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A Study of Horizontal Displacement of Laterally Loaded Piles Using Finite Element Method

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Abstract

A theoretical approach is used to analyze single pile and pile in group under lateral loading using two programs. The first one used the finite element method for single pile depending on plain strain condition while the second one used the characteristic load method for pile in group. Horizontal displacement for pile in group is measured while both horizontal displacement and shear stress for single pile are measured. A comparison between the results of horizontal displacement for both single pile and pile in group with the actual practical values are produced and shows a good agreement.

Keywords: lateral loading, Pile, Horizontal displacement, Pile group.

دراسة الازاحة الافقية لمنظومة مؤلفة من تربة–ركيزة باستخدام طريقة العناصر المحددة

الخلاصة

تم استخدام طريقة نظرية لتحليل منظومتين، الاولى مؤلفة من ركيزة بشكل منفرد والثانية من ركيزة في مجموعة، معرضة لتاثير حمل جانبي باستخدام برنامجين. حيث استخدم البرنامج الاول لتحليل الركائز المفردة وبالاعتماد على طريقة العناصر المحددة وبافتراض (مسألة ثنائية البعد وبتاثير انفعال مستوي). في حين استعمل البرنامج الثاني لتحليل الركيزة في مجموعة بالاعتماد على طريقة الحمل المميز(Characteristic Load Method). وقد تم قياس الازاحة الافقية في الحالتين مع قياس اجهاد القص المتولد اثناء التحميل في الركائز المفردة. وتم مقارنة النتائج المقاسة للازاحات الافقية للركائز المفردة والركائز في مجموعة مع قيم عملية ولوحظ الحصول على نتائج جيدة.

الكلمات الدالة الحمل الجانبي،الركيزة، الازاحة الافقية، ركيزة في مجموعة.

Notations

D: Pile diameter.
Do: Outer diameter of pile.
Di: Inner diameter of pile.
E: Modulus of Elasticity.
Ep: Modulus of elasticity of pile.
Fm: pile group efficiency based on Pile spacing,
Kp: Rankine coefficient for passive case.
L: Pile length.
Mc: Characteristic moment.
Nrow: No. of pile rows.
RI: Moment of inertia ratio = I (pile) / I (solid circular section).
S/D: Pile spacing to pile diameter ratio.
Su: Untrained shear strength of clayey soil.

Greek letters

$\sigma_x, \sigma_y, \varepsilon_x, \varepsilon_y$: Normal stress/strain in the x, y directions respectively.
τ_{xy}, γ_{xy} : Shear stress / strain in the x, y directions respectively.
υ : Poisson's ratio.
γ' : Effective unit weight for sand.
ϕ' : Effective angle of friction.

Introduction

The lateral load capacity of pile foundation is critically important in the design of structures that may be subjected to earthquake, high wind, wave action and ship impact [1]. Single piles are mainly used for coastal structures such as mooring and berthing piles but they are usually formed in groups. Tall buildings offshore, platforms, quays, viaducts and bridge piers are generally built on pile groups. The differences between the behavior of single piles and pile groups are that pile group response is influenced by the nonlinear pile-soil-pile interaction, the effect of the pile cap, the spacing of piles and the arrangement of piles with respect to the direction of applied force [2].

The behavior of pile groups under lateral loads can be analyzed using the p-y method. Extensive research has been carried out on the p-multiplier concept in which this method accounts for the loss of soil resistance due to group "shadowing" effect (that is, overlapping of shearing zones), and different values of p-multipliers are assigned to each row within the group. The p-y curves of individual piles in the group are then obtained by multiplying the soil resistance values of p-y curves for a single by the assigned values of multipliers [3].

Poulos (1971) presented elastic solutions for load – deflection relationships in both free-headed and fixed-headed single piles and further extended the solutions for groups of piles by the principal of superposition [4]. Yegian and Wright (1973) analyzed the problem of piles and pile groups by adopting plane strain conditions to produce a solution showing that the efficiency of two laterally loaded piles in arrow was considerably less when the load is parallel to the pile line rather than perpendicular to it [5]. Kim and Brungraber (1976) carried out full scale testing on laterally loaded piles and groups consisting of vertical and batter piles, their results indicated that an increase in spacing between the piles increased the resistance to lateral loads [6].

Another method called the strain Wedge (SW) model which was an approach that has been developed to predicate the response of a flexible pile under lateral loading [7]. The main concept associated with the SW model is that traditional one-dimensional beam on elastic foundation (BEF) pile response parameters can be characterized in terms of three-dimensional soil-pile interaction behavior. The strain wedge model was initially established to analyze a free-head pile embedded in one type of uniform soil (sand or clay). Later this model has been modified to include the effect of pile head conditions on soil-pile behavior [8].

Several methods have been proposed and implemented to model lateral group response. A number of codes make use of lateral springs based on Mindlin's theory. However, this method gives similar shear distributions for all the rows within the group, which disagrees with both field data and the pile shadowing theory [9]. Focht and Koch (1973) proposed another method (roots within elasticity) that combines the p-y method for single piles with Poulos's approach (1971) for pile groups [10]. Based on Focht and Koch's procedure and the characteristic load method (Duncan et al. 1994) and (Ooi and Duncan (1994)) developed a group amplification procedure. However, this method is not able to estimate the distribution of loads among piles within a group nor takes into account the pile group arrangement [11]. It is known that p-y curves can be employed in a comprehensive numerical soil-structure interaction analysis (e.g., a finite-element program) to model the soil-pile response of a structural problem involving the superstructure along with the substructure [12].

Theoretical approach

The pile-soil system under lateral loading condition for both single pile and pile in group were studied with different soil properties and condition (sand and clay). In the study, two programs are used, in the first; the finite element method was used while the second depends on the characteristic load method for single pile and pile in group, respectively.

Single pile program

A finite element method was applied through a computer program to study a single pile under lateral load with different soil condition. The pile-soil system was considered as plane strain condition. Elastic models used for both pile and soil. The program uses frontal solution method which can be considered as a particular technique for first assembling finite element stiffness and nodal forces into a global stiffness matrix and load vector then solving for unknown variables by means of Gaussian elimination and back substitution process in which, the variables are assembled and eliminated at the same time [13].

Plane Stress-Strain Matrix for condition [14]

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = A.\begin{bmatrix} 1-\upsilon & \upsilon & 0 \\ \upsilon & 1-\upsilon & 0 \\ 0 & 0 & (1-2\upsilon)/2 \end{bmatrix}.\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \quad \text{.........................(1)}$$

In which, $A = \dfrac{E}{(1+\upsilon)(1-2\upsilon)}$ ....(2)

Pile-Group program

The program that was used to study the behavior of pile group under lateral loading depends on the characteristic load method in which it was developed by performing nonlinear p-y analysis for a wide-range of free head and fixed-head piles in clay and sand [11].

Characteristic Load Method (CLM)

This method was used the following equations [14]:

For clay

$$Pc = 7.34 D^2 (Ep.R_I) \left[\frac{Su.Fm}{Ep.R_I} \right]^{0.68} \quad \text{.......................................(3)}$$

$$Mc = 3.86 D^2 (Ep.R_I) \left[\frac{Su.Fm}{Ep.R_I} \right]^{0.46} \quad \text{......................................(4)}$$

For sand

$$Pc = 1.57 D^2 (Ep.R_I) \left[\frac{\gamma'.D.\phi'.Kp.Fm}{Ep.R_I} \right]^{0.57} \quad \text{..............................(5)}$$

$$Mc = 1.33 D^2 (Ep.R_I) \left[\frac{\gamma'.D.\phi'.Kp.Fm}{Ep.R_I} \right]^{0.40} \quad \text{.............................(6)}$$

In which the principal limitation for this method is that it is applicable only to uniform soil conditions. For cases where soil conditions vary with depth, it is necessary to use an equivalent uniform soil profile [14].

Case study

Single pile

Four cases were studied for single pile under lateral loading with different soil conditions. Table (1) shows the pile and soil properties for all cases.

Pile group

Five cases were studied for pile groups under lateral loading embedded in sand/clay soil with different pile spacing. Table (2) shows the properties and all other parameters for the studied cases.

Results

(A) Single Pile

Figure (1) shows the deformed mesh of pile-soil system for all studied cases. While figure (2) shows the comparison between actual and predicated load-horizontal displacement relation at the pile head for all studied cases. Finally, figure (3) shows the shear stress at the pile tips that are developed with loading.

(B) Pile Group

Figure (4) shows the comparison between the actual and the predicated load-horizontal displacement under lateral loading for all studied cases.

Conclusions

Single Pile

1- For all the studied cases, the first third part of the pile with the surrounding soil is affected by the lateral loading which may lead to high shear stress generation in the soil for the above layers.
2- A good agreement can be noticed between the actual & predicated horizontal displacement due to lateral loading for all cases at early stages of loading.
3- In most studied cases, the predicated horizontal displacement as final values are greater than the actual at ratios 1.90, 1.11, and 1.66 for the first three studied cases. While the fourth case gives less values at ratio 0.71 because of better pile properties with respect to the soil.
4- The shear stress at the pile increases with the loading to reach a max. Values of 330 kPa, 400 kPa, 160 kPa, and 47 kPa for the studied cases respectively.

Pile Group

1- A good agreement can be obtained between the predicated & actual horizontal displacement under lateral loading for all studied cases except the last one.
2- The predicated horizontal displacement is greater than the actual for only the first and last case and at ratios (1.4, 1.66) respectively. While this ratio is less than the actual for all other cases and at ratios (0.85, 0.99, 0.76, 0.73, 0.73) respectively.
3- When the soil around the pile is sand, the predicated horizontal displacement is greater than the actual. While when the soil is clay the actual values are greater than the predicated. It can be concluded that the clayey soil gives the pile more resistance to lateral loading than the sandy soil.

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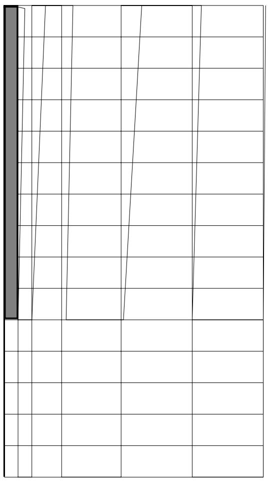
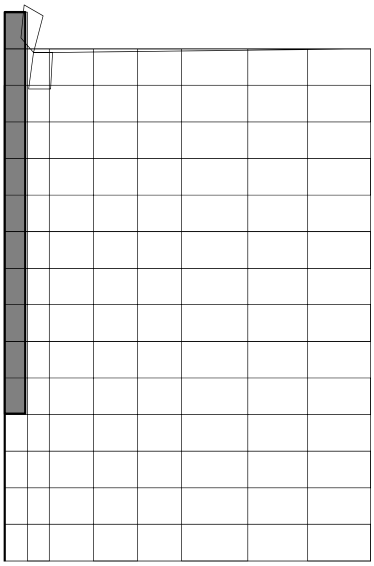


Case (1) [15]



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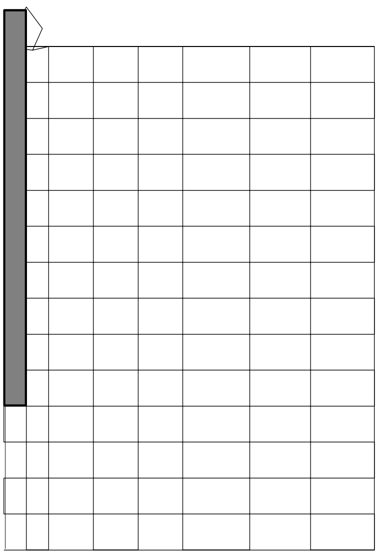

Case (3) [16]

Figure (1) The Deformed Mesh for Single Pile-Soil System After Loading.

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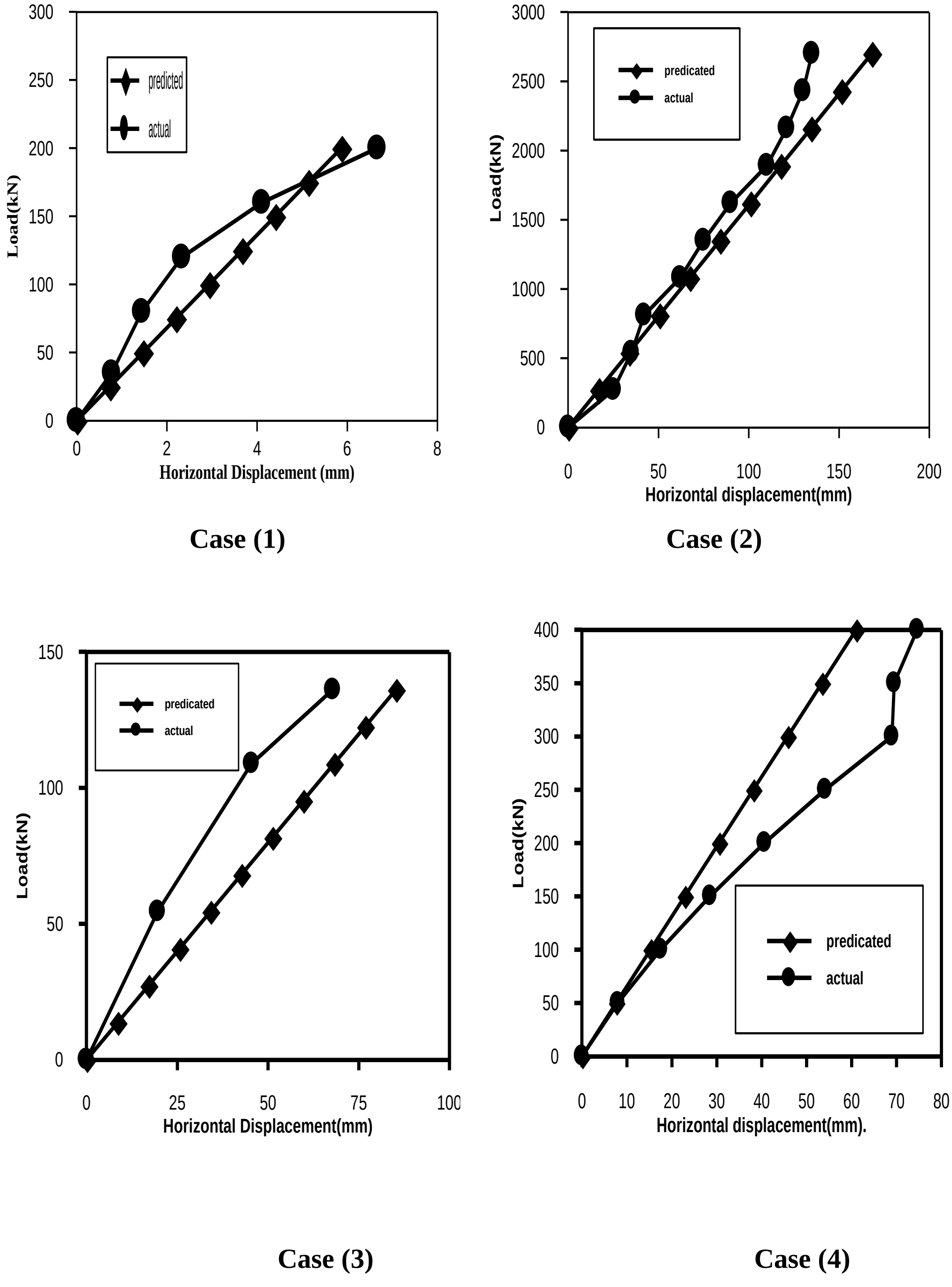

Figure (2) The Comparison Between the Actual and Predicated Horizontal Displacement with Loading for Single Pile.

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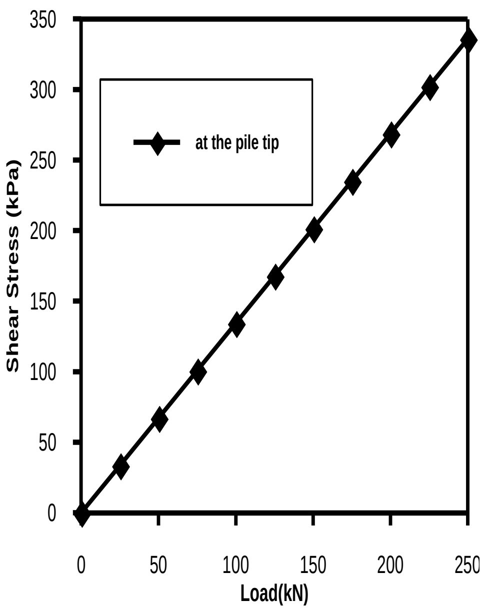
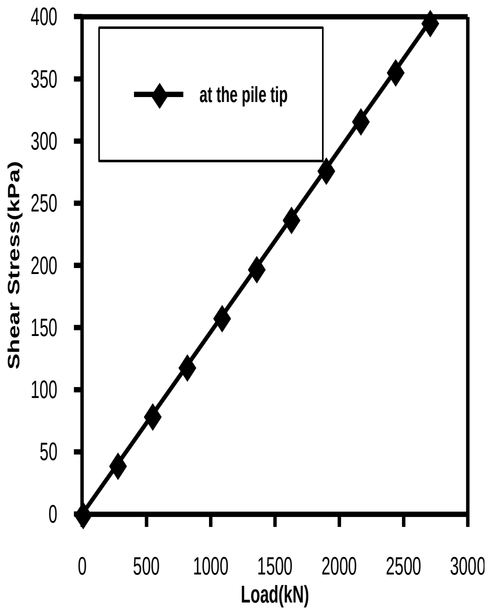
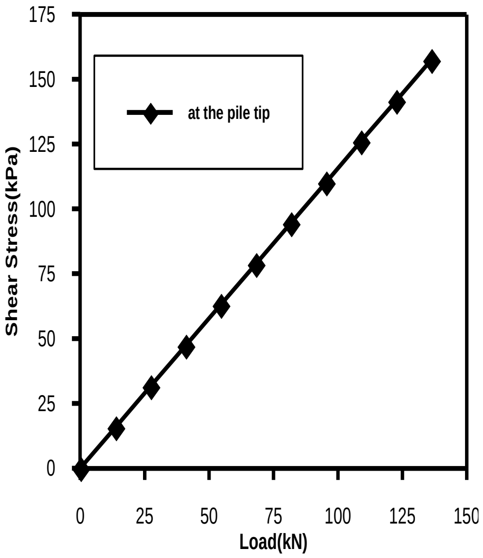


Case (1)



Case (2)



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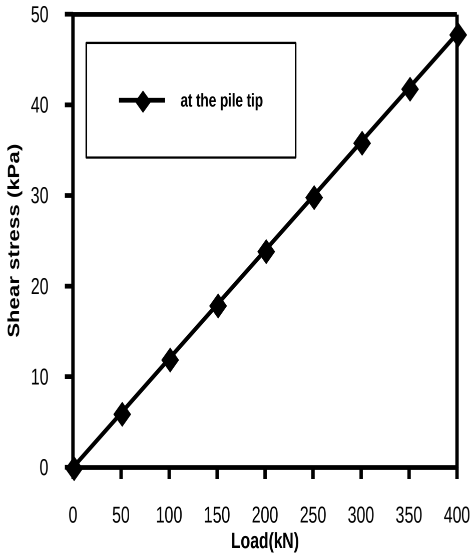

Case (4)

Figure (3) The Relation Between the Applied Lateral Loads with the Generated Shear Stress for the Single Pile.

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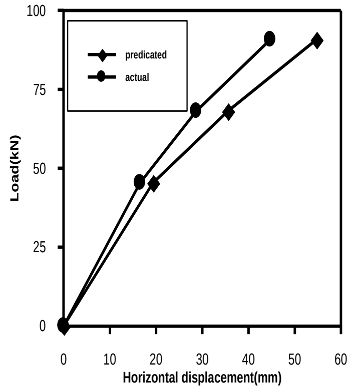
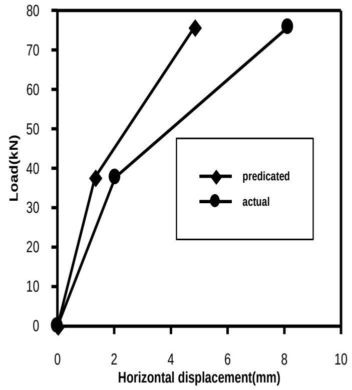
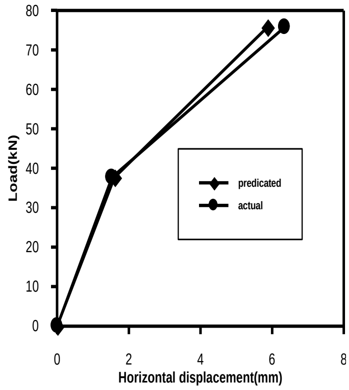


Case (1)



Case (2)



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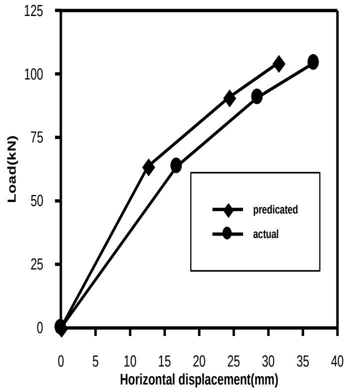
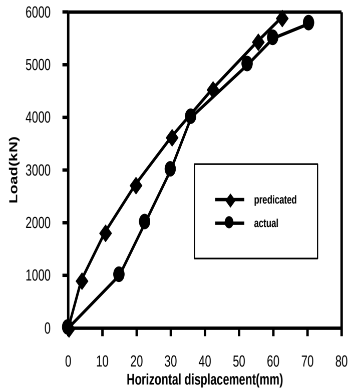
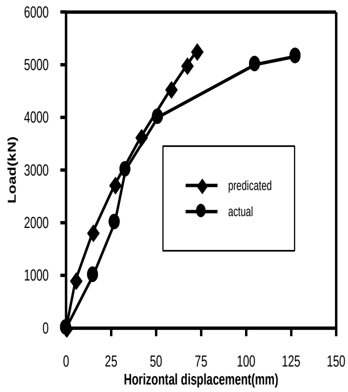


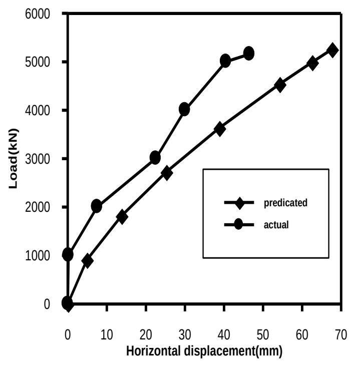
Case (4)



Case (5) (1)



Case (5) (2)



Case (5) (3)

Figure (4) The Comparison Between the Actual and Predicated Horizontal Displacement with Loading for Pile in Group.

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Table (1) Material Properties for Pile and Soil (single pile)

		Case(1)[15]	Case(2)[2]	Case(3)[16]	Case(4)[1]
Pile Elastic	E (kPa)	$2*10^6$	$3.23*10^5$	$2*10^7$	$2.5*10^7$
	ν	0.3	0.2	0.2	0.15
Soil Elastic	E (kPa)	$2*10^4$	$2*10^4$	$1.8*10^4$	$2*10^4$
	ν	0.45	0.45	0.3	0.3

Table (2) Material Properties for Pile and Soil (pile group)

		Case(1)[16]	Case(2)[17]	Case(3)[17]	Case(4)[18]	Case(5)[2]		
						(1)	(2)	(3)
pile	Do(m)	0.28	0.25	0.25	0.32	1.5	1.5	1.5
	Di(m)	0.25	-------	-------	0.3	---	---	---
	RI	1	1	1	1	1	1	1
	Ep(kN/m^2)	$20.4*10^6$	$20.4*10^6$	$20.4*10^6$	$20.4*10^6$	$20.4*10^6$	$20.4*10^6$	$20.4*10^6$
	L(m)	10.66	12.2	12.2	7.9	21	30	30
Soil	ϕ (degree)	39	------	------	------	30	30	30
	γ (kN/m^3)	11	------	------	------	21	21	21
	Kp	4.39	------	------	------	3	3	3
	Su(kN/m^2)	---------	57.5	57.5	76.5	------	------	------
Group Properties.	Nrow	3	3	3	3	2	3	2
	S/D	3	4.8	3.6	3	6	3	3