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Investigation of lateral load resistance of laterally loaded pile in sandy soil

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ABSTRACT: Investigation of the lateral load resistance of pile is made by laboratory model test on single and group piles. The experiments are carried out with varying size, spacing of piles in group and length to diameter ratio (L/d) of the piles. Lateral resistance of pile is a function of shape, size, spacing and length to diameter ratio (L/d) of the pile. In this study, model pile is single pile, and group piles having configurations are of (2x1, 2x2) which satisfy the Meyerhof's relative stiffness limit of pile for flexible pile. For model pile embedded length to diameter ratio (L/d) are 20, 30, 35 and spacing are S = 3d, 4.5d, 6d. These experiments are conducted in the sand available at North-South region (Rajshahi) in Bangladesh. Lateral loads are applied in the single and pile groups by a lateral load setup arrangement. Due to the lateral load the pile are deflected. The load-displacement responses, ultimate resistance, group efficiency of piles with different spacing and number of piles in group have been qualitatively and quantitatively investigated in the experiment. From the load-displacement curve, ultimate lateral load resistances are obtained by double tangent method. Also some analytical methods proposed by Meyerhof, Patra & Pise used to determine the ultimate lateral load resistance of pile and pile groups. Finally, the lateral resistance of pile obtains by experiment and the ultimate lateral load resistances obtained by analytical methods are compared and trying to find out a analytical methods to determine the lateral reasonably for the sand are available at North-South (region) Rajshahi In Bangladesh.

1 INTRODUCTION

Piles are structural members that are made of steel, concrete or timber. They are used to build deep foundations and which cost more than shallow foundations. Despite the cost, the use of pile often is necessary to ensure structural safety.

Some time piles are subjected to lateral load, for example piles used in quay and harbor structure. The sources of lateral load on harbor structure are impact of ship and wave action and of shore structure are also subjected to wind and wave. High rise building, tower are subjected to lateral load due to wind and earth quake forces. So, it is important to know the lateral load resistance capacity of pile foundation.

2 SCOPE OF STUDY

Laboratory model test on single and group pile are carried out with varying size, spacing, and length to diameter ratio. Lateral resistance of pile is a function of shape, size, spacing and length to diameter ratio. The analytical results have been compare with the other researcher's published experimental result.

3 BRIEF REVIEW

In general, laterally loaded pile can be divided in to two groups:

(1) Short pile and
(2) Long pile.

The lateral load on long pile can be analyze on the concept of sub grade modulus or considering soil is an elastic medium. There are a large number of analytical and field and laboratory investigation are available for predicting lateral strength of piles.

According to Winkler model, an elastic medium (soil) can be replaced by a series of infinitely close, independent elastic spring. Based on this assumption, Matloc and Reese (1960) gave a general formula of determining moment and displacement of a vertical pile which is subjected to lateral load and moment. Brom's (1965) developed a simplified solution for laterally loaded piles based on the assumption of:

(a) Shear failure on soil, which is the case of short pile and

(b) Bending of the pile governed by plastic yield resistance of pile section, which is applicable on long pile.

Meyerhof and Ranjan (1972) conducted model tests on rigid single pile and pile groups under central inclined loads in homogeneous sand and developed a semi-empirical interaction relationship assuming elliptical variation of ultimate capacity under axial to lateral load. Meyerhof et al. (1981) suggested that the ultimate resistance per unit width of a pile is greater than that of a pile is greater than that of a wall in homogeneous sand. Further more, the ultimate resistance of a wall has to be multiplied by a shape factor to get the ultimate lateral loads of piles. The solution was compared with the model test results. Chattopadhyay and Pise (1986) suggested to graphical methods to estimate the ultimate lateral resistance from the load-ground line deflection diagram of single pile. They found that the estimate values by the log load-log deflection method are in closer agreement with the experiment results and applicable to a pile of any length. Liu and Meyerhof (1987) carried out a nonlinear analysis and showed that Le/L depends not only on the pile stiffness K_{rs} but also L/d and other factors.

McVay et al. (1995) conducted centrifuge test on free head single and 3x3 pile groups at 3d and 5d pile spacing. Results of the test showed that group efficiency is independent of soil density. The behavior of the pile group was analyzed by the 3D elasto-plastic analysis soil behavior with no tension characteristic as well as frictional elements of slippage on the pile soil interface. The pile group efficiency was estimated to be 0.6-0.7 when the displacement reached 0.1d. It was found that for circular pile the pressure distribution across the diameter is not uniform, is maximum at center, and is almost zero at the two edges. A method is proposed to predict the soil pressure distribution and lateral resistance and is found to be in closed agreement with various field and laboratory data.

From the forgoing review it is seen that systematic investigation on the qualitative and quantitative influence of parameter such as length to diameter ratio, configuration/geometry of the group of piles, number of pile, spacing and pile friction angle on the ultimate lateral resistance is scanty and conflicting.

4 ANALYTICAL METHODS

There are various methods of analysis the lateral loads on pile foundation. Following are the major methods of analysis the lateral loads of pile foundation:

4.1 *Elastic method*

A general method for determining moments and displacements of a vertical pile embedded in a granular soil and subjected to the lateral load and moment at the ground was given by Matlock and Reese (1960). Consider a pile of length L subjected to a lateral force Q_g and a moment M_g at the ground surface (z = 0) as shown in the fig. 1.The figure shows the general deflected shape of the pile and the soil resistance caused by the applied load and the moment.

According to a Simpler, Winkler's model, and elastic medium can be replaced by a series of infinitely closed independent elastic springs. Based on this assumption,

$$k = \frac{p^{/}(KN/m)}{x(m)}$$

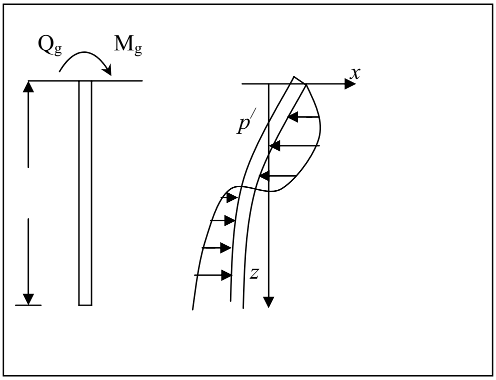

Fig. 1. (a) - Vertical pile, (b) - Elastic deflection of pile

Where, k = modulus of sub-grade reaction,
P = pressure on soil,
x = deflection.

The sub-grade modulus for granular soils at a depth z is defined as

$$K_t = n_h \text{ x } Z$$

Where, n_h = constant of modulus horizontal sub-grade reaction.

Using the theory of Brom's on an elastic foundation we can write

$$E_p I_p \frac{d^4 x}{dz^4} = p^{/}$$

Where, E_p = Modulus of elasticity in the pile material,
I_p = Moment of inertia of the pile section.

Based on Winker's model

$$p^{/} = -kx$$

The sign in the above equation is negative because the soil reaction is in the direction opposite to the pile deflection,

$$E_p I_p \frac{d^4 x}{dz^4} + kx = 0$$

The solution of the above equation results in the following expressions:

Pile deflection at any depth:

$$x_z(z) = A_x \frac{Q_g T^3}{E_p I_p} + B_s \frac{M_g T^2}{E_p I_p}$$

Slope of pile at any depth:

$$\theta_z(z) = A_\theta \frac{Q_g T^2}{E_p I_p} + B_\theta \frac{M_g T}{E_p I_p}$$

Moment of at any depth:

$$M_z(z) = A_m Q_g T + B_m M_g$$

4.2 *Meyerhof's method*

More recently, Meyerhof (1995) provided the solutions for laterally loaded rigid and flexible pile, which are summarized below. According to Meyerhof's method, a pile can be defined as flexible if

$$Kr = \text{relative stiffness of pile} = \frac{E_P I_P}{E_S L^4} < 0.01$$

Where Es = average horizontal soil modulus of elasticity.

Piles in sand:

For short (rigid) piles in sand, the ultimate load resistance can be given as

$$Q_{u(g)} = 0.12\gamma dL^2 k_b \leq 0.4 \text{ pdL}$$

Where γ = unit wt. of soil,
k_b = resultant soil pressure co-efficient,
p = limit pressure.

The limit pressure can be given as

p = 40 N_q tan φ (KPa) and
p = 60 N_q tan φ (KPa)

(For self boring and full displacement pressure meter)

Where N_q = bearing capacity factor

The maximum moment, M_{max}, in the pile due to lateral load, $Q_{u(g)}$ is

$$M_{max} = 0.35 Q_{u(g)} L \leq M_y$$

For long (flexible) piles in sand, the ultimate lateral load, $Q_{u(g)}$, can be estimated from the above equation by substituting an effective length (L_e) for L where,

$$\frac{L_e}{L} = 1.65 K_r^{0.12} \leq 1$$

The maximum moment in a flexible pile due to a working lateral load Q_g applied at the ground surface is

$$M_{max} = 0.3 K_r^{0.2} Q_g L \leq 0.3 Q_g L$$

4.3 *Patra and Pise's methods*

4.3.1 *Single pile:*

Patra and Pise (2001) modified the Meyerhof's formula on the following assumption:

- The active earth pressures on the rear sides of the piles and the vertical tip resistance is neglected.
- The passive earth pressure at failure of a pile was taken as for the wall by multiplying it by a constant shape factor 3.

Thus the ultimate lateral resistance Q_{Ls} for a rigid, free head, fully embedded pile is

$$Q_{Ls} = 3 \times 0.12\gamma dL^2 Kb$$

Where, K_b = co-efficient of passive earth pressure on the wall.

For a laterally loaded flexible pile relative stiffness of pile $K_{rs} \leq 10^{-1}$-10^{-2}, it was suggested by Meyerhof and Yalcin (1984) that in the absence of structural failure the ultimate lateral load for soil failure can be estimated for the above equation by using a corresponding effective embedment depth L_e instead of L.

Thus the ultimate lateral resistance Q_{Ls} for a flexible, free head, fully embedded pile is

$$Q_{Ls} = 3 \times 0.12\gamma d L_e^2 K_b$$

4.3.2 *Pile group 2x1*

The ultimate lateral resistance of line pile group (2x1) could be found out by extending the analysis for a single pile and considering the forces acting on piles and soil mass within the pile group. Active earth pressure develops at the back face of the front pile on the soil mass within the pile group and passive pressure at the front face of the rear pile on the soil mass within the pile group. This will develop the frictional resistance between the soil mass with in the pile group and the soil mass along the side of the piles on the vertical plane. Again, the edges of the piles along the sides of the piles generate frictional resistance between pile and soil mass.

The general configuration of line pile groups acted upon by the different forces considered as below:

$$Q_{Lg} = 2F + P_p$$

Where, F = frictional resistance on the vertical plane along the side of the pile group and
P_p = passive earth pressure for the front pile.

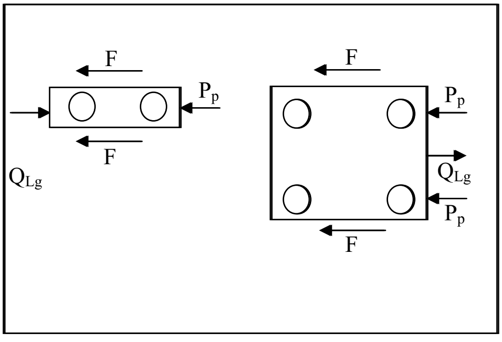

Figure 2. General configurations of pile groups acted upon by different forces.

Frictional resistance along the side of the pile group could be approximately found-out as

$$F = \gamma L^2/2K_sS$$

Where K_s= co-efficient of earth pressure along the side of the pile group

L = Embedded length of pile,

S = Spacing between piles.

The ultimate lateral resistance of a rigid 2x1 pile group is

$$Q_{Lg} = \gamma L^2 K_s S + 0.36\gamma d L^2 K_b = \gamma L^2 (K_s S + 0.36 d K_b)$$

4.3.3 *Pile group 2x2*

The ultimate lateral resistance of square pile group (2x2) could be found-out by considering that passive earth resistance develops on the front piles along with side resistance.

For a rigid square 2x2 group, it is expressed as

$$Q_{Lg} = \gamma L^2 K_s S + 2\,(0.36\gamma d L^2 K_b) = \gamma L^2 (K_s S + 0.72 d K_b)$$

4.3.4 *Group efficiency*

Variation of ultimate lateral capacity of pile group is generally expressed by group efficiency, η and it is expressed as

$$\eta = \frac{Q_{Lg}}{n_1 n_2 Q_{Ls}}$$

Where, Q_{Lg}= Ultimate lateral capacity of pile group,

Q_{Ls} = ultimate lateral capacity of single pile,

n_1= No. of rows in a pile group and

n_2= No. of columns in a pile group

5 EXPERIMENTAL SETUP AND TESTING PROGRAM

5.1 *Foundation*

Sand was foundation medium and the model tank size was 1mX1mX1m. Sand has a placement density of 95 lb/ft^3 or 15kN/m^{3}and the angle of internal friction is φ = 37.9º. Specific gravity of the sand used in the model tank is 1.82.

5.2 *Pile and pile cap*

Aluminum alloy tube of 19-mm outer diameter and 0.81mm wall thickness were used as model pile. For increasing the pile wall friction, sand was place around the pile by adhesive. The average outside diameter for rough pile was 20mm. The embedment length-to-diameter was 20, 30, and 35. Steel plate of 0.64cm thickness was taken as pile cap. The piles were attached with the pile cap by screw.

5.3 *Model pile of test*

Singe pile of embedment length-to-diameter (L/d) 20, 30, and 35 were tested. Group pile of configuration (2X1), (2X2) of embedment length-to-diameter (L/d) 20, 30, and 35 were tested.

5.4 *Experimental setup*

In this experiment, piles were subjected to lateral load and for this purpose an experimental setup were made to apply lateral load on pile. At first the model pile or piles were placed in the model tank of dimension (1mx1mx1m), then the soil medium (sand) placed in the tank from a certain height (0.5m) for maintaining fairly uniform placement density. For applying lateral pull in the pile, a flexible weir was attached in the pile cap and a vertical stand with frictionless pulley was used to change the direction of vertical load to lateral load. Two dial gauges are attached to the pile cap to measure the lateral and vertical deflection of the pile.

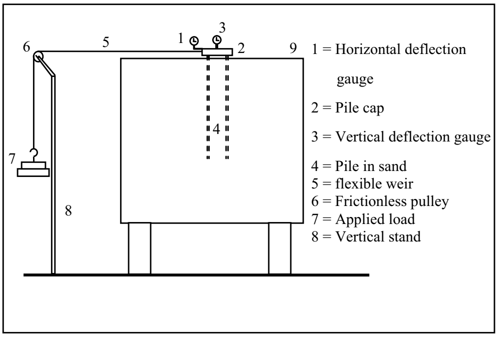

Figure 3. Layout of working arrangement

5.5 *Experimental procedure*

The arrangement of test setup is shown in fig: 4. Loading arrangement are made in such a way that it will act laterally to pile cap. After placing piles with the pile cap in the tank, sand was placed in the tank by falling from certain height of about 0.5m. The lateral load was applied to the pile cap through a pulley arrangement with flexible weir attached to the pile cap. The other end was attached to the loading apron. Load was applied by dead weight over the loading pan starting form the smallest with gradual increase in stages. Same loading sequences are maintained for all model pile. The loading sequences are 0.50, 1.0, 1.50, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10, 11, 12, 15, 17, 20, 23, 26, 28, 30, 32, 34 Kg etc. Dial gauges having sensitivity of 0.01 mm were used for measuring the lateral and vertical deflection. 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 are deflecting in the direction of the lateral load and the dial gauge gave the reading of the deflection of the pile. Deflections for corresponding load were noted. By plotting the noted value, load Vs deflection curve was obtain which non-linear in nature. Ultimate lateral resistance of the pile was obtain from the curve by double tangent method (DTM) or the point where the curve show a greater deflection without further increasing any load.

6 TEST RESULT AND DISCUSSION

The ultimate lateral resistance of the pile found out by plotting lateral load Vs displacement diagram in the plain graph paper. The curve was non-linear in nature. At the ultimate resistance, pile showed some deflection without any increase in load and this load was taken as ultimate load for the pile.

6.1 *Lateral load Vs displacement diagram*

Typical diagrams of lateral pull versus axial displacement, lateral displacement for (2x1, 2x2) pile group's in dense sand are shown in Fig: 4 to Fig: 8.The load displacement curves are in general, similar and non-linear. It is observed that the axial displacement as compared to the lateral displacements is negligible. They are shown (Fig: 10) for record and observation purpose only. From the lateral pull versus lateral displacement diagrams, for a particular value of lateral movement of pile, the magnitude of pull increases with increase in spacing. Lateral failure occurred at a pile head displacement from 4 to 8 mm (0.2d to 0.4d) for L/d=20. However, for L/d=30, the lateral failure occurred at a pile head displacement of 6 to 10 mm (0.3d to 0.5d).

6.2 *Ultimate resistances*

Ultimate resistance for different cases has been estimated from the lateral pull-displacement diagrams by the double-tangent methods (DTM). The minimum load obtained from those diagrams is considered as the ultimate resistance for a particular condition. 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.

6.3 *Experimental graph*

All graphs which are found in the experiment and are used to find out ultimate lateral resistance of the pile are listed below:

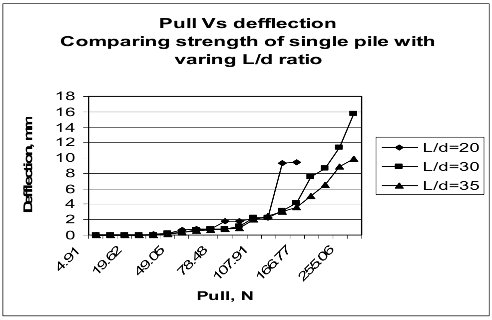

Figure 4. Variation of lateral load resistance of single pile with L/d ratio.

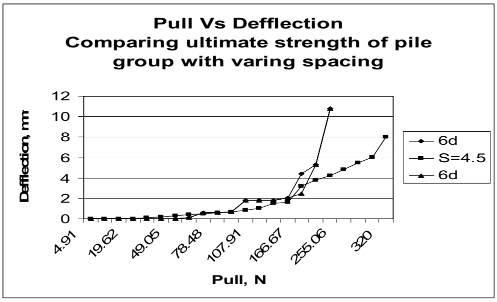

Figure 5. Variation of lateral load resistance in pile group (2x1, L/d =20) with spacing.

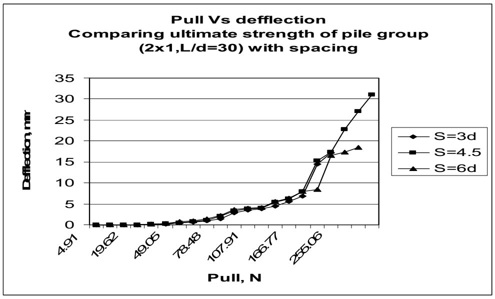

Figure 6. Variation of lateral load resistance in pile group (2x1, L/d =30) with spacing.

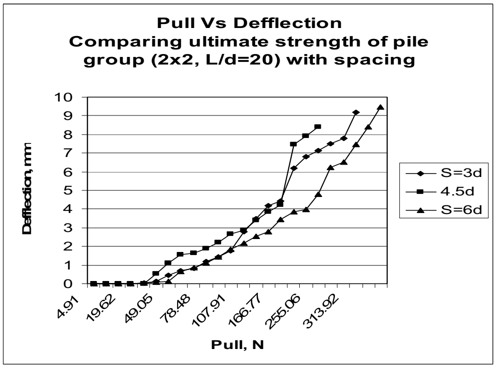

Figure 7. Variation of lateral load resistance in pile group (2x2, L/d =20) with spacing.

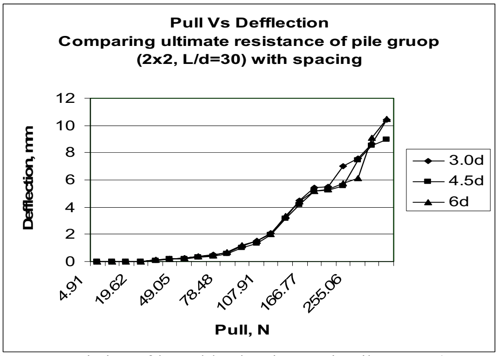

Figure 8 Variation of lateral load resistance in pile group (2x2, L/d =30) with spacing.

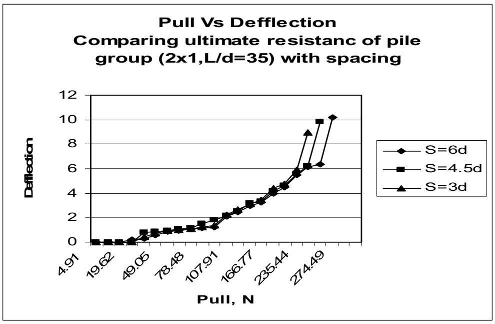

Figure 9 Variation of lateral load resistance in pile group (2x1, L/d =35) with the variation of spacing.

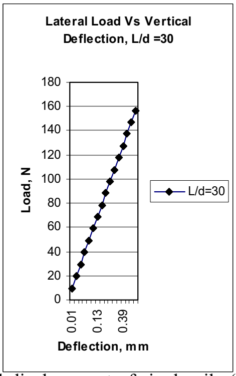

Figure 10 Axial displacement of single pile (L/d = 30) due to lateral load.

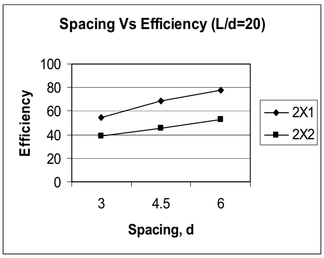

Figure 11. Variation efficiency of pile group (2x2, 2x1)

7 COMPARISON

Following are the table gives a comparison between the observed ultimate lateral resistances of the pile and pile groups to the theoretical value obtain from different methods:

Table 1. Compares of lateral load resistance of single pile by different methods to experimental value

L/d Ratio	Observed load N	Theoretical load		
		Meyerhof N	Patra & Pise N	Elastic theory N
20	107	115.2	72	178
30	196	207	163	195
35	225	282	221.7	220

Table 2. Compares of lateral load resistance of pile group (2x2) with Patra & Pise method to observed experimental value

L/d ratio	Spacing (In terms of d)	Observed value N	Theoretical value (Patra & Pise) N
20	3	166	188
20	4.5	196	209.6
20	6	225	231.2

Table 3. Compares of lateral load resistance of pile group (2x1) with Patra & Pise method to observed experimental value

L/d ratio	Spacing (In terms of d)	Observed value N	Theoretical value (Patra & Pise) N
20	3	117.2	115.6
20	4.5	147	137.2
20	6	166	158.8

8 CONCLUSION:

The following conclusions are drawn from the present study:

- The ultimate lateral capacity of pile group depends on the length to diameter ratio of pile, pile friction angle, pile group geometry, spacing of piles in a group and sand placement density. The quantitative and qualitative influence of those parameters has been investigated.
- The load displacement curves are non-linear. Lateral failure occurred at a pile head displacement from 4 to 8 mm (0.2d to 0.4d) for L/d=20. However, for L/d=30, the lateral failure occurred at a pile head displacement of 6 to 10 mm (0.3d to 0.5d).
- Ultimate resistance per pile increases with an increase in pile spacing. It has seen that resistance at 3d spacing is less than that of

4.5d spacing. Again resistance at 4.5d spacing also less than that of 6d spacing.

- Group efficiency of pile increases with an increase in pile spacing. It has seen that the efficiency at 3d spacing is less than that of 4.5d and 6d spacing.
- The method proposed by Patra & Pise is more reliable for predicting ultimate lateral load resistance of pile in North-South region (Rajshahi) of Bangladesh.

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