. The group efficiency is increased proportionally with pile spacing and approaches unity at a spacing of seven times pile diameter for the two pile group configurations.

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