Journal of Civil Engineering and Architecture 20 (2026) 340-346
doi: 10.17265/1934-7359/2026.08.003

Numerical Simulation of Laterally Loaded Pile Groups Adjacent to a Slope

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Abstract: This paper is a numerical study based on a number of numerical model tests of pile groups, subjected to static lateral loading. Tests were conducted on single, (2x1), and (2x3) pile groups at 3D (three-diameter) spacing. The model piles studied are concrete piles with 25 cm diameter and 10 m length founded in loose sand (Dr = 25%). The model is developed to study the effect of the number of piles in group on its lateral capacity on level ground and adjacent to a slope of inclination (3H:2V). The behavior of the piles was analyzed using a 3-D elasto-plastic FEM (finite element method) computer program Plaxis 3D ver. 2020, which represents a realistic model to simulate the problem. The response of the piles in the group was compared with the response of the single pile. It was found that the behavior of laterally loaded pile group depends largely on the arrangement of piles in group with respect to direction of load. In case of a slope it was found that the behavior of pile groups depends on the distance of lead row of pile groups from the slope crest (B/D) and arrangement of piles in group corresponding to load direction.

Key words: Pile groups, lateral load, sand, slope, numerical model, finite element method, Plaxis 3D 2020.

1. Introduction

In practical situations piles are subjected not only to compression and tension loads but also to lateral loads induced by wind, earthquakes loading and lateral earth loading on retaining structures. Therefore, determination of the lateral capacity of pile foundation is one of the most important factors in foundation engineering design. The majority of previous work done on the problem of laterally loaded piles was directed towards the response of individual piles subjected to lateral loads. However, piles are often used in groups. A large number of experiments have been previously conducted on model pile groups subjected to lateral. The following summarize previous work done:

Broms [1] conducted experimental model tests on a large scale group of (3x3) free head steel piles placed at three diameters, center to center, and an isolated single pile all subjected to two-way cyclic lateral loading. The tests were conducted in submerged firm to dense sand that was placed and compacted around the piles. All of the piles were extensively instrumented so that the variation in soil resistance within the group could be determined. The response of the piles in the group was compared with the response of the single pile.

Mcvay et al. [2] carried out centrifuge tests on single and (3x3) free head pile groups at three diameter and five diameter spacing. The piles were founded in medium sand (D = 33%) and dense sand (Dr = 55%). Results of the tests showed that the ratio of lateral resistance of a group to a single pile, i.e., efficiency was independent on the soil density. The group efficiency at 3D (three-diameter) was 0.74 where at 5D, the group efficiency was 0.94.

Rollins et al. [3] carried out a full-scale lateral load test on (3x3) pile group at three diameters spacing into a profile consisting of soft to medium stiff clay and silts underlain by sand. The piles were instrumented with in clinometers and strain gages. A single pile test was conducted for comparison. The pile group deflected over

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two times more than the single pile under the same average load. Group effects significantly reduced load capacity for all rows relative to single pile behaviour. Trailing rows carried less than the leading row, and the middle row piles carried the lowest loads. From the above papers, studies of pile groups under lateral load near ground slopes are either absent or very scarce.

According to Narasimba et al. [4], the influence of parameters like flexural rigidity of pile material, embedment length of pile, and arrangement of piles with respect to the direction of loading on the behaviour of laterally loaded pile groups has been studied through an experimental program. The results obtained from lateral load tests carried out on model pile groups arranged at different spacing and embedded in a marine clayey bed are presented and discussed. The results indicate that the lateral load capacity of the pile group depends mainly on the rigidity of pile soil system for different arrangements of piles within a group. This is further substantiated by a simplified finite element analysis bringing in the differences in passive resistance. The group efficiencies under lateral loading obtained from the present investigation are found to be in good agreement with the predictions of earlier researches.

Elhakim [5] conducted three dimensional numerical modelling of lateral loaded pile groups in sand. He studied the effect of sand relative density, pile spacing (s = 2.5 D, 5 D and 8 D) and pile location within the group for groups of (2x2 and 3x3 pile configurations). It was concluded that piles installed in groups at close spacings deflect more than a single pile subjected to the same lateral load per pile because of group effect, also the for pile groups with fixed head, the front row in the group carries the highest load, middle and back row piles carry smaller loads for a given displacement. It was observed that the shadowing effect diminishes at a greater rate in dense sand compared to loose sand.

Gouw [6] studied numerically the behavior of lateral loaded pile groups of configuration 3x3, 5x5 and 9x9. The numerical analysis was carried out by employing PLAXIS 3D geotechnical finite element software. Pile spacing is varied from 3D, 4D, 5D, 6D, 8D to 10D (D = pile diameter). He found that the center to center spacing of piles have significant effect on the group pile lateral efficiency where the lateral group efficiency increases with the pile spacing up to a maximum group efficiency value of one at pile spacing of around 10 pile diameters. Also, the number of piles in a group influenced the group pile lateral efficiency where the greater the number of piles in a group the smaller the lateral group efficiency.

2. Numerical Model Description

Plaxis 3D ver. 2020 software was used to simulate the behaviour of single pile and pile groups to lateral loading. This three dimensional numerical analysis software was developed for the analysis of three dimensional foundation and geotechnical problems. It is part of the Plaxis suite finite element oftware used worldwide for geotechnical engineering design. Fig. 1 shows the numerical model setup in case of level ground. The overall dimensions of the model boundaries was taken as following: length equal 120 times the pile diameter, width equal to 40 times pile diameter and height equal to two times the pile length (L). These dimensions were considered adequate to eliminate the influence of boundary effects on performance of the piles. The outer boundary of the mesh is fixed against displacements. To eliminate the effect of soil passive resistance acting on the pile cap, the pile cap is placed on the ground surface. 15-node wedge elements are uded to model the soil.

2.1 In Case of Adjacent Slope

In case of adjacent slope the model setup is shown in Fig. 2. The pile groups were tested.

Adjacent to a slope 3H:2V. The slope crest distance (B) from piles was variable from one times 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 represents long piles. Fig. 3 shows the geometry of finite element model of 6 pile group in case of adjacent slope.

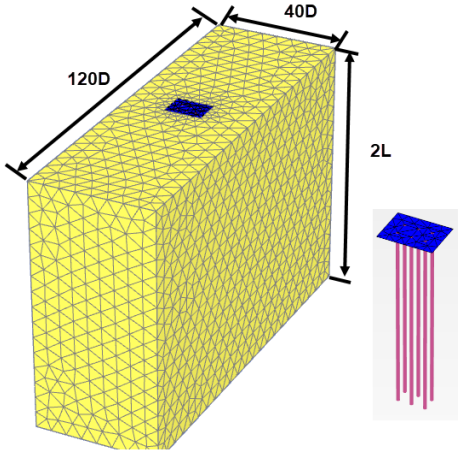

Fig. 1 Geometry of finite element model of 6 pile group in case of level ground.

Lateral load is applied at the side the of the pile cap.

Tests were performed on single pile, 2 fixed head piles group in series and parallel arrangement and 6 fixed head piles group in series and parallel arrangement as shown in Fig. 4. The piles spacing equal to 3 times pile diameter S = 3D.

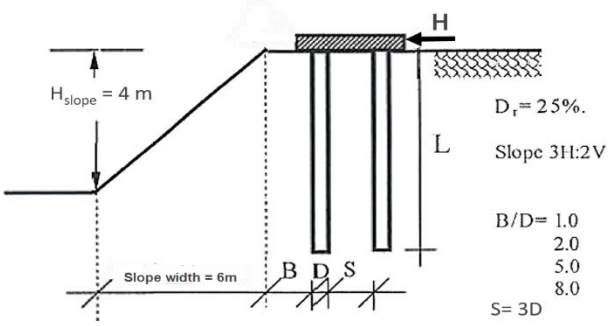

Fig. 2 Model setup in case of 3H:2V slope.

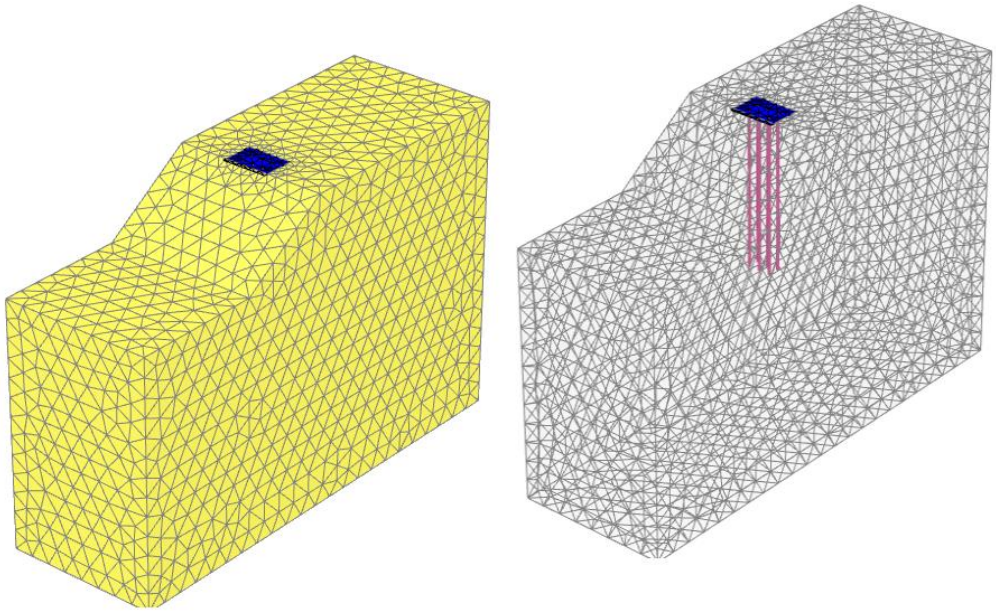

Fig. 3 Geometry of finite element model of 6 pile group in case of slope.

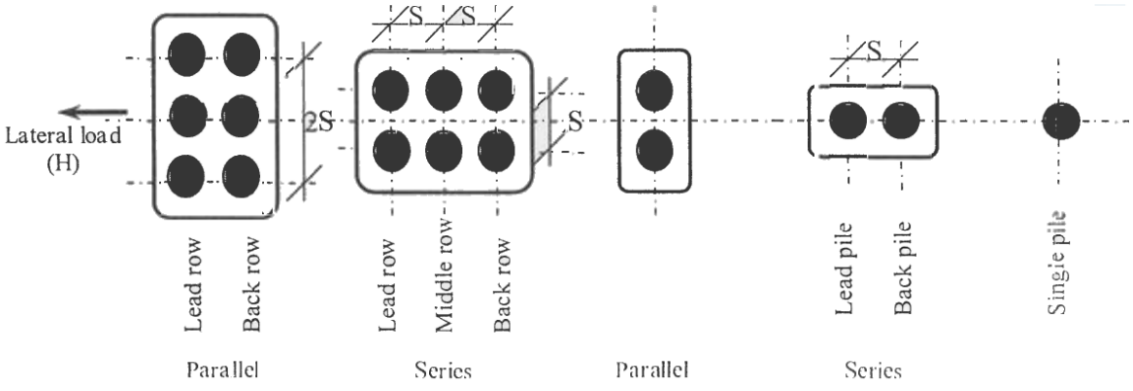

Fig. 4 Pile group arrangement.

Table 1 Properties of soil, pile and pile heads used in the computer program.

Parameter	Name	Loose sand (Dr = 25%)	Pile	Pile heads	Unit
Unit weight	γ	18	25	25	kN/m^3
Young's modulus	E	10,000	$3*10^7$	$3*10^7$	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	------

The soil used in this study for all of the tests is clean sand, classified as poorly graded sand according to the unified soil classification system. The loose sand had relative density Dr = 25%. The soil behavior was modeled based on the Mohr Coulomb model which involves five input parameters, i.e. Elastic modulus (E) and Poisson's ratio (v_s) for soil elasticity, friction angle (φ) and cohesion (c) and dilatancy angle (ψ). The piles were modelled 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 decrease of strength for the interface element is represented by a strength reduction factor $R_{inter} = 0.8$. The parameters used in finite element study are given in Table 1.

3. Results and Discussion

3.1 In Case of Level Ground

In this study, the results obtained from the numerical investigation for single pile and fixed head pile groups with slenderness ratio (L/D) equal to 40 are presented. Fig. 5 shows output of Plaxis 3D software in case of 6 pile groups in parallel arrangement.

The behavior of single pile and pile groups in series and parallel arrangement are compared. Figs. 6 and 7 show comparisons of the load deflection behavior for piles in series and parallel arrangement for L/D = 40 for 2 and 6 pile groups. Comparisons were made for typical spacing ratio (S/D = 3).

From Figs. 6-7, it can be observed that the piles in parallel arrangement deflect less than piles in series at all load levels for 2 pile groups and 6 pile groups. This is due to the overlapping of the shear zones among the neighboring piles resulting in more deflections. Based on the lateral capacities estimated at lateral deflection (0.1 D), the percentage improvement in capacity is about 6% and 9.4% from series to parallel arrangement for two and six pile groups respectively.

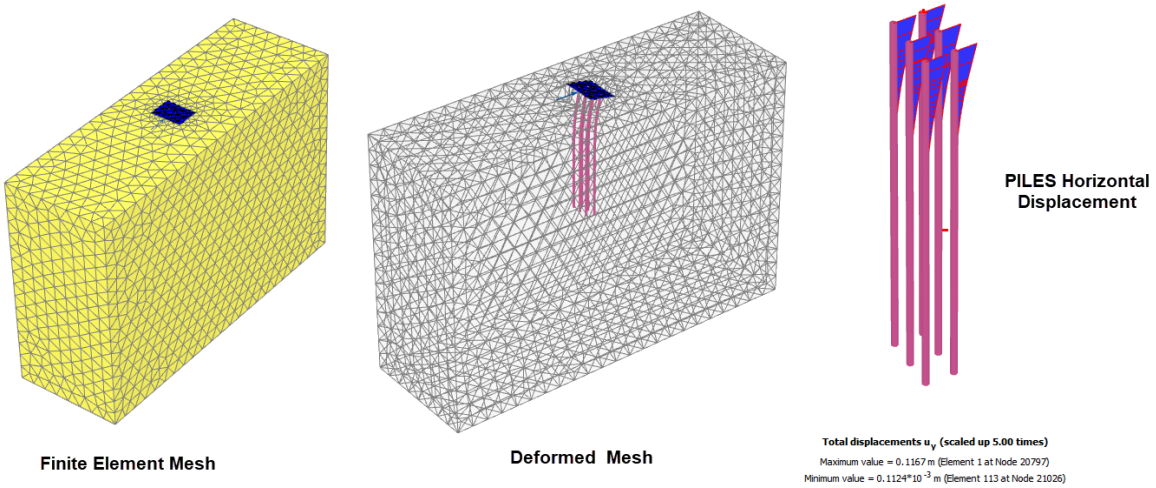

Fig. 5 Output of Plaxis 3D indicating horizontal displacements in case of 6 piles group.

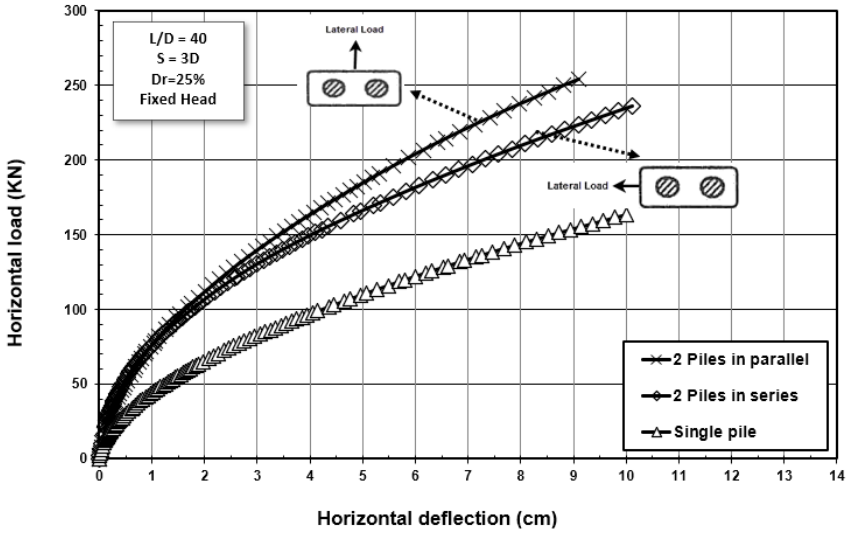

Fig. 6 Load- horizontal deflection curves for single pile and 2 pile groups.

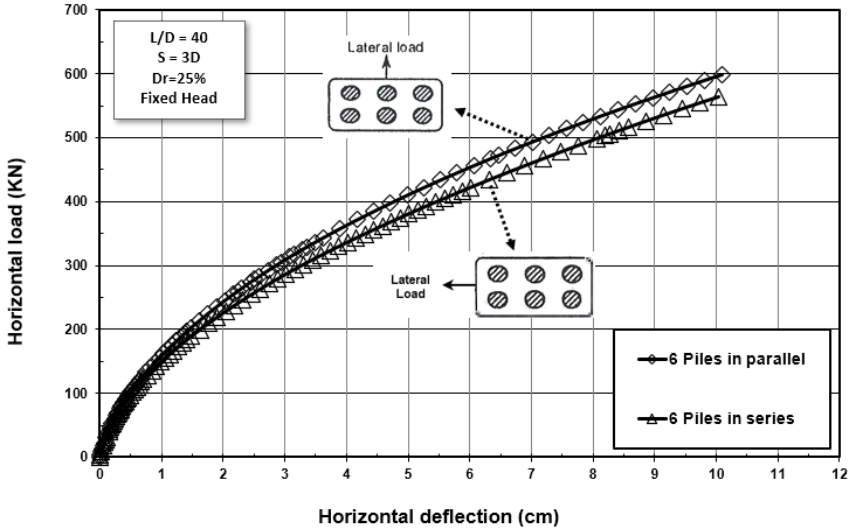

Fig. 7 Load- horizontal deflection curves for 6 pile groups.

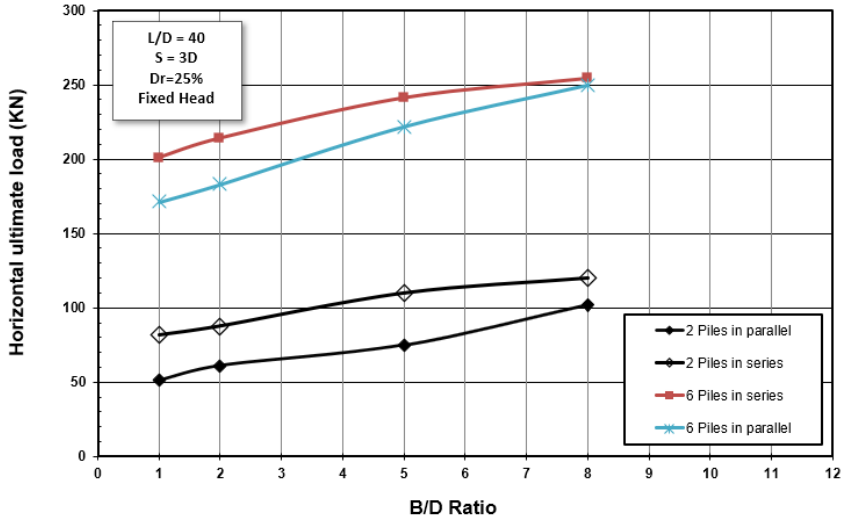

Fig. 8 Relationship between B/D ratio and horizontal ultimate load for 2 and 6 pile groups in series and parallel arrangement.

Table 2 Group efficiencies under lateral loading (L/D = 40) in case of level ground.

Group configuration	2-pile series			2-pile parallel			6-pile (P.W.)	
	P.W.	Pise	Poulos	P.W.	Pise	Poulos	Series	Parallel
Efficiency	0.81	0.66	0.71	0.85	0.91	0.81	0.57	0.63

3.2 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 observed that the lateral capacity of all pile groups increases with the increase of B/D ratio.

As shown in Fig. 8 it was noted that the effect of slope 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.

4. Pile Groups Efficiency under Lateral Loading

The lateral capacity of the pile groups is always different from the product of single pile lateral capacity and the number of piles in the group. For this reason, the reduction factor called Pile Group efficiency. The pile group efficiency is estimated using the formula:

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

where Q_g = ultimate lateral capacity of pile group; Q_s = ultimate lateral capacity of single pile; and n = number of piles in the group.

Assuming that the ultimate lateral capacity for single pile is obtained at lateral deflection equal to (0.1 D) 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 2. A comparison is made between the efficiencies obtained from the current numerical model and the published results of Poulos [7] and Pise [8] for two-pile group in series and parallel arrangement. A good agreement between obtained by comparing the present work and the predictions of Poulos and Pise.

5. Conclusions

Based on the results of numerical model performed on pile groups, the following conclusions are obtained:

- The lateral capacity of single pile in pile groups is smaller than the lateral capacity of single pile; therefore, the pile group effect is significant.
- In case of level ground pile groups are more resistant to lateral loads when they are arranged in parallel configuration than in series configuration, whereas in case of pile groups constructed near slopes the oppose is true.
- 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.
- 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.
- It was found that the effect of slope 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 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 effect of slope on lateral deflection and capacity of pile groups.

6. Directions for Future Research

A comparison of this research results with those of

field full scale tests may be investigated.

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