Chapter 14
PILES SUBJECTED TO LATERAL LOAD AND MOMENT

14.1 Single Floating Pile

14.1.1 HORIZONTAL MOVEMENTS AND ROTATIONS (Fig.14.1)

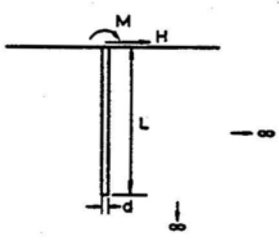


FIG.14.1

This problem has been considered by Poulos (1971a).

Influence factors for the displacement and rotation at the top of a pile in a uniform semi-infinite elastic mass are given in Figs.14.2 to 14.5 for two cases:

(i) a free-head pile i.e. free rotation at the top,

(ii) a fixed-head pile i.e. no rotation at the pile top.

For the free-head pile, the horizontal displacement ρ at the pile top is given as

$$\rho = I_{\rho H} \frac{H}{E_s L} + I_{\rho M} \frac{M}{E_s L^2} \qquad \ldots (14.1)$$

where $I_{\rho H}$ and $I_{\rho M}$ are plotted in Figs.14.2 and 14.3 against K_R, where

K_R = pile flexibility factor

$$= \frac{E_p I_p}{E_s L^4} \qquad \ldots (14.2)$$

$E_p I_p$ = pile stiffness

E_s = soil modulus.

The rotation θ at the top of a free-head pile is

$$\theta = I_{\theta H} \frac{H}{E_s L^2} + I_{\theta M} \frac{M}{E_s L^3} \qquad \ldots (14.3)$$

where $I_{\theta M}$ is plotted against K_R in Fig.14.5

$I_{\theta H} = I_{\rho M}$ (Fig.14.3).

For a fixed-head pile, the displacement at the pile top is

$$\rho = I_{\rho F} \frac{H}{E_s L} \qquad \ldots (14.4)$$

where $I_{\rho F}$ is plotted against K_R in Fig.14.4.

In Figs. 14.2 to 14.5, ν of the soil is *0.5*.

This parameter has a relatively small effect on the displacement and rotation factors.

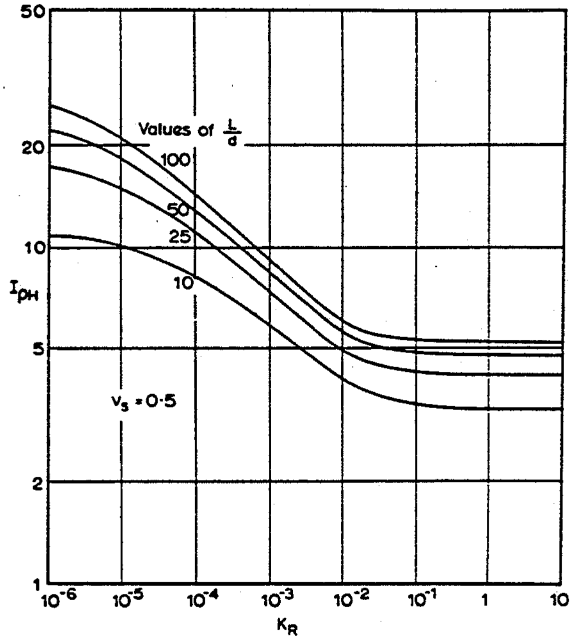


FIG.14.2 Influence factor $I_{\rho H}$ for free-head pile.

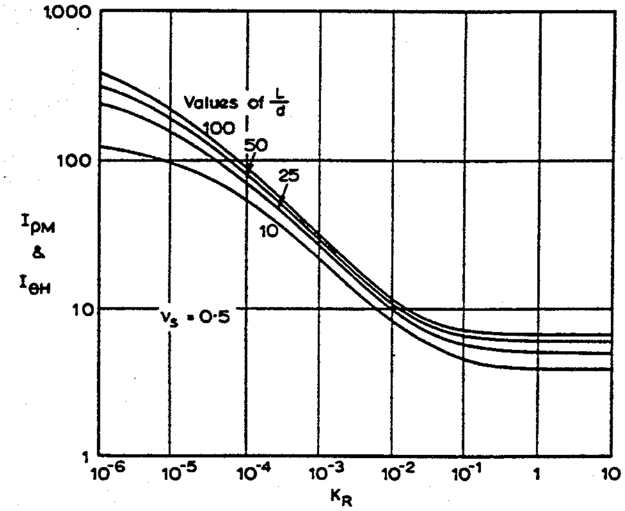


FIG.14.3 Influence factors $I_{\theta H}$ and $I_{\rho M}$ for free-head pile.

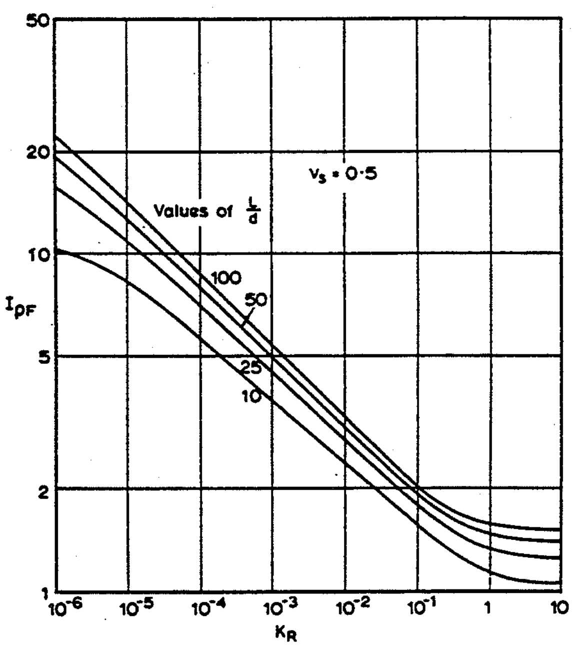


FIG.14.4 Influence factor $I_{\rho F}$ for fixed-head pile.

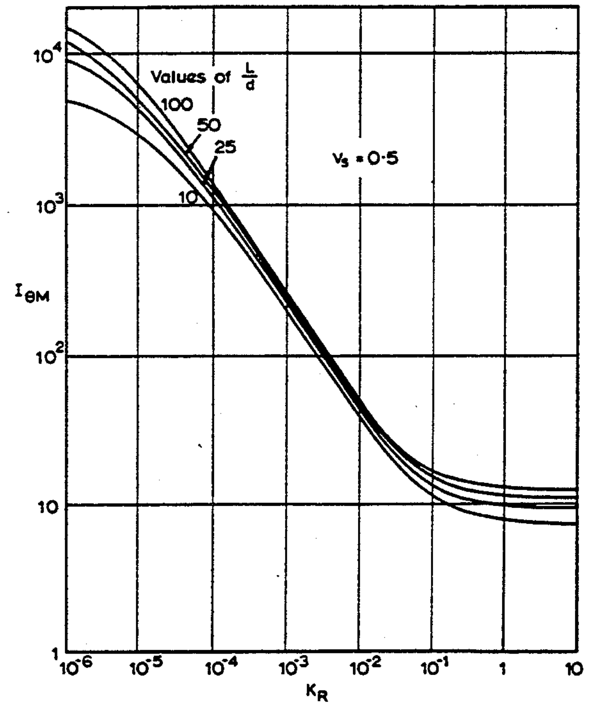


FIG.14.5 Influence factor $I_{\theta M}$ for free-head pile.

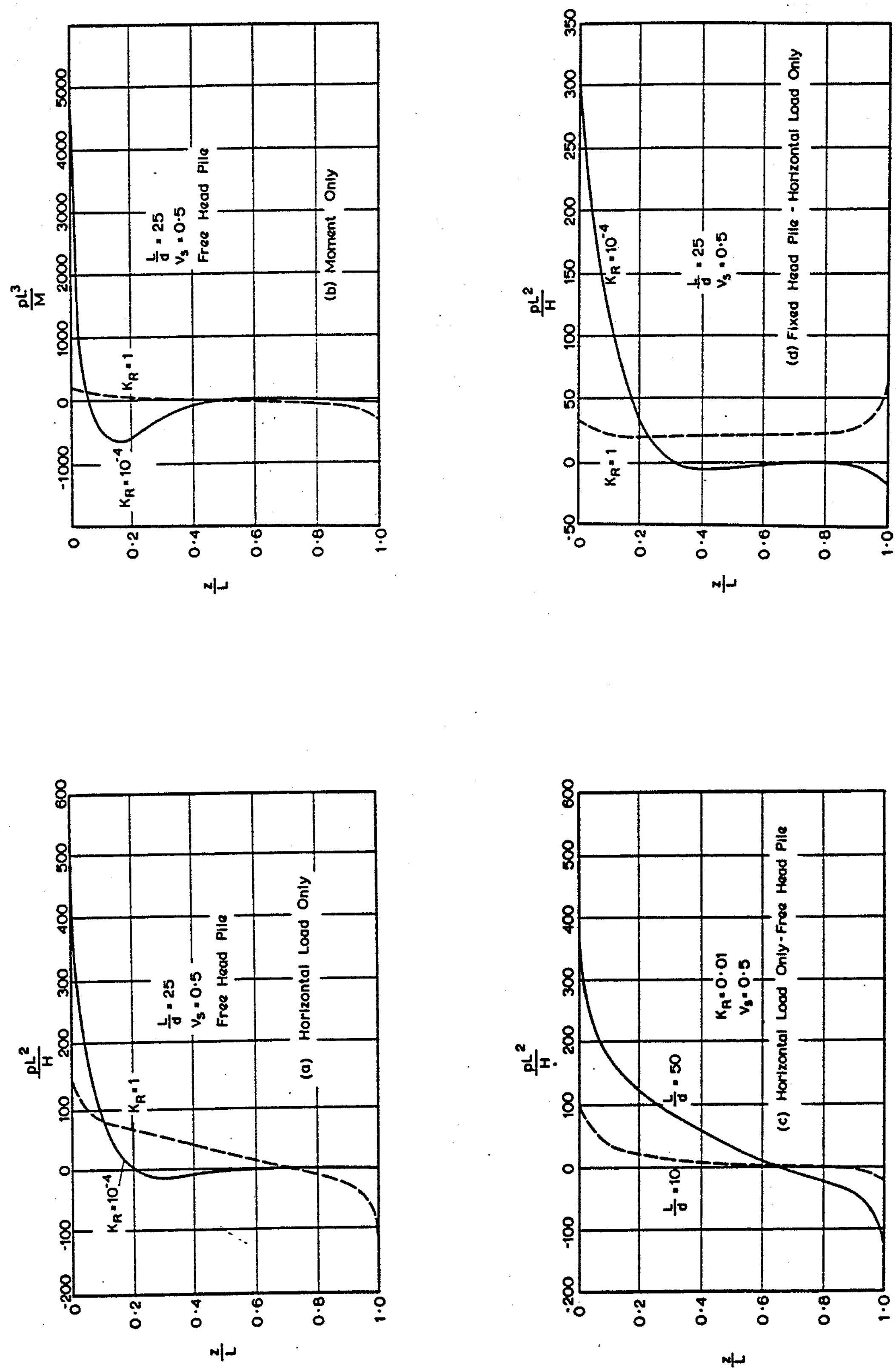


FIG.14.6 Typical horizontal pressure distributions along laterally loaded piles.

14.1.2 HORIZONTAL STRESS DISTRIBUTION

Typical horizontal pressure distributions are given in Figs.14.6(a) to (d).

14.1.3 MOMENTS IN PILE

Typical moment distributions along a free-head pile are shown in Fig.14.7 and along a fixed-head pile in Fig.14.8.

The maximum moment in a free-head pile subject to horizontal load only is plotted against K_R in Fig.14.9. For a pile subjected to moment only, the maximum moment always occurs at the pile top.

The variation with K_R of fixing moment at the top of a fixed-head pile is shown in Fig.14.10.

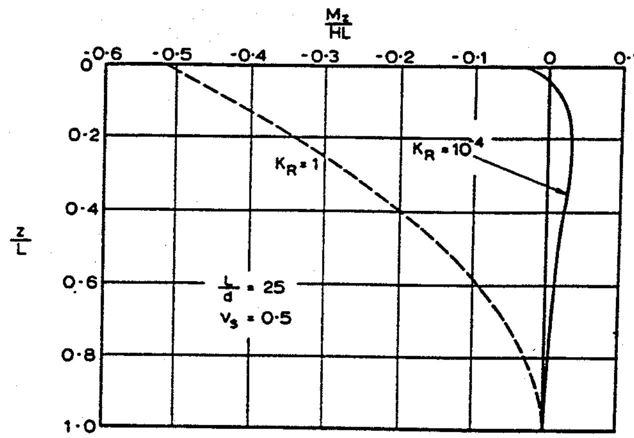
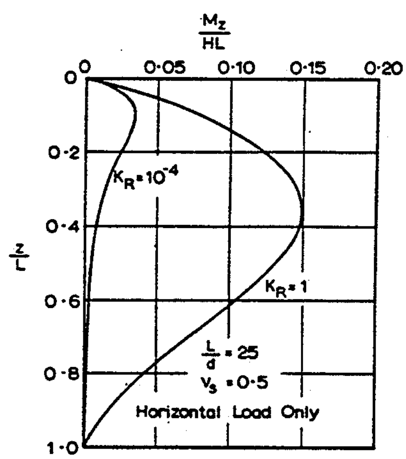
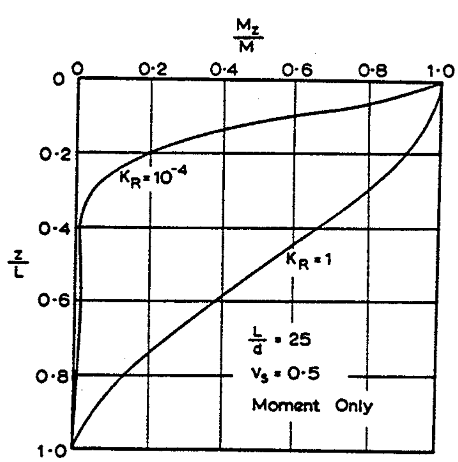


FIG.14.8 Typical moment distributions along a fixed-head pile.



(a)



(b)

FIG.14.7 Typical moment distributions along a free-head pile
(a) subjected to horizontal load only
(b) subjected to moment only.

14.2 Tip-Restrained Piles

For a pile whose tip rests on a rigid base and does not move horizontally, influence factors for the displacements and rotation at the top of the pile are given in Figs.14.11 to 14.14. The actual displacements and rotations are again given by equations (14.1) to (14.4). Two boundary conditions at the top of the pile, free-head and fixed-head, and two boundary conditions at the pile tip, a pinned tip (no displacement, free rotation) and a fixed tip (no displacement, no rotation) are considered. These figures show that the tip boundary condition does not influence displacement or rotation unless $K_R > 10^{-3}$.

For fixed head piles, the fixing moment at the pile head is shown in Fig.14.15.

For fixed tip piles, the fixing moment at the pile tip is shown in Fig.14.16 for applied horizontal load and in Fig.14.17 for applied moment.

For free-head piles, the maximum moment in the pile is plotted against K_R in Fig.14.18.

The force at the tip is shown in Fig.14.19 for free-head piles and in Fig.14.20 for fixed head piles.

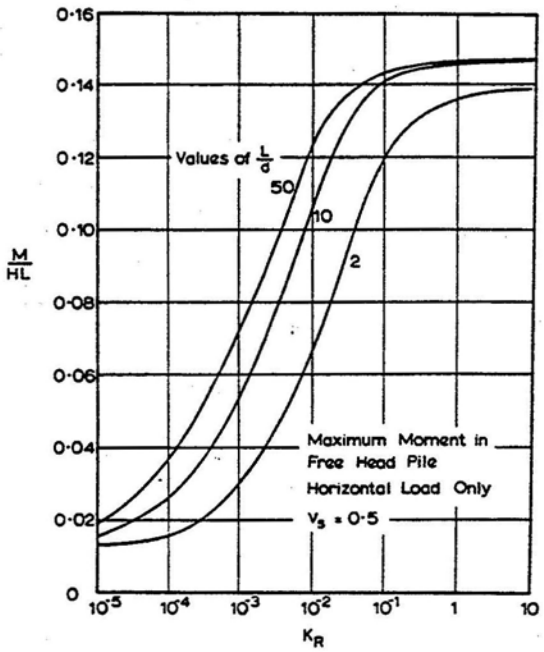


FIG.14.9 Maximum moment along a free-head pile subjected to horizontal load only.

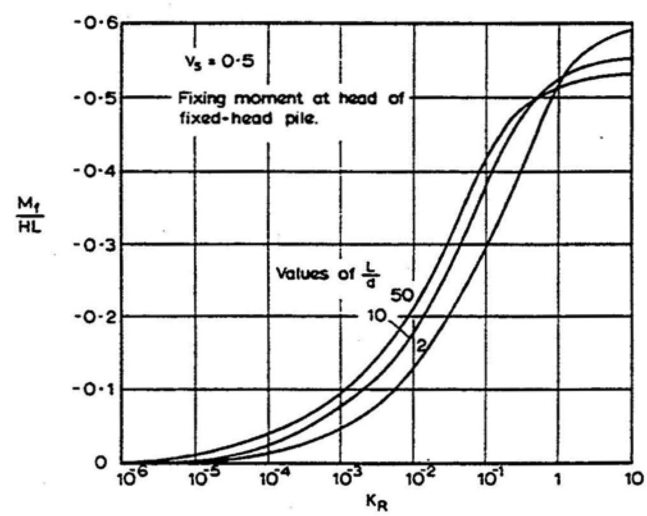


FIG.14.10 Fixing moment at head of a fixed-head pile.

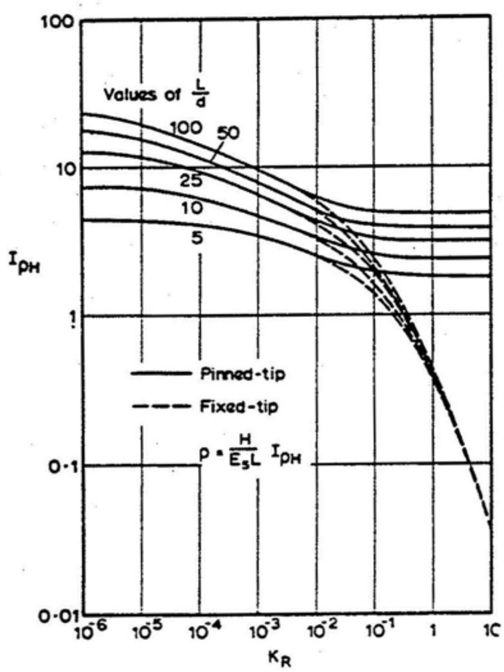


FIG.14.11 Influence factor $I_{\rho H}$ for free-head pile.

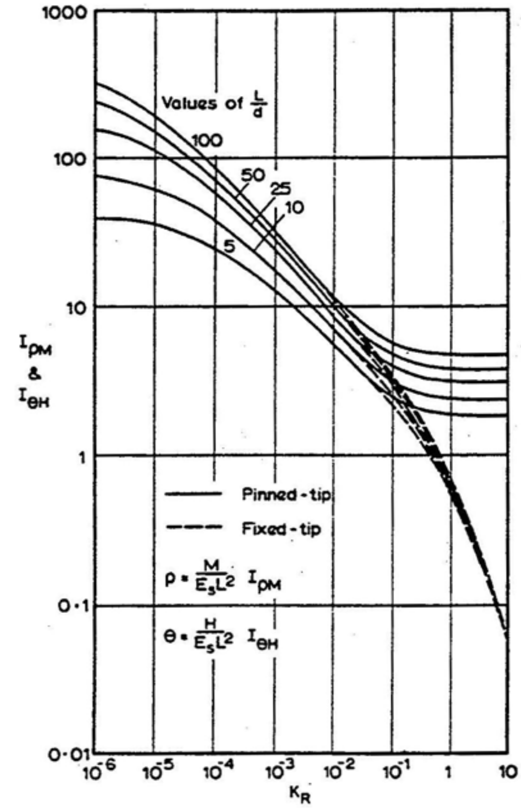


FIG.14.12 Influence factors $I_{\rho M}$ and $I_{\theta H}$ for free-head pile.

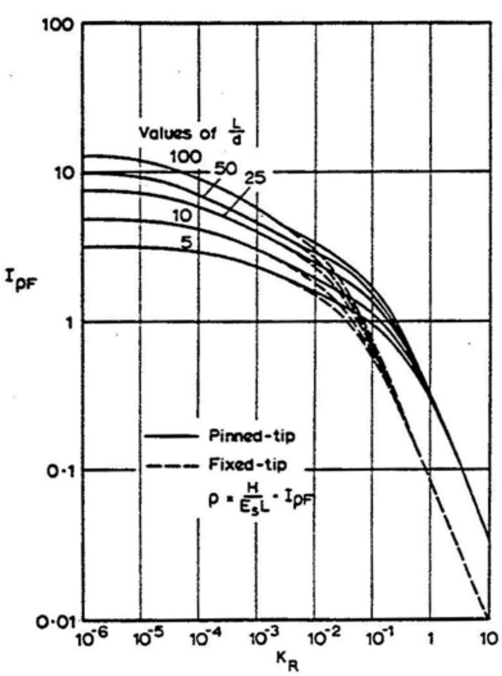


FIG.14.13 Influence factor $I_{\rho f}$ for fixed-head pile.

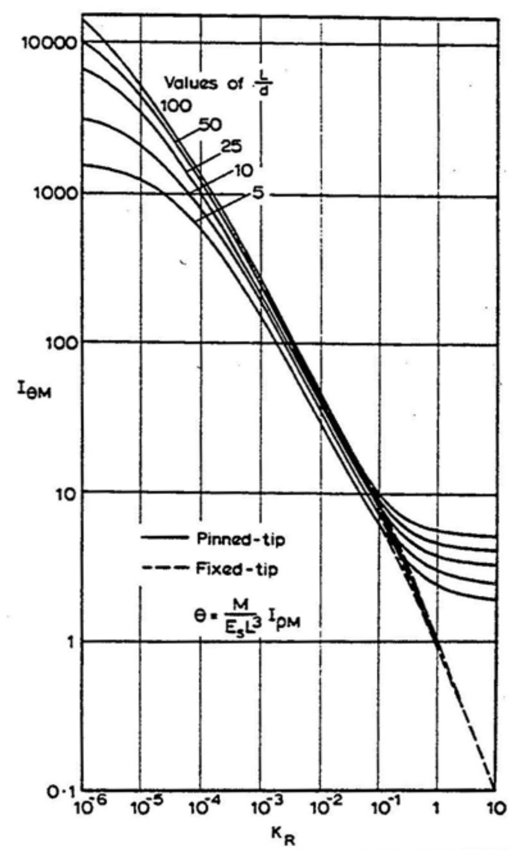


FIG.14.14 Influence factor $I_{\theta M}$ for free-head pile.

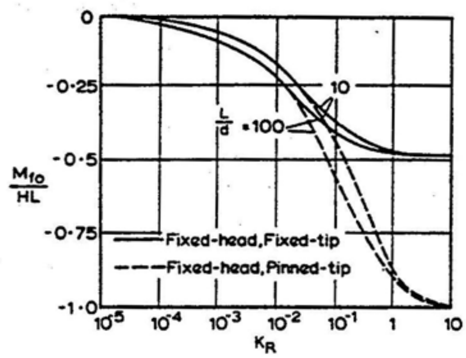


FIG.14.15 Fixing moment at head of fixed-head pile.

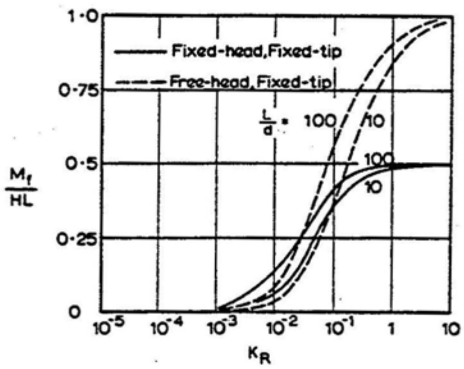


FIG.14.16 Fixing moment at tip due to horizontal load only.

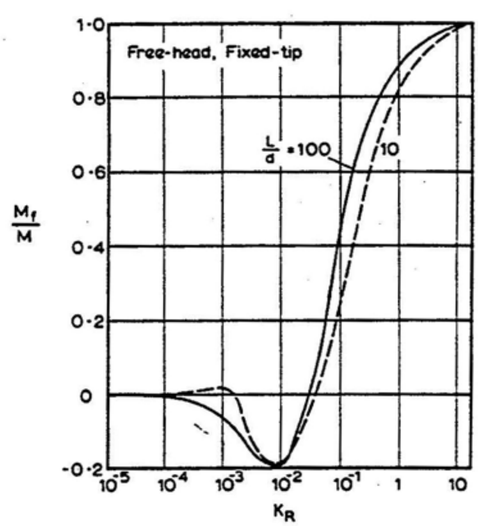
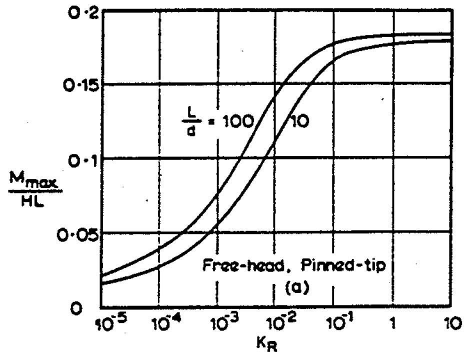
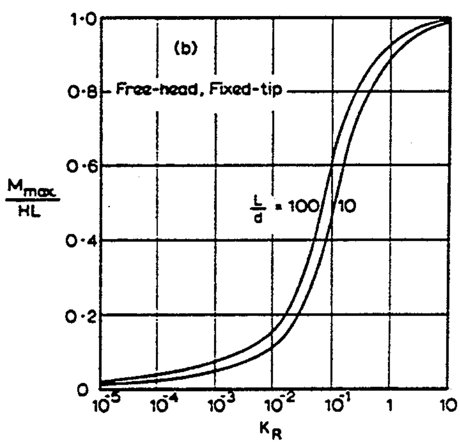


FIG.14.17 Fixing moment at tip due to applied moment only.

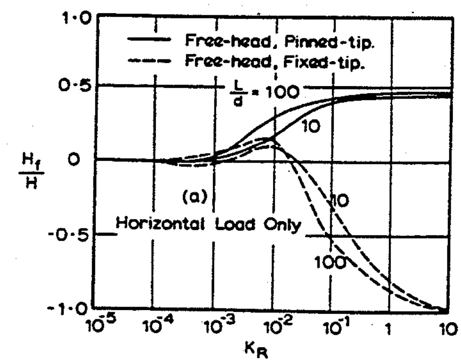


(a)

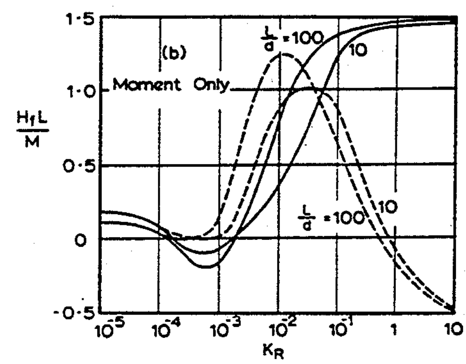


(b)

FIG.14.18 Maximum moment in free-head pile subjected to horizontal load only.



(a)



(b)

FIG.14.19 Tip force for free-head piles.

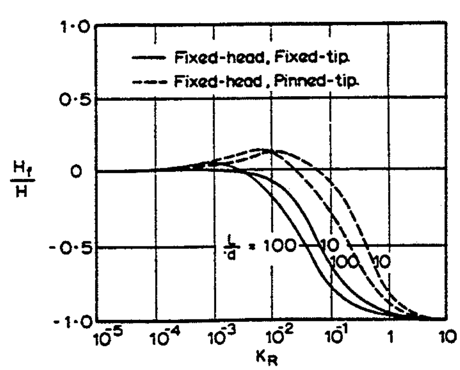


FIG.14.20 Tip force for fixed-head piles.

14.3 Pile Groups

14.3.1 INTERACTION BETWEEN TWO IDENTICAL PILES (Fig.14.21)

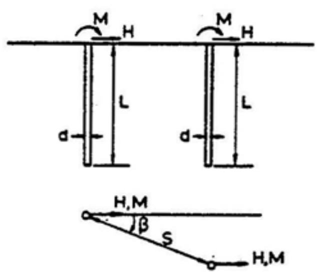


FIG.14.21

This problem has been considered by Poulos (1971b). Increases in displacement and rotation of the top of a pile due to the presence of an identical adjacent pile can be, as with axially-loaded piles, expressed in terms of an interaction factor α where

α = ratio of increase in displacement (or rotation) due to the adjacent pile to the displacement (or rotation) of a single pile.

Five interaction factors are considered:

$\alpha_{\rho H}$ = interaction factor for displacement due to horizontal load only

$\alpha_{\rho M}$ = interaction factor for displacement due to moment only

$\alpha_{\theta H}$ = interaction factor for rotation due to horizontal load only ($\alpha_{\theta H} = \alpha_{\rho M}$)

$\alpha_{\theta M}$ = interaction factor for rotation due to moment only

(the above factors apply to free-head piles)

$\alpha_{\rho F}$ = interaction factor for displacement of fixed-head piles.

Values of $\alpha_{\rho H}$, $\alpha_{\rho M}$, $\alpha_{\theta M}$ and $\alpha_{\rho F}$ are plotted against dimensionless pile spacing s/d in Figs. 14.22 to 14.37 for various values of K_R and L/d. Interaction factors are plotted for values of β (angle between the line of the piles and the direction of loading) of $0°$ and $90°$. For other values of β, it is sufficiently accurate to interpolate linearly between the curves for $0°$ and $90°$.

14.3.2 ANALYSIS OF GENERAL PILE GROUPS

As with floating axially-loaded pile groups (Section 13.5.2), the principle of superposition may be used together with the two-pile interaction factors to compute the loads and displacement within the group for the cases of equal displacement of all piles, or equal loads in all piles.

The horizontal displacement of a pile i in a group of k piles is given (for the case of free-head piles) by:

$$\rho_i = \bar{\rho}_H \left(\sum_{\substack{j=1 \\ j \neq i}}^{k} H_j \alpha_{\rho H ij} + H_i \right) + \bar{\rho}_M \left(\sum_{\substack{j=1 \\ j \neq i}}^{k} M_j \alpha_{\rho M ij} + M_i \right) \quad \text{... (14.5)}$$

where H_j = horizontal load in pile j

$\alpha_{\rho H ij}$ = value of $\alpha_{\rho H}$ for spacing and value of β between piles i and j

$\bar{\rho}_H$ = horizontal movement of single pile due to unit applied horizontal load

M_j = moment in pile j

$\alpha_{\rho M ij}$ = values of $\alpha_{\rho M}$ for spacing and values of β between piles i and j

$\bar{\rho}_M$ = horizontal movement of single pile due to unit applied moment.

A similar expression may be written for the rotation of pile i, or for the displacement of pile i for a group of fixed-head piles.

Application of the above equation to all piles in the group, together with the equilibrium equations enable solutions to be obtained from the load and moment distributions and the displacement and rotation of a group for the equal displacement case, or for the displacement and rotation distributions in a group for the equal load (and moment) case. For moment loading the effect of the axial pile loads must be considered.

Typical solutions for the displacement of a fixed-head group of piles, for the equal displacement case, are given by Poulos (1971b).

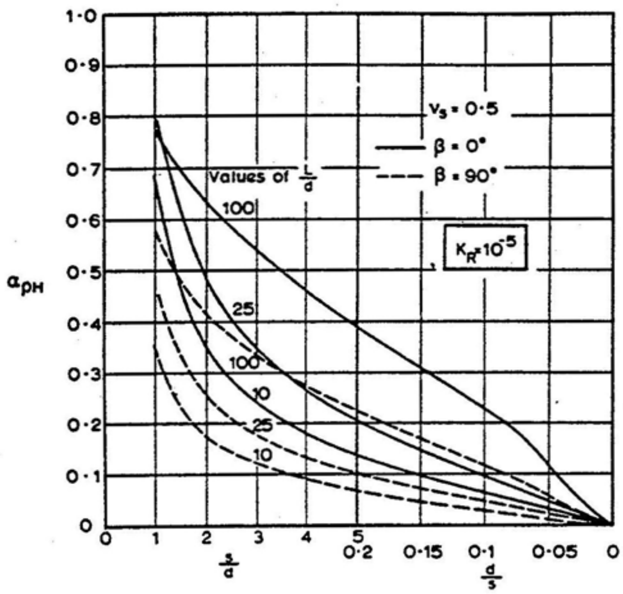


FIG.14.22 Interaction factor $\alpha_{\rho H}$. $K_R = 10^{-5}$

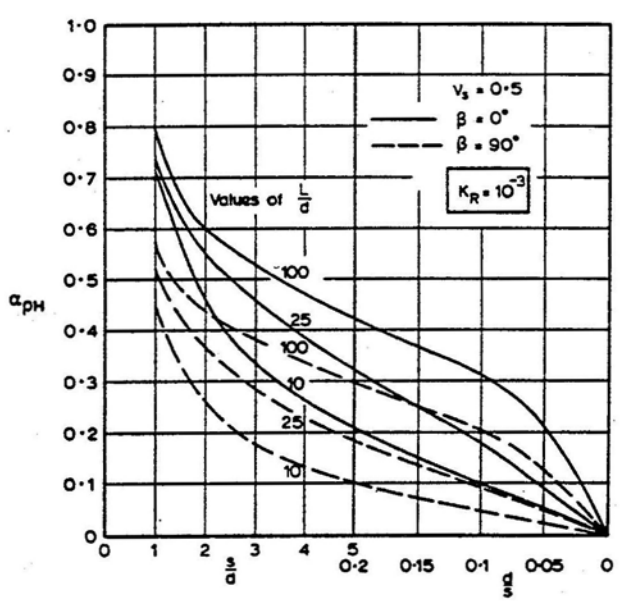


FIG.14.23 Interaction factor $\alpha_{\rho H}$. $K_R = 10^{-3}$

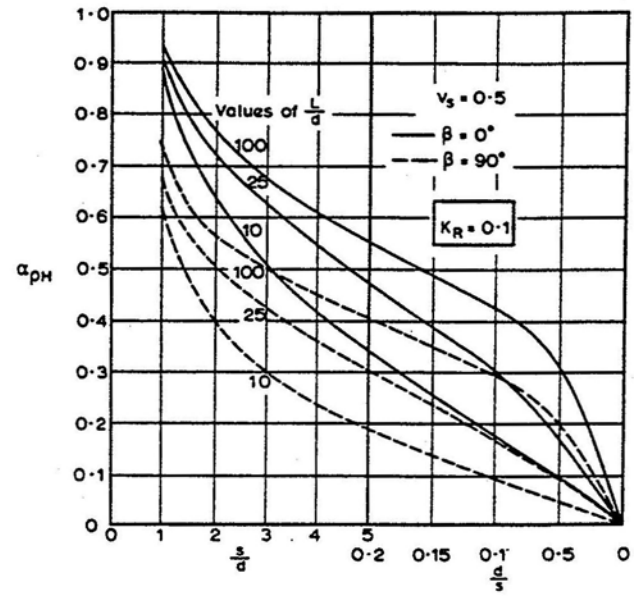


FIG.14.24 Interaction factor $\alpha_{\rho H}$. $K_R = 0.1$

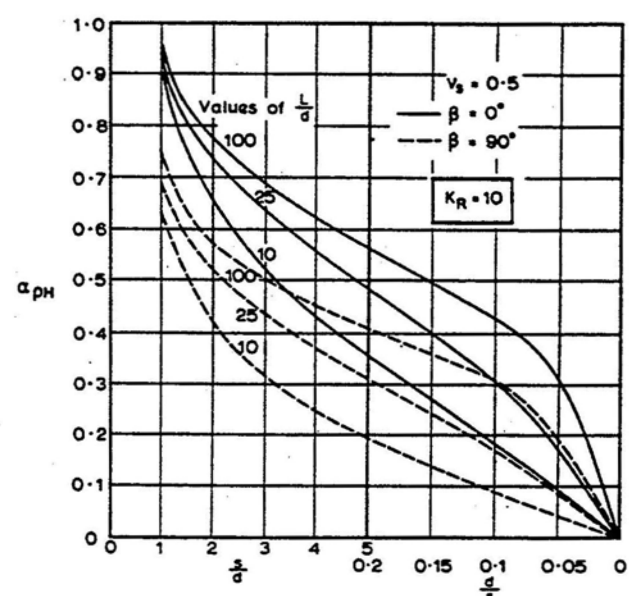


FIG.14.25 Interaction factor $\alpha_{\rho H}$. $K_R = 10$

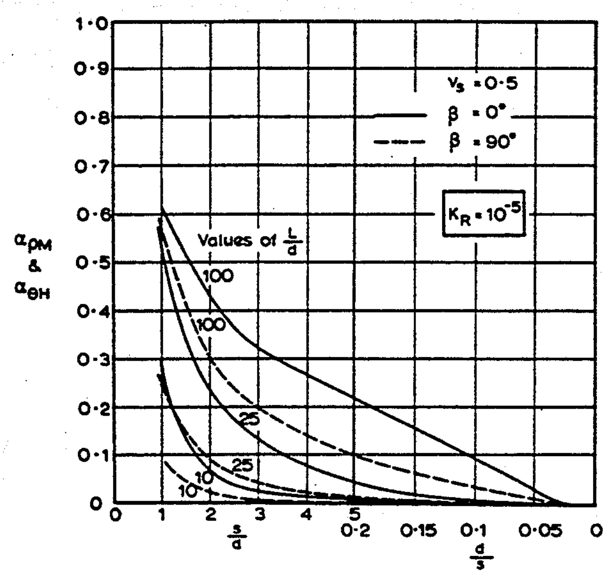


FIG.14.26 Interaction factors $\alpha_{\rho M}$ and $\alpha_{\theta H}$. $K_R = 10^{-5}$

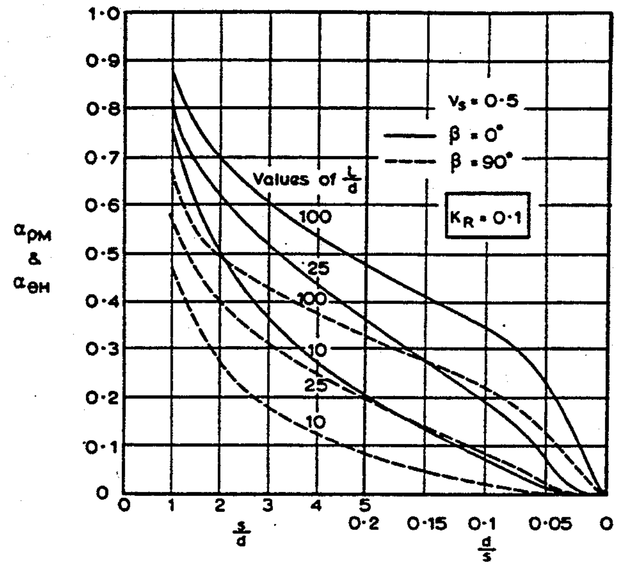


FIG.14.28 Interaction factors $\alpha_{\rho M}$ and $\alpha_{\theta H}$. $K_R = 0.1$

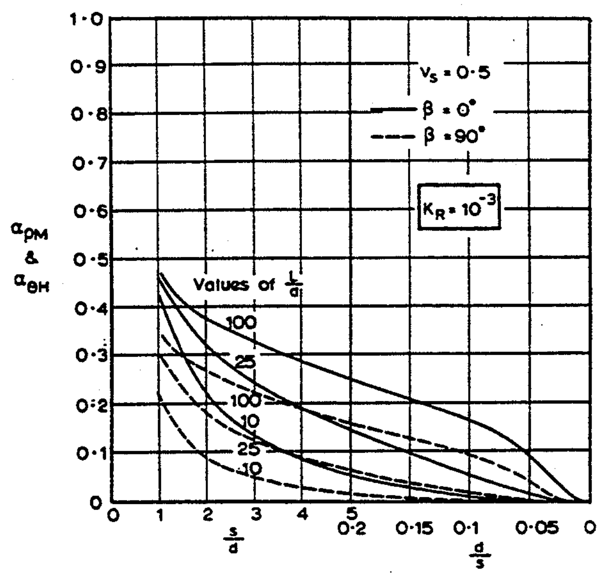


FIG.14.27 Interaction factors $\alpha_{\rho M}$ and $\alpha_{\theta H}$. $K_R = 10^{-3}$

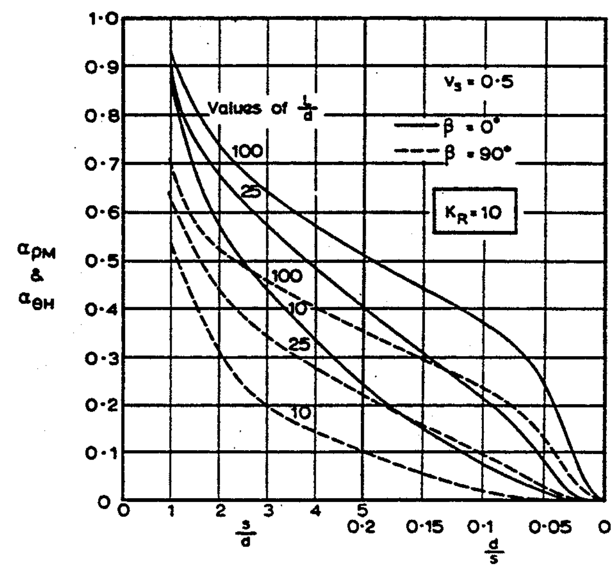


FIG.14.29 Interaction factors $\alpha_{\rho M}$ and $\alpha_{\theta H}$. $K_R = 10$

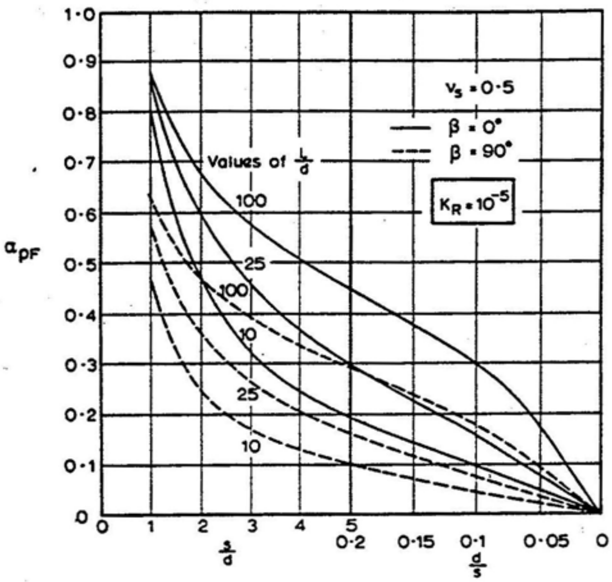


FIG.14.30 Interaction factor $\alpha_{\rho F}$. $K_R = 10^{-5}$

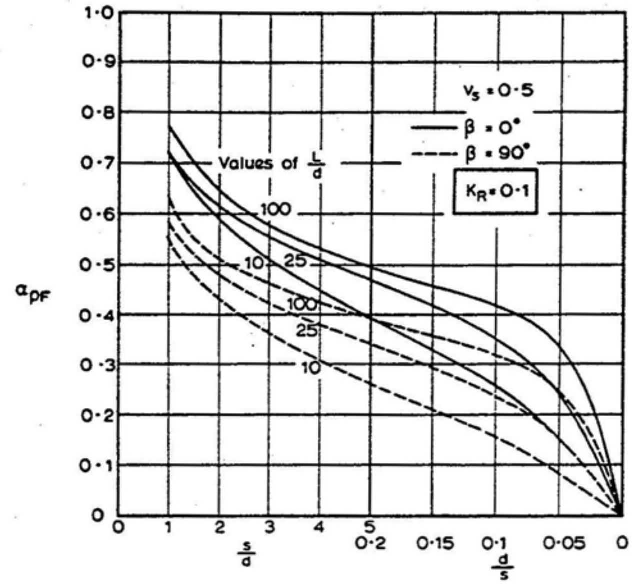


FIG.14.32 Interaction factor $\alpha_{\rho F}$. $K_R = 0.1$

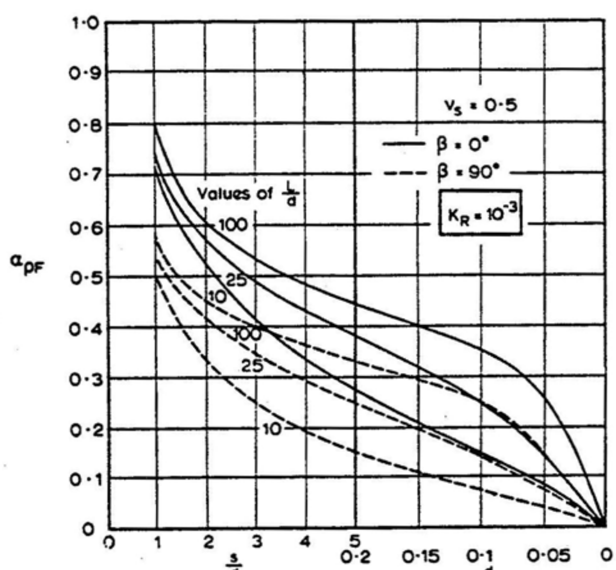


FIG.14.31 Interaction factor $\alpha_{\rho F}$. $K_R = 10^{-3}$

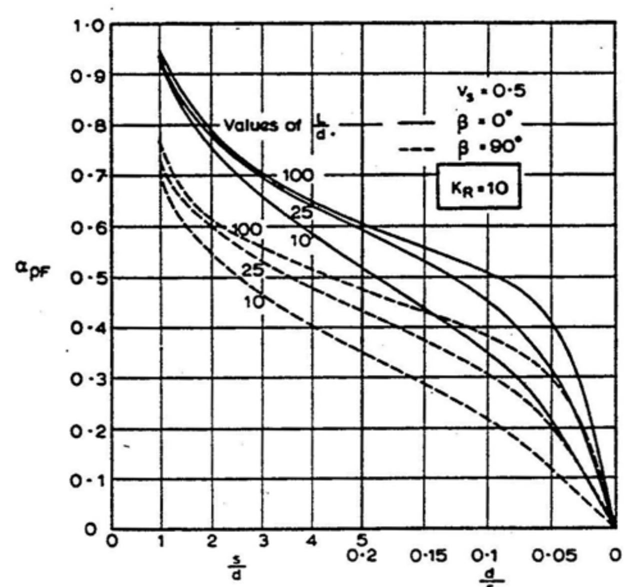


FIG.14.33 Interaction factor $\alpha_{\rho F}$. $K_R = 10$

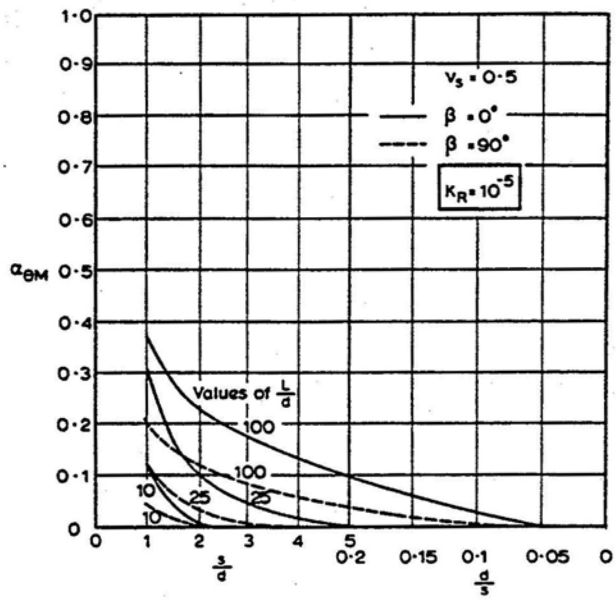


FIG.14.34 Interaction factor $\alpha_{\theta M}$. $K_R = 10^{-5}$

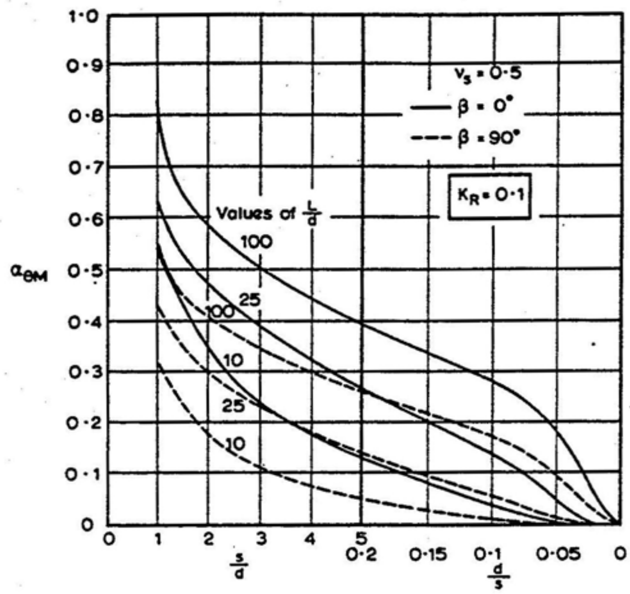


FIG.14.36 Interaction factor $\alpha_{\theta M}$. $K_R = 0.1$

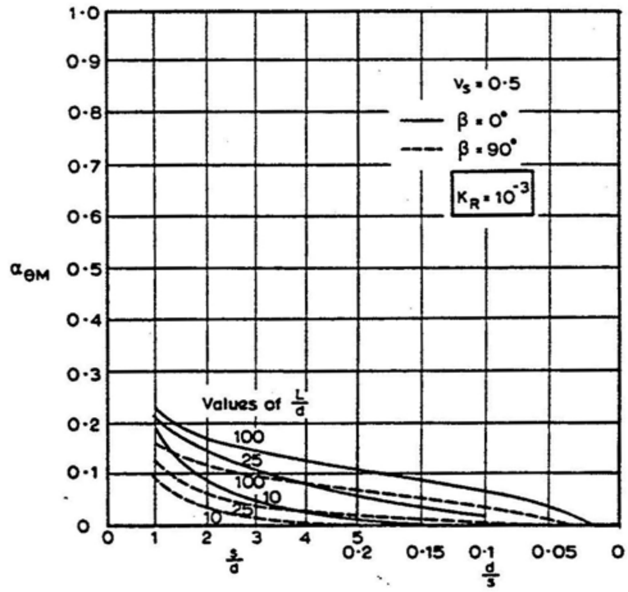


FIG.14.35 Interaction factor $\alpha_{\theta M}$. $K_R = 10^{-3}$

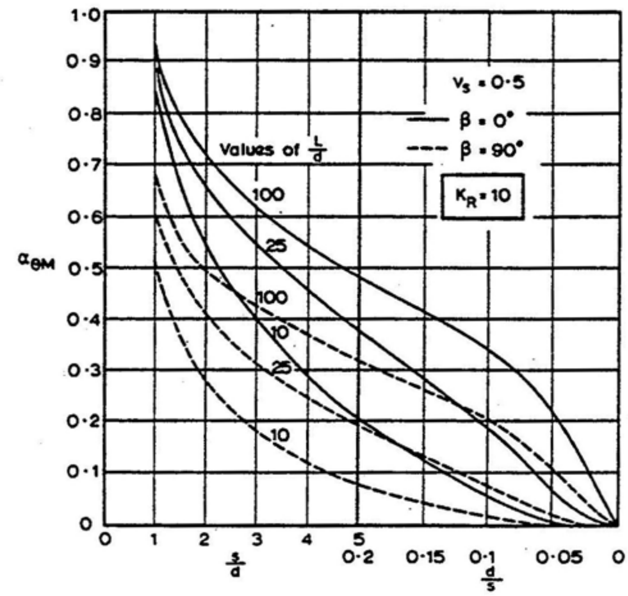


FIG.14.37 Interaction factor $\alpha_{\theta M}$. $K_R = 10$

14.4 Battered Piles

This problem has been considered by Poulos and Madhav (1971). For normal batter angles, it is found that the axial displacement due to the axial component of load on a battered pile are almost identical with the vertical displacements due to vertical load on a vertical pile (Chapter 13). Similarly, the normal displacement due to the normal component of load on a battered pile may be taken as approximately equal to the horizontal displacement due to horizontal load on a vertical pile (Sections 14.1 and 14.2).

If the simplifying assumption is made that the normal load has a negligible effect on axial displacement and that the axial load has a negligible effect on normal displacement, the following expressions may be derived for the vertical and horizontal displacements and the rotation of a battered pile subjected to a vertical load V, a horizontal load H and a moment M at the surface of the mass:

Vertical displacement:

$$\rho_V = \frac{1}{E_s L}\{V.I_{vV} + H.I_{vH} + \frac{M}{L}.I_{vM}\} \qquad \ldots (14.6)$$

where
$$I_{vV} = I_\rho \cos^2\psi - I_{\rho H} \sin^2\psi$$
$$I_{vH} = (I_\rho - I_{\rho H}) \sin\psi \cos\psi$$
$$I_{vM} = -I_{\rho M} \sin\psi$$

Horizontal displacement of free-head pile:

$$\rho_h = \frac{1}{E_s L}\{V.I_{hV} + H.I_{hH} + \frac{M}{L}\cdot I_{hM}\} \qquad \ldots (14.7)$$

where
$$I_{hV} = (I_\rho - I_{\rho H}) \sin\psi \cos\psi$$
$$I_{hH} = I_\rho \sin^2\psi + I_{\rho H} \cos^2\psi$$
$$I_{hM} = I_{\rho M} \cos\psi$$

Rotation of free-head pile:

$$\theta = \frac{1}{E_s L^2}\{V.I'_{\theta V} + H.I'_{\theta H} + \frac{M}{L}.I'_{\theta M}\} \qquad \ldots (14.8)$$

where
$$I'_{\theta V} = -I_{\theta H} \sin\psi$$
$$I'_{\theta H} = I_{\theta H} \cos\psi$$
$$I'_{\theta M} = I_{\theta M}$$

Horizontal displacement of fixed-head pile:

$$\rho_{hF} = \frac{1}{E_s L}\{V.I_{FV} + H.I_{FH}\} \qquad \ldots (14.9)$$

where
$$I_{FV} = (I - I_{\rho F}) \sin\psi \cos\psi$$
$$I_{FH} = I_\rho \sin^2\psi + I_{\rho F} \cos^2\psi$$

In equations (14.6) to (14.9)

ψ = angle of batter of pile from vertical (positive batter is in the direction of the horizontal load or moment)

I_ρ = displacement influence factor for axially loaded pile, e.g. Figs. 13.3 to 13.6, Fig.13.12

$I_{\rho H}$, $I_{\rho M}$, $I_{\theta H}$, $I_{\theta M}$, $I_{\rho F}$

= horizontal displacement and rotation influence factors for laterally loaded pile (see Sections 14.1 and 14.2).