Journal of Civil Engineering (IEB), 41 (1) (2013) 31-40

Journal of Civil Engineering IEB

Investigation of pile- soil interaction subjected to lateral loads in layered sandy soils

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Received 29 July 2012

Abstract

To stabilize infrastructures such as tall buildings, bridges, etc., piles are used to resist lateral loads created from earth pressure, wind, waves and earthquake extensively. Pile properties, soil stress-strain behavior and pile-soil interaction play important role in pile-response subjected to lateral loads. A study was carried out to investigate the effects of above–mentioned parameters on pile-soil behavior subjected to lateral forces. The experiments were carried out with varying size and spacing of piles for variable embedded length of pile on sandy soil. In this study, model pile was group pile having configurations were of (3×1, with triangular form and 3x1, with straight form) which satisfy the Meyerhof's Relative Stiffness Limit of pile for flexible pile. Embedded length, L=0.46m, 0.609m, 0.762m for pile diameter, d=0.013m, 0.019m, 0.026m variable spacing for triangular form of pile group and for straight form of pile group. And for surcharge condition embedded length of single pile, L=0.609m and surcharge of P=13478.20 Kg/m^3, 6739.1 Kg/m_3 and 3369.55 Kg/m^3 for each diameter and for saturated condition of pile diameter, d=0.013m. A comparison was made between the results of the lateral resistance of pile obtains by experiment and the ultimate lateral load resistances obtained by analytical methods. The load displacement curves were similar and non-linear. Lateral failure at a pile head displacement from 8 to 10, 7 to 9 and 6 to 8mm for single pile of d= 0.013m, 0.019m and 0.026m, respectively. In the case of saturated condition of sand a pile head displacement 15mm for single of d=0.013m. It observed that the failure load was the point at which the curve exhibits a pick or maintains continuous displacement increase with no further increase in lateral resistance.

Keywords: Group pile, lateral pile, static lateral load testing, simplified analytical method, ultimate lateral load resistance.

1. Introduction

Piles are vertical or slightly inclined relatively slender structural members 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 soil or onto rock. Piles may be required to carry uplift loads when used to support tall structures subjected to overturning forces from winds or waves and earthquake force. Some times piles are subjected to lateral load, for example piles used in marine structure, such as in quay and harbor structure. The sources of lateral load on harbor (marine) structure type of pile foundation, two criteria should be consider as safe against ultimate load failure and deflection should be within permissible limits in working load. For design such types of piles, ultimate lateral resistance of pile are required on the basis of above criteria. When plies are situate in a soft soil layer that is subjected to horizontal moment, horizontal pressure are develop between the pile and soil with a consequent development of bending moments and deflections in the piles is called lateral pile. When plies are situate in a soft soil layer that are impact of berthing ships wave action and off-shore structure are also subjected to wind and wave. High rise building, tower are subjected to lateral load due to wind and earthquake force. Combination of vertical and horizontal loads is carried where piles are used to support retaining walls, bridge piers and abutment and machinery foundations. So, it is important to know the lateral load to resistance capacity of pile foundation. When determining the resistance capacity of such tips subjected to horizontal moment, horizontal pressures are developed. The square cross-section piles is one of the most common type of deep foundation to support high rise building especially in southeast Asia (Fellenius *et al.*, 1999 and Zhang, 2003).

The various forces act on the laterally loaded pile such as wind forces, water forces, ship impact, surge, swing and sway of ship, ship mooring, ice thrust, force acting railway on bridge, ice thrust, force acting railway on bridge, soil flow, earthquake force etc. Vertical pile resists horizontal loads or moments by deflecting until the necessary reaction in the surrounding soil is mobilized. This lateral load resistance of pile foundations is critically important in the design of structures under loading from earthquakes, soil movement, waves etc. To keep the structures safe against lateral load, it is a grand design factor for the construction under such condition. As conducting lateral load tests on pile groups is logistically difficult and cost is too high very few studies was performed in past. From the previous studies, it is observed that few researches are available that show the distribution of load within a pile group (Broms, 1964; Anagnostopoulos, and Georgiadis, 1993; Gandhi, and Selvam, 1997; Rahman et al., 2003 and Zhang et al., 2005). It is observed from these tests that the average load for a pile in a closely spaced group will be substantially less than that for a single isolated pile at the same deflection and that leading pile or group piles carry significantly higher loads than trailing row piles at the same deflection.

According to Poulos and Davis (1980) the maximum deflection of the pile is the major criterion on the design. The piles transfer the load of the superstructure through two ways: (a) Shear generated along the surface of the pile due to soil–pile friction; (b) Point resistance due to the bearing of the pile at its bottom. The behaviour of the foundation under such loading conditions depends essentially on the relative stiffness of the pile and the soil. Three main factors are very important to be considered in most of the projects including soil stress, bearing capacity of pile and lateral displacement of pile, respectively (Avaei *et al.,* 2008). Despite the recent progress in soil mechanics, determination of piles behaviour especially under lateral loads and in the layered soils is difficult. Properties of soil, the length of the piles, the diameter, the section shape and the employed empirical method are led to complexity of the interaction between pile and the surrounding soil.

2. Materials and methods

2.1 Methods of analysis

In this research, three methods are investigated in the layered soils which include Matlock and Reese (1960), Meyerhof's (1995) and Patra and Pise's (2001) method, respectively.

2.2 Experimental setup and testing program foundation

Layered sand (coarse sand is overlying the finer sand) was the foundation medium and the model tank size was 1m×1m×1m of RCC. The dry density of sand and specific gravity were determined by laboratory experiment. The angle of internal friction of the sand was determined by direct shear test method in the laboratory. Placement density, γ_1 = 15.57 KN/m^3 and angle of internal friction, φ_1=58.28º of upper layer sand and γ_2 = 15.2 KN/m^3 and φ_2= 67.09º of lower layer.

Pile cap and model pile

In this experiment, G.I weir was used as pile cap. Each pile of group piles were of 1m length and hollow aluminum pipes of same diameters (2.5 cm) were used as model piles for the test. Two different lengths of piles (45 cm or 60 cm) were used to investigate the effect of pile length. Steel plate of uniform thickness (0.6 cm) was used as pile cap. its embedded length, L=0.460m, 0.609m and 0.762m for each pile of diameter, d=0.013m, 0.019m and 0.026m were tested.

2.2.3 Experimental procedure

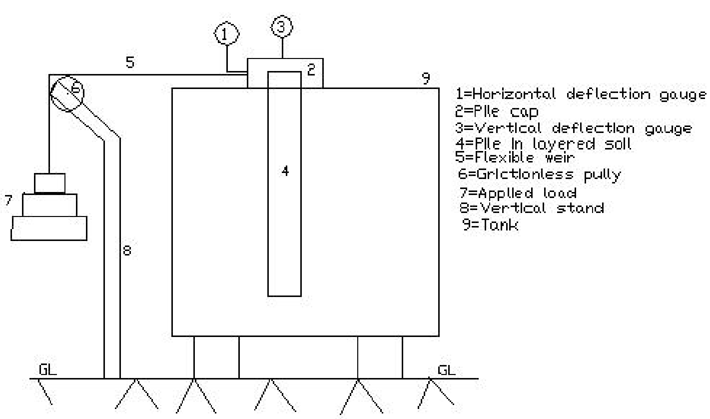

Fig. 1. Layout of working arrangement

In this experiment, piles were subjected to lateral load and for this purpose an experimental setup were made same as the above layout (Figure 1). At first, the model pile or piles were placed in the model tank dimension of 1m×1m×1m, then the local sand placed at 0.50m depth from bottom of the tank and *domar* sand placed over the local sand at 0.50m depth and both were placed in the tank from a certain height (0.50m) for maintaining fairly uniformly placement density. For applying lateral pull in the pile, a flexible weir was attached in the pile cap and vertical stand with frictionless pulley was used to change the direction of vertical load to lateral load. One dial gauges were attached to the pile cap to measure the lateral and vertical deflection of the pile. Load was applied by dead weight over the loading pan starting form the smallest with gradual increase in stages. Same loading were maintained for all model pile. The loading sequences were 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18,19 2,21,22 ,23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40 Kg etc. Dial gauge having sensitivity 0.01mm was used for measuring the lateral vertical direction. When load was placed in the loading pan, it moves down and due to the pulley it act laterally to the pile cap. Due to the lateral load, the piles were deflecting in the direction of the lateral load and the dial gauge gave the reading of the deflection of the pile. Due to lateral load the piles were deflecting in the direction of lateral load and dial gauge gave the reading of the deflection of the pile. Deflections for corresponding load were noted.

3. Results and discussion

The ultimate lateral resistance of the group pile found out by plotting lateral load versus displacement diagram in the plain graph paper. The load displacement curves are in general, similar and non-linear. At the ultimate resistance, pile showed some deflection without any increase in load and this load was taken as ultimate load for the pile. The lateral loads versus lateral displacement diagrams are drawn to study the effect of number of piles, pile length and pile spacing.

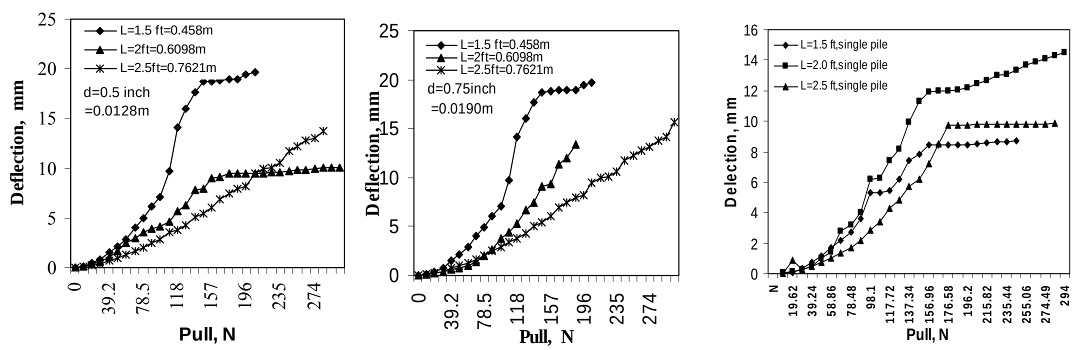

Fig. 2 Variation of ultimate lateral resistance of single pile of different diameter with the variation of embedded length, L.

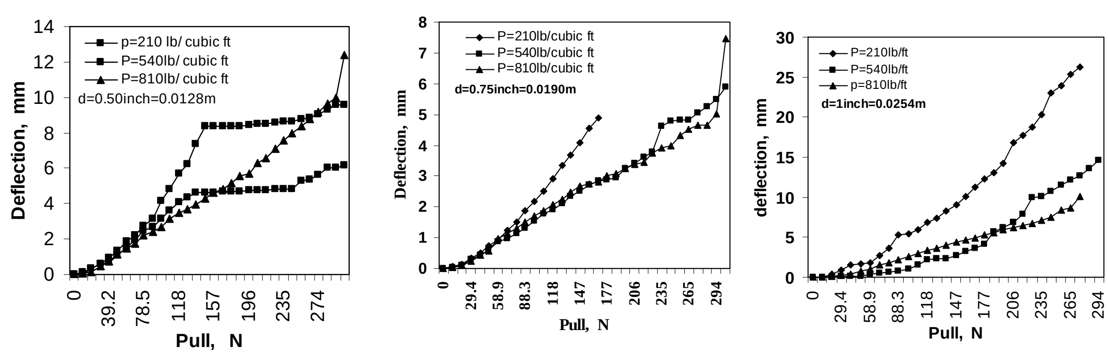

Fig. 3 Variation of ultimate lateral resistance of single pile of different diameter with the embedded length, L= with different surcharge condition.

The results are shown in Figure 2, illustrate the relationship between loads and horizontal deflection of single pile for different embedded lengths of pile of different diameter (d=0.0128m, 0.0609m and 0.762m). In this case, it is observed that the load carrying capacity of embedded length, L=0.762m is grater than the L= 0.609m and 0.458m. Also the load carrying capacity of diameter, d=0.0254m is grater than the d= 0.019m and 0.0128m.

The results are shown in Figure 3, illustrate the relationship between loads and horizontal deflection of single pile for embedded length, L= of pile of different diameter (d=0.0128m, 0.0609m and 0.762m) with varying surcharge load. In this case, it is observed that the load carrying capacity of surcharge load, P=13478.20 Kg/m^3 is grater than the P= 6739.1 Kg/m^3 and 3369.55 Kg/m^3.Also the load carrying capacity of diameter, d=0.0254m is grater than the d= 0.019m and 0.0128m.

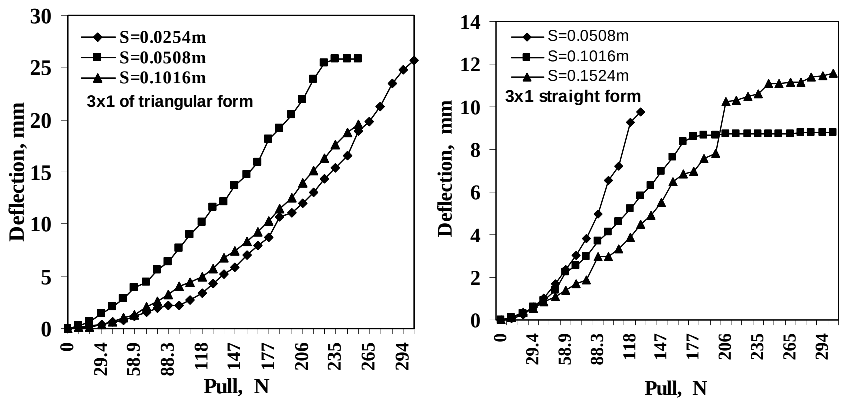

Fig. 4. Variation of ultimate lateral resistance of group of piles d=0.5 inch=0.013m with the variation of spacing and embedded length, L=2.0 ft=0.609m.

The results are shown in Figure 4, illustrate the relationship between loads and horizontal deflection of group of piles d=0.5 inch=0.013mwith the variation of spacing and embedded length, L=2.0 ft=0.609m. In this case, it is observed that the load carrying capacity of the straight form piles is greater than triangular form of pile.

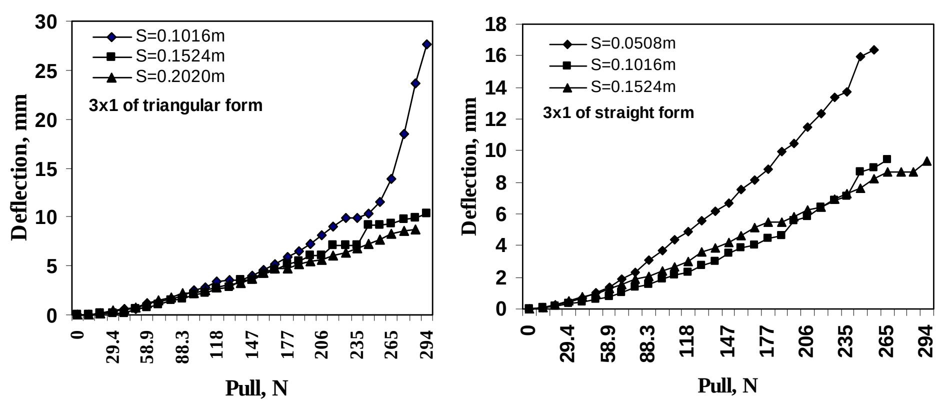

Fig. 5. Variation of ultimate lateral resistance of group of piles d=0.75 inch=0.019m with the variation of spacing and embedded length, L=2.0 ft=0.609m.

The results are shown in Figure 5, illustrate the relationship between loads and horizontal deflection of group of piles d=0.75 inch=0.019m with the variation of spacing and embedded length, L=2.0 ft=0.609m. In this case, it is observed that the load carrying capacity of the triangular form having spacing, S= 0.202m is greater than triangular form of pile having spacing, S=0.1524m and 0.1016m. It is also observed that the load carrying capacity of the straight form having spacing, S= 0.1016m is greater than the spacing S=0.1524m and 0.202m. Overall, the load carrying capacity of the straight form of piles is greater than the triangular forms of piles.

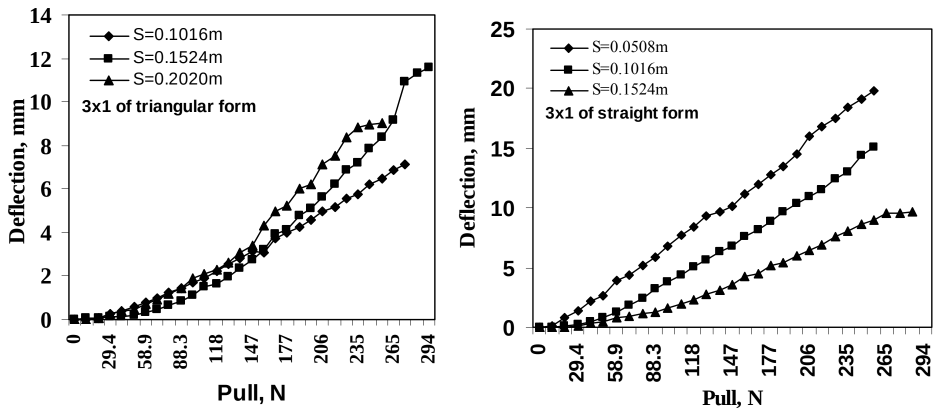

Fig. 6. Variation of ultimate lateral resistance of group of piles d=1.0 inch=0.026m with the variation of spacing and embedded length L=2.0 ft=0.609m.

The results are shown in Figure 6, illustrate the relationship between loads and horizontal deflection of group of piles d=0.1 inch=0.026m with the variation of spacing and embedded length, L=2.0 ft=0.609m. In this case, it is observed that the load carrying capacity of the triangular form having spacing S= 0.1524m is greater than triangular form of pile having spacing S=0.2020m and 0.1016m. It is also observed that the load carrying capacity of the straight form having spacing S= 0.1524m is greater than the spacing S=0.0508m and 0.1524m.Overall, the load carrying capacity of the triangular form of piles is greater than the straight forms of piles.

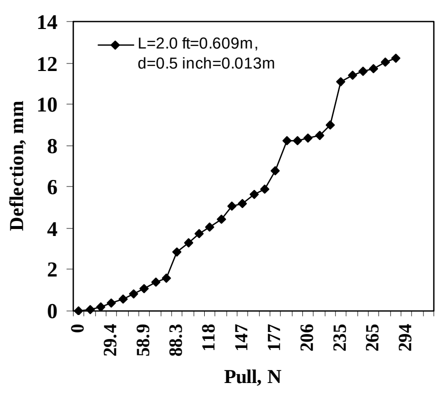

Fig. 7. Variation of ultimate lateral resistance of single pile of d=1.0 inch =0.026m of fully saturated condition and embedded length, L=2.0 ft=0.609m.

The results are shown in Figure 7, illustrate the relationship between loads and horizontal deflection of group of piles d=0.5 inch=0.013m of embedded length, L=2.0 ft=0.609m of fully saturated condition which doses not shown linearity but deflection increasing due to increasing loading.

3.1 Comparison

A comparison study has been done between the observed ultimate lateral resistances of the pile and groups to the theoretical value obtain from different methods: lateral failure at a pile head displacement from 8 to 10 mm for single pile of pile diameter, d=0.013m. However, for d=0.019m, the lateral failure occurred at a pile head displacement of 7 to 9 mm of single pile. Also lateral failure at a pile head displacement from 6 to 8mm for single of d=0.026m. In the case of saturated condition of sand a pile head displacement 15mm for single of d=0.013m. It is observed that the failure load is the point at which the curve exhibits a pick or maintains continuous displacement increase with no further increase in lateral resistance. The observed load were 156N, 205N and 284.49N for L=0.46m, 0.609m and 0.762m of pile d= 0.013m where the calculated load found from Meyerof theory (205.59N, 227.36N & 292.67 N), Patra & Pise method (190.89N, 204.31N & 349.90N) and Elastic theory load (118.60N, 104.63N & 91.07N), respectively (Table.1). In that case, Meyerof, Patra & Pise method resistance load increase with the increase of embedded length but and Elastic theory the resistance load decrease with the increase of embedded length.

Table 1
Comparison of resistance of single pile of d=0.5 inch=0.013m
by different methods to experimental methods.

d=0.013m	Observed load N	Theoretical load		
		Meyerhof N	Patra & Pise N	Elastic theory N
L=0.46m	156	205.59	190.89	118.60
L=0.609m	205	227.36	204.31	104.63
L=0.762m	284.49	292.67	349.90	91.07

Note: Ultimate lateral load resistance of pile in elastic theory depends on the allowable displacement of the pile.

The observed load were 137.34N, 186.39N & 304.11N for L= 0.46m, 0.609m and 0.762m of pile d=0.019m where the calculated load found from Meyerof theory (300.48N, 332.3.N & 477.5N), Patra & Pise method (278.99N, 337.10N & 411.70N) and Elastic theory load (212.34N, 184.82N & 161.05N), respectively (Table.2). In that case, Meyerof, Patra & Pise method resistance load increase with the increase of embedded length but and Elastic theory the resistance load decrease with the increase of embedded length.

Table 2
Compares of lateral load resistance of single pile of d=0.75 inch=0.019m by different methods to experimental methods.

D=0.019m	Observed load N	Theoretical load		
		Meyerhof, N	Patra & Pise N	Elastic theory N
L=0.46m	137.34	300.48	278.99	212.34
L=0.609m	186.39	332.30	337.10	184.82
L=0.762m	304.11	427.75	411.40	161.05

The observed load were 156.96N, 176.58N & 304.11N for L=0.46m, 0.609m and 0.762m of pile d=0.026m where the calculated load found from Meyerof theory (411.17N, 454.70N & 585.31N), Patra & Pise method (381.77N, 461.28N & 699.80N) and Elastic theory load

(291.05N, 253.28N & 216.93N), respectively (Table. 3). In that case, Meyerof, Patra & Pise method resistance load increase with the increase of embedded length but and Elastic theory the resistance load decrease with the increase of embedded length.

Table 3
Comparison of lateral load resistance of single pile of d=1.0 inch=0.026m by different methods to experimental methods.

D=0.026m	Observed load	Theoretical load		
		Meyerhof N	Patra & Pise N	Elastic theory N
L=0.46m	156.96	411.17	381.77	291.05
L=0.609m	176.58	454.70	461.28	253.60
L=0.762m	304.11	585.31	699.80	216.93

The observed maximum load were 196.20N, 264.87N & 294N for d=0.013, 0.019m and 0.026m where the calculated load found from Patra & Pise method (352.08N, 510.20N & 634.39N), respectively (Table. 4) for the triangular for of pile.

Table 4
Comparison of lateral load resistance of pile group (3x1, with triangular form) with Patra & Pise method to observed experimental value.

L=0.609m	Spacing, m	Observed value N	Theoretical load (Patra& Pise) N
d=0.013m	0.101	127.53	270.754
	0.152	186.39	317.20
	0.202	196.20	352.08
d=0.019m	0.101	194.00	423.65
	0.152	235.44	467.35
	0.202	264.87	510.20
d=0.026m	0.101	274.79	547.84
	0.152	294.00	591.55
	0.202	264.87	634.39

Table 5
Comparison of lateral load resistance of pile group (3x1, with straight form) with Patra & Pise method to observed experimental value.

L=0.609m	Spacing, m	Observed value N	Theoretical load(Patra& Pise) N
d=0.013m	0.026	204.11	239.52
	0.038	225.63	263.20
	0.052	265.06	275.20
d=0.019m	0.026	255.06	360.89
	0.038	264.87	369.66
	0.052	266.00	383.90
d=0.026m	0.026	255.06	486.54
	0.038	255.12	493.85
	0.052	264.87	505.85

The observed maximum load were 265.06N, 266N & 264.87N for d=0.013, 0.019m and 0.026m where the calculated load found from Patra & Pise method (275.20N, 383.90N &

505.85N), respectively (Table 5) for the straight form of pile for the spacing 0.052m. It was noted that ultimate lateral load resistance of pile in elastic theory depends on the allowable displacement of the pile.

In saturated condition of soil, the observed load was 180N whereas the calculated load from the Meyerof theory and Patra & Pise method load were 142.21N and 144.04N, respectively (Table. 6).

Table 6
Comparison of lateral load resistance of single pile of d=0.5 inch=0.152m for saturated condition by different methods to experimental methods.

L=0.152m	Observed value N N	Theoretical load	
		Meyerhof N	Patra & Pise N
d=0.013m	180	142.21	144.04

4. Conclusions

In this study, laboratory model tests were carried out to find out lateral load resistance of pile foundation under varying conditions such as number of pile, embedded length of pile and pile spacing in the foundation medium of layered sand. From this study, the following conclusions are drawn from the relationship between lateral load and displacement:

(i) The load-displacement curves are non-linear. Lateral failure occurred at a pile head displacement from 8 to 10 mm for d=0.013m with the variation of embedded length for single pile and variation of spacing pile group. However, for d=0.019m the lateral failure occurred at a pile head displacement from 7 to 9 mm with the variation of embedded length for single pile and variation of spacing of pile group. Also lateral failure occurred at a pile head displacement from 6 to 8 mm for d=0.026m with the variation of embedded length for single pile and variation of spacing pile group.

(ii) Ultimate resistance per pile increases with an increase in pile spacing. It has seen that resistance at 0.101m spacing is less than that of 0.152m spacing. Again 0.152m spacing is also less than that of 0.202 spacing for triangular form of group pile.

(iii) Ultimate resistance of d=0.013m of single pile increase in dry condition is greater than single pile of d=0.013m in saturated condition.

(iv) Group efficiency of pile increases with an increase in pile spacing. It has seen that efficiency at 0.101m spacing is less than that of 0.152m and 0.202m spacing for both triangular form straight form of group pile.

Acknowledgement

The facilities provided by Soil Mechanics Lab, Department of Civil Engineering Rajshahi University of Engineering & Technology (RUET) hereby, acknowledged.

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