e = eccentricity of load above ground

L = embedded length

A4 CALCULATION OF ULTIMATE LATERAL RESISTANCE OF PILES.

A4.1 Single Pile in Purely Cohesive Soil. The ultimate lateral resistance H_u of a free-head pile is given by the lesser of—

$$H_u = \lambda_s c_u d^2 \quad \ldots \quad \text{A4.1(A)}$$

$$H_u = \lambda_L c_u d^2 \quad \ldots \quad \text{A4.1(B)}$$

where

λ_s = factor tabulated in Table A4.1

$$\lambda_L = 9\left\{-\left(\frac{e}{d} + 1.5\right) + \sqrt{\left[\left(\frac{e}{d} + 1.5\right)^2 + \frac{2M_y}{9c_u d^3}\right]}\right\}$$

If the pile head is fixed against rotation, the ultimate lateral resistance is increased and can be calculated as described by Broms (1964a).

TABLE A4.1

VALUES OF FACTOR λ_s

L/d	Value of factor λ_s					
	e/d					
	0	1	2	4	8	16
4	4	3	2	1	1	1
8	16	14	12	10	8	4
12	30	28	25	21	16	10
16	47	42	40	32	26	15
20	60	56	51	45	36	26

A4.2 Single Pile in Non-cohesive Soil. The ultimate lateral resistance of a free head is given by the lesser of—

$$H_u = \frac{\gamma d L^3 \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right)}{2(e + L)} \quad \ldots \quad \text{A4.2(A)}$$

and

the value of H_u which is the solution to the following equation:

$$H_u\left\{e + 0.54\sqrt{\left[\frac{H_u}{d\gamma \tan^2(45 + \phi/2)}\right]}\right\} = M_y \quad \ldots \quad \text{A4.2(B)}$$

If the pile head is fixed against rotation, the ultimate lateral resistance is increased and can be calculated as described by Broms (1964b).

A4.3 Pile Groups. The ultimate lateral resistance of a pile group can be estimated as the lesser of—

(a) the sum of the ultimate lateral resistance of the individual piles in the group, and

(b) the ultimate lateral resistances of the group considered as an equivalent single pile.

NOTE: The provision of raking piles increases the ultimate lateral resistance of a pile group and the effect of raking piles can be calculated by considering statical equilibrium of the group. The raking of the outer piles of the group generally has the major influence in producing such an increase.

A5 CALCULATION OF LATERAL PILE DEFLECTIONS.

A5.1 Single Vertical Pile. The deflection and rotation of a fully-embedded single vertical pile can be determined as follows:

(a) *Uniform soil modulus with depth.* This case is appropriate for piles in heavily over-consolidated clay.

(i) *Free-head pile:*

Ground-line deflection ρ =

$$\left(\frac{H}{E_s L}\right) I_{\rho H} + \left(\frac{M}{E_s L^2}\right) I_{\rho M} \quad \ldots \quad \text{A5.1(A)}$$

Ground-line rotation θ =

$$\left(\frac{H}{E_s L^2}\right) I_{\theta H} + \left(\frac{M}{E_s L^3}\right) I_{\theta M} \quad \ldots \quad \text{A5.1(B)}$$

(ii) *Fixed-head pile:*

Ground-line deflection ρ =

$$\left(\frac{H}{E_s L}\right) I_{\rho F} \quad \ldots \quad \text{A5.1(C)}$$

The pile deflection and rotation factors are primarily functions of the length/diameter ratio L/d and a dimensionless pile flexibility factor K_R, where—

$$K_R = \frac{E_p I_p}{E_s L} \quad \ldots \quad \text{A5.1(D)}$$

Values of $I_{\rho H}$, $I_{\rho M}$ $(= I_{\theta H})$, $I_{\rho F}$ and $I_{\theta M}$ are tabulated in Table A5.1(A).

(b) *Linearly increasing soil modulus with depth.* This case is appropriate for piles in normally consolidated clay and piles in sand.

(i) *Free-head pile:*

Ground-line deflection ρ =

$$\left(\frac{H}{N_h L^2}\right) I'_{\rho H} + \left(\frac{M}{N_h L^3}\right) I'_{\rho M} \quad \text{A5.1(E)}$$

Ground-line rotation θ =

$$\left(\frac{H}{N_h L^3}\right) I'_{\theta H} + \left(\frac{M}{N_h L^4}\right) I'_{\theta M} \quad \text{A5.1(F)}$$

(ii) *Fixed-head pile:*

Ground-line deflection ρ =

$$\left(\frac{H}{N_h L^2}\right) I'_{\rho F} \quad \ldots \quad \text{A5.1(G)}$$

The pile deflection and rotation factors are primarily functions of the length/diameter ratio L/d and a pile flexibility factor K_N, where—

$$K_N = \frac{E_p I_p}{N_h L^5} \quad \ldots \quad \text{A5.1(H)}$$

Values of $I'_{\rho H}$, $I'_{\rho M}$ $(= I'_{\theta H})$, $I'_{\rho F}$ and $I'_{\theta M}$ are tabulated in Table A5.1(B).

If the pile is partially embedded, the deflection of the free-standing portion due to pile rotation and bending is added to the ground-line deflection to obtain the deflection at the pile head.

NOTE: The most satisfactory means of obtaining a suitable secant modulus of the soil is to carry out a lateral pile load test and to use the theory with the measured deflection and/or rotation to back-figure the soil modulus.

Alternatively, plate load tests (preferably on vertical plates) carried out at the same average applied stress as expected to occur along the pile may give an indication of the soil modulus.

In the absence of pile load test or other data, Table A5.1(C) gives a guide to previously-experienced values of the secant modulus. Large variations in these values may occur.

length ratio of L/d = 20. Piles having L/d ratios in excess of 20 are considered to be long piles. For long piles a plastic hinge is assumed in the vicinity of the maximum moment. The yield moment M_Y of long piles will generally limit the soil resisting maximum moment **M_{ULT}** so that **$M_{ULT} = M_Y$** should be used.

The maximum moment for short piles occurs at the location of zero shear. For cohesive soils the plane of zero shear is located at a pile depth of e + 1.5d + **f_c** below the plane of application of the horizontal force. The distance **f_c** develops from equating horizontal forces:

$$f_c = H_{ULT}/9C_ud$$

The maximum moment occurs at a depth of e + 1.5d + f_c:

$$M_{ULT} = H_{ULT}(e + 1.5d + 0.5f_c)$$

Based on failure of the soil.

If the moment **M_{ULT}** is calculated, to be greater than the yield moment M_Y of the pile, a long pile is indicated and **H_{ULT}** must be limited by using **$M_{ULT} = M_Y$**.

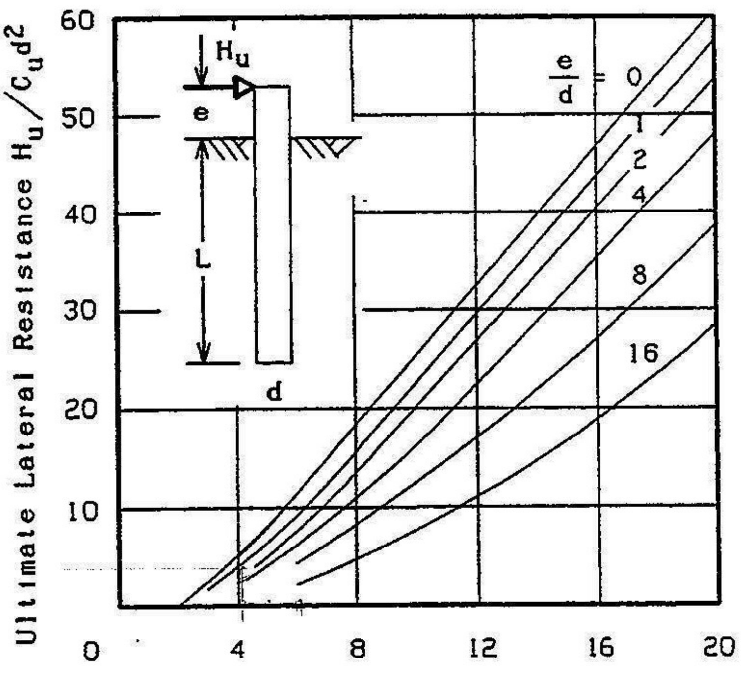

FIGURE 6

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Figure 6 contains curves developed by Broms for short piles which relates the pile embedment depth ratio L/d to the ultimate lateral soil resistance for various e/d ratios.

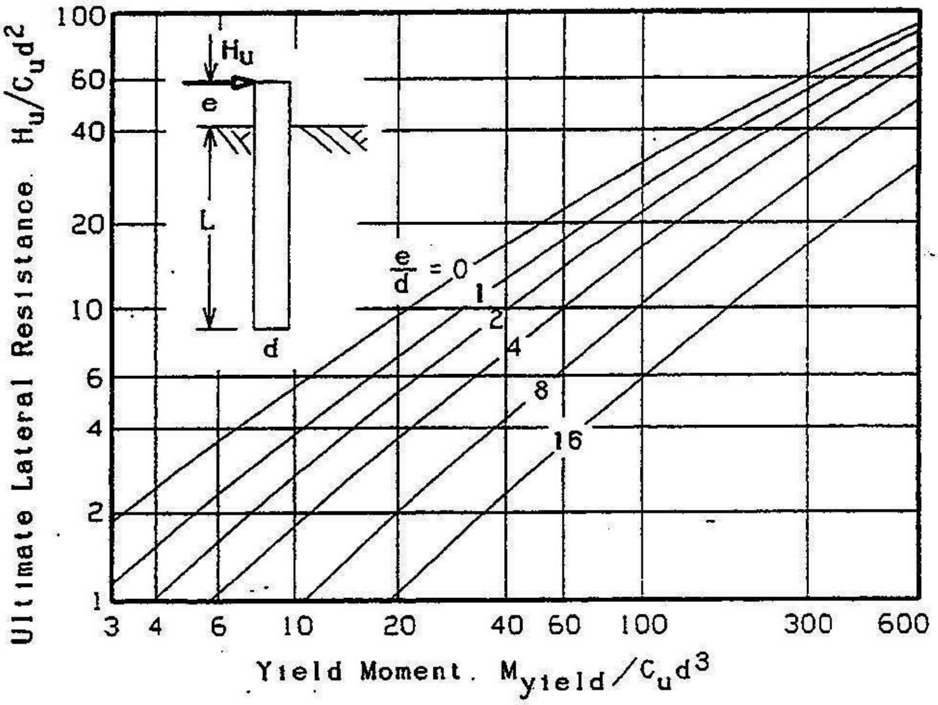

FIGURE 7

Figure 7 may be used for long piles. Curves developed by Broms for e/d values relate the soils ultimate lateral resistance to the yield moment of the pile. This figure is used when the pile embedment length ratio L/d is greater than 20 and when the yield moment of the pile is less than the moment due to the ultimate lateral soil resistance.

The safe single use working load for free headed piles in cohesive soil may be taken as one-half of the ultimate load value.