Load Carrying Capacity of Raked Piles Subjected To Eccentric Loading

by

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Introduction

Acceptable standards for verticality and position tolerances of piles have been set down by different codes. However for one reason or the other, these standards are not or cannot be achieved. This may be attributed to eccentric driving, change in physical properties of soil. Very little is published or known about some of the causes. If one part of the pile projecting above ground during driving looked straight and vertical then for many years it was considered that all was well below ground. It is shown by Hanna (1968) that quite large deviations from vertical do occur especially when the piles are driven through soft clays.

The commonly specified tolerance for verticality is 1 : 75 which cannot always be achieved. Therefore it is necessary to examine the effect of deviations outside tolerance. When a pile is not subjected to a rigid lateral restraint, the pile can be considered as having an axial load, a transverse load, and a moment applied at its head. This is very similar to the case of pile subjected to a lateral force as considered by Broms (1964).

Fleming and Lane (1970) have studied on raked piles driven in cohesive and cohesionless soils based on the work presented by Broms (1964) on lateral load capacity of vertical piles. Based on the work of Fleming and Lane (1970), analysis for the axial load carrying capacity of raked piles subjected to eccentric loading is done in this investigation.

Ultimate Lateral Resistance

The failure mechanism and the resulting distribution of lateral earth pressures along laterally loaded, free headed pile driven into a cohesive soil is shown in Fig. 1 as given by Broms (1964). The distribution of soil reactions and bending moments along relatively short pile at failure as given by Broms (1964) is shown in Fig. 2. The maximum bending moment occurs at a level where the total shear force in the pile is equal to zero. This corresponds to a depth of $f+1.5D$, where f is the depth of the position of maximum moment from the restraining surface and D is the dameter of the pile. It has been assumed by Broms (1964) that the full value of lateral resistance will not be achieved for a depth of three pile

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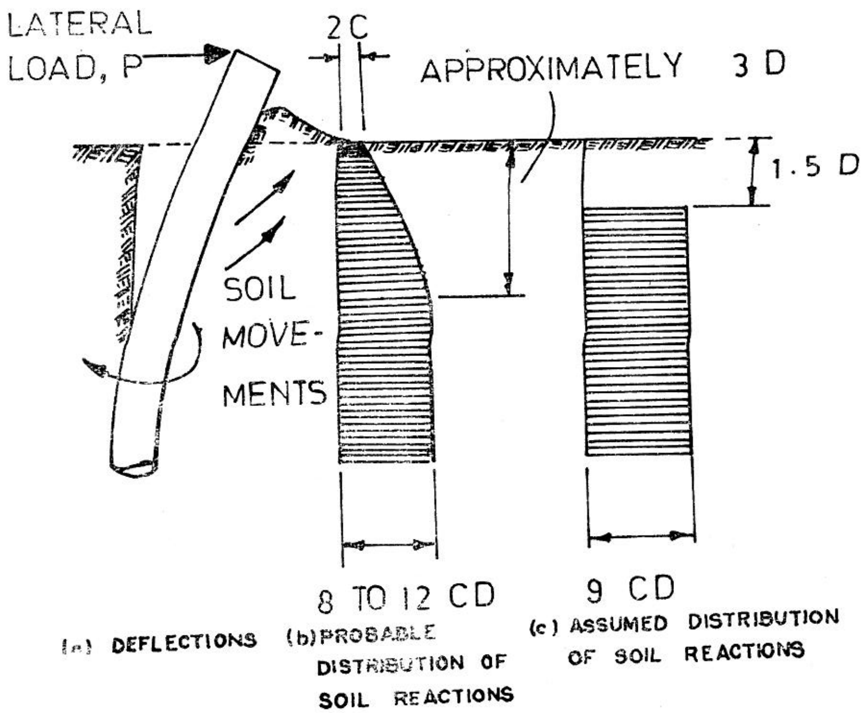

FIGURE 1 Distribution of Lateral Earth Pressure

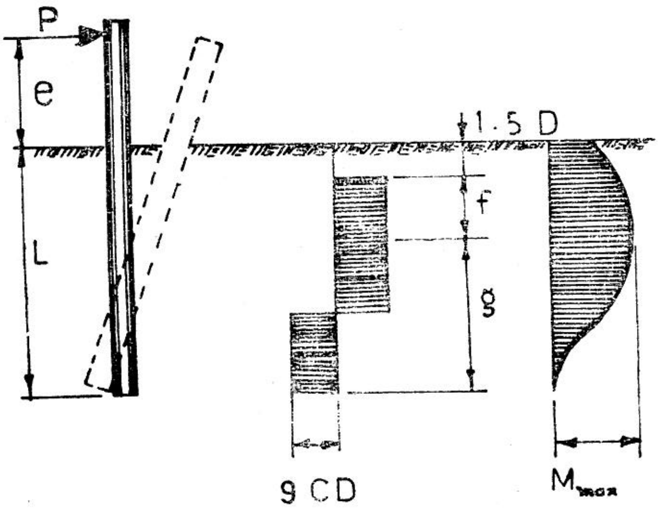

FIGURE 2 Deflection, Soil Reaction and Bending Moment Distribution for a Short Free Headed Pile

diameters into the clay stratum. He, therefore, postulated that the full value should be taken as mobilised at a depth of 1.5 diameters into the stratum and that the ultimate resistance should be taken as $9c$, where c is the cohesion.

Slightly Inclined Pile

Fleming and Lane (1970) have presented a design method to determine the structural capability for a slightly inclined pile which is subjected to an eccentric vertical force. In such circumstances, the pile can be considered as having an axial load, a transverse load and a moment applied at its head. This is very similar to the case of a pile subjected to a lateral force as considered by Broms (1964).

Soft or unreliable strata near the top of the pile may offer very little lateral restraint and are probably best ignored for this purpose. But once a consistent firm or moderately dense stratum is reached, the lateral forces may be taken into account. Broms (1964) suggests that in order to limit deflection, the lateral safe resistance should be limited to one third the ultimate value, but where the soft surface strata are deep, it may be desirable to investigate the deflection performance of the pile as a cantilever above the restraining stratum, and possibly also to increase the factor of safety to keep deflection within reasonable limits. Figure 3 represents the forces on inclined pile restrained in cohesive soils as given by Fleming and Lane (1970). Fleming and Lane have assumed the allowable lateral restraining force as 3cD per metre run of pile. By equating the forces at right angles to the pile,

$$P\triangle = 3cDf \qquad \ldots(1)$$

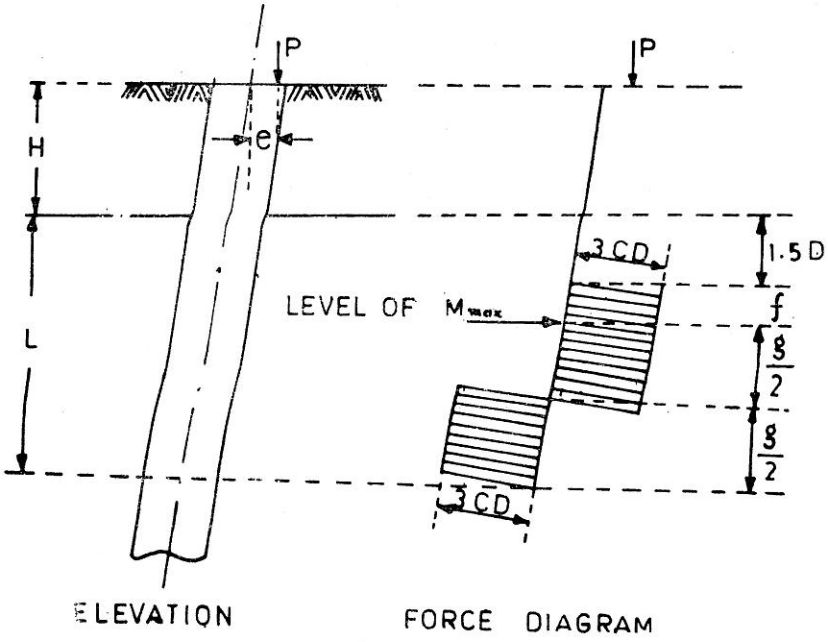

FIGURE 3 Forces on Pile Restrained in Cohesive Soil

where P is the vertical load coming on the top of the pile with an eccentricity, e, as shown in Fig. 3, and

$\triangle$ = angular deviation of the pile from true vertical and is called the rake alignment.

By taking moments about the point of maximum moment for the upper length of the pile,

$$M_{max} = P[e+(1.5D+H+f)\Delta]-\frac{3}{2}cDf^2 \qquad \ldots(2)$$

where M_{max} is the maximum bending moment occurring at a depth, f from the restraining surface.

By taking moments about the point of maximum moment for the length of the pile below,

$$M_{max} = 3cD\frac{g}{2}\left(\frac{3}{4}g-\frac{g}{4}\right) = 0.75\,cDg^2 \qquad \ldots(3)$$

in which g = depth from the position of maximum bending moment to the bottom of the pile, where the lateral force is considered to cease.

From Eq. (1)

$$f = \frac{P\triangle}{3\,cD}$$

The length of the pile can be represented as

$$L = 1.5\,D+f+g \qquad \ldots(4)$$

$$g = L-1.5D-\frac{P\triangle}{3cD}$$

The above equations are obtained assuming a factor of safety of 3 for cohesion.

Percentage Load Carrying Capacity of Raked Pile

For an eccentrically loaded raked pile, the method of analysis is assumed similar to that of a method of analysis for an eccentrically loaded column, according to IS : 456 (Teng, 1969).

$$\frac{f_a}{F_a}+\frac{f_b}{F_b} = 1 \qquad \ldots(5)$$

where f_a = calculated axial stress $= \frac{P}{A}$

$$A = A_c + 1.5m\,A_s$$

$$= A_g[1+(1.5m-1)\frac{A_s}{A_g}]$$

A_g = gross cross-sectional area of pile

A_s = area of vertical reinforcement

$$100\times p_g = \frac{A_s}{A_g}\times 100 = p_g \text{ percent} = \text{percent reinforcement}$$

F_a = allowable direct stress in concrete

F_b = allowable bending stress in concrete

f_c = characteristic cube strength of concrete

Rearranging Eq. (2)

$$M_{max} = Pe+3cDf\,(H+1.5D+\frac{f}{2})$$

The bending stress, f_b is given by

$$f_b = \frac{M}{Z_s} = \frac{M}{\frac{I/D}{2}}$$

$$= \frac{Pe+3cDf\,(H+1.5D+\frac{f}{2})}{\frac{\frac{\pi D^4}{64}\;[1+2(m-1)(1-2\frac{a}{D})^2\,p_g]}{D/2}}$$

$$= \frac{32P\,[e+\triangle\,(H+1.5D+\frac{P\triangle}{6cD})]}{\pi D^3[1+2(m-1)(1-2\frac{a}{D})^2\,p_g]}$$

where $I = \frac{\pi D^4}{64}\,[1+2(m-1)(1-2\frac{a}{D})^2\,p_g]$

a = distance from extreme surface of pile to centre of reinforcement.

Substituting in Eq. (5)

$$\frac{P}{A_g[1+(1.5m-1)\,p_g]}\,\frac{1}{F_a}+\frac{32P[e+\triangle(H+1.5D+\frac{P\triangle}{6cD})]}{\pi D^3[1+2(m-1)(1-2\,\frac{a}{D})^2\,p_g]}\,\frac{1}{F_b} = 1$$

$$\frac{4P}{\pi D^2[1+(1.5m-1)p_g]}\;\frac{1}{F_a}+\frac{[\frac{e}{D}+(\frac{H}{D}+1.5+\frac{P\triangle}{6cD^2})]}{[1+2(m-1)(1-2\,\frac{a}{D})^2\,p_g]}\;\frac{32PD}{\pi D^3F_b} = 1$$

using characteristic strength f_c

$$\frac{P}{D^2 f_c} \frac{f_c}{F_a} \frac{4}{\pi[1+(1.5m-1)\,p_g]}$$

$$+ \frac{P}{D^2 f_c} \frac{f_c}{F_b} 32 \left[\frac{\frac{e}{D} + (\frac{H}{D} + 1.5 + \frac{P}{D^2 f_c} \frac{f_c}{c} \frac{\triangle}{6})}{1+2(m-1)(1-2\frac{a}{D})^2 p_g} \right] = 1$$

Let $X = \frac{P}{D^2 f_c}$

$$Q = \frac{f_c^2}{F_b} \left[\frac{32}{1+2(m-1)(1-2\frac{a}{D})^2 p_g} \right] \frac{\triangle^2}{6c}$$

$$G = \frac{f_c}{F_a} \left[\frac{4}{\pi[1+(1.5\,m-1)p_g]} \right] + \frac{f_c}{F_b} \frac{32}{1+2(m-1)(1-2\frac{a}{D})^2 p_g} \left[\frac{e}{D} + \triangle \frac{H}{D} \right.$$

$$\left. +1.5\,\triangle \right] \quad QX^2 + GX - 1 = 0$$

Taking positive root and calling it as X_1

$$X_1 = \frac{-G + \sqrt{G^2 + 4Q}}{2Q} \qquad \text{...(6)}$$

For axial load on vertical pile (i.e. $\triangle = e = 0$)

$$f_a = F_a$$

$$P_a = F_a A_g [1 + (1.5m-1)\,p_g]$$

where P_a = axial load carrying capacity of vertical pile.

$$\frac{P_a}{D^2 f_c} = \frac{F_a A_g [1+(1.5m-1)p_g]}{D^2 f_c} \qquad \text{...(7)}$$

$$X = \frac{\frac{P}{D^2 f_c}}{\frac{Pa}{D^2 f_c}} \times 100 = \frac{\left[\frac{-G+\sqrt{G^2 + 4Q}}{2Q}\right]}{\frac{F_a \pi D^2 [1+(1.5m-1)\,p_g]}{4D^2 f_c}} \times 100$$

where X = percentage load carrying capacity when compared with a straight vertical pile with axial load .

$$X = A_1 \left[\frac{-G + \sqrt{G^2 + 4Q}}{2Q} \right] \times 100$$

where

$$A_1 = \frac{f_c}{F_a} \frac{4}{\pi[(1+(1.5m-1)p_g]}$$

Results and Discussion

An attempt is made in this investigation to find out the load carrying capacity of a raked pile, once the value of cohesion of the soil strata and the concrete properties are known. The rake alignment can be obtained by measuring the slope of the pile at the top. It can also be measured with the help of an inclinometer. Results are presented for the following range of parameters.

$$\frac{H}{D} = 0, 1 \text{ and } 3.$$

$$\frac{e}{D} = 0.025, 0.05, 0.1, 0.2, 0.3 \text{ and } 0.5.$$

$$\frac{f_c}{c} = 100 \text{ and } 1000.$$

$$p_g = 0.01, 0.03 \text{ and } 0.05.$$

$$\frac{a}{D} = 0.15.$$

Concrete Mixes = *M* 15 *M* 20 *M* 25 *M* 30

m = 19 14 11 10

The ratios of allowable bending (F_b) and direct (F_a) stresses with respect to characteristic cube strength of concrete for various mixes are presented in Table 1 as per IS: 456-1978.

TABLE 1

Allowable Bending and Direct Stresses

Allowable stresses \ *Mix*	*M 15*	*M 20*	*M 25*	*M 30*
F_b (bending)	5	7	8.5	10
F_a (direct)	4	5	6	8

Indian Standards specify, for driven precast short concrete piles, the minimum percentage of longitudinal steel as 1.25 percent. In practice, it will be slightly more than this. In case of R.C. columns which are subjected to both direct stress and bending, maximum reinforcement upto 6 percent is allowed as per IS: 456-1978. The stresses as given in Table 1 are pertaining to IS: 456-1978. Since an eccentrically loaded raked pile is subjected to bending, a maximum of 5 percent reinforcement is considered in the analysis.

Figures 4 through 15 represent the design graphs for the four mixes

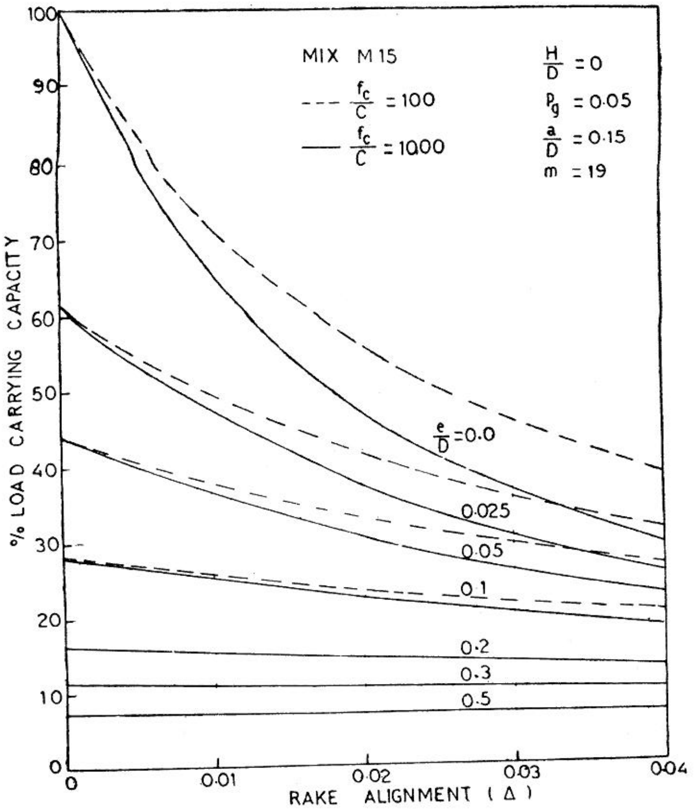

FIGURE 4 **Relationship Between Rake Alignment and Percentage Load Carrying Capacity for Different *e/D* Ratios**

mentioned above. These charts represent relationships between percent load carrying capacity of raked pile and rake alignment (Δ) for different values of $\frac{e}{D}$.

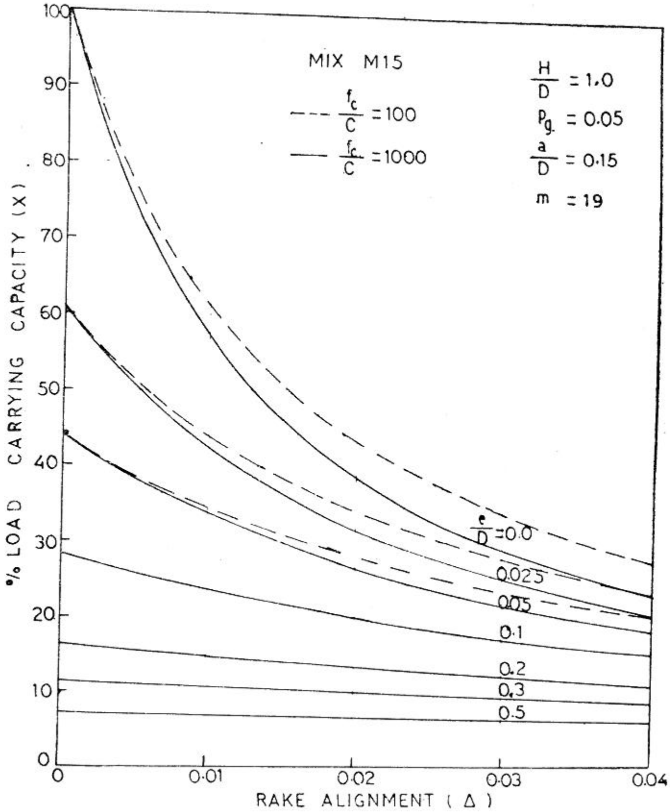

FIGURE 5 Relationsphip Between Rake Alignment and Percentage Load Carrying Capacity for Different e/D Ratios

These design curves are greatly helpful for a practicing engineer for evaluating the load carrying capacity of an eccentrically loaded raked pile.

The following conclusions can be drawn from the design curves. It is observed that as $\frac{e}{D}$ ratio increases the effect of $\frac{f_c}{c}$ has become insignificant. It is also observed from the curves that for a particular rake alignment, as $\frac{e}{D}$ ratio increases the percentage load carrying capacity

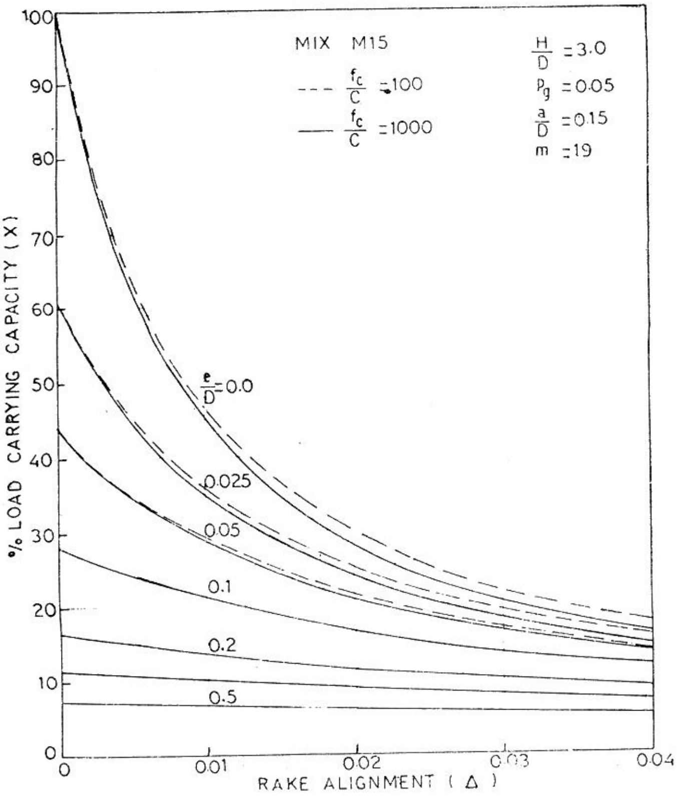

FIGURE 6 Relationship Between Rake Alignment and Percentage Load Carrying Capacity for Different *e/D* Ratios

decreases at a faster rate. The load carrying capacity of a straight pile is very greatly influenced by the eccentricity of the application of the load. It is also observed from the results that the effect of rake alignment is considerable for an axially loaded pile.

In Fig. 16, the effect of $\frac{a}{D}$ is studied for $M15$ keeping the other parameters constant. It is observed that as $\frac{a}{D}$ increases, the percentage load carrying capacity decreases for a given rake alignment.

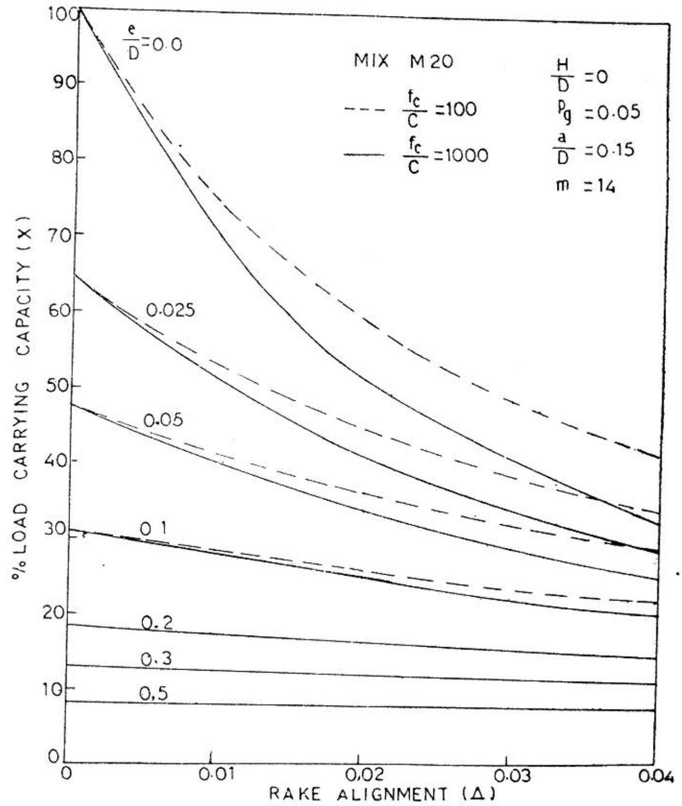

FIGURE 7 Relationship Between Rake Alignment and Percentage Load Carrying Capacity for Different *e*/*D* Ratios

Figure 17 represents the effect of percentage reinforcement on percentage load carring capacity for different rake alignments. It is observed that the percentage reinforcement has no effect practically on the percentage load carrying capacity for a given rake alignment when all the other parameters are kept constant.

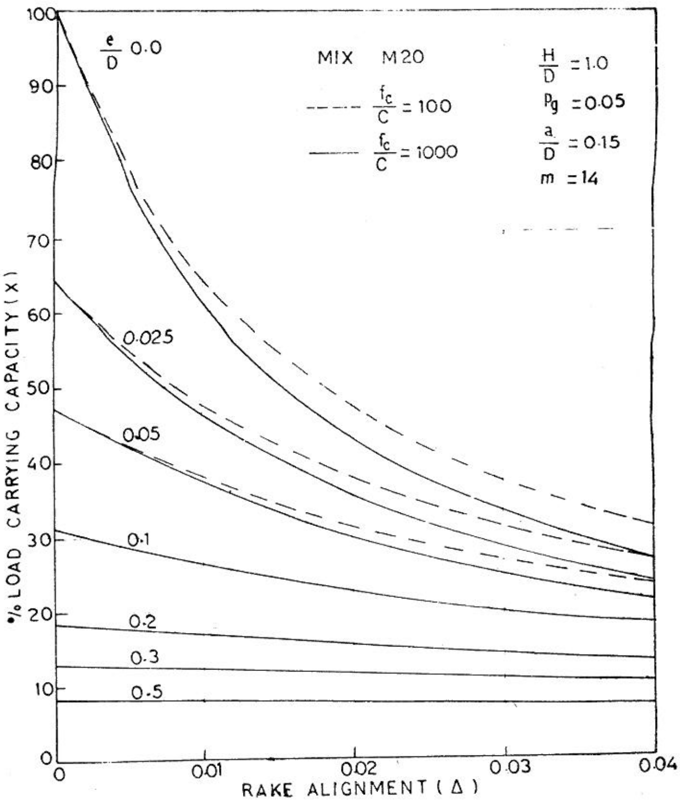

FIGURE 8 **Relationship Between Rake Alignment and Percentage Load Carrying Capacity for Different** ***e/D*** **Ratios**

Figure 18 represents the effect of $\frac{H}{D}$ ratio. As $\frac{H}{D}$ ratio increases, it is observed that the percentage load carrying capacity decreases for any given rake alignment. Figure 19 represents the relationship between

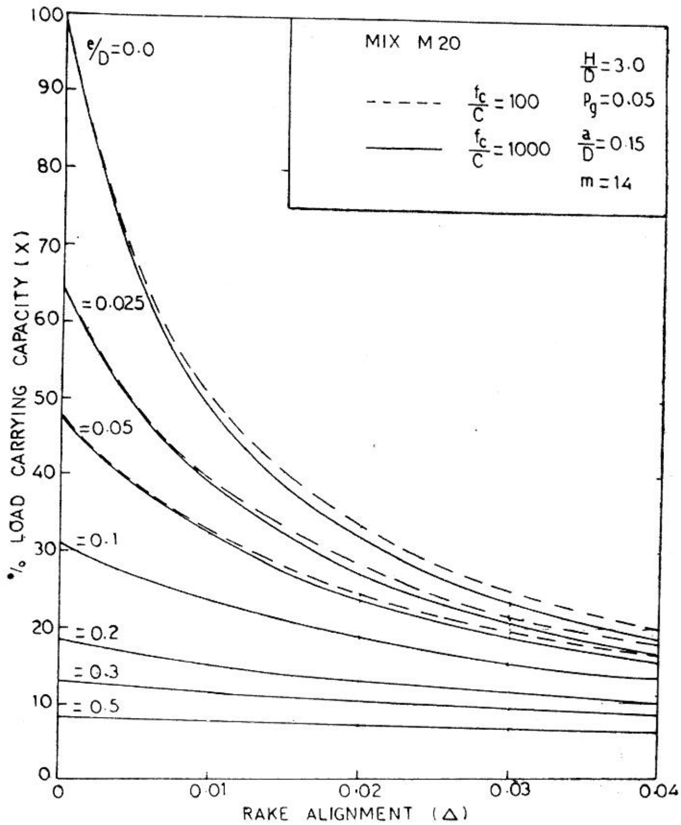

FIGURE 9 Relationship Between Rake Alignment and Percentage Load Carrying Capacity for Different *e/D* Ratios

$\frac{e}{D}$ ratio and the percentage load carrying capacity. These graphs are drawn for various rake alignments. It is observed that for a maximum eccentric loading i.e. $\frac{e}{D} = 0.5$, the percentage load carrying capacity for

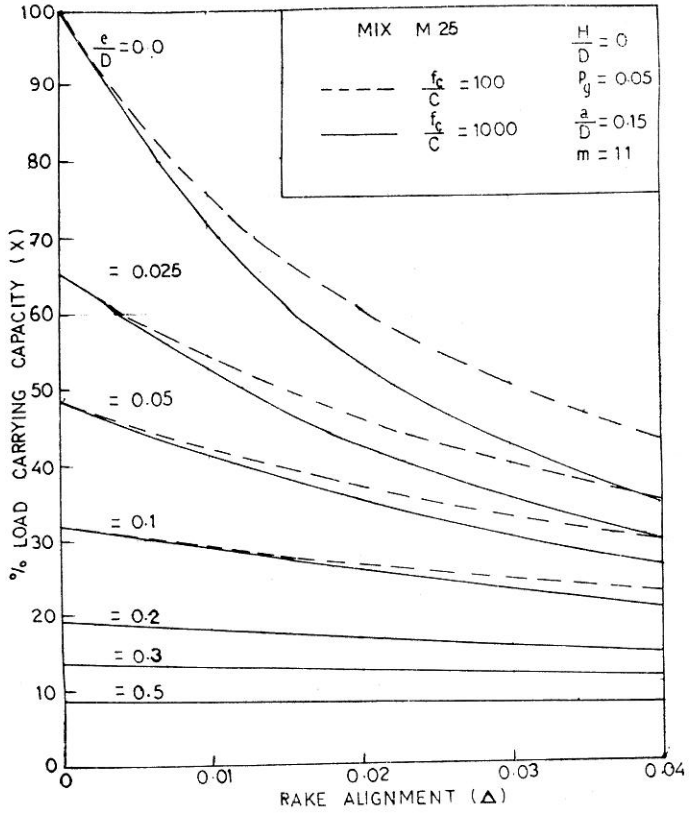

FIGURE 10 Relationship Between Rake Alignment and Percentage Load Carrying Capacity for Different *e*/*D* Ratios

different rake alignments converges around 8 percent. Rake alignment is an important parameter with respect to load carrying capacity of a pile. From Fig. 19 for 4 percent rake alignment the load carrying capacity reduces to 30 percent of a straight pile.

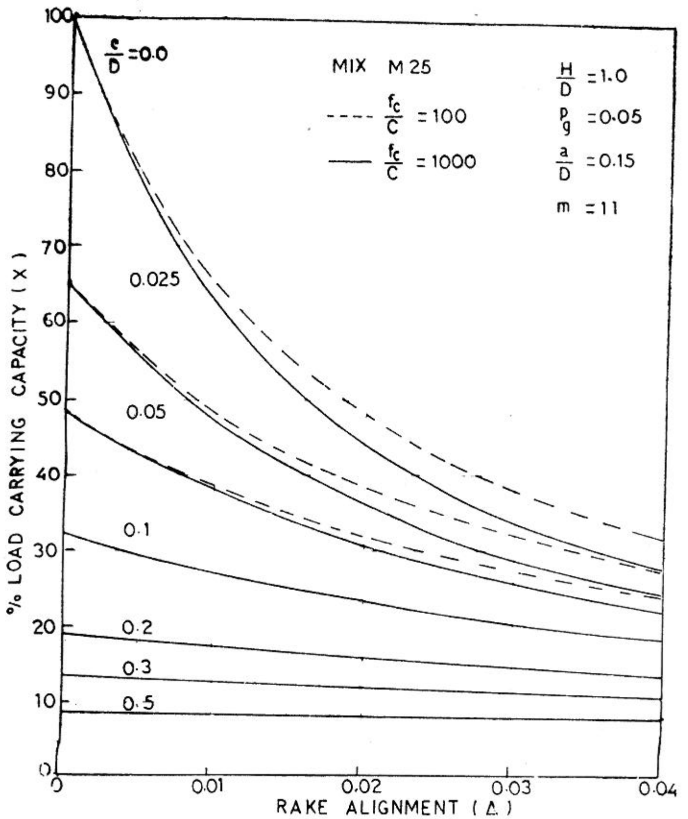

FIGURE 11 Relationship Between Rake Alignment and Percentage Load Carrying Capacity for Different *e/D* Ratios

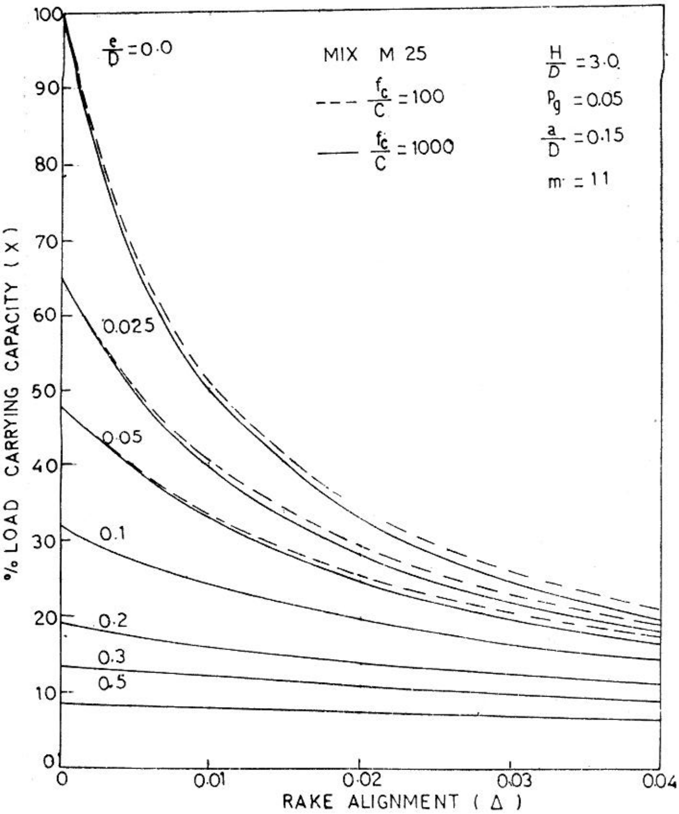

FIGURE 12 Relationship Between Rake Alignment and Percentage Load Carrying Capacity for Different e/D Ratios

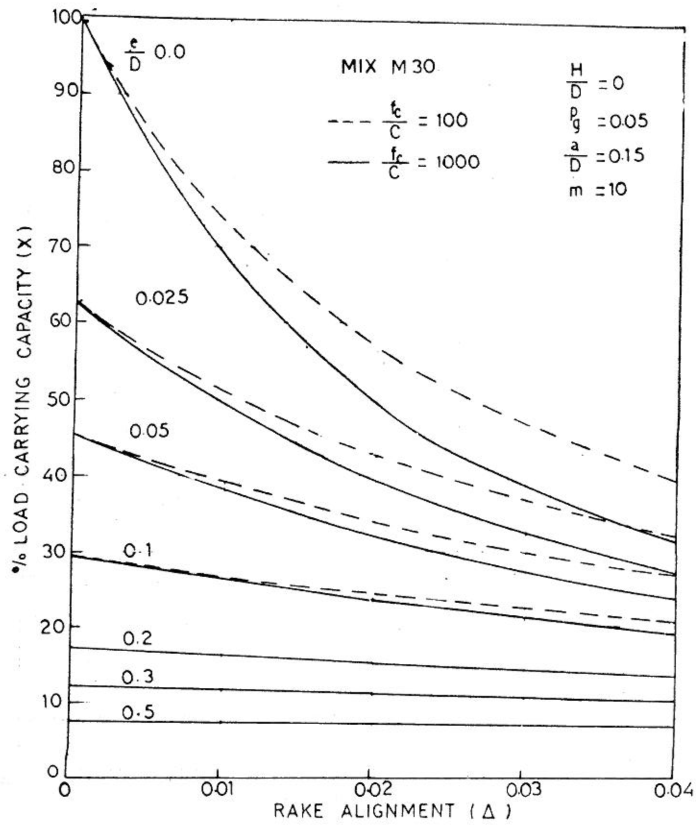

FIGURE 13 Relationship Between Rake Alignment and Percentage Load Carrying Capacity for Different e/D Ratios

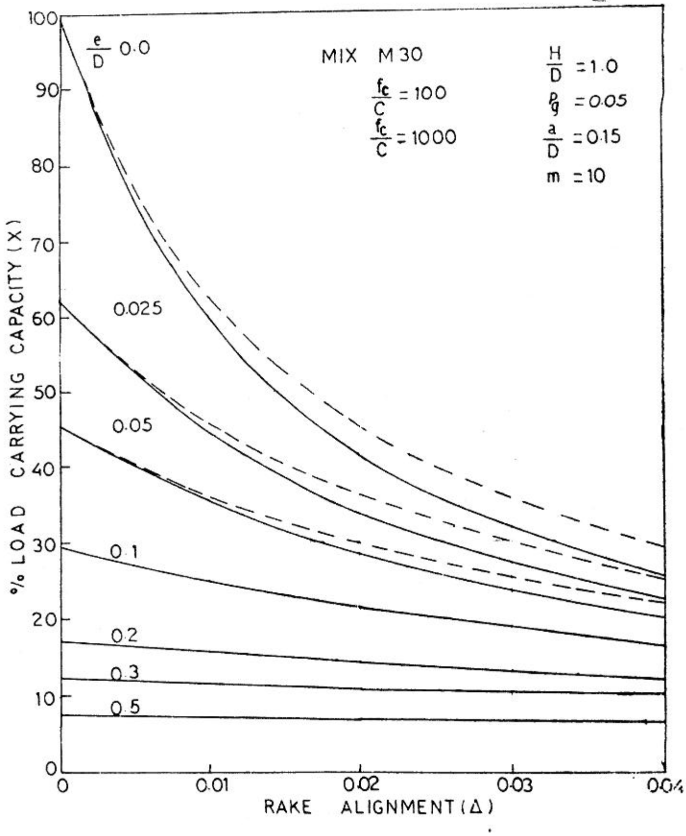

FIGURE 14 **Relationship Between Rake Alignment and Percentage Load Carrying Capacity for Different** ***e/D*** **Ratios**

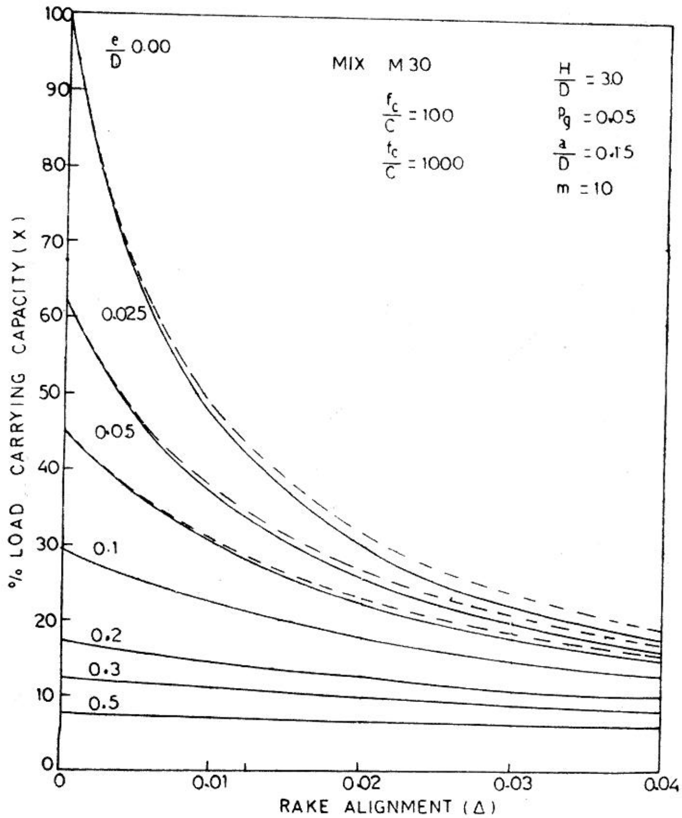

FIGURE 15 Relationship Between Rake Alignment and Percentage Load Carrying Capacity for Different ***e/D*** **Ratios**

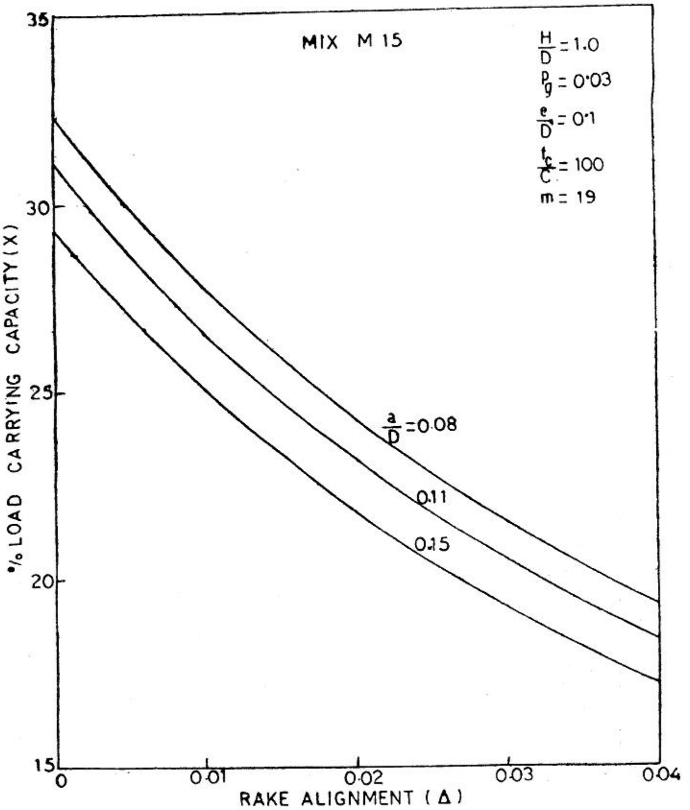

FIGURE 16 Relationship Between Percentage Load Carrying Capacity and Rake Alignment for Different a/D Ratios

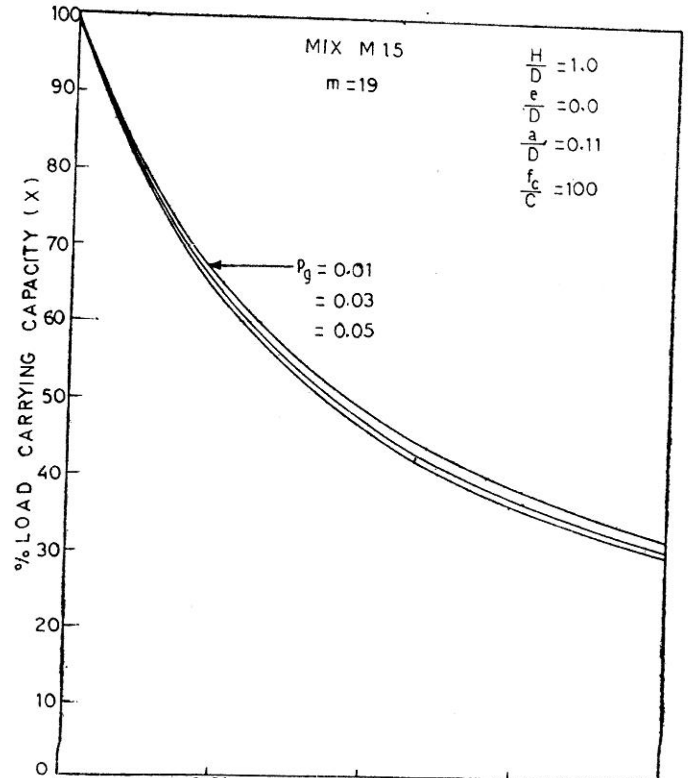

FIGURE 17 Relationship Between Percentage Load Carrying Capacity and Rake Alignment for Different Percentage Reinforcement

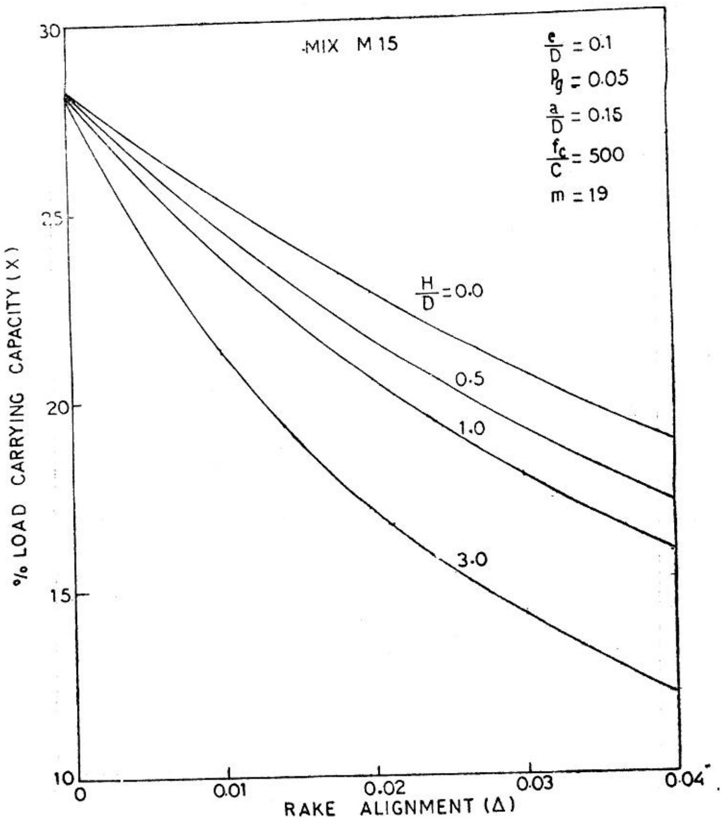

FIGURE 18 Relationship' Between Percentage Load Carrying Capacity and Rake Alignment for Different H/D Ratios

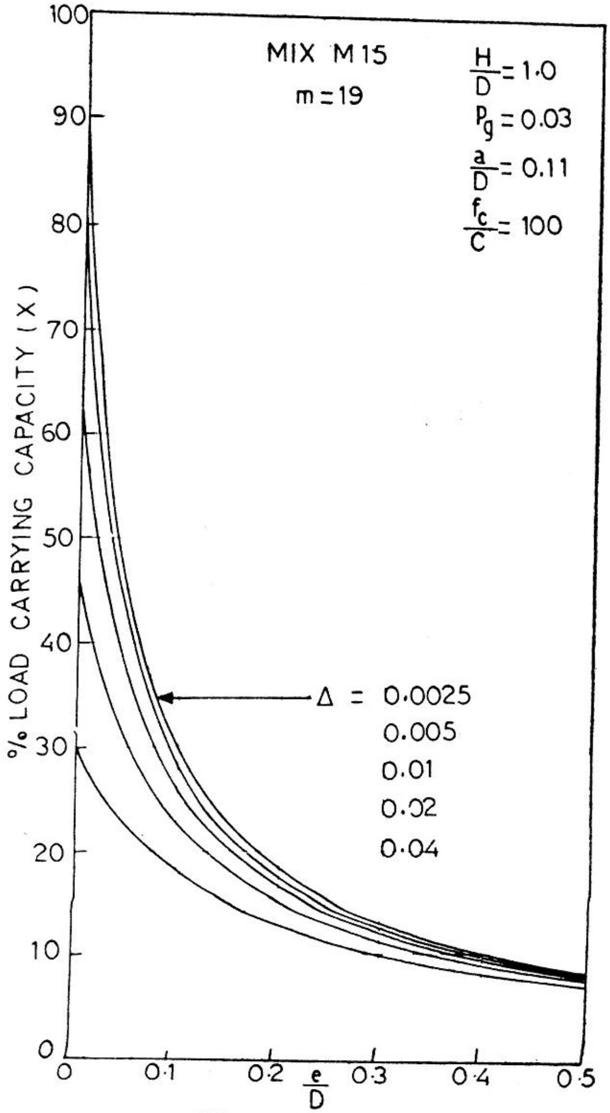

FIGURE 19 Relationship Between Percentage Load Carrying Capacity and e/D Ratio for Different Rake Allgnments

Conclusions

Design charts are prepared in this investigation for finding the load carrying capacity of any raked pile once the soil and pile properties are known along with the rake alignment.

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