Comparison of *p-y* Curves of Pile Group in Parallel Arrangement near Sloping Ground

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Abstract. The behavior of laterally loaded pile group founded in a sandy soil profile has been investigated. Numbers of studies are available in literature to predict behavior of piles subjected to lateral load located in the horizontal ground. However, the effect of nearby slope on pile response is not thoroughly investigated yet. Assessment of pile response encountering sloping ground is still a challenging task. For this purpose, a series of experimental investigations were performed to examine the behavior of pile group (two piles in parallel) near sloping ground (n = slope). Series of tests in medium sandy soils considering ground slope (n = 1.5) and four edge distances from the slope crest have been performed. Similarly, pile group response for horizontal ground condition is also obtained to compare the result with sloping ground. Displacements and bending moments are significantly increased for pile group near slopes. As the edge distance increases, the pile response approaches to that of level ground case. From the measured bending moments, the *p-y* curves have been established for pile group near slope.

Keywords: Pile group, edge distance, ultimate load capacity, *p-y* curve.

1 Introduction

There are many locations in hilly regions where sometimes buildings or other super structures have to be provided near slope and when there is significant amount of horizontal forces acting on it. Also, the major other causes of development of the lateral forces are earthquake, wind and waves. Movement of motor vehicle and wind gusts are the main causes of the horizontal force generation in the bridge abutments and piers (Fig. 1). Water pressure transfers the horizontal forces on the supporting piles in the dam structure. In all these cases the reason of major failure is the development of the lateral forces, those acts in the supporting structures. When the large lateral loads are to be transferred from super-structures to foundation soil, pile groups are preferred. If shallow foundation is provided in such case, load on footing will act as surcharge. In sloping ground, slope stability is of more concern. Stability of slope is a function of geometrical properties of slope and material properties of soil.

Though many methods are suggested in past to assess slope stability, monitoring of slope with appropriate instrumentation is most reliable technique. Literature review had revealed that response of pile groups located near slope has not been explored in detail. Very few numerical studies have been published on behaviour of single pile and pile group near slope [1,5, 6]. Khati and Sawant [7, 8] reported experimental studies on response of pile and pile groups near slope. Behaviour of pile groups in parallel arrangement near sloping ground has not been explored yet. The present experimental work is directed to study the behaviour of pile groups located near slope.

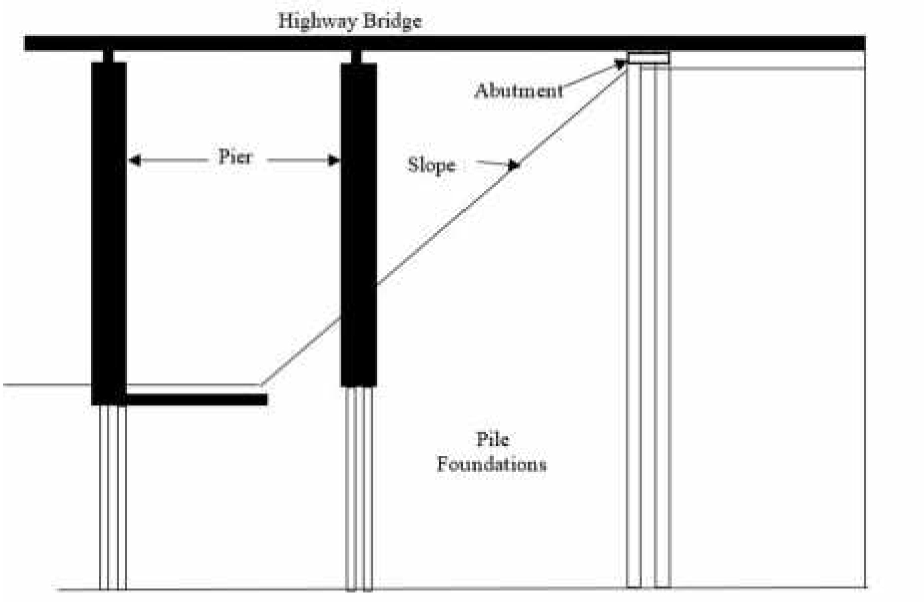

Fig. 1. Pile foundations provides near highway Bridge.

2 Methodology

The experimental investigation is executed in different stages. It started with determination of pile and soil physical properties as summarized in Table 1. Simultaneously development of experimental setup was planned. Aluminium piles of diameter D = 25 mm were used in the current study. Lengths were considered with length to diameter ratio L/D = 30. The flexural rigidity of the pile was experimentally determined by measuring flexural strains in simple beam bending test. From the ratio of calculated bending moment M and flexural strain ε, the flexural rigidity was calculated as $EI = (M/\varepsilon) \times (0.5D) = 310\times10^6$ N-mm^2. Material properties of pile are reported in Table 2. The values of coefficient of horizontal subgrade reaction (η_h) are selected from Matlock and Reese [2]. Poulos and Davis [3] identified pile flexibility factor $k_R = EI / (\eta_h L^5)$ as non-dimensional parameter useful in comparison of pile response. It is assumed that model test results for a specified k_R in the laboratory can be extrapolated to field case having the same value of k_R. Matlock and Reese [2] defined a pile to be a long flexible pile if L/T ratio is greater than 4. In which, T is the relative stiffness of pile defined as $T = \sqrt[5]{EI/\eta_h}$. The values of η_h, k_R, T and L/T ratio are reported in Table 2.

Table 1. Physical properties of sand.

Parameters	Values
Specific gravity of soil solids, G_s	2.60
Effective diameter, D_{10} (mm)	0.11
Coefficient of uniformity, C_u	2.73
Coefficient of curvature, C_c	1.60
Angle of internal friction (ϕ)	37.5°
Minimum density, ρ_{min} (g/cm^3)	1.40
Maximum density, ρ_{max} (g/cm^3)	1.59
Maximum void ratio, e_{max}	0.86
Minimum void ratio, e_{min}	0.64
Natural void ratio, e_{nat}	0.75

Table 2. Relative pile stiffness parameter.

η_h (Soil) MN/m^3	T (mm)	L (mm)	L/T	Pile flexibility factor (k_R)	Remarks
6	138.88	750	5.40	0.000217188	Long pile

A tank of dimensions 2.50 m×1.22 m×1.12 m was used in the study which was open from one side at the laboratory. The strain gauges (electric resistance) were used for measurement of flexural strains in the pile. Six strain gauges were fixed at six different locations along the length of the pile (L/8, 2L/8, 3L/8, 4L/8, 5L/8 and 6L/8). In a parallel group configuration both piles were instrumented to measure bending moment. From measured strains (£), bending moments were computed as $M_b = \pounds \times EI/y$. LVDT was used to measure top displacement. Flexural strains and displacements are recorded using data acquisition system at each load increment. Both the pile was connected to pile cap. Cable connected to hanger at one end was passing over a pulley and it was connected to center of pile cap. The full experimental setup along with cable and pulley arrangement to apply lateral load on the embedded pile, LVDT, strain gauges and data acquisition system are shown in the Fig. 2. Achieving preferred density throughout the sand bed is very important in parametric study for comparison of pile response. For this purpose, sand raining technique was employed to achieve uniform density. Lateral load was applied on pile top by applying known downward weight on hanger. Pile top displacement was checked. Bending moments along the length of pile were calculated by measuring flexural strains at each load increment. After reaching a stable reading, the lateral load was incremented. Procedure was continued till the observed pile top displacement reached 5 mm. Respective load was considered as ultimate load for pile group parallel configuration. In the absence of exact criterion, the ultimate load is taken at the load corresponding to the displacement of 20% of the pile diameter [4], which is 5 mm in the present study.

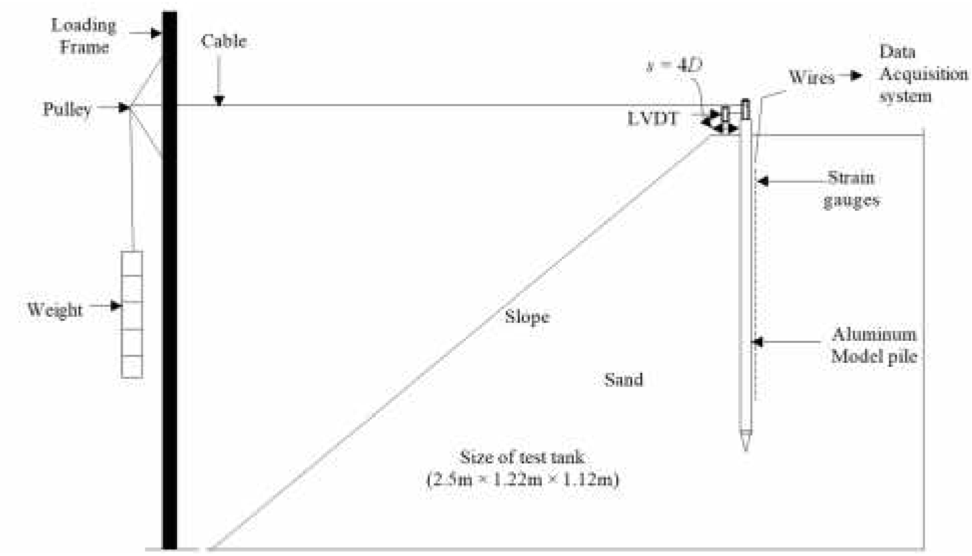

Fig. 2. Schematic representation of laboratory set up for sloping ground.

Relative density of 52% was considered to study their effect. To understand the effect of edge distance (*s*), four different positions of piles from the crest of the slope were considered. First row of piles was placed at four different locations from the crest of the slope (*s* = 0, 4*D*, 8*D*, 12*D*) to account for the effect of edge distance. To quantify the effect of slope geometry, tests were also performed in level ground condition at the corresponding relative density. In the study pile spacing was taken as 3*D*.

3 Results and Discussion

Pile groups in parallel arrangement embedded in level ground were tested first. So that pile response obtained for respective group configuration can be used as datum for normalizing pile response at sloping ground conditions. The lateral passive resistance offered by soil is considerably reduced for piles near slope as compared to piles in horizontal ground. For the pile located at crest, the passive soil resistance is least resulting larger displacement. However, as the edge distance increases, more soil passive resistance is available offering more stiffness. For two piles in parallel, effect of edge distances on load-displacement behaviour is highlighted in Fig. 3. With increase in the edge distance from crest slope, pile group transforms in to stiffer nature approaching towards level ground condition. Ultimate loads corresponding to 5 mm displacement are 50.48 N, 83.24 N, 93.84 N and 110.09 N for *s*/*D* ratio 0, 4, 8 and 12 respectively. It is to be noted that for level ground case ultimate load is 145 N. Increase in the ultimate load may be attributed to increase in the passive resistance offered by soil. For parallel arrangements ultimate loads are increasing with edge distance. For comparison of responses, the ultimate load ratio P_s is defined as the ultimate load in sloping ground case with reference to level ground case as $P_S = H_S^u / H_{Hor}^u$. In parallel arrangement, ultimate load ratio was observed to vary with edge distance from 0.35 to 0.76.

Maximum bending moments are summarized in Table 3. Comparison is made for constant load level (127 N) for pile groups and compare maximum bending moments in both piles for parallel arrangement. Maximum bending moments in both piles are not much different indicating equal load sharing. Maximum bending moment is increased by 62.64% in pile P_1 as compared to level ground case at s/D = 0. With increase in edge distance, this increase was observed to reduce. It was 14.58% at s/D = 12. It is clear that maximum bending moments were observed to decrease with edge distance.

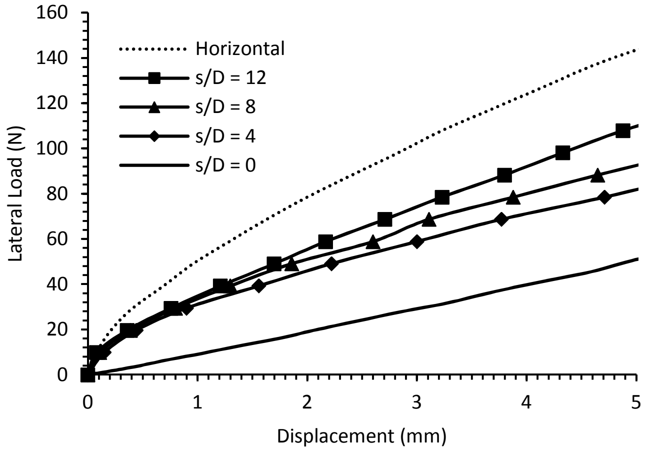

Fig. 3. Effect of edge distance for parallel pile.

Table 3. Comparison of maximum bending moments for parallel pile P_1 and P_2.

Pile	Maximum moment M_{max} (kN-mm)				
	Horizontal	s/D = 0	s/D = 4	s/D = 8	s/D = 12
P_1	8.44	13.73	11.89	11.65	9.68
P_2	8.60	13.33	12.74	10.78	9.22

From recorded strains, bending moments were computed for each load increment. Then statistical analysis was exercised on bending moment variation for a load level to fit a third degree polynomial function.

$$M = EI\frac{d^2y}{dz^2} = \sim_0 + \sim_1 z + \sim_2 z^2 + \sim_3 z^3 \tag{1}$$

At z = L, bending moment is equal to zero.

$$\sim_0 = -\left(\sim_1 L + \sim_2 L^2 + \sim_3 L^3\right) \tag{2}$$

From which,

$$M = EI\frac{d^2y}{dz^2} = \sim_1\left(z - L\right) + \sim_2\left(z^2 - L^2\right) + \sim_3\left(z^3 - L^3\right)$$

(3)

Constants $\sim_1$, $\sim_2$, $\sim_3$ are fitting parameters and determined with minimization of error. Integrating of Eq. (3) twice yields horizontal displacement y as:

$$EI\,y = \sim_0 \frac{z^2}{2} + \sim_1 \frac{z^3}{6} + \sim_2 \frac{z^4}{12} + \sim_3 \frac{z^5}{20} + c_1 z + c_2 \tag{4}$$

Differentiating Eq. (3) twice to get soil reaction p as,

$$p = \frac{d^2 M}{d z^2} = 2\sim_2 + 6\sim_3 z \tag{5}$$

This exercise was executed for each load increment. Clubbing data of evaluated soil reactions p and displacement y at each depth for all load levels p-y relationship for a particular depth can be plotted. A typical set of p-y relationships are represented in Fig. 4.

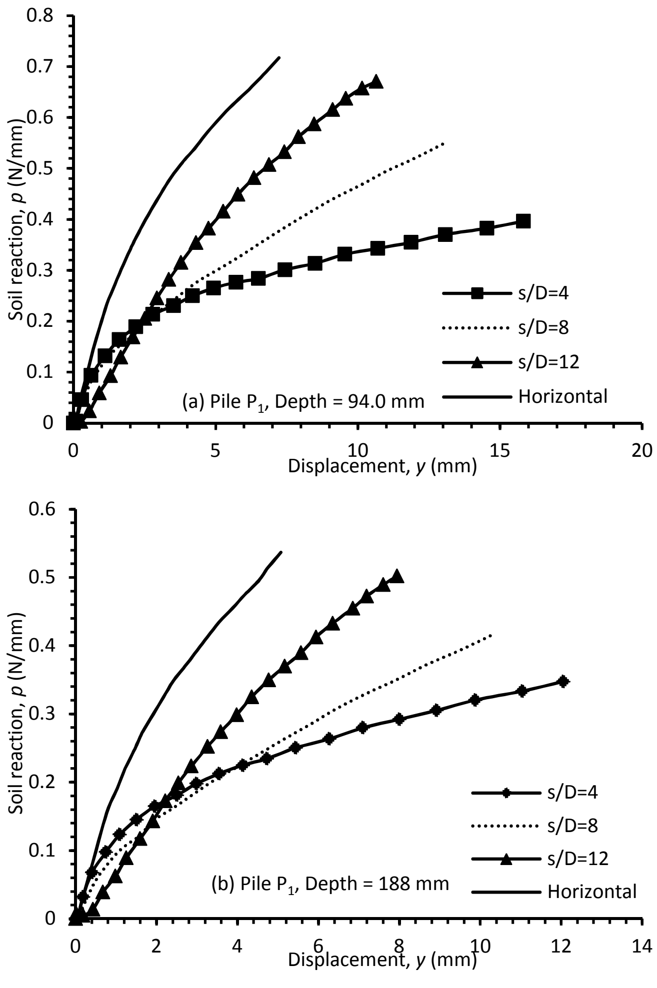

Fig. 4. Comparison of p-y relationship between horizontal and sloping ground.

From the comparisons, average value of constant *p*-multiplier $p_m = p^{slope} / p^{hor}$ are evaluated and reported in Tables 4. In general *p*-multiplier (p_m) is observed to increase with the edge distance.

Table 4. *p*-multiplier values at different depth.

Pile	Depth (mm)	s/D = 4	s/D = 8	s/D = 12
P_1	94	0.48	0.52	0.72
	188	0.45	0.50	0.75
	281	0.60	0.45	0.75
P_2	94	0.45	0.55	0.70
	188	0.45	0.57	0.65
	281	0.50	0.55	0.66

Initial slope k_{max} and ultimate soil resistance p_u for horizontal ground case are reported in Table 5. For horizontal ground case (depth = 94 mm), value of k_{max} is 0.239 and p_u is 1.184. In the mathematical form *p*-*y* relationship can be expressed using the initial slope k_{max} and the ultimate soil resistance p_u as follows:

$$p = \frac{k_{max} y}{1 + \frac{k_{max} y}{p_u}} \tag{6}$$

Table 5. k_{max} and p_u at different depths for horizontal ground condition.

Depth (mm)	k_{max} (N/mm/mm)	p_u (N/mm)
94	0.2390	1.1840
188	0.2315	0.9416
281	0.1767	0.8157

From comparison with level ground case, a general *p-y* relationship is suggested for sloping ground.

$$p = \frac{\tilde{k}\, k_{\max} y}{1 + \frac{\tilde{k}\, k_{\max} y}{\tilde{p}\, p_u}} \tag{7}$$

4 Conclusions

The study is intended to explore the response of pile group near sloping ground subjected to lateral load through experimental investigation. To quantify the effect of slope geometry, one test was also performed in level ground condition with piles in parallel. An attempt is made to suggest *p-y* relationship and *p*-multiplier for pile group to demonstrate the effect of sloping ground. From the present study, following key observations can be drawn:

1. With increase in the edge distance from crest slope, pile group transforms in to stiffer nature approaching towards level ground condition. Ultimate load capacity ratio is 0.348, 0.574, 0.647 and 0.759 for s/D ratio 0, 4, 8 and 12 respectively.
2. Maximum bending moment is increased by 62.64% in pile P_1 as compared to level ground case at $s/D = 0$. With increase in edge distance, this increase was observed to reduce. It was 14.58% at $s/D = 12$. It is clear that maximum bending moments were observed to decrease with edge distance.
3. In general *p*-multiplier (p_m) observed to increase with the edge distance. In parallel arrangement at depth 281 mm, value of p_m was increasing from 0.60 at $s/D = 4$ to 0.75 at $s/D = 12$.
4. A hyperbolic *p-y* relationship is suggested for analysis of the experimental values of bending moments.

References

1. Chae, K.S., Ugai, K. and Wakai, A.: Lateral resistance of short single piles and pile groups located near slopes. International Journal of Geomechanics, ASCE, 4(2), 93-103 (2004).
2. Matlock, H. and Reese, L.C.: Generalized solutions for laterally loaded piles. Transactions of the American Society of Civil Engineers, ASCE, 127(1), 1220-1247 (1962).
3. Poulos, H.G., Davis, E.H.: Pile Foundation Analysis and Design. John Wiley & Sons, New York (1980).
4. Rao, S.N., Ramakrishna, V.G.S.T. and M. R. Babu.: Influence of rigidity on laterally loaded pile groups in marine clay. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 124(6), 542-549 (1998).

5. Rathod, D., Muthukkumaran, K. and Sitharam, T.G.: Analysis of laterally loaded group of piles located on sloping ground. International Journal of Geotechnical Engineering (2018). doi: 10.1080/19386362.2018.1448521
6. Chandaluri, V.K. and Sawant, V.A.: Influence of sloping ground on lateral load capacity of single piles in clayey soil. International Journal of Geotechnical Engineering (2018). doi:10.1080/19386362.2017.1419538
7. Khati, B. S. and Sawant, V. A.: Variation in lateral load capacity of pile embedded near slope with ground inclination and edge distance. International Journal of Geotechnical Engineering (2018). doi: 10.1080/19386362.2018.1541149
8. Khati, B. S. and Sawant, V. A.: Comparison of lateral response of pile group in series and parallel arrangement near sloping ground. International Journal of Geotechnical Engineering (2019). doi: 10.1080/19386362.2019.1617478