CHAPTER 4

RESULTS AND DISCUSSIONS
STRAIGHT-SHAFTED PILES IN HOMOGENEOUS SOILS

4.1. INTRODUCTION

In this chapter, the results and discussions of straight-shafted piles embedded in homogeneous expansive clays is presented.

4.2. DISTRIBUTION OF FORCES WITH DEPTH

4.2.1. SINGLE PILE ANALYSIS

Fig. 4.1 shows the effect of the ratio of the depth below the ground surface with respect to the over all pile length ‘Z/L’ for a single pile of uniform cross-section (straight-shafted pile) on ‘P/PS’, the ratio of the pile load at any depth to the maximum pile load. This plot is made for different ‘L/d’ ratios for the constant K=1,000 and v=0.30. As can be seen from the plot, the ratio of ‘P/PS’ is maximum when the depth is about 0.45 times the length of the pile i.e., around the mid-depth of the pile. For low values of ‘L/d’ i.e., up to the ratio of ‘P/PS’ is negative i.e. , the uplift forces dominate. After ‘L/d’ exceeds 10, ‘P/PS’ becomes positive. This means that at small pile lengths, the negative forces i.e., uplift forces dominate. However, as the pile length increases, the downward or withholding forces outweigh the uplift forces and therefore ‘P/PS’ values becomes positive. As ‘L/d’ increases, for any ‘Z/L’, the length over which the uplift forces act increases. But, along with it, ‘P/PS’ value also increases. Thus, there is a slight decrease in the value of ‘P/PS’, when
\( Z/L = 1.0 \), i.e., at the pile tip, it attains a constant value, irrespective of the \( L/d \) value because, \( P \) will have its maximum value at the pile tip.

4.2.2 ANALYSIS OF PILE GROUPS

Fig 4.2 to 4.4 gives the variation of \( P/P_{IS} \) with depth on a pile in 2-, 3-, 4-pile groups. Because of symmetry and the assumption of flexible cap being provided for the piles, the load on each pile will be same.

4.2.2.1 EFFECT OF PILE LENGTH

The trend here is almost similar to that obtained in the case of a single isolated pile except that the absolute values of \( P/P_{IS} \) are smaller in these cases for any \( L/d \). Here the value of \( P_{IS} \) is the maximum load in a pile for a single isolated pile where \( P \) is the cumulative load at any depth on any pile in the group. Here also, as \( L/d \) increases, the value of \( P/P_{IS} \) decreases for the same reasons as given above.

4.2.2.2 EFFECT OF NUMBER PILES IN A GROUP

Fig 4.5 gives, the variation of \( P/P_{IS} \) with respect to the dimensionless parameters \( Z/L \) for a single isolated pile and any pile in a 2-, 3- and 4-pile group. The figure is drawn for a \( L/d = 30, K = 1000, v = 0.30 \), pile spacing to dia ratio, \( x/d \) equal to 3 and \( Z/L = 0.60 \). It reflects the effect the presence of other piles in a group. When number of piles increases the load on pile is less. However, the denominator \( P_{IS} \) is obtained on a single isolated pile and hence is constant. Therefore, the value of \( P/P_{IS} \) decreases as the number of piles in a group increases. The percentage reduction in the pile cumulative load corresponding to 2-, 3- and 4-pile groups, with reference to that in a single isolated pile around the mid-depth of the pile are 29.5%, 45.5% and 53.3% respectively. This means that on account of the presence of
another pile the load on a pile in a 2-pile group, corresponding to a spacing equal to 3d, reduces by nearly 30%. Likewise, the presence of three other piles at the same spacing brings down the pile load in a 4-pile group by more than 50%.

4.2.2.3 EFFECT OF PILE SPACING

While Figs 4.2 to Fig.4.4 give the variation of the ‘P/P_{I2S}’ with respect to depth for different ‘L/d’ ratios for a constant ‘s/d’ =3 in different groups, Figs 4.6 to Fig.4.8 show the variation of ‘P/P_{I2S}’ with respect to the dimensionless parameter ‘Z/L’ for different ‘s/d’ ratios for a constant ‘L/d’ =30. The other parameters ‘K’, ‘ν’ and ‘Z_{d}/L’ are kept the same as previously at 1000, 0.30 and 0.60 respectively. It can be seen from the figures that, for any group, as ‘s/d’ increases, the pile cumulative load at any depth increases. This can be only expected since the influence of the neighbouring piles would be reduced if the spacing between piles is increased and vice versa.

Table 4.1 gives the percentage reductions caused in the pile load on account of the presence of other piles in a group. For this purpose, the maximum load in a single isolated pile is taken as the reference and the cumulative maximum load on any pile in the group is compared with it.

Table 4.1. EFFECT OF NUMBER OF PILES AND SPACING ON PILE LOAD

<table>
<thead>
<tr>
<th>Spacing-to-diameter ratio</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>35.45</td>
<td>52.29</td>
<td>60.47</td>
</tr>
<tr>
<td>3</td>
<td>29.48</td>
<td>45.44</td>
<td>53.31</td>
</tr>
<tr>
<td>4</td>
<td>25.11</td>
<td>39.92</td>
<td>47.30</td>
</tr>
</tbody>
</table>
It can be seen that, increase in the number of piles causes reduction in the maximum load of a single pile in a group. This was already established from Fig. 4.5. However, the spacing also effect the maximum pile load. With decrease in the spacing the maximum pile load gets reduced. When compared with a single isolated pile, the percentage reduction at spacing of 2d in a 2-pile group is 35.45%. The corresponding percentage reduction at spacing of 4d is the same group is 25.11%. Juxtaposed with this, the percentage reduction at a spacing of 2d in a 4-pile group is 60.47% and the corresponding value for a spacing of 4d is 47.3%. This clearly shows that at a smaller spacing of 2d, the maximum load reduction in a pile in a 2-pile group is about 35% which rises to in a pile, in a 2-pile group risen to as high as 60% a 4-pile group which is quite significant. This reduction which is given with respect to the maximum pile load in a single isolated pile, is quite significant.

4.2.3. ANALYSIS OF PILE GROUPS-MAXIMUM PILE LOAD

4.2.3.1 EFFECT OF POISSON’S RATIO

Fig 4.9 shows the effect of the Poisson’s ratio, ν, on the maximum pile load. The value of \( P_{\text{max}}/E_s d S_0 \), a dimensionless parameter which gives the maximum load in a single straight-shaft pile is plotted with reference to the modulus of the soil \( E_s \) and heave in the soil \( S_0 \). For \( \nu = 0.15 \) and 0.30, at small ‘\( L/d \)’ values, \( P_{\text{max}}/E_s d S_0 \) decreases initially, even attains a negative value, and then from a value of ‘\( L/d \)’ equal to 10, starts to increase and takes a positive value. However, for a ‘\( \nu \)’ value equal to 0.45, \( P_{\text{max}}/E_s d S_0 \) initially increases upto ‘\( L/d \)’ =10,then decreases upto about ‘\( L/d \)’ = 15. From ‘\( L/d \)’=15, its once again starts to increase. Beyond a ‘\( L/d \)’ value of 20, \( P_{\text{max}}/E_s d S_0 \) attains a value which is almost the same as for \( \nu =0.15 \) and 0.3. Thus, for a pile which is smaller in length, i.e., which lies mostly within the
active zone, 'v' has some effect but, for longer piles, 'v' has very little significance. Generally, it is observed that 'v' has very little effect on the load-carrying capacity of piles. Hence, its effect on maximum load in a group is not discussed hereafter.

4.2.3.2 EFFECT OF PILE STIFFNESS FACTOR

The effect of the pile stiffness factor 'K' and 'L/d' on the maximum load of a single pile can be assessed from Fig 4.10. This figure is given for 'Zd/L' = 0.2 and 'v' = 0.3. Upto a 'L/d' ratio of 10, i.e., for relatively shorter piles the maximum pile load is negative. This is understandable because for piles of shorter length the depth of embedment in the inactive zone, i.e., the firm soil zone is insufficient. Therefore, the uplift force dominate and hence the negative value. Once the pile length increases, sufficient length of the pile will be inside the inactive zone, which causes the pile load to attain a positive value. As the pile length increases the pile load increases. However, it can be seen that the pile stiffness factor, 'K' has less significance particularly at low 'L/d' ratio. However, at higher 'L/d' ratios, pile stiffness also contributes considerably to the maximum pile load.

The above variation is plotted for 'Zd/L' = 0.6 in Fig 4.11. The trend remains the same as above. But the absolute values of 'P_{max}/E_dS_0' increase with increase in 'Zd/L'. The value increase rapidly upto K=1000, beyond which the increase is only gradual. The effect of different values of 'L/d' is almost the same as that obtained for 'Zd/L' = 0.2. It is seen that there is a continuous increase in the values of 'P_{max}/E_dS_0' with increase in 'K' unlike in the case of 'Zd/L' = 0.2, where there is a
decrease initially that is up to \( K = 1000 \) beyond which there is a marginal increase with \( 'K' \) for any \( 'L/d' \) value.

From the above analysis of the maximum pile load on a single pile, it can be seen that up to \( 'L/d' = 10 \), that is for piles of shorter length, the maximum pile load is either negative or small because the pile length is inadequate to overcome the uplift forces. Once the pile length increases, beyond a value of \( 'L.d' = 10 \), the maximum pile load begins to attain higher and positive values.

4.2.3.3 EFFECT OF SPACING

Figs 4.12 to 4.14 show the variation of \( 'P_{max}/E_s dS_0' \) with \( 'L/d' \) for different \( 's/d' \) ratios for a straight-shafted 2-, 3- and 4-pile group, for \( Z_s/L = 0.2 \).

In Fig 4.12 i.e., for a 2-pile group, it can be seen that as \( 'L/d' \) increases, the maximum pile load increases. The reasons are obvious and have already been dealt with in the earlier section. As \( 's/d' \) increases, the pile tends to behave more like a single isolated pile and hence the maximum load in it increase. Almost an identical pattern is obtained in respect of a \( 2 \times 2 \) or \( 4 \)-pile group, except that the point where the low peak or trough occurs is shifted to \( 'L/d' \) of about 20, this can be attributed to greater interference of the neighbouring piles in longer groups. Nevertheless, the groups of square pattern behave identically. When it comes to a three-pile group (Fig. 4.13), however, the effect of spacing is unclear. At low \( 'L/d' \) values there is an initially increase followed by a trough in the \( 'P_{max}/E_s dS_0' \) value. But, beyond \( L/d = 25 \), all the values, irrespective of \( 's/d' \) and \( 'L.d' \) almost remain constant. It is found difficult to explain this phenomenon.

For \( Z_s/l = .6 \) also, similar trends with respect to pile spacing have been obtained in respect of straight-shafted pile groups corresponding to a \( 'Z_s/L' \)
values of 0.6 (Fig.4.15 to 4.17). Only the absolute values of $P_{\max}/EI_s d S_0$ have increase from those corresponding to $Z_{(L)}$ value of 0.2

A similar trend, i.e., increase in the dimensionless maximum pile load, $P_{\max}/E_s d S_0$ with increase in $Z_{(L)}$ values was reported for a straight-shafted single incompressible pile by Poulos and Davis (1980). It was observed that the dimensionless maximum pile load ratio increases up to $Z_{(L)}$ equal to 0.75. It was further reported that above $Z_{(L)}$ equal to 0.75, decreases.

From the above analysis, it is generally seen that, the maximum pile load increases with the length of the pile and the spacing between the piles in a group and decreases with increase in the number of piles in a group.
Fig 4.1. Depth-wise variation of $P/P_{1S}$ for a single straight-shafted pile

Fig 4.2. Depth-wise variation of $P/P_{1S}$ for a group of straight-shafted piles
Fig 4.2: Depth-wise variation of $P / P_{1s}$ for 2-pile group of straight-shafted piles.
Fig 4.3: Depth-wise variation of $P/P_{1S}$ for a 3-pile group of straight-shafted piles
Fig 4.4: Depth-wise variation of $P/P_{1s}$ for 4-pile group of straight-shafted piles

- $K=1000$
- $v=0.30$
- $s/d=3$
- $Z_s/L=0.6$
Fig 4.5: Depth-Wise variation of $P/P_{IS}$ for piles in different groups
Fig 4.6: Depth-wise variation of $P/P_{1S}$ for 2-pile group of straight-shafted piles, for different s/d ratios
Fig 4.7: Depth-wise variation of $P/P_{1s}$ of 3-pile group of straight-shafted piles for different $s/d$ ratios.
Fig 4.8: Depth-wise variation of $P/P_{1s}$ for 4-pile group of straight-shafted piles for different $s/d$ ratios.
Fig. 4.9: Effect of Poisson’s ratio on $P_{max}/E_dS_0$ for single straight shafted pile

$K=1000$, $Z_s/l=0.6$
Pile stiffness factor 'K' for straight-shafted single pile

Fig 4.10: Variation of $P_{\text{max}}/E_dS_0$ with Pile Stiffness factor 'K'

$Z_s/L=0.2, \nu=0.30$
Fig 4.11: Variation of $P_{\text{max}}/EsdS_0$ with pile stiffness factor 'K' for single straight-shafted pile
fig. 4.12: Variation of $P_{\text{max}}/E_s dS_0$ for straight-shafted 2-pile group

$K=1000$
$v=0.30$
$Z_s/L=0.2$
Fig 4.13: Variation of $P_{\text{max}}/E_s dS_0$ for straight-shafted 3-pile group.

$K=1000, \gamma=0.30, Zs/L=0.2$
Fig 4.14: Variation of $P_{\text{max}}/E_0 dS_0$ for straight-shafted 4-pile group
Fig. 4.15. Variation of $P_{max}/E_dS_0$ for straight-shafted 2-pile group

$K=1000$
$v=0.30$
$Zs/L=0.6$
Fig. 4.16. Variation of $P_{\text{max}}/E_s dS_0$ for a straight-shafted 3-pile group

$K=1000, v=0.30, Z_s/L=0.6$
Fig. 4.17: Variation of $P_{\text{max}}/E_dS_0$ for straight-shafted 4-pile group

$K=1000, Z_s/L=0.6, v=0.3$