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Behaviour of Rigid Batter Piles and Pile Groups Subjected to Horizontal Load in Sand

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Introduction

Pile foundations are generally preferred when heavy structural loads have to be transferred through weak subsoil to firm strata. These foundations in some situations are subjected to significant amount of lateral loads besides vertical loads. Lateral forces may be due to impact of ships during berthing and wave action in the case of off shore structures. Piles are commonly used to support bridge structures, tall buildings, and transmission line towers. Towers and offshore structures are usually subjected to overturning moments due to wind, wave pressure and ship impact. These overturning moments are transferred to the foundation of the structure in the form of horizontal and vertical loads. The type of foundation usually recommended for such loading conditions is combination of vertical and batter piles. In practice piles are used in groups and are connected by a cap at the pile heads. The spacing between the piles, arrangement of piles, their batter and direction of load has an important role in the assessment of load deformation behavior of pile groups under lateral loads.

When the piles are inclined at an angle to the vertical they are called as batter piles. Batter piles are quite effective for taking lateral load. Normally batter of 1 horizontal to 12 vertical, to 5 horizontal to 12 vertical is used. If batter exceeds 3 horizontal to 12 vertical, special consideration is taken under construction. The usual assumption in design of a batter pile is that the pile is capable of resisting the same axial load as a vertical pile of the same type and size and driven to same stratum.

For the proper functioning of these structures two criteria must be satisfied:

1. Piles should be safe against ultimate lateral failure load.
2. Normal deflection at working load should be within the prescribed limits depending on functional requirements of the structure.

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Brief Review of Literature

Ultimate Resistance of Piles and Pile Groups

The behaviour of laterally loaded pile groups has been generally analyzed using the concept of subgrade modulus or considering the soil as an elastic continuum. Broms (1964) proposed analysis to predict ultimate lateral soil resistance and lateral deflections of piles. Meyerhof et al. (1981) suggested that the ultimate resistance per unit width of pile is greater than that of wall in homogeneous sand. Furthermore, the ultimate resistance of a wall has to be multiplied by a shape factor to get the ultimate lateral load of piles.

Meyerhof and Yalcin (1992) investigated behavior of single free headed model flexible vertical and batter pile under central inclined loads in two layered soil. The ultimate capacity of pile is found to depend on the layered soil, load inclination and pile batter. Practical equations for horizontal and vertical displacement of flexible batter piles are presented on the basis of resultant influence factors that are related to batter angle, load inclination and distribution of soil modulus with depth. Prasad and Chari (1999) measured actual soil pressure distribution in rigid model pile, embedded in sand, along its length across the diameter. It was found that for circular piles the pressure distribution across the diameter is not uniform. A method is proposed to predict the soil pressure distribution and lateral resistance and is found to be in close agreement with various field and laboratory data.

Zhange et al (1999) performed centrifuge lateral load tests on single batter piles founded in sand. The effects of pile batter and soil density on lateral resistance were studied. Based on test results, nonlinear p-y curves were developed for single batter piles. Patra and Pise (2001) have investigated load-displacement response, ultimate resistance and group efficiency with spacing and number of piles in a group. Analytical methods have been proposed to predict the ultimate lateral capacity of single pile & pile groups. Zang, et al (2005) developed a method for determination of ultimate soil resistance to piles including frontal side resistance and side shear resistance in cohesionless soil.

Load-Deflection Behaviour of Piles and Pile Groups

Studies on deflections of single batter piles and pile groups are reported by Murthy (1965). He investigated the behaviour of model instrumented piles subjected to horizontal load. He has developed non dimensional solutions for the case of lateral loads acting at ground level for batter piles. Poulos and Madhav (1971) carried out parametric studies of pile groups to study the effect of pile stiffness, batter angle, pile spacing, number of piles in a group and pile group configuration. Pise (1983) investigated the load - deflection characteristics of pile groups, interaction factors, and displacement ratios experimentally in the light of Poulos analysis (1971, 1973). Sun (1994) presented a numerical approach and parametric study for the calculation of the soil and pile interaction under lateral loading. Simple analytical equations are presented to predict the response of laterally loaded piles for engineering design.

Ooi and Duncan (1994) presented a simple method for estimating pile group deflection and maximum bending moments based on the theories of Poulos (1971) and Focht and Koch (1973). Lateral deflection and maximum bending moment are calculated using the group amplification procedure.

Systematic investigations on the qualitative and quantitative influence of parameters such as embedment length to diameter ratio, spacing, soil-pile friction angle, on ultimate horizontal resistance are practically scanty. Limited information is available regarding batter piles subjected to horizontal loads. In the majority of field studies, detail information regarding soil, piles, soil-pile interfaces properties are not available. Research work is required to understand the behavior of batter piles and pile groups subjected to horizontal loads.

Scope of the study

Laboratory model tests on single batter piles and 2-pile groups have been carried out in uniform sand under horizontal loads. The qualitative and quantitative influence of parameters such as configuration of the pile group, spacing, batter angle and direction of loading on ultimate horizontal resistance and group amplification factor have been investigated.

Experimental Set up and Testing Programme

Foundation

Dry local river sand was used as foundation medium in a model tank of size 900mm x 700mm x 900mm deep. The specific gravity and uniformity coefficient of sand were 2.69 and 3.2 respectively. The placement density of sand during testing was 1.78 g/cc, corresponding to relative density of 70% and angle of shearing resistance Φ was 37°.

Model Piles

Stainless steel pipe piles of 19mm outer diameter and 0.75mm wall thickness were used as a model piles. For increasing the wall friction of pile, fine sand was pasted around the pile by adhesive. The average outside diameter for rough pile was 20mm. The embedment length-to-diameter ratio of vertical pile was 15. The soil - pile friction angle δ was found to be 24° by direct shear test. The pile flexibility factor, K_{rs}, is expressed as $K_{rs} = E_pI_p / \eta_h (L)^5$ (Poulos and Davis, 1980). Where, E_p = modulus of elasticity of pile, I_p = moment of inertia of pile. E_pI_p of the pile was 383.75 x10^3 kg-cm^2. Length of pile, L was 285mm. Coefficient of horizontal subgrade reaction, η_h, was 0.56 kg/cm^3 [Terzaghi, (1955) for dense sand]. K_{rs} of the test pile was found to be 3.64 x10^{-2}. It indicates that the test piles were rigid piles.

The relative stiffness factor, $T = [E_pI_p / \eta_h]^{1/5}$; T = 147mm. L/T of the pile was $1.94 \leq 2$; and so the piles were short and rigid.

Loading Plate

Loading plate is used for applying horizontal load and to measure pile head displacement. Length of the loading plate was 225mm and width 45mm. Inner slot opening length is 200mm and width 21mm. The slot is provided to fix up the pile in loading plate as well as in the fixing plate. On the loading plate holes are drilled 15mmc/c on both sides of the plate to adjust pile spacing of 3d, 4.5d & 6d with the help of angle fixing plate. On the loading side one hole is drilled at the center of loading plate to attach wire rope which passes over frictionless pulley for applying horizontal load. On the rear side of plate two drill holes are provided to fix up a plate which is used for resting dial gauge for measuring horizontal displacement. Thickness of the loading plate is 3mm and all hole sizes of 5mm diameter. Figure1 shows loading plate.

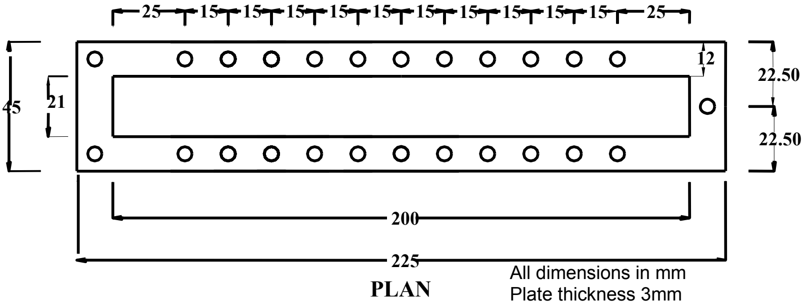


Fig. 1 Loading Plate

Angle Fixing Plates

To make optimization in fabrication for experimental programme three types of angle fixing vertical plates were fabricated to change the batter angle between - 30 ° to + 30° for the piles. Figure 2 and Plate 1 in page 225 show angle fixing plates and its arrangement.

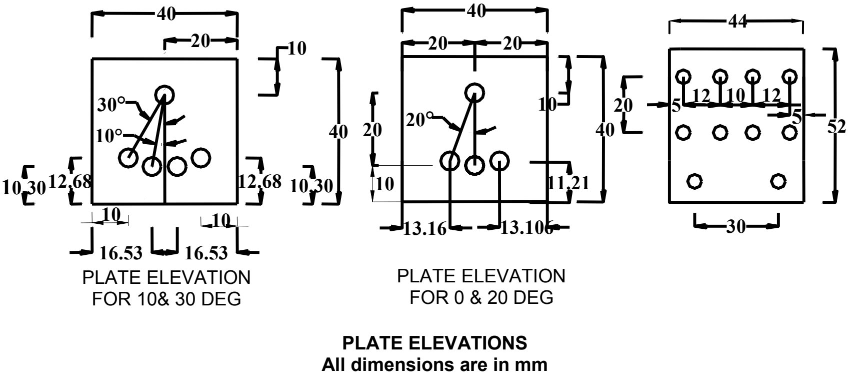


Fig. 2 Angle Fixing Plates

Model Tests

Model test were carried out on 2-pile groups configuration (2 x 1) and single piles. Spacing between piles were 3d, 4.5d, and 6d. The piles and pile groups were subjected to horizontal load which was applied at the center of loading plate through wire rope passing over frictionless pulley as shown in Figure 3. The tests were carried out in dense sand (R.D. = 70%). Table 1 shows the testing programme.

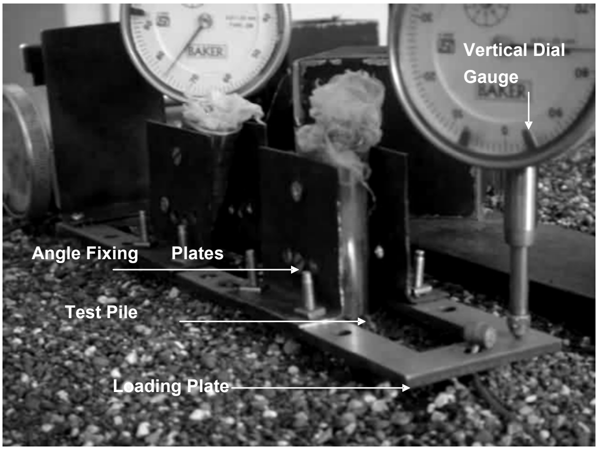
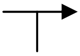
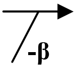
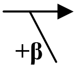
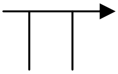
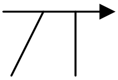
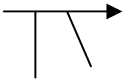
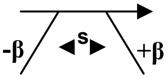


Plate 1 Arrangement of Angle Fixing Plates and Loading Plate

Table 1 Testing Programme

Test	Spacing (s)	Batter angle in deg. (β)	No. of tests
	-	0	1
 	-		6
	3d, 4.5d, 6d	0	3
	3d, 4.5d, 6d	(-10 ,0) , (-20, 0) (-30, 0)	9
	3d, 4.5d, 6d	(0, +10) , (0, +20) (0, +30)	9
	3d, 4.5d, 6d	(-10,+10), (-20, +20) (-30, +30)	9

Experimental Procedure

The schematic diagram of test set-up, loading arrangement and model pile group with loading plate is shown in Figure 3.

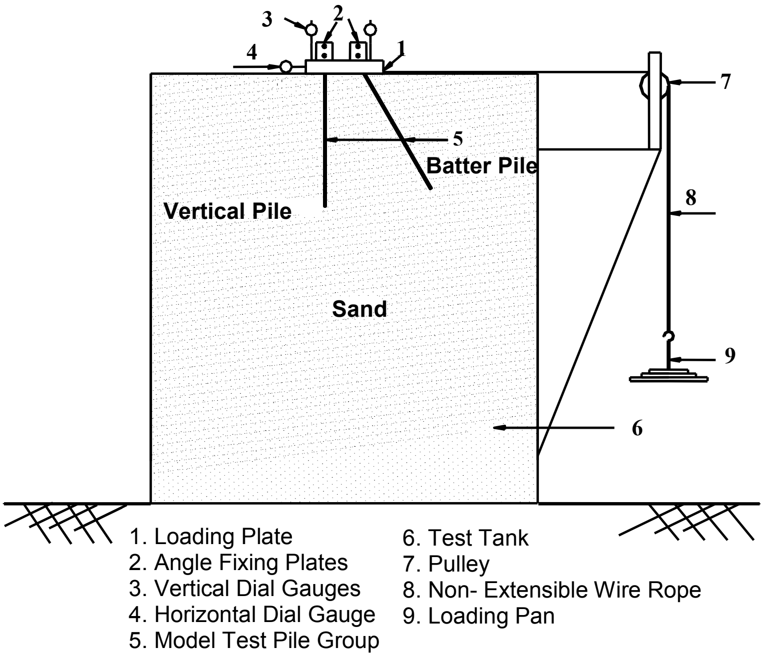


Fig. 3 Model Testing Tank and Loading Arrangement (Schematic)

Loading plates of stainless steel were fabricated for single piles and pile groups (2 x 1) for different spacing (3d, 4.5d and 6d). After placing the piles with the loading plate and angle fixing plates in the tank, sand was poured in the tank through slot hopper keeping the height of fall 350 mm and continuously moving the hopper horizontally manually (rainfall technique) similar to Patra and Pise (2001).

The horizontal load was applied to the loading plate through a pulley arrangement with flexible wire attached to the plate. The other end was attached to the loading pan. The loads were applied by dead weight over the loading pan starting from smallest with gradual increase in stages to get the load-deflection response. Mechanical magnetic base dial gauges having sensitivity of 0.01 mm were used for measuring horizontal displacement, vertical displacement and rotational displacements. Rotation of the loading plate was determined from the corresponding vertical displacements. Vertical displacement is the average of the two vertical dial gauges placed equidistant from the center of the pile/pile group

Test Results

Horizontal Load versus Horizontal Displacement Diagrams

The basic observations from the tests were applied horizontal loads and corresponding horizontal displacement, rotation and vertical displacement. The observed horizontal loads vs. horizontal displacement diagrams were plotted for every test to find out the ultimate horizontal resistance of each pile and pile groups by double tangent method as shown in Figure 4. Typical diagrams of horizontal load vs. horizontal displacement in dense sand are shown through Figures 4 - 7. The trend of horizontal load – displacement diagram is geometrically similar for all test conditions. All the curves are practically linear at an early stage of loading and afterwards they are non- linear.

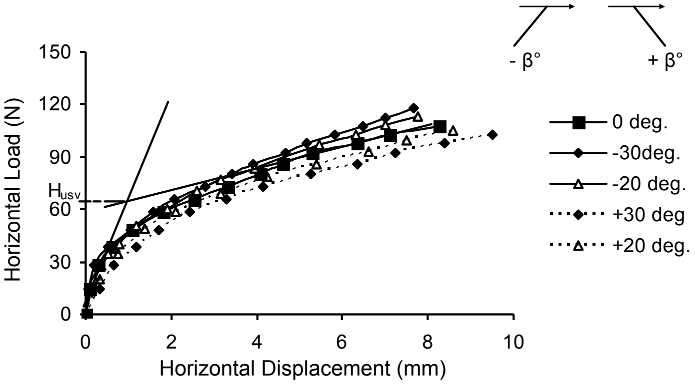


Fig. 4 Horizontal Load vs. Displacement Diagram for Single Pile

For single piles (Figure 4), it is observed that negative batter piles (-10° to -30°) offer more resistance than vertical pile. Positive batter piles (+10° to +30°) offer less resistance than vertical pile.

From Figure 5, it is observed that pile groups (0°, +10°) to (0°, +30°) offer less resistance than vertical pile group.

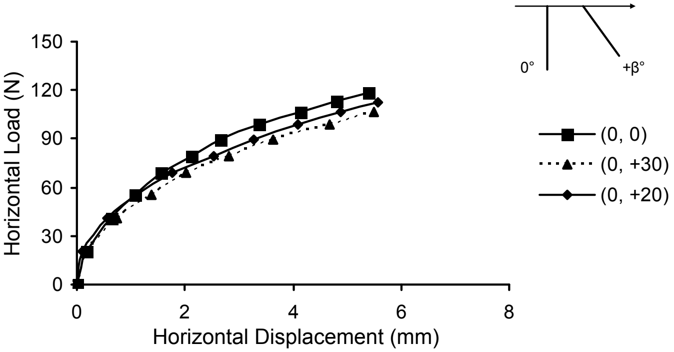


Fig. 5 Horizontal Load vs. Displacement Diagram for Spacing (s = 3d) 2–Pile (0, + β) Group

From Figure 6, it is observed that pile groups (-10°, 0°) to (-30°, 0°) offer more resistance than vertical pile group.

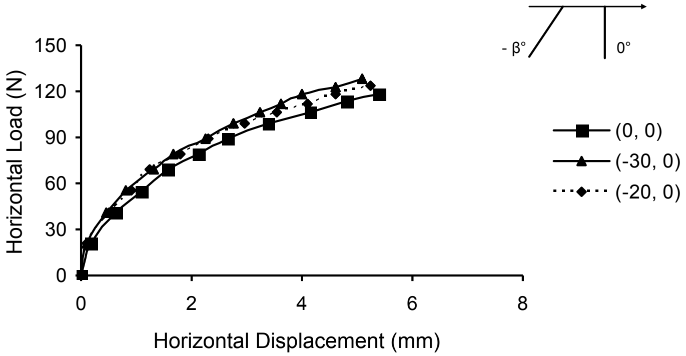


Fig. 6 Horizontal Load vs. Displacement Diagram for Spacing (s = 3d) 2–Pile (-β, 0) Group

From Figure 7, it is observed that pile groups (-10°, +10°) to (-30°, +30°) offer more resistance than vertical pile group.

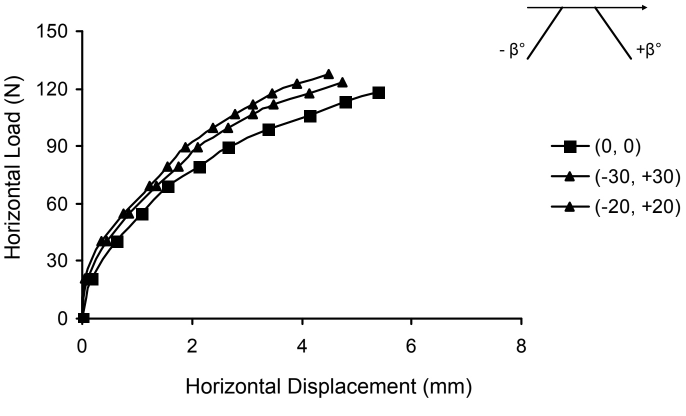


Fig. 7 Horizontal Load vs. Displacement Diagram for Spacing (s = 3d) 2–Pile (-β, + β) Group

Rotation and Vertical Displacement of Single Piles & Pile Groups

The observed horizontal loads vs. rotation and vertical displacement diagrams were plotted for typical tests to study the effect of batter on rotation & vertical displacement of single piles and pile groups (Figures. 8 to 11).

From Figure 8, it is observed that negative batter piles (-30°) offer more resistance to rotation than positive batter piles (+30°).

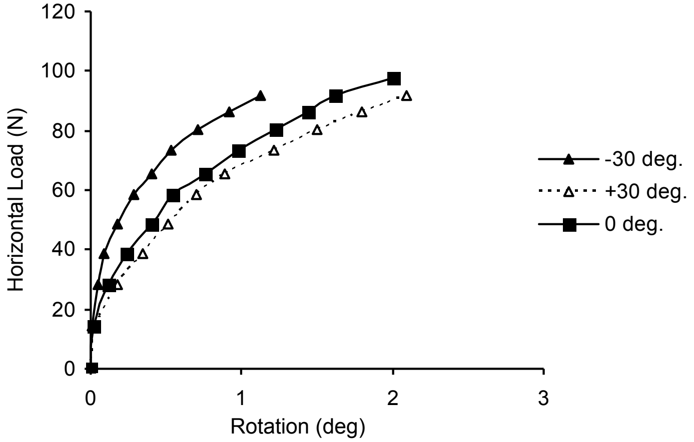


Fig. 8 Horizontal Load vs. Rotation Diagram for Single Pile

From Figure 9, it is observed that vertical displacement of negative batter piles (-30°) is downward whereas, positive batter piles (+30°) it is upward compared to the original position of the pile head.

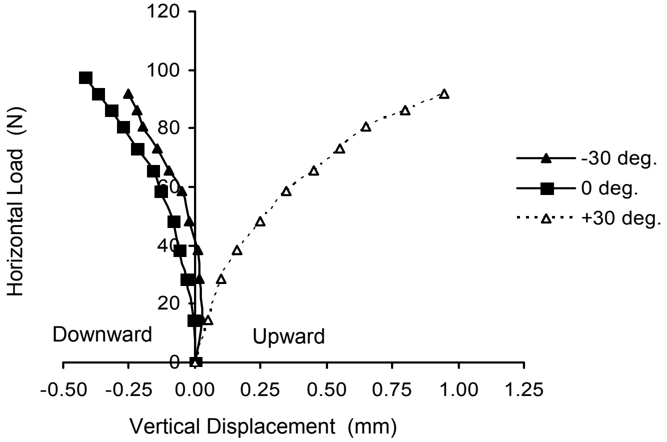


Fig. 9 Horizontal Load vs. Vertical Displacement Diagram for Single Pile

From Figure 10, it is observed that pile groups (-30°, +30°) and (-30°, 0°) offer more resistance to rotation than (0°, +30°) pile groups.

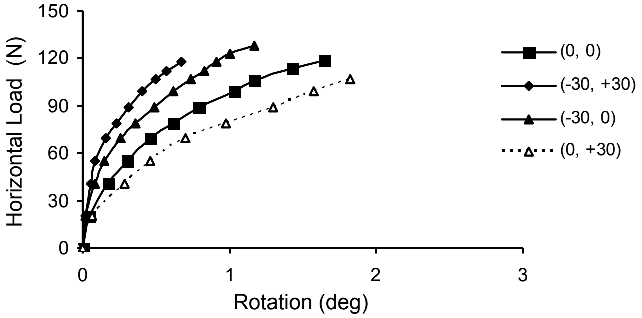


Fig. 10 Horizontal Load vs. Rotation Diagram for Spacing (s = 4.5d) 2– Pile Group

From Figure 11, it is observed that vertical displacement of (-30°, +30°) and (-30°, 0°) pile groups and (0°, +30°) pile groups is downward compared to original position of the pile head.

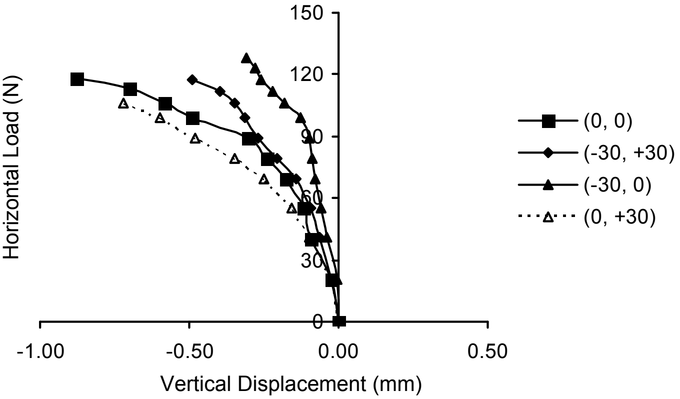


Fig. 11 Horizontal Load vs. Vertical Displacement Diagram for Spacing (s = 4.5d) 2– Pile Group

Group Amplification Factor

Group amplification factor is used for predicting horizontal deflection of pile group considering deflection of a single vertical pile at a particular load in the linear part of load displacement curve. The experimental group amplification factors have been calculated from the load displacement curves. The group deflection per pile is divided by a single vertical pile deflection at a particular load. Accordingly,

$$G_{AF} = y_{gB} / y_s \qquad (1)$$

Where, G_{AF} = group amplification factor with respect to a vertical pile at a particular load, y_{gB} = displacement of a group, y_s = displacement of a single vertical pile.

Analysis of Results

Prediction of Group Amplification Factor

Group amplification factor has been used for predicting the horizontal deflections of pile groups considering the single pile deflection. Analytically, group amplification procedure (GAP) is suggested by (Ooi and Duncan, 1994) for vertical pile groups. The above method has been modified here.

Concept of Deflection

A group of piles deflects more than a single pile subjected to the same lateral load per pile. This is because each pile in a group causes deflection of the surrounding soil, thereby causing added deflections of the other piles. Because the deflections are larger, the bending moments in the piles are also larger. It is useful to define a group deflection amplification factor which, when multiplied by the deflection of a single pile yields the group deflection i.e.

$$y_{gv} = C_y.y_s \qquad (2)$$

Where, y_{gv} = group deflection for vertical pile group, C_y = deflection amplification factor, y_s = single vertical pile deflection under same load.

Deflection Amplification Factor For Vertical Pile Group

Deflection amplification factor C_y is given as (Ooi and Duncan, 1994).

$$C_y = \frac{A + N_{pile}}{B\left(\frac{s}{D} + \frac{P}{CP_N}\right)^{0.5}} \qquad (3)$$

C_y = deflection amplification factor, A = 16 for clay and 9 for sand, N_{pile} = number of piles in group, B = 5.5 for clay and 3 for sand , s = avg spacing of piles, D = dia.of pile, Ps = Pg / N_{pile} = Avg. lateral load per pile, P_g = total lateral load on group of piles, C = 3 for clay and 16 for sand, $P_N = S_uD^2$ clay, $K_p\gamma D^3$ sand, S_u = average undrained shear strength for clay, K_p = passive earth pressure coefficient = $\tan^2 (45 + \Phi/2)$, Φ = average angle of internal friction of sand. From Equation 3 deflection amplification factor is calculated.

Deflection Amplification Factor For Batter Pile Group

For calculating deflection for batter pile groups following modifications are made in the analysis suggested by (Ooi and Duncan, 1994).

Average spacing (s_a) between two piles, at effective depth of 0.25L from the top of soil has been considered. This has been according to the studies of Pise (1981), wherein he has concluded that at $K_R \geq 10^{-2}$ (rigid piles), top layer of depth 0.25L controls the behaviour.

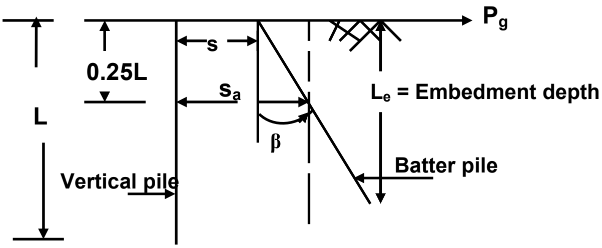


Fig. 12 Evaluation of Average Spacing between Two Piles.

From Figure 12 above,

$$s_a = s + 0.25L\,(\tan\beta) \tag{4}$$

Where,

s_a = average spacing between two piles
s = spacing between two piles at ground surface.

Single pile deflection of a front pile has been considered.

(y_B) = deflection of a front batter pile.

Deflection amplification factor is:

$$C_{yB} = \frac{A + N_{pile}}{B\left(\dfrac{s_a}{D} + \dfrac{P_s}{CP_N}\right)^{0.5}} \tag{5}$$

Where, C_{yB} = deflection amplification factor for a batter pile

Therefore, Group deflection for a batter pile group is:

$$y_{gB} = C_{yB} \,.\, y_B \tag{6}$$

Where, y_{gB} = group deflection for a batter pile group, y_B = deflection of front batter pile.

From Eq. 6 group deflection for batter pile group is calculated. For predicting deflection amplification factor with respect to a single vertical pile, group deflection is divided by single vertical pile deflection as:

$$G_{AF} = y_{gB} / y_s \tag{7}$$

Where, G_{AF} = group amplification factor with respect to vertical pile at a particular load.

Group amplification factors for 2-pile groups have been plotted in Figures 13 to 14. Along with the observed values; the predicted values are also shown in Figures.13 to 14. It is observed that group amplification factor for pile groups

(-β°, 0°) decreases gradually from pile group (0°, 0°) to (-30°, 0°) pile group. Whereas, for pile groups (0°, +β°) amplification factors increase gradually from pile group (0°, 0°) to (0°, +30°) pile group. Predicted (analytical) amplification factors are closer to the experimental factors.

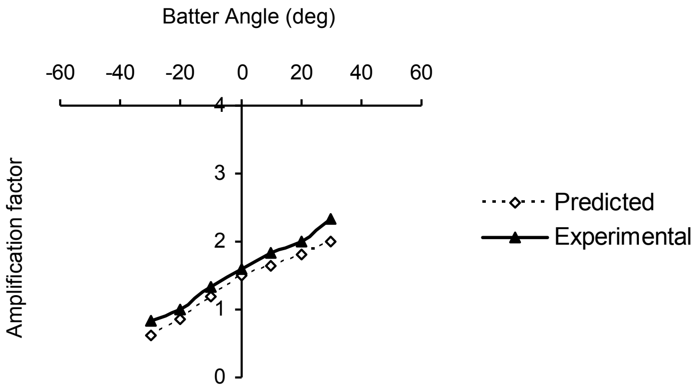


Fig. 13 Effect of Amplification Factor with Respect to Batter Angle for Spacing (s= 3d) 2- Pile Group

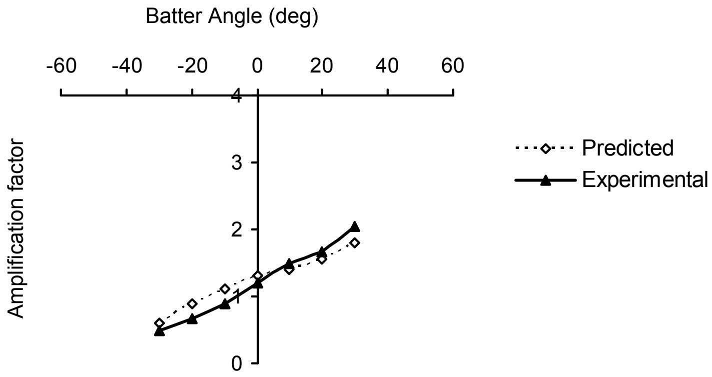


Fig. 14 Effect of Amplification Factor with Respect to Batter Angle for Spacing (s= 4.5d) 2- Pile Group

Prediction of Ultimate Horizontal Resistance

Single vertical pile [Patra and Pise (2001)]

They have made following assumptions for predicting ultimate horizontal load for a single vertical rigid pile.

The passive earth pressure on the front face of the pile can be determined according to Kerisel and Absi (1990) and taking a suitable shape factor.

The active earth pressure on the rear sides of the piles and 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 (Broms 1964)

For a free head fully embedded single vertical rigid pile the ultimate horizontal resistance (H_{usv}) can be calculated as:

$$H_{usv} = 3 \times 0.12\ \gamma\ d\ L^2\ k_b \tag{8}$$

Where,

H_{usv} = ultimate horizontal resistance for a single vertical pile

γ = unit wt. of soil

d = diameter of pile.

L = embedment depth

k_b = coefficient of passive earth pressure on wall [Kerisel & Absi (1990)].

Single batter pile

Equation 8 has been modified here to predict the ultimate horizontal resistance for batter piles:

Following modifications are suggested:

For batter piles, embedment depth is measured vertically from the ground line to the tip of the batter pile with respect to the batter angle as shown in Figure 12. i.e.

$$L_e = L \cos \beta \tag{9}$$

Where,

L_e = embedment depth for batter pile

L = embedment depth for vertical pile

β = batter angle with respect to vertical pile

For calculating passive earth pressure on pile, Kerisel and Absi (1990) have given k_b values according to the batter angle (β), delta (δ), and angle of friction (φ) on retaining wall as shown in Figure 15(a).

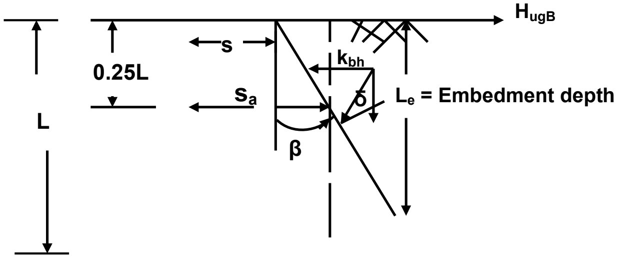


Fig. 15 (a) Component of Forces on Pile Group

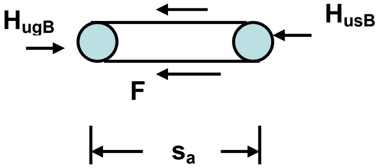


Fig. 15 (b) Batter Pile Group Acted Upon by Different Forces

Putting (L_e) instead of L and using Kerisel and Absi coefficients (1990) (k_b) in the (Eq.8), ultimate horizontal resistance of a single batter pile (H_{usB}) is:

$$H_{usB} = 3 \text{ X } 0.12 \, \gamma \, d \, L_e^2 \, k_{bh} \tag{10}$$

Where,

k_{bh} = horizontal component of passive earth pressure coefficient k_b on inclined wall = $k_b [\cos (\delta + \beta)]$

δ = soil-pile friction angle

Two Pile Group [Patra and Pise (2001)]:

According to them, for 2-pile group ultimate horizontal resistance (H_{ugv}) of vertical piles can be calculated as follows. The general configuration of line pile groups acted upon by forces considered is as shown in Figures 15(a) and 15(b). The ultimate horizontal resistance on a group will be the passive resistance developed on the front pile along with the side resistance.

$$H_{ugv} = 2F + H_{usv} \tag{11}$$

Where,

H_{ugv} = ultimate horizontal resistance of a vertical pile group

F = frictional resistance on the vertical plane along the side of the pile group of width equal to center to center distance between extreme piles

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

$$2F = \gamma L^2 \times k_s s \tag{12}$$

Where,

k_s = coefficient of earth pressure along the side of pile group governing frictional resistance [(1- sin φ) tan δ]

s = spacing between two piles

From Equations 8 and 12, the ultimate horizontal resistance for 2-pile group is,

$$H_{ugv} = \gamma L^2[k_s s + 0.36\ d\ k_b] \tag{13}$$

Two Pile Group of Batter Piles

Equation 13 has been modified here to calculate ultimate horizontal resistance for batter pile groups. The following modifications have been made.

Passive resistance is considered on the front pile only. For calculating frictional resistance, (F) modified embedment depth (L_e) is used. For calculating the average spacing (s_a) between two piles, the spacing at effective depth of 0.25L from the top of soil has been considered (Eq.3). Further,

$$2F = \gamma L_e^2 \times k_s s_a \tag{14}$$

Therefore, the ultimate horizontal resistance for 2-pile group of batter piles is:

$$H_{ugB} = \gamma L_e^2\ [k_s s_a + 0.36\ d\ k_{bh}] \tag{15}$$

Where,

H_{ugB} = ultimate horizontal resistance for batter pile group

Comparison of Experimental and Analytical Ultimate Horizontal Resistance

Figure16 shows the ultimate horizontal resistance vs. batter angle for single piles along with experimental and analytical results. Geometrically the trend is similar. It is observed that horizontal resistance of negative batter piles (- β°) gradually increases from 0° batter to -30° batter. Whereas, for positive batter piles (+ β°) the resistance decreases gradually from 0° batter to +30° batter. For negative batter piles slip surfaces are deflected downward and for positive batter pile slip surfaces are deflected upward. Also for negative batter piles where the face in contact have higher coefficients of passive lateral earth pressure than piles where the face in contact with the soil has positive batter. Therefore, negative batter piles offer more resistance than positive batter piles.

Similarly for 2- pile groups Figures 17 to 19 geometrically the trend is similar. It is observed that as the spacing between the piles increases horizontal resistance increases.

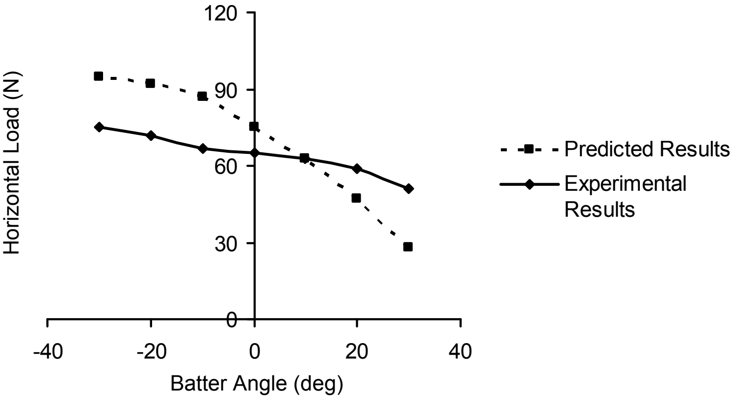


Fig. 16 Ultimate Horizontal Resistance vs. Batter Angle for Single Pile

At constant spacing for (0°, +β°) pile groups (Figure 17) horizontal resistance decreases from (0°, +10°) to (0°, +30°) groups as compared to vertical pile groups.

At constant spacing for (-β°, 0°) pile groups (Figure 18) horizontal resistance increases from (-10°, 0°) upto (-30°, 0°) groups as compared to vertical pile groups.

At constant spacing for (-β°, +β°) pile groups (Figure 19) horizontal resistance increases from (-10°, +10°) upto (-30°, +30°) groups as compared to vertical pile groups.

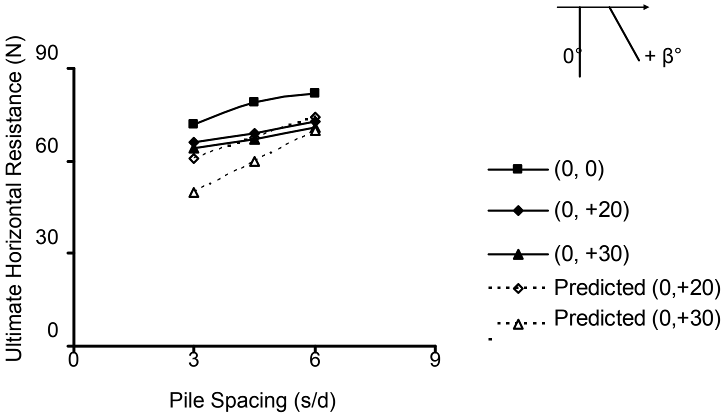


Fig. 17 Ultimate Horizontal Resistance vs. Spacing for 2-Pile (0, + β) Group

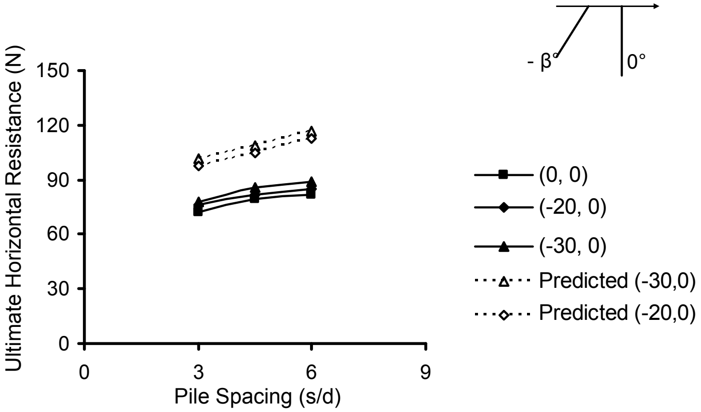


Fig. 18 Ultimate Horizontal Resistance vs. Spacing for 2-Pile (-β, 0) Group

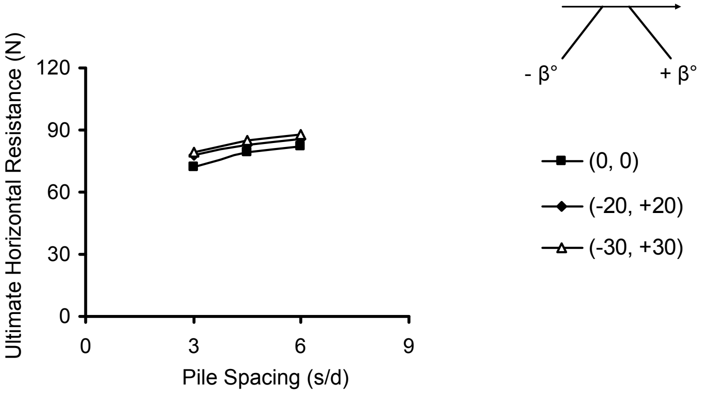


Fig. 19 Ultimate Horizontal Resistance vs. Spacing for 2-Pile (-β, + β) Group

Figures 16 to 19 show ultimate horizontal resistance vs. batter angle for single piles and pile groups. It is observed from Figures 16 to 18, that the ultimate horizontal resistance predicted by proposed method overestimates the resistance by 25% to 40% for negative batter piles (- β°) and (-β°, 0°) pile groups. However, positive batter piles (+β°) and pile groups (0°, +β°) the method underestimates the resistance by 10% to 35%.

Group Efficiency

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

$$\eta = H_{ugB} / n_1 n_2 H_{usv} \quad (16)$$

Where,

η = group efficiency

H_{ugB} = ultimate horizontal capacity of a pile group

H_{usv} = ultimate horizontal capacity of a single vertical pile

n_1 = number of rows in a pile group

n_2 = number of columns in pile group

The group efficiency has been estimated with respect to the single vertical pile here from experimental results.

Figures 20 to 22 show the group efficiency vs. pile spacing. It is observed that the efficiency increases with increase in pile spacing. It is influenced marginally by the presence of batter piles in a group and direction of loading. Group efficiency values lie between 0.5 to 0.7 for all groups tested. The lower values are associated with 3d spacing and higher values with 6d spacing.

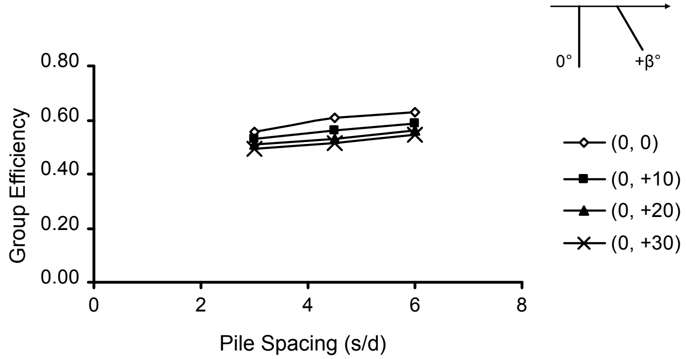


Fig. 20 Group Efficiency vs. Spacing for (0, + β) Pile Group

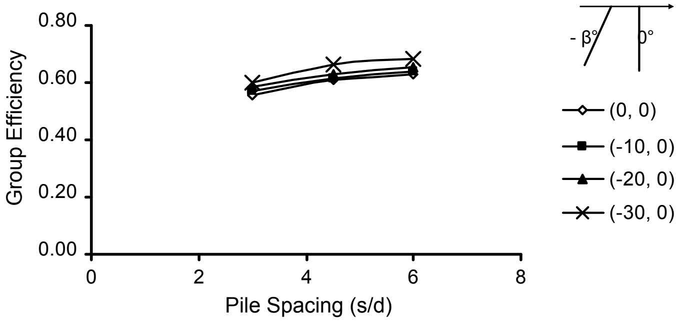


Fig. 21 Group Efficiency vs. Spacing for (-β, 0) Pile Group

At constant spacing, for (0°, +β°) pile groups (Figure 20), the efficiency decreases with respect to vertical pile group (0°, 0°). Further, efficiency decreases with increasing batter angle (0°, +10°) to (°0, +30°).

At constant spacing, for (-β°, 0°) pile groups (Figure 21), the efficiency increases with respect to vertical pile group (0°, 0°) upto (-30°, 0°) pile group.

At constant spacing, for (-β°, + β°) pile groups (Figure 22), the efficiency increases with respect to vertical pile group (0°, 0°) upto (-30°, +30°) pile group.

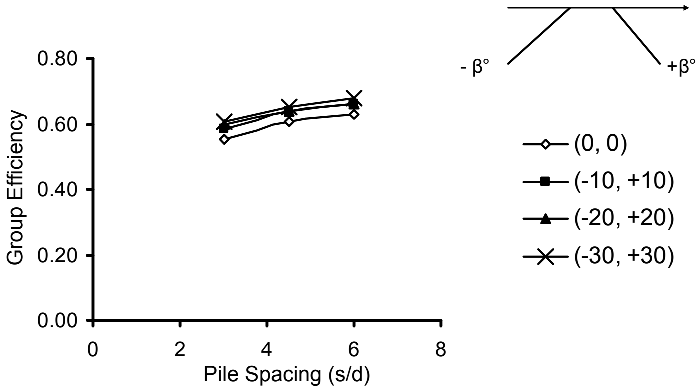


Fig. 22 Group Efficiency vs. Spacing for (-β, + β) Pile Group

Conclusions

The following conclusions are drawn from the present study:

The horizontal load – horizontal displacement curves are practically linear at early stage of loading and afterwards they are non-linear.

Negative batter single piles (-10° to -30°) offer 15-25% more resistance and positive batter piles (+10° to +30°) offer 20-30% less resistance than vertical pile.

Pile groups (0°, +10°) to (0°, +30°) offer 25-35% less resistance as compared to vertical pile group. Pile groups (-10°, 0°) to (-30°, 0°) and (-10°, +10°) to (-30°, +30°) offer 15-35% more resistance as compared to vertical pile group.

Group amplification factors for pile groups (-β°, +β°) and (-β°, 0°) decreases gradually from 0° to -30° batter. Whereas, for pile groups (0°, +β°) amplification factors increase gradually from 0° to +30° batter. Proposed method predict results which are closer to the experimental values.

The proposed method of predicting ultimate resistance overestimates the resistance by 25- 40% for negative batter piles and (-β°, 0°) pile groups. However, for positive batter piles and (0°, +β°) groups the method underestimates the resistance by 10 – 35%.

Group efficiency increases with increase in pile spacing and it is influenced marginally by the presence of batter piles in a group and direction of loading.

Notations

The following symbols are used in this paper:

C_y = deflection amplification factor
C_{yB} = deflection amplification factor for batter pile
E_pI_p = flexural rigidity of pile
G_{AF} = group amplification factor
H_{usv} = ultimate horizontal resistance for single vertical pile
H_{usB} = ultimate horizontal resistance for single batter pile
H_{ugv} = ultimate horizontal resistance for vertical pile group
H_{ugB} = ultimate horizontal resistance for batter pile group
k_b = coefficient of passive earth pressure on wall
k_{bh} = horizontal component of passive earth pressure coefficient k_b on a pile
k_s = coefficient of earth pressure along the side of pile group governing frictional resistance
K_p = passive earth pressure coefficient
K_{rs} = pile flexibility factor
L = length of pile
L_e = embedment depth for batter pile
N_{pile} = number of piles in a group
s_a = average spacing between two batter piles
T = relative stiffness factor
y_{gB} = group deflection for batter pile group
y_s = deflection of single vertical pile
y_B = deflection of single batter pile
β = batter angle with respect to vertical axis
η = group efficiency

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