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Behavior of Laterally Loaded Pile Groups Adjacent to a Slope - A Numerical Study

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Behavior of Laterally Loaded Pile Groups Adjacent to a Slope - A Numerical Study

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Abstract- **The current work comprises of a variety of experiments conducted on single piles and pile groups exposed to static lateral stress. Studies were carried out on single, 2x1, and 2x3 pile groups with pile spacing 3 times the diameter of each pile (S=3D). The model piles analyzed are long concrete piles with L/D ratio of 40. The piles have length of 10-m and a 25-cm diameter that are anchored in loose sand with relative density Dr=25%. The numerical model is created to investigate the influence of pile group size on group lateral capability on flat ground and near to an incline (3H:2V). The behavior of the pile groups was analyzed using 3-D finite element method (FEM) computer program (Plaxis 3D ver.21) to simulate the problem. A comparison was made between the behavior of the group of heaps and the behavior of the single pile. The behavior of laterally loaded pile groups was shown to be strongly reliant on the orientation of the piles within the group with regards to the applied load direction. The behavior of pile groups in the presence of a slope is revealed to be dependent on the distance of the lead row of pile groups from the slope crest (B/D) and the positioning of piles in groups related to the load direction.**

KEY WORDS: Pile groups, Lateral load, Sand, Slope, Numerical Model, Finite element method,

I. INTRODUCTION

Pile foundations are employed to support structures that are subjected to a variety of loads. These loads include axial tension and compression. In addition to compressive and tensile resistance, a pile also offers lateral resistance. Piles may be subjected to significant lateral loads due to the lateral earth forces on retaining structures, wind and earthquake loading on buildings, and ship impact or wave forces on offshore structures. Therefore, estimation of the lateral capacity of pile foundation is one of the most important factors in foundations design. The majority of earlier research on the topic of piles subjected to horizontal loads examined the reaction of individual piles exposed to lateral loads. Nonetheless, piles are typically utilized in groups.

The main aim of the current study is to predict using numerical analysis the behavior of full-scale single piles and pile groups subjected to lateral loading and adjacent to a slope. Study investigates the parameters affecting the lateral capacity of pile groups such as arrangement of piles in a group in case of level ground and when a nearby slope was present, the shadowing effect on pile behavior as shown in figure 1. Finally, to validate numerical model ultimate lateral loading obtained using numerical analysis was compared with the results of previous experimental work done by [5].

A large number of research had been done previously to simulate pile groups exposed to horizontal loadings. The following summarize previous work done on this issue.

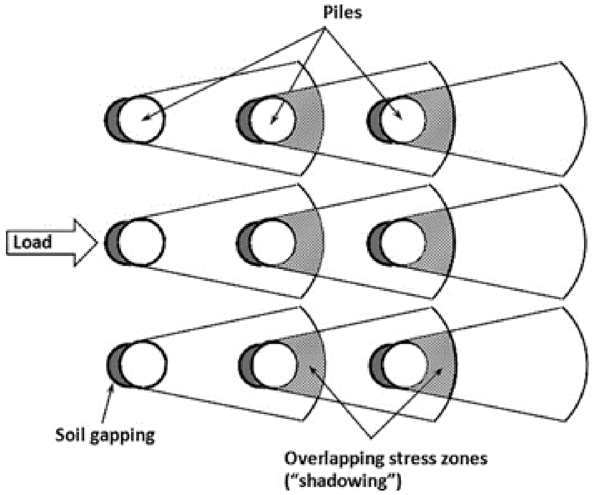

Figure 1. Shadowing effect in pile groups

(Brown, D.A., Morrison, C. and Reese, L.C. 1988) They conducted experimental model tests on a large-scale group of (3x3) free head steel piles placed at three diameters, center to center, and a single pile where, all groups were subjected to two-way cyclic horizontal loading. The experiments are conducted in submerged sand that was firm to dense and compacted around piles. All piles were carefully interfaced to assess the soil resistance variance within the pile group. The performance of the group of heaps was contrasted to that of a single pile [1].

(McVay, M., Casper, R., and Shang, T. 1995) carried out centrifuge tests on single and (3x3) free head pile groups at three diameter and five diameters spacing. The foundation of the piles consisted of medium sand (Dr= 33%) and dense sand (Dr= 55%). The test results demonstrated that the proportion of lateral loads of a group to a single pile, i.e., efficiency, was independently of soil density. At 3D, the group efficiency was 0.74, while at 5D, it was 0.94 [2].

(Rollins, K.M., Peterson, K.T. and Weaver, T.J. 1998) carried out a full-scale lateral load test on (3x3) pile group at spacing equal to three times the piles diameters. The ground profile consists of soft to medium stiff clay followed by silts and underlined by sand. The piles were instrumented with in clinometers and strain gages. A single pile test was performed for comparative purposes. Under the same average loading, the pile groups displaced twice more than the single pile. Group influences significantly lower load capacity for all rows compared to the behavior of a single pile. The trailing rows carried less weight than the leading rows, with the middle rows carrying the least [3].

(Narasimha, S., Ramakrishna, V.G.S., and Babu, R. 1998) they evaluated Through experimental testing, pile embedment length, the influence of flexural stiffness of pile material, and pile configuration matching to the loading direction on the reaction of laterally loaded pile groups. The findings of experiments conducted on model pile groups buried in marine clayey bed and organized with varying pile spacing are given and discussed. According to the findings, the lateral maximum load of pile groups is mostly determined by the stiffness of the pile soil system for various pile layouts [4].

(Sakr, Moheb & M.A. Nasr, Ahmed. 2010) They studied the effect of presence of a sloped ground on the behavior of lateral loaded single piles and pile groups. An experimental program is carried out using lab model. The parameters studied are the effect of piles arrangement corresponding to the slope crest, Proximity of the slope crest to the pile groups. The outcomes of tests conducted on single piles and pile groups are compared between cases of level ground and sloping terrain. It was concluded that maximum lateral loading or capacity of a single pile and pile groups were higher on level ground than sloped ground. Also, the effect of slope crest proximity and configuration of piles arrangement in a group have significant influence on lateral capacity [5].

(Amr Farouk Elhakim et al. 2014) They conducted 3D numerical modelling of lateral loaded pile groups in sand. They investigated the influence of relative density of sand (Dr), pile distance (S = 2.5, 5, and 8D), and pile position within groups (2x2 and 3x3 pile configurations). Due to the group effect, it was determined that piles in groups with shorter distances deflect more than a single pile exposed to same lateral force per pile. Also, for pile groups with a fixed head, it was discovered that the front row bears the greatest weight, while the middle and rear rows carry lesser loads for a given displacement. It has been noticed that the shadowing effect diminishes more rapidly in thick sand than in loose sand [6].

(GOUW Tjie-Liong 2017) studied numerically the behavior of lateral loaded pile groups of configurations 3x3, 5x5 and 9x9. The numerical analysis was performed using PLAXIS 3D numerical analysis program. pile spacing varies from 3D, 4D, 5D, 6D, 8D to 10D (D=pile diameter). He discovered that the center-to-center spacing of piles has a substantial influence on the group pile lateral efficiency, with the lateral group efficiency increasing with pile spacing up to a maximum group efficiency value of one at around 10 pile diameters of pile spacing. In addition, the number of piles in a group affected the group pile's lateral efficiency, with the group's lateral efficiency decreasing as the number of heaps increased [7].

(Reda A. Abdelhalim. et. al. 2020) Experimentally and statistically, the response piles loaded horizontally near an oil-contaminated sand slope was investigated. The research evaluated the effects of contaminated sand layer thickness, pile slenderness ratio, oil content, and distance between pile heads and slope crest [8].

(Bhishm Singh Khati & V. A. Sawant. 2020) The lateral response of pile groups in series and parallel arrangement near a slope was investigated experimentally by [11] where, pile groups were tested in medium density sands. They found hat the distance between slope crest and edge of pile groups have significant effect on lateral response of pile groups especially, in case of parallel arrangement [9].

II. NUMERICAL MODEL DESCRIPTION

A. Numerical model setup

Plaxis 3D 2020 [9] software was used to simulate the behavior of single pile, pile groups to lateral loading. This program for three-dimensional numerical analysis was designed for the evaluation of three-dimensional foundation and geotechnical issues. It is a component of the Plaxis suite of finite element software, which is utilized globally for geotechnical engineering design. Figure 2 shows the numerical model setup in case of level ground. The dimensions of the model boundaries were chosen as following: length equal 120 times the pile diameter, width equal to 40 times pile diameter and height equal to twice the pile length (L). Selected measurements were deemed sufficient to eliminate the impact of boundary influences on the piles' behavior.

The model outside edge is secured against displacements. Pile cap was placed on the ground surface to reduce the influence of soil passive resistance. Using 15-node wedge elements, the soil is modeled. The mesh size employed in the analysis was enough for enhancing the model precision.

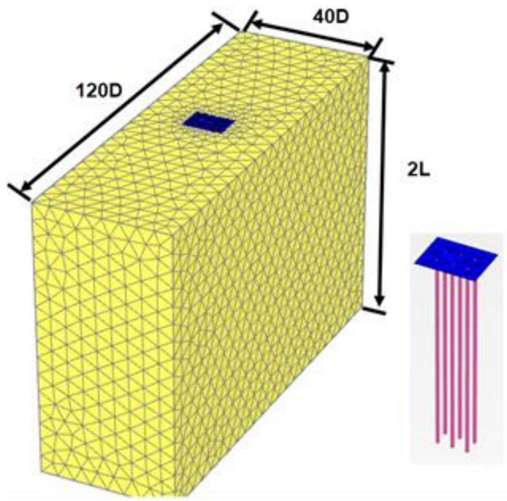

Figure 2. Geometry of finite element model of 6 pile group in case of level ground and adjacent slope

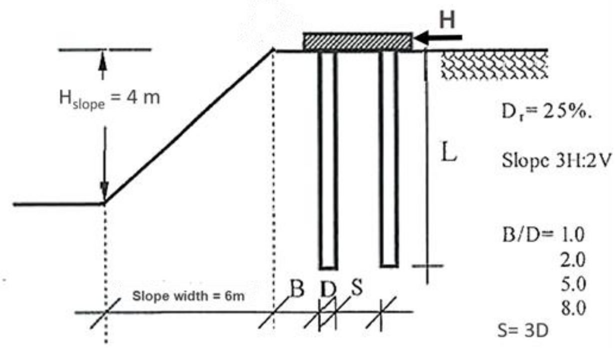

Figure 3. Model setup in case of 3H:2V slope

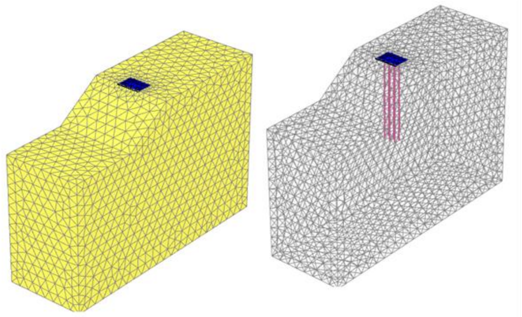

Figure 4. Geometry of numerical model of pile group of 6 in case of slope

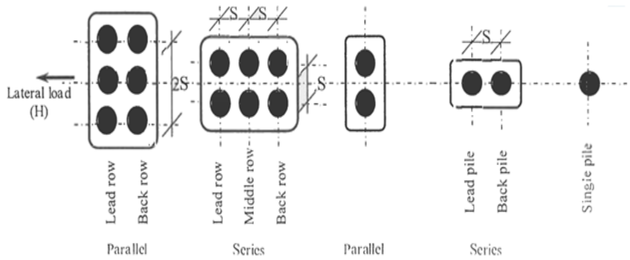

Figure 5. Pile group arrangement after [5]

In case of adjacent slope, the model setup is illustrated in Figure 3 The pile groups were tested Adjacent to a slope 3H:2V. The slope crest distance (B) from piles was variable from one time the pile diameter up to 8 times the pile diameter. The slenderness ratio of piles was chosen to equal 40 times the pile diameter L/D = 40 which represent long piles. Figure 4 shows the geometry of finite element model of 6 pile group in case of adjacent slope.

Pile caps were loaded horizontally by applying a lateral force. As shown in figure 5, tests were carried out on a single pile, a group of two fixed head heaps formed in parallel and series configuration, and another group of six fixed head heaps were arranged in and series and parallel configuration. Three pile spacing used was S=3D or 3 times the pile diameter.

According to the USCS classification system, the soil utilized in all of the present testing was clean sand, which is classed as uniform graded sand. The loose sand had relative density Dr= 25%. The soil behavior was modeled based on the Mohr Coulomb model which is used in much previous research and is adequate to model the problem. This model consists of five input parameters, i.e., Elastic modulus (E) and Poisson's ratio (v_s) for soil elasticity, cohesion (c), friction angle (φ) and dilatancy angle (ψ). Piles were odelled as embedded beam elements. Pile heads are modelled using rigid plate element. To simulate the interaction between piles, pile caps and soil interface elements were applied. The interface element's decreased strength is indicated by a strength reduction factor R_{inter} equal to 0.8. The finite element study parameters are presented in the Table 1.

Analysis consists of three stages: initial stage, pile and plate construction and loading. Firstly, at initial stage all piles, plate and interfaces are inactivated. At second stage all piles, plate and interfaces are activated. Finally, at loading stage lateral load was applied using point load.

Table 1. Material properties of soil, pile and pile heads used in Plaxis software

Parameter	Name	Loose Sand (Dr=25%)	pile	Pile heads	Unit
Unit weight	γ	18	25	25	kN/m^3
Young's modulus	E	10000	$3*10^7$	$3*10^7$	kN/m^2
Angle of internal friction	ϕ	30°	-----	-----	degree
Dilatency Angle	Ψ	0°	------	-----	degree
Cohesion	C	0	-----	-----	kN/m^2
Poisson's ratio	υ	0.3	0.1	0.1	------
Length	L	-----	10	----	m
Diameter	D	-----	25	----	cm

B. Numerical model Verification

In order to verify the numerical software output results accuracy a comparison was conducted between the experimental model results obtained by (Sakr, Moheb & M.A. Nasr, Ahmed. 2010) [5] and the results obtained by current numerical analysis plaxis software before starting the analysis on full scale piles. To simulate the reality the numerical model dimensions were selected to be 1m length, 0.5m width and depth of 0.7m which are the same as experimental model conducted shown in figure 6. Figure 7 shows the verification model setup in case of pile groups of six in parallel arrangement at slope crest.

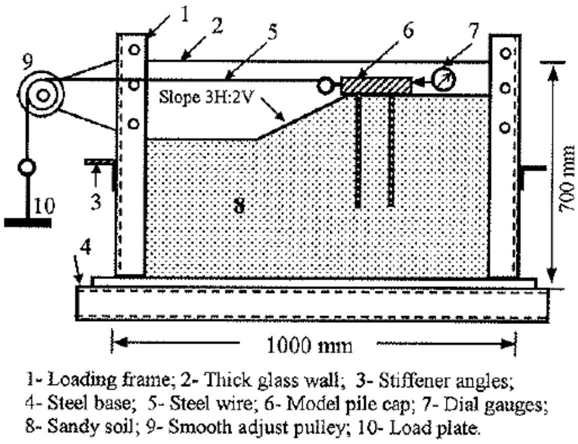

Figure 6. Experimental model setup by (Sakr, Moheb & M.A. Nasr, Ahmed. 2010) [5]

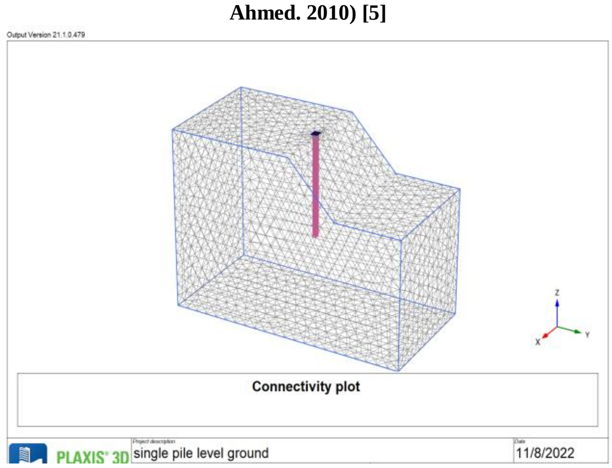

Figure 7 Verification model setup

Figure 8 shows the load-displacement relationship in case of single fixed pile in level ground for both experimental model and current numerical model. Table 2 illustrates the comparison between numerical results and previous experimental work results. From figure 8 and table 2 it was observed a good agreement between numerical analysis results and previous experimental model result where the values of ultimate horizontal capacity of obtained using numerical analysis in case of single piles and pile groups in level ground and at slope crest are close to values obtained previously using an experimental model.

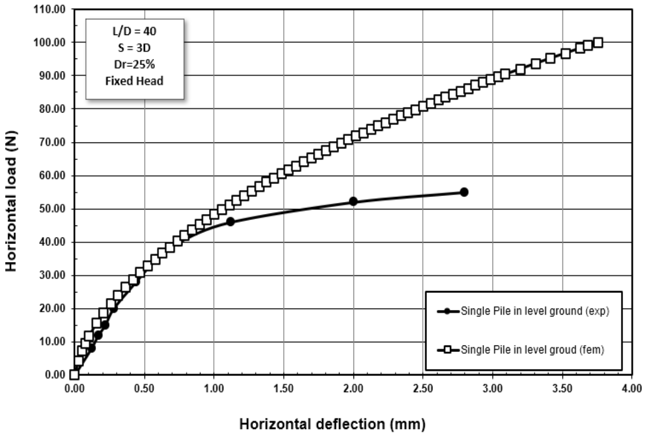

Figure 8. Comparison between experimental model and numerical analysis results for single fixed head pile in level ground

Table 2. Comparison between ultimate lateral load for piles and six pile groups obtained from finite element method versus experimental results by [5] (L/D=40) and (Dr=25%)

Case	Single Fixed piles (N)		Pile Groups in series config. (N)		Pile Groups in parallel config. (N)	
	Exp.	FEM	Exp.	FEM	Exp	FEM
Level ground	45	48	205	200	218	207
Slope crest	36	38	175	143	125	123

From above it was concluded that Plaxis3d software is capable of predicting the behavior of lateral loaded individual piles and pile groups in level ground and in case of sloped ground.

III. RESULTS AND DISCUSSION

A. In case of level ground

In this study, the results obtained from the numerical investigation for full scale single pile and fixed head pile groups with slenderness ratio (L/D) equal to 40 are presented. Figure 9 shows output of plaxis3d software in case of 6 pile groups in parallel arrangement on level ground. Figure 10 shows the output of plaxis3d software for 6 piles groups in case of sloped ground.

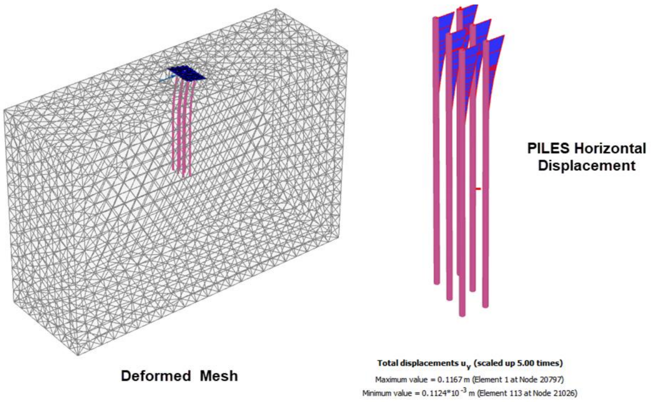

Figure 9. Output of Plaxis 3D indicating horizontal displacements in case of 6 piles group

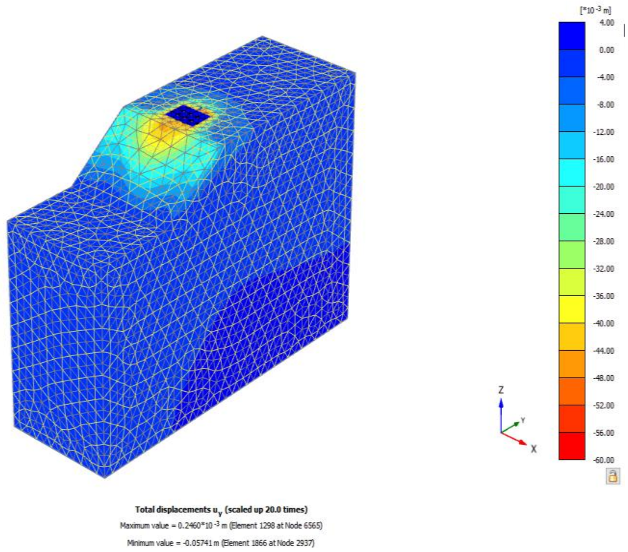

Figure 10a. Output of Plaxis 3D indicating horizontal displacements of piles in case of 6 piles group

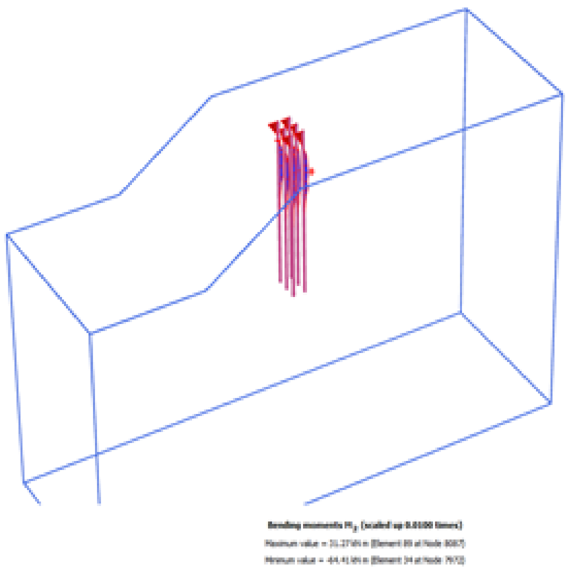

Figure 10b. Output of Plaxis 3D indicating bending moments of piles in case of 6 piles group

Vol. 6 – No. 5, 2022 Journal of Engineering Research (ERJ)

The behavior of a single pile as well as pile groups stacked in series and parallel is assessed and contrasted. Figure 11 and 12 show a comparison of the load-deflection behavior of piles organized in series and parallel for L/D=40 in two and six pile groups, respectively. There were comparisons done for the normal spacing ratio (S/D = 3).

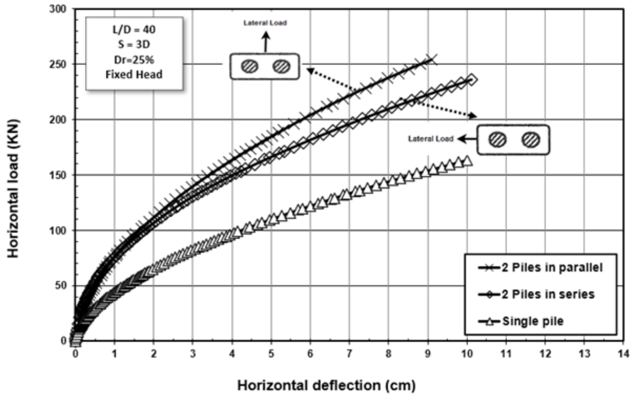

Figure 11. Load- horizontal displacement curves for single pile and 2 pile groups

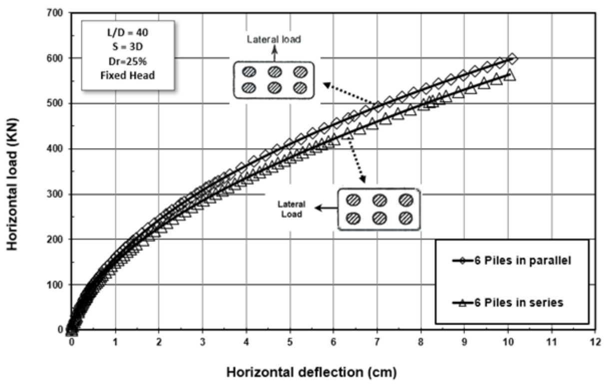

Figure 12. Load- horizontal displacement curves for 6 pile groups

According to Figures 11 and 12, at all load levels, piles organized in parallel setup deflect less than piles arranged in series for 2 pile and 6 pile groups. This is because in case of series arrangement with the increase of piles number in a row, overlapping of shear zones between neighbouring piles occurs, which leads to weakness in soil causing greater deflections. It is clear that the behaviour of piles in series arrangement is influenced by shadowing effect while for piles in parallel arrangement overlapping of stress zones (edge effect) occurs. The edge effect is always less than shadowing effect as shown in figure 13. Based on the predicted lateral abilities at lateral deflection (0.1D), the percentage improvement in capacity is about 6% and 9.4% from series to parallel arrangement for two and six pile groups respectively.

B. In case of adjacent slope

Pile groups behavior was studied in case of sloped ground (3H:2V) to determine the effect of slope on lateral deflection and ultimate lateral capacity of (2x2), (2x3) pile groups in series and parallel arrangement. Pile groups were tested at different distances from slope crest B/D = 1, 2, 5 and 8. It was noted that the lateral capacity of all pile groups increased with the increase of B/D ratio.

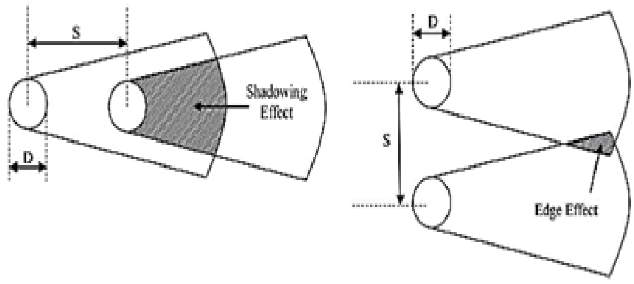

Figure 13. Edge and shadow effect for group of piles arranged in series and parallel according to [10]

As shown in figure 14 it was concluded that the slope effect on the lateral capacity of pile groups in series arrangement was neglected when the pile groups are at distance more than or equal to 5 times the pile diameter B/D=5 from slope crest for 2 and 6 pile groups. For pile groups in parallel arrangement, it was found that the slope effect extends to a distance of 8 times the pile diameter B/D = 8 where, after that the pile group acts as on level ground.

From previous results it is clear that the slope effect is more pronounced in case of using parallel configuration than the case of series configuration at lower edge distances from slope crest. This may be due the reduction of passive resistance of piles near slope crest in case of parallel configuration. But in case of series configuration only rear piles are close to slope crest while the front piles have additional space to develop passive resistance. But when series pile groups are located at greater edge distance of slope crest the slope effect was neglected and the pile group acts like on level ground where shadowing effect is present.

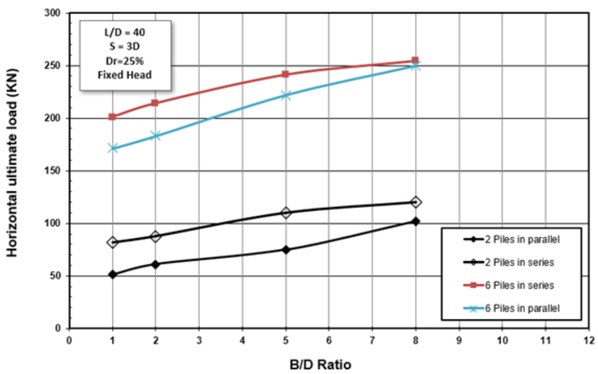

Figure 14. B/D ratio Versus Horizontal ultimate load for 2 and 6 pile groups in series and parallel arrangement

C. Efficiency of laterally loaded pile groups

Horizontal capacity of the pile groups is always different from the product of a single pile horizontal capacity multiplied by piles number in a group. For this reason, a reduction factor called Pile Group efficiency. The pile group efficiency is calculated using the following formula:

$$\text{Horizontal group efficiency} = Q_g / (n \times Q_s) \quad (1)$$

Where, Q_g = ultimate horizontal capacity of pile group;

Q_s = ultimate horizontal capacity of single pile; and n = piles number in a group.

Assuming that ultimate horizontal capacity for single pile is obtained at lateral deflection equal to (0.1D) and by calculating the load of a group at this deflection, the group lateral capacity efficiency is obtained using eq. (1) and shown in table 3. A comparison is made between the efficiencies obtained from the current numerical model and the published results of (Poulos, H.G.,1971) [11] and (Pise, P.J.,1983) [12] for two-pile group in parallel and series arrangement.

Also, current work is compared by findings obtained by (Amer Alkloub. et. al. 2018) [13] and recommendation of bridge design manual (BDM) of Department of Transportation of Washington State [14] which recommend a reduction factor of a group equal to 0.5 for groups with spacing S=3D in direction of lateral loading. A good agreement between obtained by comparing the present work and the predictions of Poulos, Pise and Alkloub et. al..

Table 3 Group efficiencies under lateral loading (L/D=40) in case of level ground of present versus previous work

Group Configuration	Efficiency (Previous work)			Efficiency (P.w)
	Pise	Poulos	Alkloub	
2- Piles series	0.66	0.71	0.81	0.81
2- Piles parallel	0.91	0.81	----	0.85
6- Piles series	------	------	0.57	0.57
6-Piles parallel	------	------	-----	0.63

IV. CONCLUSIONS AND RECOMMENDATIONS

By studying the results of numerical model performed, the conclusions obtained are as following:

1. Lateral capacity of a single pile in a group is always smaller than the lateral capacity of single pile, therefore, pile group effect is significant.
2. In case of level ground pile groups have bigger lateral resistance when grouped in parallel than when formed in series, whereas in case of pile groups constructed near slopes the oppose is true. This confirms the results obtained by [5] where similar findings obtained.
3. In case of level ground, the group efficiency obtained at a deflection of (0.1 D) for fixed head pile group, varies from 81% to 85% for two pile group and from 57% to 63% for six pile group.
4. The behavior of pile group constructed near slopes depends on the distance between slope crest and lead row of pile group (B/D), arrangement configuration of piles in pile group.
5. The influence of slope on horizontal capacity of groups arranged in series was found to be disregarded when the pile groups are at distance more than or equal to 5 times pile diameter or B/D=5 from slope crest.
6. In case of pile groups in parallel arrangement, it was found that the slope effect extends to a distance of at least 8 times the pile diameter B/D=8. Therefore, it is recommended to use pile group of series configuration arrangement near slope crest to minimize the slope effect on lateral deflection and capacity of pile groups.
7. It is possible to compare the findings of this study to those of full-scale field trials. Also, other parameters affecting the behavior of lateral loaded pile groups such as piles spacing

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