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# Oblique Pull-out Resistance of Model Pile Groups

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## Introduction

Structures such as transmission towers, jetty structures, and mooring system for surface and submerged platforms, bridge abutments are constructed on pile foundations wherein piles are subjected to oblique pulling loads. Pile groups are in use to resist and sustain pulling loads. It is, therefore, imperative to understand the pile group-soil-loading interaction phenomenon and the ultimate resistance of pile groups under oblique pulling loads. To make the foundation safe, both in economy and design, the effects of various parameters like group size, its configuration, embedment length to diameter ratio of piles, soil-pile friction angle, soil type and angle of inclination of the load on pile groups need to be investigated.

## Brief Review of Literature

Earlier experimental results on pile groups under uplift loads are reported by Meyerhof and Adams (1968), Das et al. (1976a), Subba Rao and Venkatesh (1985), Chattopadhyay (1994), Mukherjee and Venkatnarayana (1996). Similarly studies on the ultimate lateral resistance of single pile and pile groups are reported by (Broms, 1964; Oteo, 1972; Williams, 1979; Meyerhof et al., 1981a; Chattopadhyay and Pise, 1986a; Meyerhof et al., 1988; McVay et al., 1995; Wakai et al., 1999; Prasad and Chari, 1999; and Patra and Pise, 2001).

Model test results and field test results of single pile under oblique pulling load have been reported by Yoshimi (1964), Meyerhof (1973a, b), Das et al. (1976b), Chattopadhyay and Pise (1986b) and Ismael (1989).

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Investigations on pile groups under inclined compressive loads were carried out by Meyerhof and Ranjan (1973), and Meyerhof et al. (1981b). Experimental results on pile groups under oblique pull and up to the failure load are not reported in the literature.

However, systematic investigations on the qualitative and quantitative influence of parameters such as embedment length L to diameter d ratio, L/d, of piles, configuration and geometry of the group, number of piles, spacing, soil-pile friction angle and angle of obliquity of the load, on the ultimate oblique resistance are practically unavailable. Therefore, there is a need to study the behaviour of pile groups subjected to oblique pulling load considering above parameters for proper understanding of pile-soil-loading interaction.

## Scope of the Study

Laboratory model tests on group of piles of size 2 × 1, 3 × 1, 2 × 2 and 3 × 2 along with single pile have been carried out in uniform sand under oblique pulling loads. The qualitative and quantitative influence of the parameters such as L/d ratio, configuration/geometry of the pile group, number of piles in a group, spacing, soil-pile friction angle and the angle of obliquity on the ultimate resistance and efficiency of the pile groups has been investigated

## Experimental Set-up and Testing Programme Foundation

Dry Ennore sand was used as foundation medium in a model tank of size 0.914 m × 0.762 m × 0.914 m deep. The selection of sand as foundation medium was made because reproducible densities can be achieved reasonably well. The specific gravity and uniformity coefficient of sand were 2.64 and 1.6 respectively. The sand grains were sub angular. The limiting void ratios were $e_{min} = 0.552$ and $e_{max} = 0.864$ corresponding to maximum and minimum dry densities $(g_d)_{Max} = 1.70$ g/cc and $(g_d)_{Min} = 1.43$ g/cc.

The technique of sand placement plays an important role in the process of getting reproducible density in a reasonable amount of time. Sand was poured manually in the tank through the slot hopper moving it horizontally (rainfall technique) and keeping the height of fall of sand particles constant. When the height of fall was 450 mm, the density of 1.64 g/cc is achieved and the corresponding relative density was 80%. The corresponding angle of shearing resistance $\phi$ measured by direct shear test was 37° .

## Piles and Pile Caps

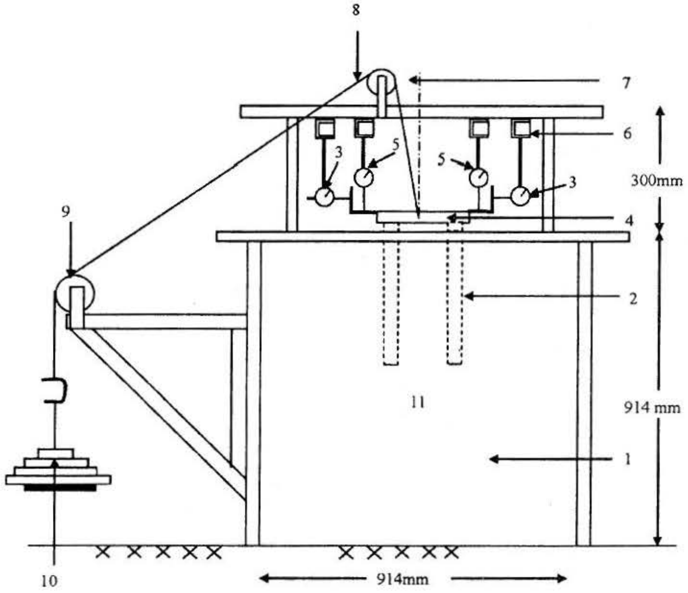
Aluminium alloy tubes of 19 mm outer diameter, 0.81 mm wall thickness were used as model piles. Fine Ennore sand passing through 600 micron sieve and retaining on 425 micron sieve was coated on the surface of smooth piles by adhesive (feviquick) to make them rough. The average out side diameter for rough pile was 20 mm. The L/d ratios of piles used were 12 and 38. For convenience, piles having L/d = 12 are referred as short and L/d = 38 as long. The soil-pile friction angle $\delta$ between the surfaces of piles and foundation medium was evaluated from the direct shear test. In direct shear test, the aluminium plates were placed over the sand. Two aluminium plates have been used for direct shear test, out of which one plate has been coated on its surface by fine Ennore sand. The sand has been filled in the shear box by rainfall technique to achieve the density 1.64 g/cc. The soil-pile friction angles were found to be 20° (for aluminium tube, referred as smooth) and 31° (for aluminium tube surface coated with fine Ennore sand, referred as rough). The relative stiffness of pile, $K_{rs}$, may be expressed as $K_{rs} = \left(E_p I_p\right) / \left(\eta_h L^5\right)$ (Poulos and Davis, 1980), where, $E_P$ = modulus of elasticity of pile, $I_P$ = moment of inertia of pile, L = length of pile, $\eta_h$ = coefficient of horizontal sub-grade reaction. The coefficient of subgrade reaction'$h_h$', for a free head long pile (L/d = 38) is calculated from the experimentally obtained load-deflection curves and the solutions given by Matlock and Reese (1961). It is estimated at the ultimate and at half the ultimate load, and the average of these two values is considered here. The short (L/d = 12) and long piles (L/d = 38) have pile flexibility factors $K_{rs}$ of $1.02 \times 10^{-2}$ and $3.43 \times 10^{-4}$ (Patra and Pise, 2001). The model piles were open-ended. Aluminium plate was used as pile cap for different spacing.

## Model Tests

Pile groups of configuration 2 × 1, 3 × 1, 2 × 2 and 3 × 2, having L/d ratios 12 and 38, spacing between the piles as 3d, 4.5d and 6d were tested. In addition to the groups, single pile tests were also carried out. The piles and pile groups were subjected to oblique pulling loads at angles 0°, 30°, 60° and 90° with the vertical axis of the pile group. The inclination angle lied in the vertical plane. The plane passed through the axis of the group and was parallel to the length of the group. Four sets of flexible wire ropes with one end connected with specially fabricated knobs were used for the application of load. The wire ropes were connected with the knobs at angles of 0°, 30°, 60° and 90° with the vertical. The load was applied at the bottom of the pile cap at the desired angle through the double pulley arrangement as shown in Fig.1.

## Experimental Procedure

The schematic diagram of test set-up showing loading arrangement is shown in Fig.1. Pile caps of aluminium alloy were fabricated for both single



1. Model Tank
2. Model Piles in a Pile Group (2 × 1)
3. Horizontal Dial Gauge
4. Pile Cap
5. Vertical Dial Gauge
6. Magnetic Base Plate
7. Pulley 1
8. Wire Rope
9. Pulley 2
10. Loads
11. Sand Deposit

**FIGURE 1 : Experimental Setup**

pile, 2 × 1, 3 × 1, 2 × 2 and 3 × 2 groups for spacing 3d, 4.5d and 6d. After placing the piles with the pile cap in the empty model tank, the sand was poured in the tank through slot hopper keeping the height of fall 450 mm and continuously moving the hopper horizontally manually (rainfall technique). Flexible wire rope was attached to the pile top through specially fabricated knob fitted at the center of the pile cap so that the load can be applied at the bottom of the pile cap at the desired obliquity without inducing eccentricity. The other end of the wire rope was attached to the loading pan. The loads were applied by dead weight over the loading pan starting from the smallest and increasing gradually in stages. Mechanical magnetic base dial gauges having sensitivity of 0.01 mm were used for measuring axial and lateral displacements. The density of sand was checked by a specially fabricated laboratory dynamic penetrometer. It consists of a 9.5 mm diameter solid mild steel rod with a conical tip (angle 60°) at the bottom. It was provided with an arrangement for the free fall of 2.49 kg annular weight through a height of 300 mm on square platform, which was fixed to the penetrometer rod. The penetrometer rod was 750 mm high. Typical values of the number of blows for penetration of 150 mm, 300 mm, 400 mm and 500 mm at density 1.64 g/cc were 2, 5, 9 and 13. This gave the qualitative idea about the uniformity of density attained along the depth. The numbers of blows were recorded by the penetrometer at some distance from the edges of the tank. They were more or less the same for equal penetration confirming the uniformity of density in all the tests. As the penetrometer rod was 750 mm high from the fixed platform, it covers the entire depth of the model tank for checking the sand density.

## Test Results

### *Oblique Pull-Displacement Diagrams*

Typical diagrams of oblique pull versus axial displacements, normal displacements and rotation diagrams for L/d = 38 and 3 × 1 pile groups ($\theta$ = 60° condition) are shown through Figs.2(a) to 2(c). These diagrams are discussed, for convenience, under three broad category as (i) Pile groups under axial pull ($\theta$ = 0°), (ii) Pile groups under oblique pull ($\theta$ = 30° and 60°) and (iii) Pile groups under lateral pull ($\theta$ = 90°). In general, all the load-displacement curves are non-linear.

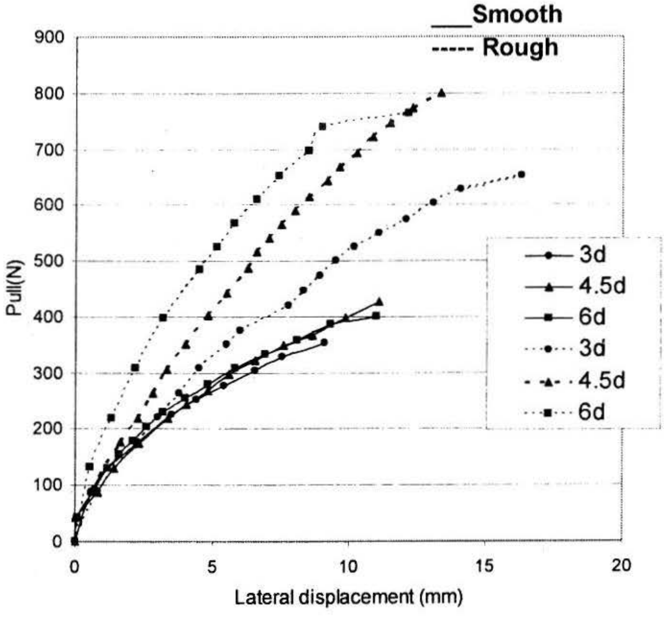


**FIGURE 2(a) : Oblique Pull versus Lateral Displacement ($\theta$ = 60°, L/d = 38, 3 × 1 Pile Group)**

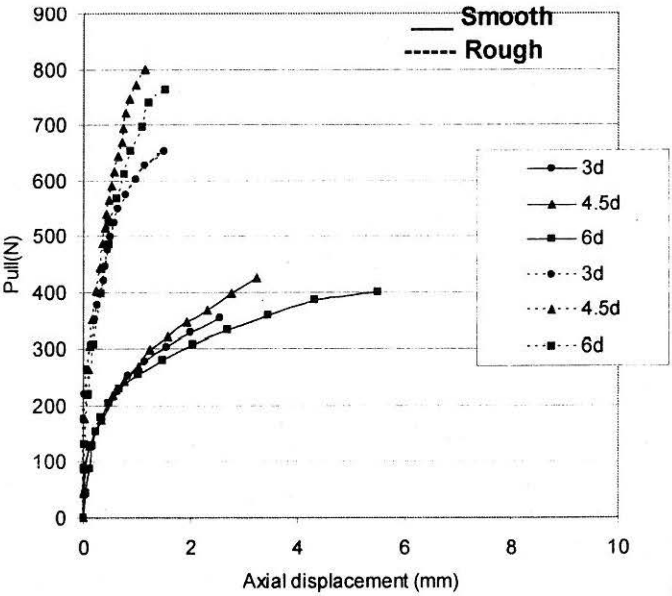


FIGURE 2(b) : Oblique Pull versus Axial Displacement ($\theta$ = 60°, L/d = 38, 3 × 1 Pile Group)

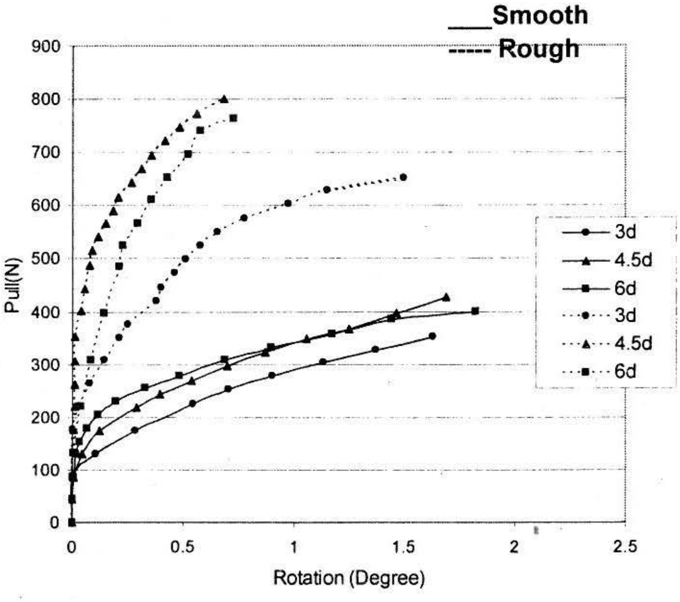


FIGURE 2(c) : Oblique Pull versus Rotation ($\theta$ = 60°, L/d = 38, 3 × 1 Pile Group)

### *Pile Groups under Axial Pull*

At a particular displacement, the axial pull increases with the increase in spacing of piles in a group. Axial failure is considered when addition of a small load increment results in large movements. In this condition the load –displacement curves become roughly parallel to the displacement axis.

For smooth pile groups the axial movement of 0.026d to 0.16d for L/d = 12, and 0.25d to 0.65d for L/d = 38, is required to mobilize the ultimate resistance. For rough pile groups it is small and lies between 0.05d to 0.16d for all spacing.

It may, therefore, be concluded that in general the axial movement required to attain the ultimate resistance for smooth pile groups is higher than that required for rough pile groups. Rough pile groups offer more resistance than the smooth ones.

### *Pile Groups under Oblique Pull*

Three types of displacement curves are observed for the pile groups under oblique pull ($\theta = 30°$ and $\theta = 60°$ conditions). They are pull versus axial displacement, pull versus normal displacement and pull versus rotation. The natures of these curves on the verge of failure are of two types. In one case, these curves are asymptotic to the displacement axis and in other case they fall into a straight line after maintaining a nonlinear profile (as noted by Meyerhof, 1973). Generally, rough pile groups offer more resistance than smooth groups.

#### *Pull Versus Axial Displacement Diagrams*

For smooth pile groups it is observed that whenever the axial failure occurred large axial displacement in the range 0.26d to 0.65d is noted. For rough pile groups it is associated with smaller values in the range of 0.105d to 0.16d. At a particular axial movement the magnitude of pull increases with increase in $\theta$ (30° and 60°) indicating the influence of the normal component and rotation on the pull versus axial displacement of the groups. Also, the pull increases with the increase in spacing.

#### *Pull Versus Normal Displacement Diagrams*

From the pull versus normal displacement diagrams, it is observed that bending failure occurs at a pile head displacement in the range of 0.11d to 0.63d for all the groups. In general, the magnitude of the pull at failure for $\theta = 30°$ and 60° conditions increases with the increase in spacing and inclination of the load. However for long (L/d = 38) rough pile groups it decreases at failure for $\theta = 30°$ and $60°$ conditions. This indicates that the influence of axial component on the normal-load displacement response for long rough pile groups is less.

### *Pull Versus Rotation Diagrams*

Rotation of the pile head is measured from the relative axial displacements of the pile group by the dial gauges. Rotation of the pile head is observed for $\theta \geq 30°$condition. They are more predominant at larger pile spacing. For smooth pile groups, bending failure due to rotation is observed at about 0.5° to 2.5°. Rotation increases with the increase in the inclination of the load and spacing.

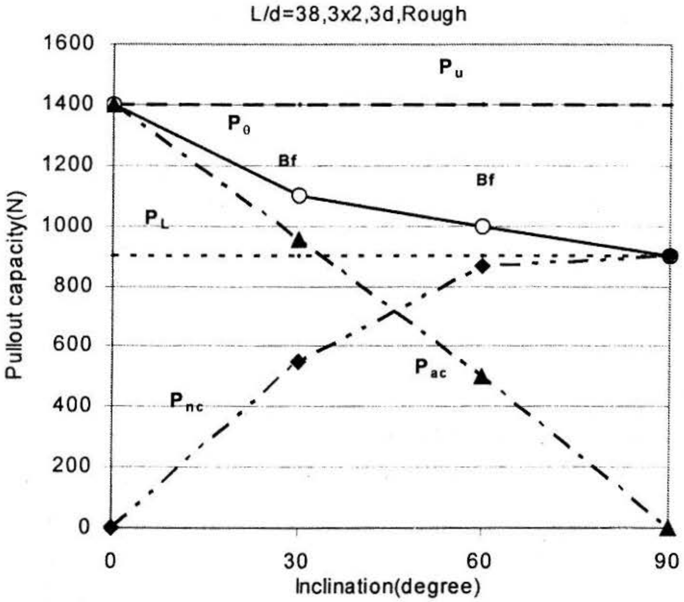
### ***Pile Groups under Lateral/Normal Pull***

For a particular normal movement of the pile group the pull increases with the increase in spacing. Bending failure occurs at pile head displacement between 0.1d to 0.4d for short pile groups ($L/d = 12$), and between 0.35 to 0.6d for long pile groups ($L/d = 38$). Rotation of the pile cap is observed for all the groups. Bending failure due to rotation occurs at a rotation of about 0.5° to 1° for short pile groups ($L/d = 12$) and at about 0.5° to 1.5° for long pile groups ($L/d = 38$). For a particular value of the pull, the rotation decreases with the increase in soil-pile friction angle, $\delta$.

### ***Failure Modes***

The modes of failure of a pile group are classified based on the relative magnitude of the ultimate axial uplift capacity and ultimate lateral resistance of the pile group. If the axial component of the oblique pull attains first the critical value equal to the ultimate axial uplift capacity, while the normal/lateral component remains less than the ultimate lateral capacity, it is termed as the axial failure mode (AF). However, if the normal component reaches first the critical value equal to the ultimate lateral capacity while the axial component is smaller than the ultimate axial capacity bending failure mode (BF) will occur. The failure mode is referred here as either axial (AF) or bending (BF) accordingly. Generally the modes of failure, axial or bending failure modes are decided from the load–displacement curves.

It is noted that the axial failure occurred at $\theta \leq 30°$ and bending failure for $\theta \geq 60°$ for all smooth pile groups (short and long) for all spacing. For rough short ($L/d = 12$) pile groups, the axial failure occurred for $\theta \leq 30°$ and bending failure for $\theta \geq 60°$. However, for rough long ($L/d = 38$) pile groups, the axial failure is noted for $\theta = 0°$ and bending failure for $\theta \geq 30°$. Typical diagram of failure mode is shown in Fig.3.



$P_u$ = Ultimate Axial Capacity of Pile Group
$P_L$ = Ultimate Lateral Capacity of Pile Group
$P_q$ = Oblique Pull-out Capacity
$P_{ac}$ = Axial Component of Oblique Pull
$P_{nc}$ = Normal/Lateral Component of Oblique Pull
BF = Bending Failure

**FIGURE 3 : Failure Mode under Oblique Pull (L/d = 38, Rough, 3 × 2 Pile Group, 3d Spacing)**

### *Ultimate Resistance of Pile Groups*

#### *Pile Groups under Axial Pull*

The ultimate resistance of pile groups under axial pull has been estimated from the load-axial displacement diagrams. It is taken as the load at which the piles move out of the soil. In such conditions the pull versus axial movement curves become parallel to the displacement axis and maintains continuous displacement increase with no further increase in pull.

#### *Pile Groups under Oblique Pull*

The ultimate resistance of a pile group under oblique pull for $\theta = 30°$ and $60°$ conditions have been estimated from the oblique pull versus displacement diagrams. It is taken as the point at which the curve exhibits a peak or maintains a continuous displacement increase with no further increase in pull. The minimum load obtained from these diagrams is taken as the ultimate resistance.

### *Pile Groups under Normal/Lateral Pull*

Ultimate resistance of pile groups under normal/lateral pull has been estimated from the load versus normal displacement and rotation diagrams. The minimum load obtained from these diagrams is taken as the ultimate resistance. It is taken as the point at which the curve maintains a continuous displacement increase with no further increase in pull.

### ***Group Efficiency***

The variation of the ultimate resistance of a pile group under oblique pull is expressed by the group efficiency '$\eta$'. It reflects the effect of spacing of piles in a group. It also gives an idea about the effect of group size and its configuration. Group efficiency '$\eta$' is expressed as

$$\eta = \frac{Q_g}{nQ_s} \tag{1}$$

where $\eta$ = group efficiency
$Q_g$ = ultimate resistance of a pile group
$Q_s$ = ultimate resistance of a single pile
n = number of piles in a pile group

### ***Pile Groups under Axial Pull***

The group efficiencies of the pile groups under axial uplift are shown in Fig.4. Generally, the group efficiency increases with the increase in spacing. For short pile groups ($L/d = 12$), it is about 65 to 80% for 2 × 1 groups, 80 to 120% for 3 × 1 groups, 50 to 100% for 2 × 2 groups and 50 to 85% for 3 × 2 pile groups. The efficiency for rough pile groups is about 10 to 30 % more than the smooth groups.

For long pile groups ($L/d = 38$) the efficiency is about 80 to 180% for 2 × 1 groups, 65 to 135% for 3 × 1 groups, 75 to 120% for 2 × 2 groups and 60 to 150% for 3 × 2 pile groups. The efficiency for smooth pile groups is about 20 to 40% more than the rough groups.

For rough pile groups the efficiency decreases with an increase in number of piles in a group and with the change in pile group configuration from a line to square or to a rectangular group. Meyerhof and Adams (1968) and Das et al. (1976a) have reported similar trend for rough pile groups.

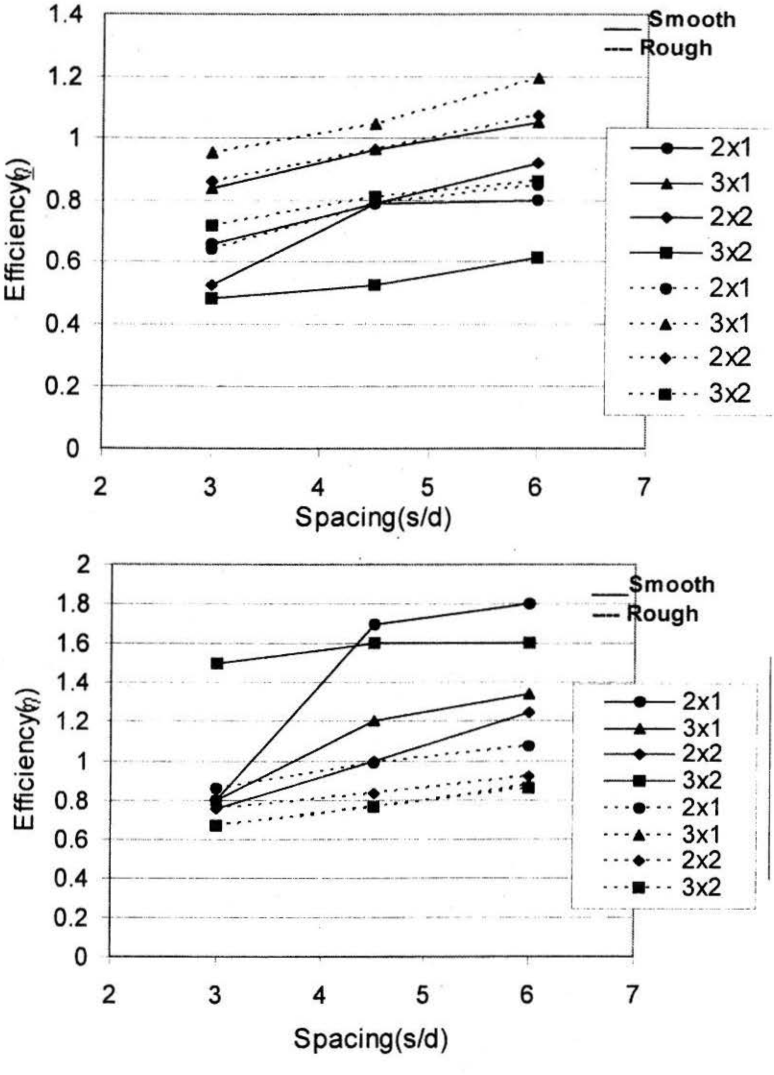


**FIGURE 4 : Group Efficiency versus Pile Spacing ($\theta$ = 0°)**
**(a) L/d = 12, (b) L/d = 38**

### *Pile Groups under Oblique Pull*

#### *$\theta$ = 30° Condition*

The group efficiencies of pile groups under $\theta$ = 30° condition are shown in Fig.5. It increases roughly linearly with increase in spacing. For short pile groups (L/d = 12), it is about 50 to 90% for 2 × 1 groups, 80 to 95% for 3 × 1 groups, 60 to 80% for 2 × 2 groups and 50 to 80% for

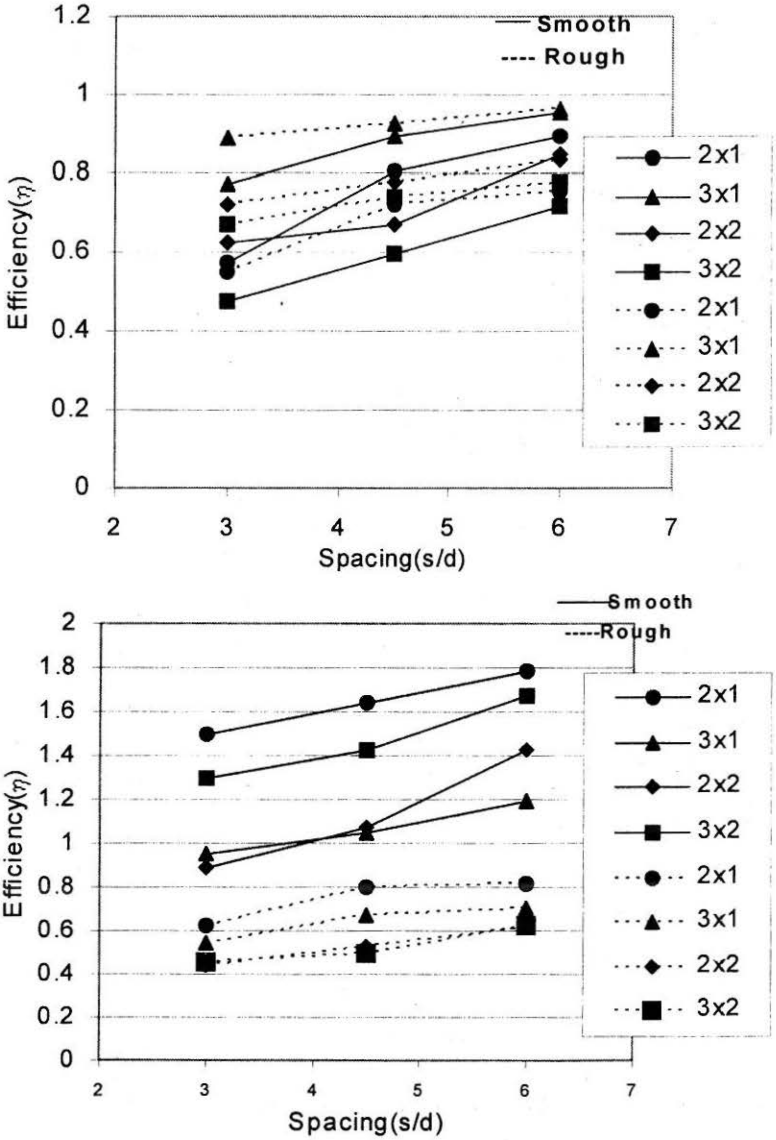


**FIGURE 5 : Group Efficiency versus Pile Spacing ($\theta$ = 30°)**
**(a) L/d = 12, (b) L/d = 38**

3 × 2 pile groups. The efficiency for rough pile groups is about 10 to 15% more than the smooth groups

For long pile groups, the group efficiency is about 60 to 180% for 2 × 1 groups, 50 to 120% for 3 × 1 groups, 40 to 120% for 2 × 2 groups and 45 to 160% for 3 × 2 groups. The efficiency for smooth pile groups

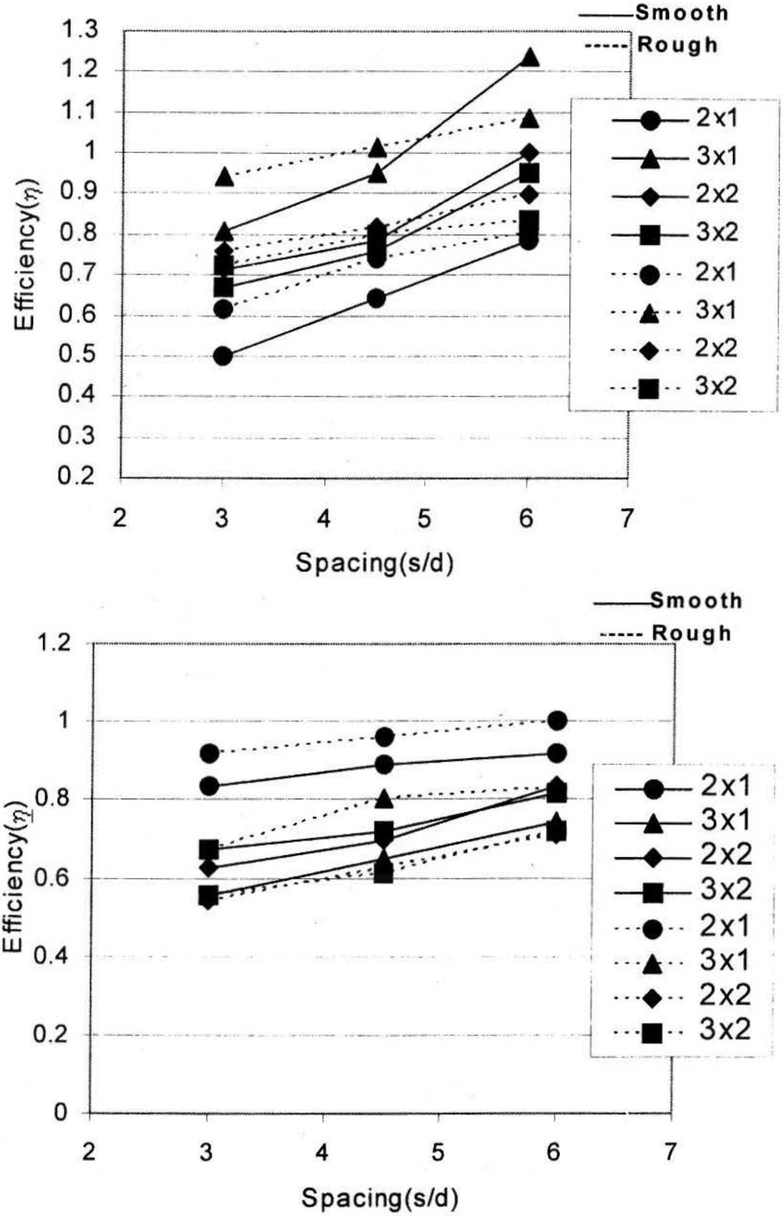


**FIGURE 6 : Group Efficiency versus Pile Spacing ($\theta$ = 60°)**
**(a) L/d = 12, (b) L/d = 38**

is about 40 to 50% more than the rough pile groups.

For all rough pile groups it decreases with increase in the number of piles in a group and with the change in pile group configuration from a line

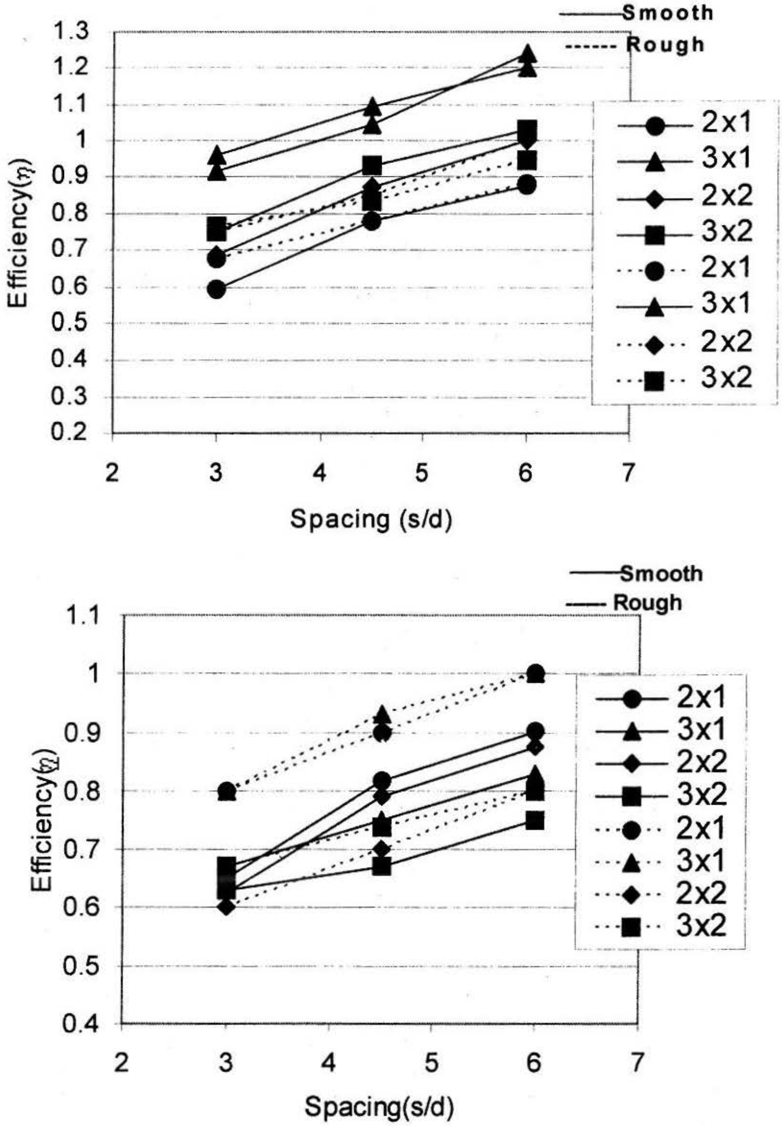


**FIGURE 7 : Group Efficiency versus Pile Spacing ($\theta$ = 90°)**
**(a) L/d = 12, (b) L/d = 38**

to square or to a rectangular group. Similar observations are noted for the pile groups for $\theta = 0°$ condition.

*$\theta$ = 60° Condition*

The group efficiencies of pile groups for $\theta = 60°$ condition are shown in Fig.6. The group efficiency increases linearly with spacing. For short pile groups (L/d = 12), it is about 50 to 80% for 2 × 1 groups, 80 to 120% for 3 × 1 groups, 75 to 100% for 2 × 2 groups and 60 to 90% for 3 × 2 pile groups. The efficiency for rough pile groups is about 10% higher than for smooth groups.

For long pile groups (L/d = 38), the efficiency is about 90 to 100% for 2 × 1 groups, 60 to 80% for 3 × 1 groups, 50 to 80% for 2 × 2 groups and 45 to 80% for 3 × 2 groups. In general, the efficiency for rough pile groups is about 10-20% more than the smooth groups. It decreases with increase in number of piles in a group and with the change in pile group configuration from a line to square or to a rectangular group as reported for $\theta = 0°$ and 30° conditions.

### *Pile Groups under Normal/Lateral Load*

The group efficiencies of pile groups for $\theta = 90°$ condition is shown through Fig.7. In general, the group efficiency increases linearly with increase in spacing.

For short pile groups, the group efficiency is about 60 to 90 % for 2 × 1 groups, 90 to 124 % for 3 × 1 groups, 68 to 100% for 2 × 2 groups and 75 to 100% for 3 × 2 pile groups. Generally rough pile groups are more efficient than smooth pile groups. The efficiency for rough pile groups is marginally i.e., about 5-10 % more than the smooth groups.

For long pile groups, the group efficiency is about 65 to 100% for 2 × 1 groups, 70 to 100 % for 3 × 1 groups, 60 to 90% for 2 × 2 groups and 60 to 80% for 3 × 2 pile groups. In general, the efficiency for rough pile groups is marginally i.e, about 5-10 % more than that of smooth groups. It decreases with increase in number of piles in a group and also with the change in pile group configuration from a line to square or to a rectangular group as reported for $\theta = 0°$, 30° and 60° conditions.

For L/d = 12, it has been noted that for $\theta = 0°$ and 30° conditions, rough pile groups are having more efficiencies than the smooth groups. Reverse trend is observed for L/d = 38.

For smooth pile groups having L/d = 38, and $\theta = 0°$ and 30° conditions, where axial failure occurred, partial slip has been observed for a single smooth pile while loading. However, a smooth pile group behaves like a pier and at failure the pile group and the soil inside the pile group moves out of the soil mass as one unit. The increase in the ultimate resistance of a smooth pile group is responsible for the increase in the group efficiency of smooth groups.

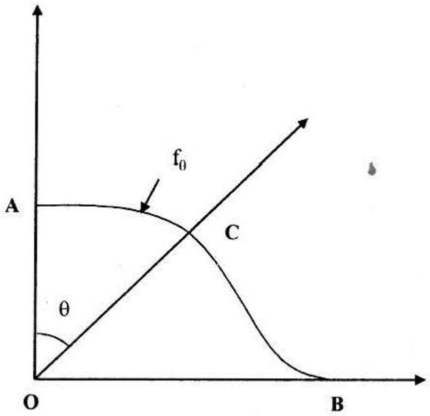


FIGURE 8 : Polar Diagram

On the other hand for L/d = 12 and 38, and for $\theta$ = 60° and 90° conditions, interestingly, rough pile groups, in general, are having more efficiencies than the smooth groups. Bending failure occurred for these conditions and the influence of axial component of the load is less effective as compared to the $\theta$ = 0° and 30° conditions wherein axial failure occurred.

### *Polar Diagram*

When the value of a function changes with the direction, the function can conveniently be represented through a polar diagram. In a polar diagram an origin called a pole is chosen and the direction is given by $\theta$, measured clockwise at the origin from a reference line through the origin. The value of the function is plotted radially from the origin along that direction. It is shown in Fig.8. To read the value of the function, $f(\theta)$, for which ACB is the plotted curve, an angle $\theta$ is measured from OA and a line OC is drawn. The value of the function $f(\theta)$ is given by OC. The presentation of the ultimate resistance of piles to oblique pulling loads has been extensively done through polar diagrams by Meyerhof (1973a), Meyerhof (1973b), Meyerhof and Gopal Ranjan (1973), Meyerhof et al. (1981b), Chattopadhyay and Pise (1986).

Generally the advantage of the polar diagram to the oblique load is to know the compressive view of the effect of the inclination of the load. As it is a continuous function it gives the inclination at which the pile group offers maximum resistance.

The ultimate resistance under oblique pull, $P_\theta$, of a pile group has been expressed in dimensionless form, $P_\theta/P_u$, in terms of the net axial uplift capacity, $P_u$, and ultimate lateral resistance, $P_L$, and the angle of inclination '$\theta$'.

At $\theta = 0°$, $P_\theta/P_u = 1 \Rightarrow P_q = P_u$ and at $\theta = 90°$, $P_q = P_L$

The value of $P_\theta/P_u$ for different values of $\theta$ for all the pile groups are plotted for $\alpha = P_u/P_L < 1$ and $\alpha = P_u/P_L \geq 1$ and are shown through Figs.9 and 10. The optimum resistance to oblique pull for piles and pile groups are shown in Table 1. The optimum resistance is defined as the resistance at which the pile groups offer maximum resistance under oblique pull ($\theta = 0°$, 30°, 60°, 90°)

*Smooth Pile Groups*

For single pile and pile groups the value of $\alpha = P_u/P_L$ is less than 1. For short ($L/d = 12$), single pile, the maximum resistance to oblique pull ($\theta = 0°$, 30°, 60°, 90°) is at $\theta = 90°$ and minimum at $\theta = 0°$. For all short pile groups the optimum resistance is mobilized when the inclination of the pull is at $\theta = 90°$ at all spacing.

For long ($L/d = 38$) single pile, the optimum resistance to oblique pull is at $\theta = 90°$. For all long pile groups except 3 × 1 pile groups, the optimum resistance is mobilized when the inclination of the pull is at $\theta = 60°$ at all spacing. However, for long pile groups 3 × 1, it is found to be at $\theta = 90°$.

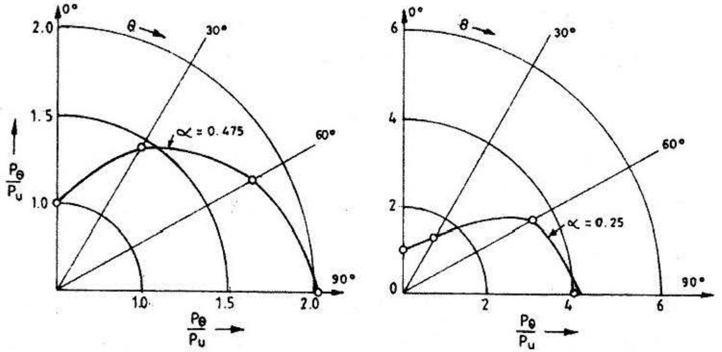
*Rough Pile Groups*

For short single pile and pile groups, the values of $\alpha = P_u/P_L$ are less than 1. Short pile groups offer minimum resistance when $\theta = 0°$ and maximum at $\theta = 90°$.

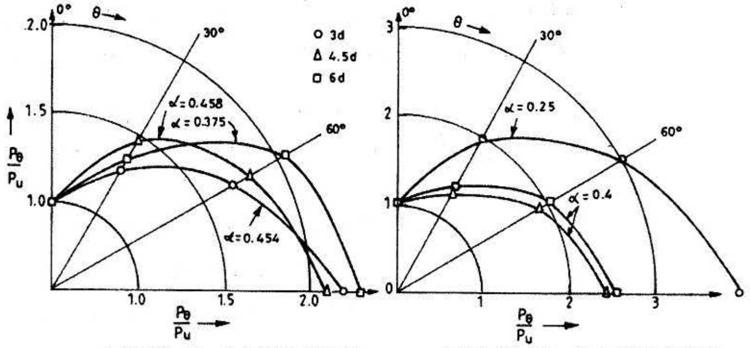
For long single pile, the optimum resistance to oblique pull is mobilized at $\theta = 30°$. However, for long pile groups the optimum resistance is mobilized at $\theta = 0°$ at all spacing. The resistance to oblique load decreases with an increase in $\theta$. At $\theta = 0°$, the pile group behaves like a pier and at failure, pile group and the soil inside the pile group comes out as single unit. Hence, for long pile groups the optimum resistance to oblique pull is maximum at $\theta = 0°$ at all spacing.

## ***Scale Effect***

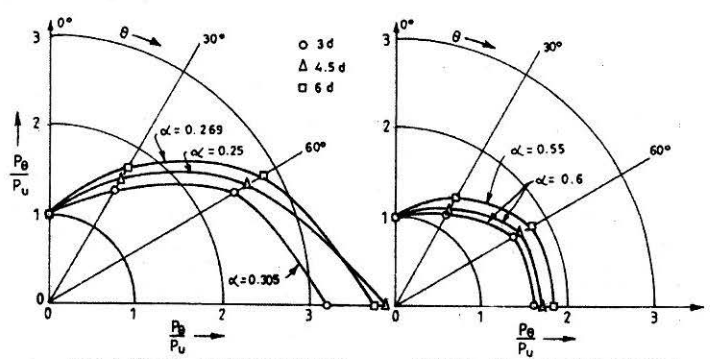
Turner and Kulhawy (1994) from tests on tension piles, have shown that the non-linearity in the failure envelop and soil dilation at low effective



(a) L/D=12; SINGLE PILE (b) L/D = 38; SINGLE PILE

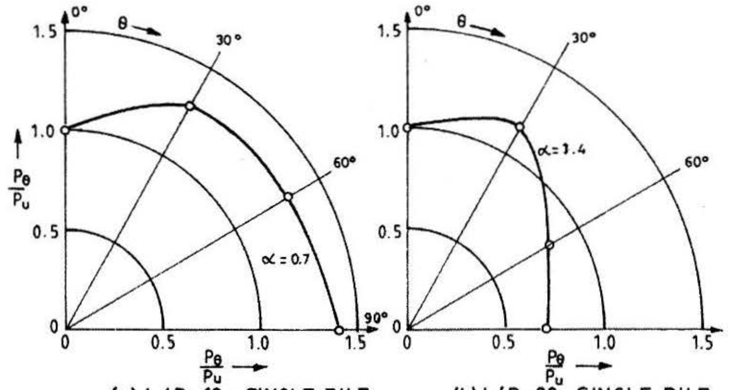


(c) L/D = 12; 3×1 PILE GROUP (d) L/D=38; 3×1 PILE GROUP

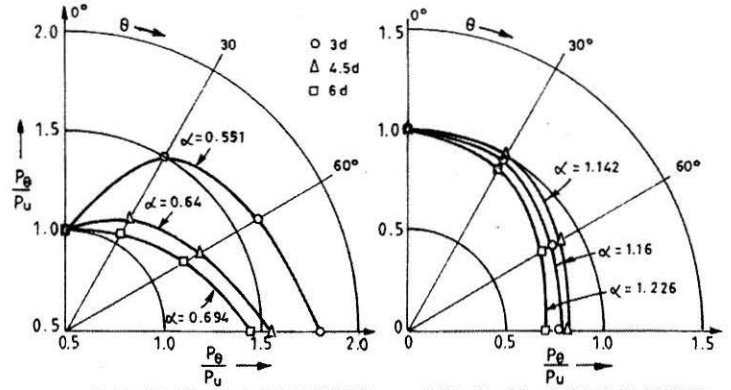


(e) L/D=12; 3×2 PILE GROUP (f) L/D=38; 3×2 PILE GROUP

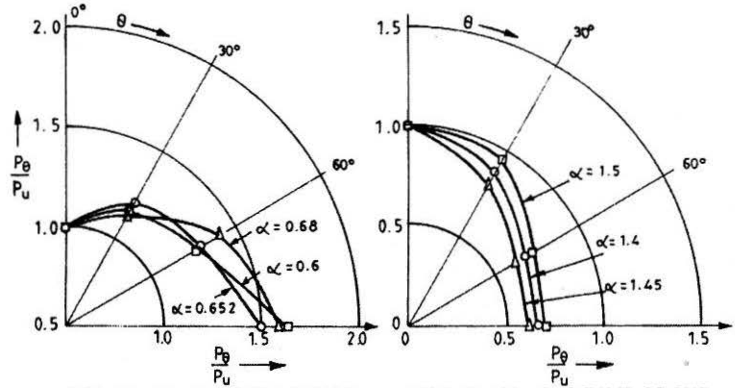
**FIGURE 9 : Experimental Values of $P_\theta/P_U$ (Smooth Pile Groups)**



(a) L/D = 12 ; SINGLE PILE (b) L/D = 38 ; SINGLE PILE



(c) L/D = 12 ; 3×1 PILE GROUP (d) L/D = 38 ; 3×1 PILE GROUP



(e) L/D = 12 ; 3×2 PILE GROUP (f) L/D = 38 ; 3×2 PILE GROUP

**FIGURE 10 : Experimental Values of $P_\theta/P_U$ (Rough Pile Groups)**

**TABLE 1 : Optimum Resistance to Oblique Pull**

| Surface Characteristic (1) | Piles and Pile Groups (2) | Spacing (3) | Optimum Resistance (4) |
|---|---|---|---|
| Smooth | Single | ALL | $\theta = 90^\circ$ |
| L/d = 12 | 2 × 1 | (3d, 4.5d, 6d) | $\theta = 90^\circ$ |
| | 3 × 1 | | $\theta = 90^\circ$ |
| | 2 × 2 | | $\theta = 90^\circ$ |
| | 3 × 2 | | $\theta = 90^\circ$ |
| Smooth | Single | ALL | $\theta = 90^\circ$ |
| L/d = 38 | 2 × 1 | (3d, 4.5d, 6d) | $\theta = 60^\circ$ |
| | 3 × 1 | | $\theta = 90^\circ$ |
| | 2 × 2 | | $\theta = 60^\circ$ |
| | 3 × 2 | | $\theta = 60^\circ$ |
| Rough | Single | ALL | $\theta = 90^\circ$ |
| L/d = 12 | 2 × 1 | (3d, 4.5d, 6d) | $\theta = 90^\circ$ |
| | 3 × 1 | | $\theta = 90^\circ$ |
| | 2 × 2 | | $\theta = 90^\circ$ |
| | 3 × 2 | | $\theta = 90^\circ$ |
| Rough | Single | ALL | $\theta = 30^\circ$ |
| L/d = 38 | 2 × 1 | (3d, 4.5d, 6d) | $\theta = 0^\circ$ |
| | 3 × 1 | | $\theta = 0^\circ$ |
| | 2 × 2 | | $\theta = 0^\circ$ |
| | 3 × 2 | | $\theta = 0^\circ$ |

confining stress can combine to cause apparent scale effects. They concluded that the effect of curvature in the failure envelope (high friction angles) at low effective confining stresses is insignificant for depth greater than 600 mm. The model pile groups for L/d = 38 were installed for greater depths.

However, for driven piles in sand, in field, the soil is compacted by displacements and vibrations resulting in change in the of value of $\phi$. This effect has to be considered before using model pile data for design purpose. The angle of shearing resistance gets modified. They are explained by Kishida (1967) for a single pile and successfully applied by Chattopadhyay and Pise (1987) for driven piles.

However, more studies on scale effect are needed to understand the field behaviour of piles.

## Conclusions

### *Pile Groups under Axial Uplift Load*

- Axial failure is considered when addition of a small load increment results in large movements. Axial displacement of 0.026d to 0.16d for L/d = 12 and 0.25d to 0.65d for L/d = 38 are observed at failure loads for all smooth pile groups. They are between 0.05d to 0.16d for rough pile groups.

- The group efficiency increases roughly linearly with an increase in spacing. The efficiency for short rough pile groups is about 10-30 % more than the short smooth groups.

- The group efficiency for long smooth pile groups is about 20-40 % more than the long rough groups. The decrease of the overlap of the failure zones of the individual piles in smooth pile group may increase the efficiency. It decreases with an increase in number piles in a group and with change in pile group configuration from a line to square or to a rectangular group.

### *Pile Groups under Oblique Pull*

- Three types of displacement curves are observed for pile groups under oblique pull. They are pull versus axial displacement, pull versus normal displacement and pull versus rotation. The axial displacement at failure is in the range 0.26d to 0.65d for smooth pile groups and 0.1d to 0.16d for rough groups.

- For smooth pile groups, the axial failure occurred at $\theta \leq 30°$ and bending failure for $\theta \geq 60°$ for all the groups (short and long).

- For rough short (L/d = 12) pile groups, the axial failure occurred for $\theta \leq 30°$ and bending failure for $\theta \geq 60°$. For rough long (L/d = 38) pile groups, the axial failure is noted for $\theta = 0°$ and bending failure for $\theta \geq 30°$.

- The group efficiency increases linearly with an increase in spacing. For $\theta = 30°$ condition, the efficiency for short rough pile groups is about 10-15% more than the short smooth groups. Reverse trend is noted for long pile groups. The efficiency for long smooth pile groups is about 40-50% more than the long rough groups

- For $\theta = 60°$ condition, in general, the efficiency for rough pile groups is about 10-20 % more than the smooth pile groups.

- For long rough pile groups and $\theta = 30°$ and $\theta = 60°$ conditions, the efficiency decreases with an increase in number of piles in a group and with the change in pile group configuration from a line to square or to rectangular group. It is due to the effect of pile group configuration. Similar observations are noted for $\theta = 0°$ condition.

- The ultimate resistance of a pile group under oblique pull is a continuous function of the inclination of the pull. It depends on the net uplift capacity and ultimate lateral resistance of a group.

### *Pile Groups under Lateral Load*

- Pile groups having rough surfaces offer more resistance than smooth surfaces. Lateral displacements from 0.1d to 0.4 d for $L/d = 12$ and 0.35d to 0.6d for $L/d = 38$ were respectively observed for all groups. Bending failure due to rotation occurred at a rotation of 0.5°-1° for $L/d = 12$ and 0.5°-1.5° for $L/d = 38$.

- Group efficiency increases with an increase in pile spacing. For, $L/d = 38$, rough pile groups, the group efficiency decreases with an increase in number of piles in a group and with the change in pile group configuration from a line to square or to a rectangular group. Similar trend has been noted for $\theta = 0°$, 30° and 60° conditions.

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## Notations

$d$ = diameter of pile
$L$ = length of pile
$s$ = spacing between piles
$\eta$ = group efficiency
$Q_g$ = ultimate resistance of a pile group
$Q_s$ = ultimate resistance of a single pile
$n$ = no. of piles in a pile group
AF = axial failure mode
BF = bending failure mode
$\alpha$ = $P_u / P_L$
$P_U$ = net axial uplift capacity
$P_L$ = ultimate lateral resistance