where Q_d = ultimate load on group, tons
B = width of pile group, out to out, ft
L = length of pile group, out to out, ft
l = pile length, ft
q_{u1} = average unconfined compressive strength of clay within length l, tons/sq ft
q_{u2} = average unconfined compressive strength within a distance B below the pile tips, tons/sq ft

The maximum probable loading on the group should not exceed $Q_d/3$. Although the base bearing capacity may contribute considerably to the capacity of the pile group, it should be noted that the greatest benefit of a friction pile foundation is obtained with the longest piles possible within the limits of economy. The longer the pile the smaller the settlement in most instances.

Piles driven into clays that increase materially in strength with depth may be analyzed as for friction piles. However, the point resistance, which may represent a sizable proportion of the pile capacity, can be determined only by means of loading tests. The safe load on a group may be taken as the safe load per pile as determined from load tests times the number of piles in the group. In some localities pile-driving formulas have been adjusted to indicate safe loads corresponding to the pile-driving resistance. Such formulas should never be used outside the geological region in which they were developed.

Piles driven through relatively soft materials to a stiff or hard clay act in point bearing. The load capacity of a group of such piles is equal to the product of the number of piles in the group and the safe load per pile without regard to their spacing. However, these conditions are ideal for the development of negative skin friction (Art. 73), which may be a sizable proportion of the pile load capacity. The magnitude of the negative skin friction can be determined from pile load tests (Art. 35). It may also be estimated as the average shearing resistance of the soft material multiplied by the surface area of the embedded piles.

76. Settlement of Pile Foundations Any pile foundation which has a compressible stratum located below the pile tips is likely to settle, and the magnitude of the settlement should be predicted. It is computed in the same manner as for footings on clay except that the change in pressure Δp is determined somewhat differently depending upon whether the piles act in point bearing or as friction piles.

For a point-bearing pile foundation, the load on the pile group is assumed to be applied to the subsoil at the level of the pile tips on an area equal to the plan area of the pile group. Below the tips, it is considered to be spread uniformly at an angle of 30° from the vertical.

The settlement of a group of friction piles is computed in a similar manner. However, the level of the application of the load to the subsoil is less certain, as load is transferred through much of the length of the piles. A commonly used approximate procedure is based on the assumption that the load is applied at the lower third point of the piles. The load is assumed to spread at an angle of 30° from the vertical, and any compressible material below the lower third point is assumed to contribute to the settlement of the group.

77. Laterally Loaded Piles Where a pile-supported structure is subjected to lateral loads, the vertical piles may provide more lateral resistance than is commonly realized. Prevailing rules of thumb commonly permit an arbitrary lateral load per pile—often 1000 lb—without any consideration as to the type of pile or the soil in which it is driven. Since a pile-supported structure does not transmit load directly to the soil beneath the pile cap, frictional resistance should not be assumed between the base of the structure and the underlying soil. Therefore, the piles must be adequate to resist all lateral loads.

The ultimate lateral bearing pressure per unit length of pile at a given depth in clay is

$$Q_d = 9cB = 4.5q_uB \tag{44}$$

and in sands

$$Q_d = 3B\gamma' z \frac{1 + \sin\phi}{1 - \sin\phi} \tag{45}$$

where Q_d = ultimate load per unit length of pile, lb/ft
c = cohesion, psf
q_u = unconfined compressive strength, psf
B = width of pile, ft

γ' = effective unit weight of soil, pcf
z = depth, ft
ϕ = angle of shearing resistance

The working load should not exceed $Q_d/2$ beyond a depth of $4B$ under any circumstance.

For lateral loads smaller than $Q_d/2$, the soil reaction at any depth is given by

$$w = \frac{C_w Q_{hg}}{T} \tag{46}$$

where w = soil reaction, lb/ft
C_w = soil reaction coefficient from Fig. 47
Q_{hg} = shear at ground surface, lb
T = relative stiffness of pile = $\sqrt[5]{EI/n_h}$, in.
EI = flexural stiffness of pile, lb-in.^{2}
n_h = constant of horizontal subgrade reaction, lb/in.^{3}

The modulus of subgrade reaction $k = w/y$ is the ratio of the total reaction per unit length of pile to the corresponding deflection. For granular soils k is directly proportional

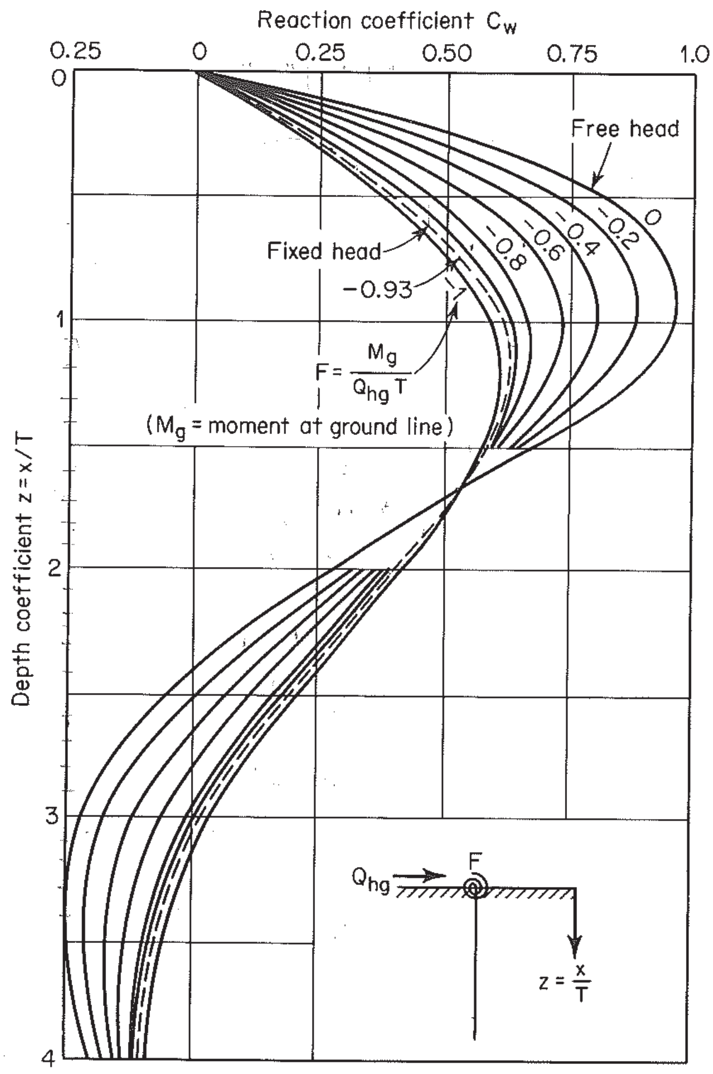

Fig. 47 Coefficients for soil reaction, laterally loaded piles. *(From Prakash, 1961.)*

to the depth x, and it has been shown that k is also proportional to depth for normally consolidated clays and silts. However, for overconsolidated clays k is usually assumed to be a constant and the corresponding relative stiffness is $\sqrt[4]{EI/k}$. Since k is proportional to depth for most soils of interest, the case of constant k is not considered here.

The constant of horizontal subgrade reaction is $n_h = k/x$. Typical values of n_h are presented in Table 18. Actual values can be determined experimentally by driving two instrumented piles relatively close together and jacking them apart. By measuring the loads and deflections at various depths (with a tiltmeter), k can be determined.

The lateral deflection y, in inches, given by

$$y = C_y \frac{Q_{hg}T^3}{EI} \tag{47}$$

where C_y = deflection coefficient from Fig. 48, may also be used to evaluate k from a jacking test as well as to determine anticipated deflections.

The moment in a laterally loaded pile (in.-lb) is

$$M = C_m Q_{hg} T \tag{48}$$

where C_m = moment coefficient from Fig. 49. It is noted in Figs. 47, 48, and 49 that a fixed-head pile is generally more favorable than one with a free head. The fixity depends

TABLE 18 Typical Values of n_h*

Soil type	N	n_h, lb/in.^{3} Dry	n_h, lb/in.^{3} Submerged
Sand:			
Loose	<10	9.4	5.3
Medium	10–30	28	19
Dense	>30	75	45
Very loose under repeated loading	<5	....	1.5
Silt, very soft, organic	<3	....	0.4–1.0
Clay:			
Very soft	<3		
Static loads	.....	....	2
Repeated loads	.....	....	1

* M. T. Davisson, 1963.

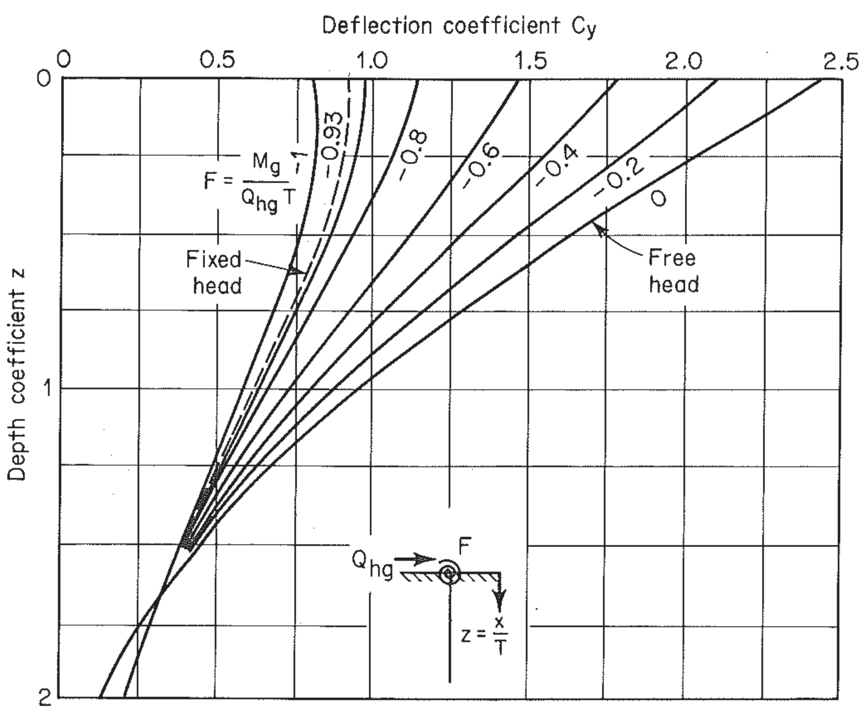

Fig. 48 Deflection coefficients for laterally loaded piles. *(From Matlock and Reese, 1961.)*

on the structural characteristics of the pile cap and the connection between the pile and the pile cap. The latter is attained by embedding the pile at least 24 in. into the pile cap.

The preceding analyses are for single piles, which corresponds to a minimum spacing of eight pile diameters in the direction of the lateral load and three pile diameters normal to the direction of load. Closer spacings cause a reduction in the modulus of subgrade reaction and an increase in the relative stiffness. From the limited information available, it is recommended that a minimum spacing of $3B$ be maintained normal to the load and that T be increased linearly to a limiting value of $1.3T$ as the pile spacing in the direction of the load decreases from $8B$ to $2.5B$.

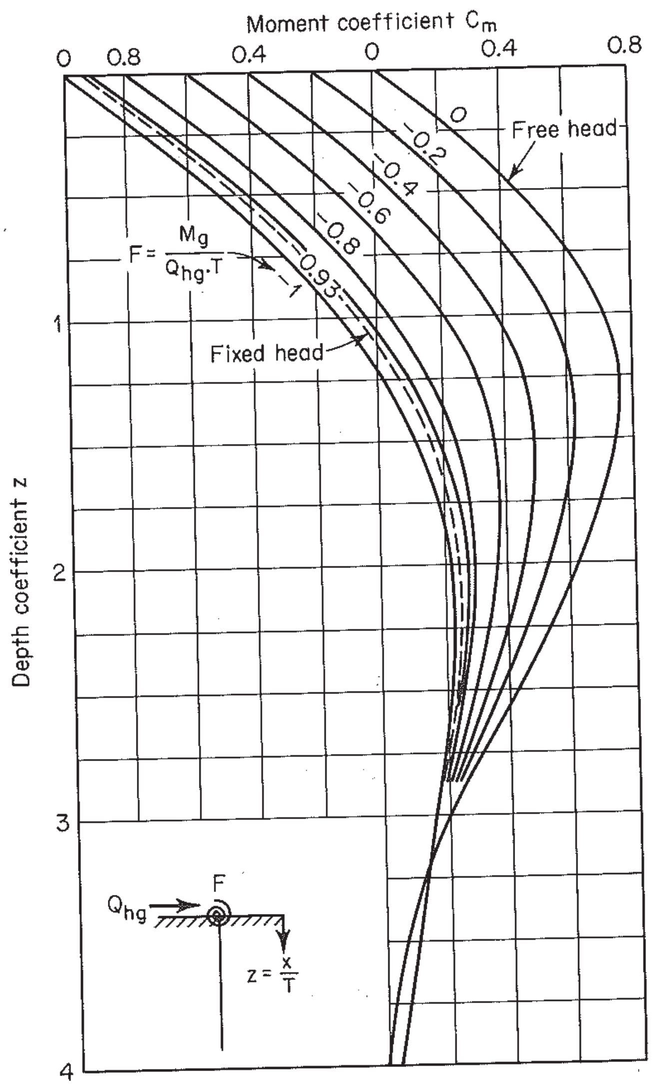

Fig. 49 Moment coefficients for laterally loaded piles. *(From Prakash, 1961.)*

78. Batter Piles Batter piles are often used where the lateral loads exceed the lateral resistance of vertical piles. It is commonly assumed that a batter pile has the same axial load capacity as a vertical pile of the same size driven to the same stratum. In the design of a batter-pile foundation, the sum of the horizontal components of the allowable axial loads must equal or exceed the required lateral resistance.

The vertical component Q of load in a batter pile is given by

$$Q = \frac{\Sigma V}{n} \pm \frac{\Sigma Md}{\Sigma d^2} \tag{49}$$

where ΣV = sum of vertical loads acting on foundation
n = number of piles in group
ΣM = sum of moments about center of gravity of pile group
d = distance from center of gravity of group to pile