Subgrade Modulus of Laterally Loaded Piles in Clays

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Pile-soil interaction of laterally loaded piles may be characterized by either linear subgrade modulus methods or the nonlinear load transfer relationships, termed *p-y* curves. The selection of a subgrade modulus to analyze lateral behavior of piles relies heavily on individual judgment because the subgrade modulus itself is a function of pile deflection. Analyses of laterally loaded piles by means of *p-y* curves often require extensive numerical procedures on a digital computer. A concept of equivalent subgrade modulus, which incorporates the nonlinear nature of the *p-y* model, is derived from a parametric study of the effects of pile-soil stiffness under three well-known clay criteria: soft clay and stiff clay above and below the water table. Design curves of equivalent subgrade modulus versus a dimensionless lateral load factor are developed. A design procedure to predict maximum deflection and maximum moment of laterally loaded piles in clays is proposed and used to predict published field test data.

Deep foundations are frequently designed to resist lateral loading. Typical examples include pile-supported bridges, buildings, and offshore structures. Of primary interest to geotechnical and structural engineers is the prediction of deflection and bending moment of deep foundations under lateral loads. The most convenient method of analysis for laterally loaded piles involves the theory of subgrade reaction (*1*), in which load-deflection relationships for the supporting soil are assumed to be linear functions. However, soil response to lateral loading is highly nonlinear, especially at high stress levels. Lateral soil response is also greatly affected by soil depth and in situ stress conditions. To overcome the aforementioned difficulties, soil response can be modeled by nonlinear unit load transfer functions, termed "*p-y*" relationships, which are mathematical representations of the soil reaction versus the lateral pile deflection per unit length along the pile. There are several *p-y* criteria for clays based on various soil properties and conditions: soft clay (*2*), stiff clay above the water table (*3*), and stiff clay below the water table (*4,5*). Analysis of laterally loaded piles can be performed with these *p-y* criteria by employing finite difference or finite element analyses on a digital computer (*6,7*). However, computer analysis is a more extensive numerical procedure compared with the linear subgrade modulus method, such that the latter method may be preferred by design engineers in preliminary computations and for relatively simple design cases. There have been attempts in the past to develop a simplified method to analyze laterally loaded piles (*8*).

The objective of this paper is to provide engineers with a representative subgrade modulus in which nonlinear pile-soil interaction is implicitly taken into account and a step-by-step design procedure to analyze laterally loaded piles in clays. A family of design curves of equivalent subgrade modulus k_{eq} in terms of dimensionless lateral load factor for soft clay and stiff clay above and below the water table is developed by means of a parametric study of a hypothetical problem. The parametric study is basically an analytical procedure to integrate the simplicity of the linear method with the complex rationality of the load transfer criteria. It involved determining the deflection of a hypothetical pile in clays using a numerical model on a computer. A subgrade modulus under a lateral load was then backcalculated from the obtained deflection using a linear equation. Relationships of subgrade moduli and corresponding lateral loads were developed. Among the parameters investigated in this study are lateral load, pile stiffness, and soil properties.

AVAILABLE ANALYTICAL METHODS

The theory of subgrade reaction assumes that the unit soil reaction p with respect to a laterally loaded pile increases linearly with the lateral deflection y, as expressed in the following equation:

$$p = ky \tag{1}$$

where k is the subgrade modulus. Once a subgrade modulus is known, the behavior of a laterally loaded pile may be evaluated by linear methods such as the Broms equations (*1*) and nondimensional solutions (*9,10*). A brief description of the Broms equations and the nondimensional solutions is included in the following paragraphs.

Broms Equations

Broms used a dimensionless βL to define short or long piles, where L is the length of the pile and β is defined as

$$\beta = (kB/4EI)^{0.25} \tag{2}$$

where B is the diameter of the pile and EI is its stiffness.

Broms recommended that the lateral deflection y_o of a free-head long pile in clays ($\beta L > 2.5$) at the ground surface may be determined as

$$y_o = 2P\beta \, (e\beta + 1)/kB \tag{3}$$

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or

$$y_o = 2P\beta/kB \qquad \text{for } e = o \tag{3a}$$

in which P is the applied lateral load and e is the distance of the lateral load above the ground surface and can also be calculated from an applied moment at the ground surface M as

$$e = M/P \tag{4}$$

For a restrained-head long pile in clays ($\beta L > 1.5$) where the slope at the pile head is zero, deflection can be calculated from

$$y_o = P\beta/kB \tag{5}$$

Nondimensional Solutions

Nondimensional solutions for laterally loaded piles require an iterative procedure to achieve convergence of the relative stiffness factor T, which is defined as

$$T = (EI/k_n)^{0.2} \tag{6}$$

where k_n is a constant relating to the subgrade modulus of soil to depth Z as

$$k_n = kB/Z \tag{6a}$$

The lateral deflection y and bending moment m of the pile can be obtained from the following equations:

$$y = \frac{A_y PT^3}{EI} + \frac{B_y MT^2}{EI} \tag{7}$$

$$m = A_m PT = B_m M \tag{8}$$

in which A_y, B_y are deflection coefficients due to applied lateral load P and applied moment M, respectively, and A_m, B_m are moment coefficients due to applied lateral load P and applied moment M, respectively.

Depending on the value of the maximum depth coefficient Z_{max}, deflection and moment coefficients can be obtained at any depth along the pile. Coefficient charts are available in the paper by Matlock and Reese (9). Z_{max} is defined as

$$Z_{max} = \frac{L}{T} \tag{9}$$

In the absence of applied moment at the pile head, the maximum deflection and moment coefficients can be found

in Table 1. Using the maximum coefficients in Table 1, the maximum deflection and maximum moment of piles under lateral loads can be calculated from Equations 7 and 8, respectively.

The accuracy of the Broms equations lies heavily on the selection of the subgrade modulus k, which is recommended by Broms to be taken as the average value within a depth equal to $0.8\beta L$. Because it has been suggested that the load-deflection relationship is highly nonlinear, the value of this average k is obviously dependent on the magnitude of the lateral load. Therefore, the Broms equations are convenient and simple to use at low stress levels where linearity is not a severe modeling limitation. The nondimensional solutions may handle nonlinearity problems but require a somewhat time-consuming iteration procedure and also the availability of respective p-y data. Nonlinear modeling of a laterally loaded pile problem can be performed, as previously mentioned, by the load transfer method.

PARAMETRIC STUDY

It is the intent of this study to integrate the linear Broms procedures and the nonlinear load transfer methods empirically on a parametric basis to develop a simple procedure as convenient as the Broms solutions and with the power and broad range of applications of the load transfer solutions. The purpose of the parametric study is to develop an equivalent subgrade modulus under a specific pile-soil condition. The procedures to develop the equivalent subgrade modulus are presented in this section.

By employing a numerical computer solution for laterally loaded piles, COM 624 (7), a parametric study was performed on a hypothetical problem to determine the lateral deflections under various prescribed conditions. Soil models selected for investigation in the study were soft clay (2), stiff clay above the water table (3), and stiff clay below the water table (5).

The soil parameters investigated in this study are represented by a selected range of subgrade modulus k and summarized as follows (1 pci = 271.7 kN/m³):

● Soft clay: 30, 100, and 300k (pci);
● Stiff clay above or below the water table: 300, 1,000, and 3,000k (pci).

The pile parameters considered in this study are as follows (1 in. = 2.54 cm; 1 psi = 6.89 kN/m²):

Pile Material	Pile Diameter B (in.)	Young's Modulus E (psi)	Moment of Inertia I (in.⁴)
Concrete	36	3×10^6	82447.9
Steel	12	30×10^6	1017.9

TABLE 1 MAXIMUM DEFLECTION AND MOMENT COEFFICIENTS DUE TO LATERAL LOAD ONLY

Z_{max}	A_y		A_m	
	Free-Head	Restrained-Head (Slope = 0.0)	Free-Head	Restrained-Head (Slope = 0.0)
10	2.435	0.820	0.772	0.93
4	2.445	0.829	0.767	0.93
3	2.723	0.968	0.704	0.97
2.2	4.011	1.268	0.557	1.06

The soil and pile parameters selected in this study are believed to cover the spectrum of regular design conditions.

On the basis of the control parameters shown above and a selected pile length of 40 ft (12.2 m), values of βL are determined and summarized in Table 2. The Broms assumption of an infinitely long pile is satisfied by all these βL values for both free-head and restrained-head cases of the hypothetical pile.

Relationships between undrained cohesion of clay C_u with subgrade modulus k and strain at one-half of the maximum principal stress difference ε_{50} were used based on Reese and Sullivan's recommendation (7) and are shown in Table 3.

Average values of cohesion in Table 3 were plotted against k and ε_{50} and presented in Figure 1. The relationships in Figure 1 were used to develop the *p-y* relationships and relevant input data for the parametric study in this paper.

Once deflection y_o was determined using COM624 for a prescribed condition under a particular lateral load P, the equivalent subgrade modulus k_{eq} was found by substituting Equation 2 into Equations 3a and 5 and rewriting Equations 3a and 5 as follows:

$$k_{eq} = \left(\frac{P^4}{y_o^4} \frac{4}{B^3 EI}\right)^{0.33} \quad \text{for free-head pile} \quad (10)$$

$$k_{eq} = \left(\frac{P^4}{y_o^4} \frac{1}{4B^3 EI}\right)^{0.33} \quad \text{for restrained-head pile} \quad (11)$$

It should be noted that one value of k_{eq} would be found corresponding to a lateral load magnitude. Different values of k_{eq} would be determined from a range of lateral loads under the same soil conditions. Eventually relationships of equivalent subgrade modulus and lateral load may be developed for the three clay criteria employed in this study.

Soft Clay

Matlock proposed a method to generate *p-y* curves for laterally loaded piles in soft clays based on the analyses of field and laboratory data (2). Two failure modes are defined for the ultimate lateral resistance of soils: wedge failure above a critical depth Z_{cr} and plastic failure below Z_{cr}, which is defined as

$$Z_{cr} = \frac{6B}{\dfrac{\gamma B}{c_u} + J} \quad (12)$$

TABLE 3   RELATIONSHIPS OF C_u, k, AND ε_{50} (7)

Cohesion, Cu (psf)	k (pci)	ε_{50}
250 - 500	30	0.02
500 - 1000	100	0.01
1000 - 2000	300	0.007
2000 - 4000	1000	0.005
4000 - 8000	3000	0.004

Note: 1 psf = 47.9 N/m²; 1 pci = 271.7 kN/m³

where γ is the effective unit weight and J is an empirical constant (0.5 for offshore soft clays in the Gulf of Mexico and 0.25 for stiffer clays). The ultimate lateral resistance per unit length of pile p_u is written as

$$p_u = Np c_u B \quad (13)$$

where Np is the ultimate lateral soil resistance coefficient.

For depth $Z < Z_{cr}$, c_u is taken as the average value between the ground surface and depth Z. Np can be calculated as

$$Np = 3 + \frac{\gamma Z}{c_u} + \frac{JZ}{B} \quad (14)$$

For depth $Z > Z_{cr}$, c_u is taken as the value at depth Z and Np is 9.0.

The characteristic *p-y* curve for Matlock's soft-clay criterion is defined as

$$p = 0.5 p_u (y_o/y_c)^{0.33} \quad (15)$$

where

p = lateral soil resistance per unit length,
y_o = pile deflection, and
y_c = reference pile deflection = $2.5\varepsilon_{50}B$,

and ε_{50} can be obtained from Figure 2.

By employing the soft-clay criterion, a parametric study was performed using computer program COM624 as described in the previous section. The *p-y* curves were internally generated in the program and deflections were computed for various values of lateral load P. Figures 2 and 3 show the relationships of equivalent subgrade modulus k_{eq} and dimensionless lateral load factor $P\beta/kBu$ for free-head and restrained-head conditions,

TABLE 2   CONTROL PARAMETERS

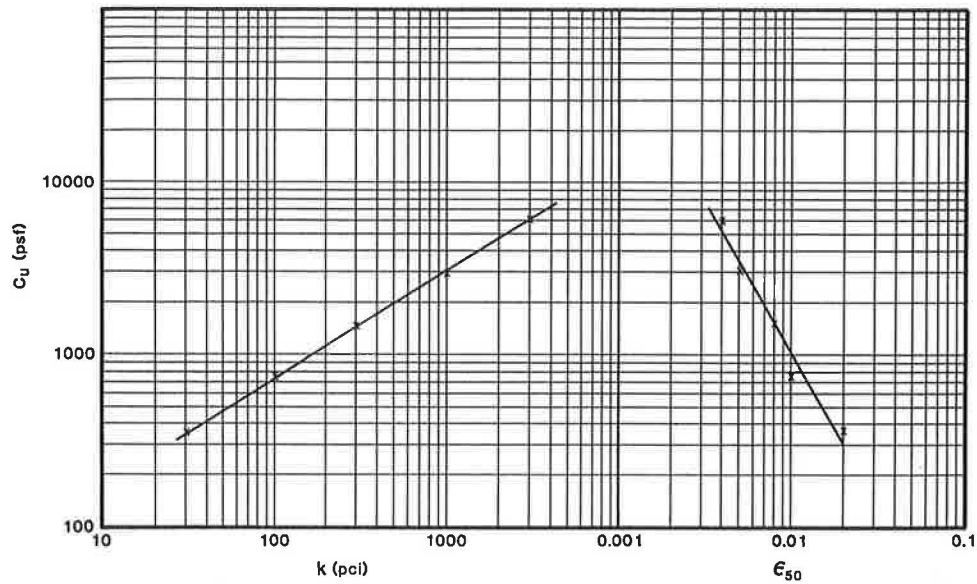| Pile Material	Pile Diameter B (in)	Initial Subgrade Modulus k (pci)	β (Eq.2)	β L
Steel	12	30	0.0074	3.6
		100	0.0100	4.8
		300	0.0131	6.3
		1000	0.0177	8.5
		3000	0.0233	11.2
Concrete	36	30	0.0058	2.8
		100	0.0078	3.7
		300	0.0102	4.9
		1000	0.0138	6.6
		3000	0.0182	8.7

Note: 1 in = 2.54 cm; 1 pci = 271.7 kN/m³

FIGURE 1 Relationships of C_u versus k and ε_{50} (1 psf = 47.9 N/m²; 1 pci = 271.7 kN/m³).
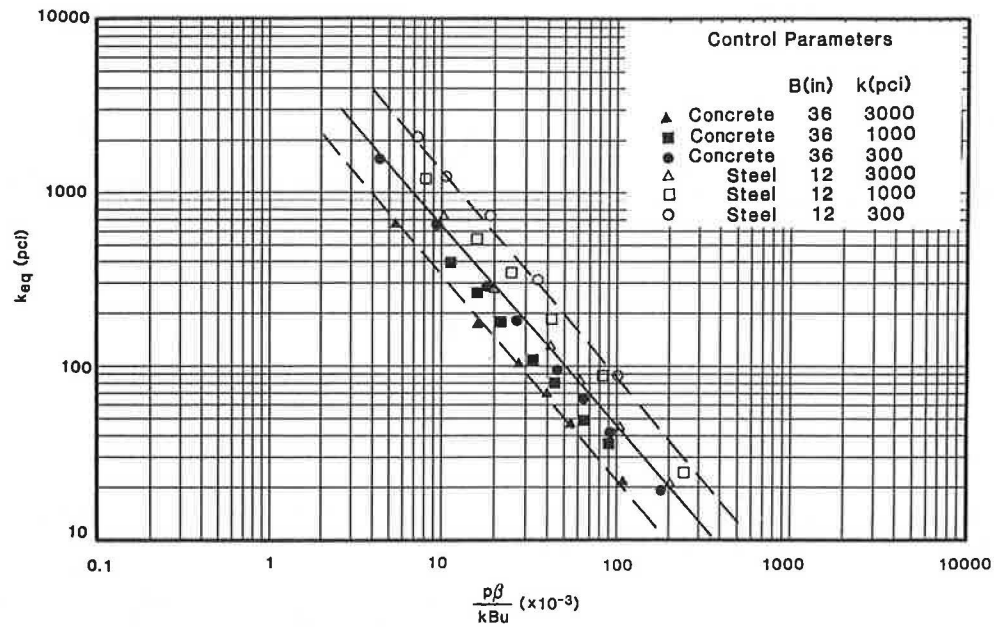

FIGURE 2 Equivalent subgrade modulus versus dimensionless lateral load factor for soft clay: free-head conditions (1 in. = 2.54 cm; 1 pci = 271.7 kN/m³).

respectively. The parameter u is defined as a unit pile length and is used to make the lateral load factor dimensionless.

Different slopes for k_{eq}-dimensionless lateral load factor curves are observed for free-head and restrained-head cases. The observation implies that in the absence of applied moment, lateral deflection at ground surface for free-head piles, as calculated in Equation 3a, would not be exactly twice (i.e., twice flexible) that for restrained-head piles (Equation 5), as suggested by the Broms equations.

Stiff Clay Above the Water Table

The criterion was developed on the basis of the experimental data from a series of lateral load tests on instrumented drilled

piers documented by Reese and Welch (3). Matlock's expression to estimate the ultimate soil resistance p_u was adopted in this criterion, as shown in Equations 13 and 14. The characteristic shape of the p-y curve for stiff clay above the water table is expressed as follows:

$$p = 0.5p_u(y_o/y_c)^{0.25} \qquad (16)$$

Equations 15 and 16 are expressed similarly, with the only difference being the exponent values.

COM624 was used with internally generated p-y curves to estimate lateral deflection under a specified range of lateral loads. The equivalent subgrade modulus k_{eq} was obtained from Equations 10 and 11. Figures 4 and 5 show k_{eq} versus
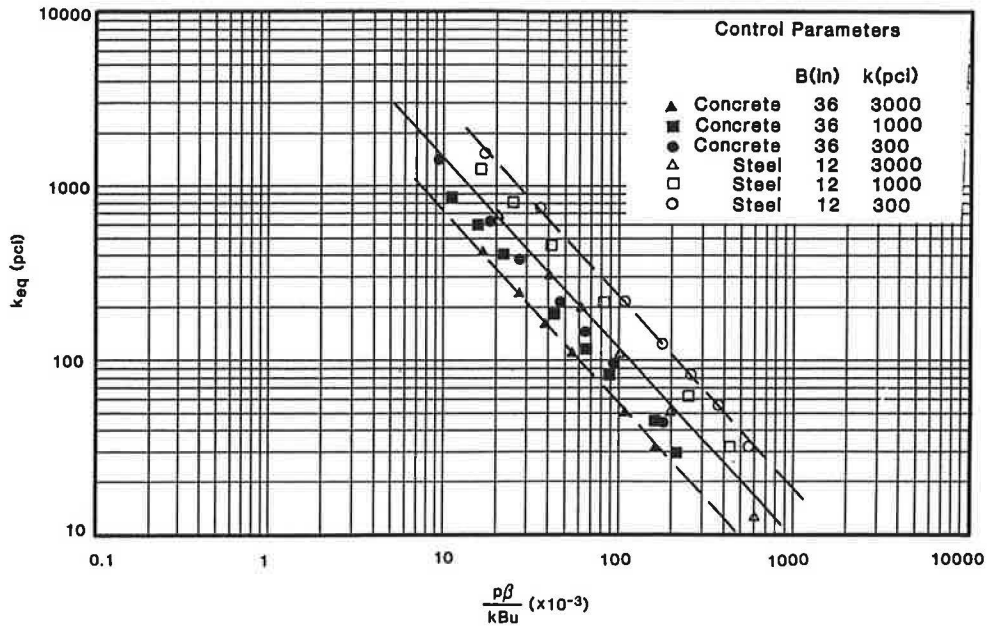
FIGURE 3   Equivalent subgrade modulus versus dimensionless lateral load factor for soft clay: restrained-head conditions (1 in. = 2.54 cm; 1 pci = 271.7 kN/m³).
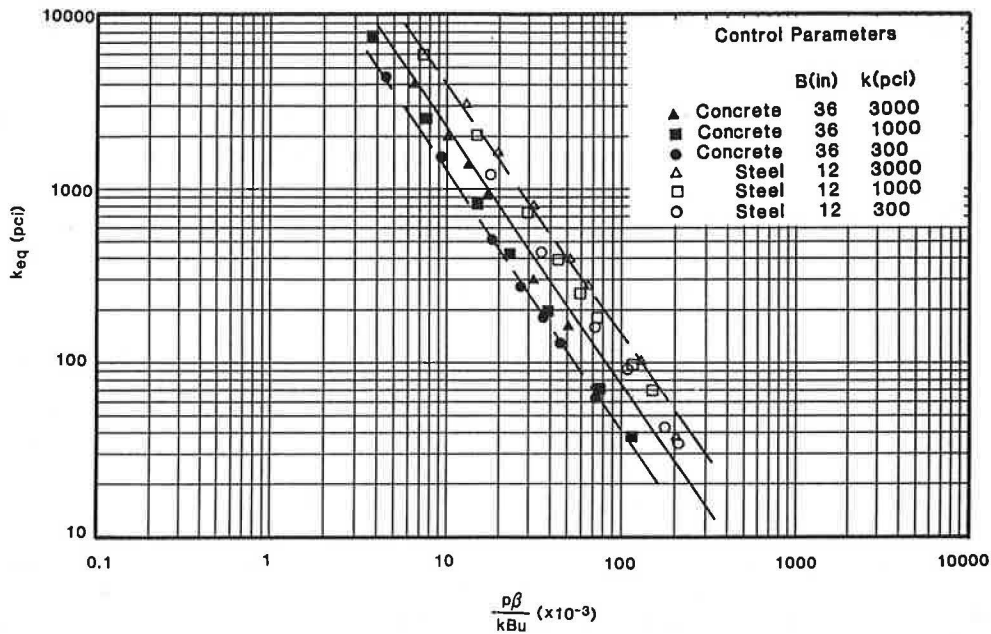

FIGURE 4   Equivalent subgrade modulus versus dimensionless lateral load factor for stiff clay above water: free-head conditions (1 in. = 2.54 cm; 1 pci = 271.7 kN/m³).

the dimensionless lateral load factor for free-head and restrained-head conditions, respectively.

Stiff Clay Below the Water Table

The submerged stiff-clay criterion for the p-y relationship based on full-scale pile test data was developed by Reese et al. (*4*). A statistical evaluation by Gazioglu and O'Neill (*11*) was performed on all the available p-y criteria for clays to assess the levels of uncertainty. O'Neill and Gazioglu (*12*) concluded that Reese's criterion for stiff clay below the water

table yields the greatest uncertainty on the grounds that the criterion was derived from the field data collected in an expansive clay environment. Dunnavant and O'Neill (*5*) performed an independent series of full-scale lateral pile tests in submerged stiff clays and proposed an improved p-y criterion. The characteristic p-y curve for the improved criterion is defined as

$$p = 1.02p_u \tanh [0.537(y_o/y_{50})^{0.7}] \qquad y \leq 8y_{50}$$

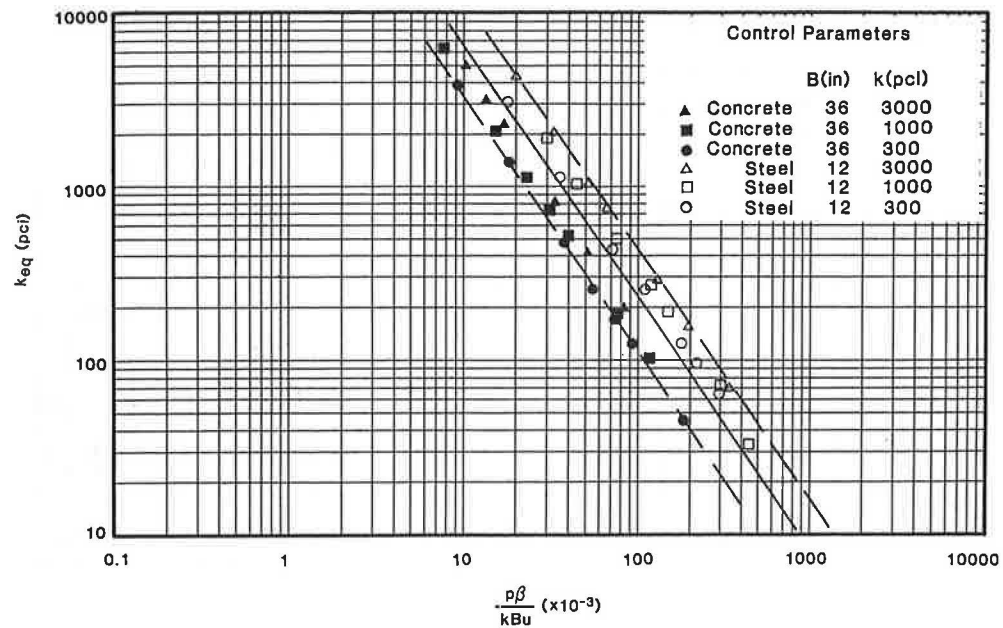$$p = 1.02p_u \qquad y > 8y_{50} \qquad\qquad (17)$$

FIGURE 5 Equivalent subgrade modulus versus dimensionless lateral load factor for stiff clay above water: restrained-head conditions (1 in. = 2.54 cm; 1 pci = 271.7 kN/m³).

The ultimate lateral resistance p_u is calculated by employing Matlock's expression, but with a different lateral resistance coefficient Np, as shown in Equations 18 and 19.

$$p_u = Npc_uB \tag{18}$$

$$Np = 2 + \frac{\gamma Z}{c_u 2} + \frac{JZ}{B} \leq 9 \tag{19}$$

where J is 0.4. The term y_{50} is suggested to be a nonlinear function of the pile diameter and is expressed as

$$y_{50} = 0.0063\varepsilon_{50}BK_R^{-0.875} \tag{20}$$

$$K_R = (EI/E_S L^4) \tag{21}$$

where E_s is the soil modulus, which may be represented by a secant modulus at a deviator stress level one-half the deviator stress at failure in undrained triaxial compression tests. A correlation between the average UU triaxial compression shear strength and the soil modulus is tabulated in the paper by Gazioglu et al. (*11*). The mean values are plotted in Figure 6. The pile length L in Equation 21 is limited numerically to $3B(EI/E_S B^4)^{0.286}$, below which the pile has a negligible effect on pile-head behavior.

Table 4 summarizes the parameters used to generate the required *p-y* curves for the submerged stiff clay criterion in this study.

Figures 7 through 9 give the *p-y* curves generated using the submerged stiff clay criterion of Dunnavant et al. (*5*). The curves were used as input data in the computer program COM624 to conduct the described parametric study. Relationships of k_{eq} versus the dimensionless lateral load factor for stiff clay below the water table under free-head and restrained-head conditions are presented in Figures 10 and

11, respectively. It is shown that k_{eq} seems to be constant below a threshold lateral load factor; that is, the load-deflection relationship is a linear function. Furthermore, when Figures 2 and 3 are compared with Figures 7 and 9, the curves for the submerged stiff clay criterion above the threshold lateral load factor tend to overlap those corresponding to the soft clay criterion, which is shown in the next section.

DESIGN PROCEDURE

A compilation of curves for k_{eq} versus the dimensionless lateral load factor is presented in Figures 12 and 13 for free-head and restrained-head piles, respectively, for the three *p-y* criteria employed in this study. The simplified design procedure to estimate the maximum deflection and moment for laterally loaded piles in clays involves the use of these relationships. The required known parameters for the proposed procedure are pile diameter B, pile bending stiffness EI, and undrained cohesion of soils c_u. Using Broms's criterion for coefficient of subgrade reaction (*1*), the value of c_u can be taken as the average within a depth equal to 0.8 βL. Once the undrained cohesion has been determined, the following step-by-step design procedure is recommended:

1. Find the subgrade modulus k from Figure 1,
2. Obtain the coefficient β using Equation 2,
3. Calculate the dimensionless lateral load factor $P\beta/kBu$,
4. Determine the equivalent subgrade modulus k_{eq} from either Figure 12 or Figure 13 depending on given boundary conditions and clay criteria,
5. Calculate the maximum deflection from Equation 3 or Equation 5 by using β from Step 2 and substituting k_{eq} into k, and
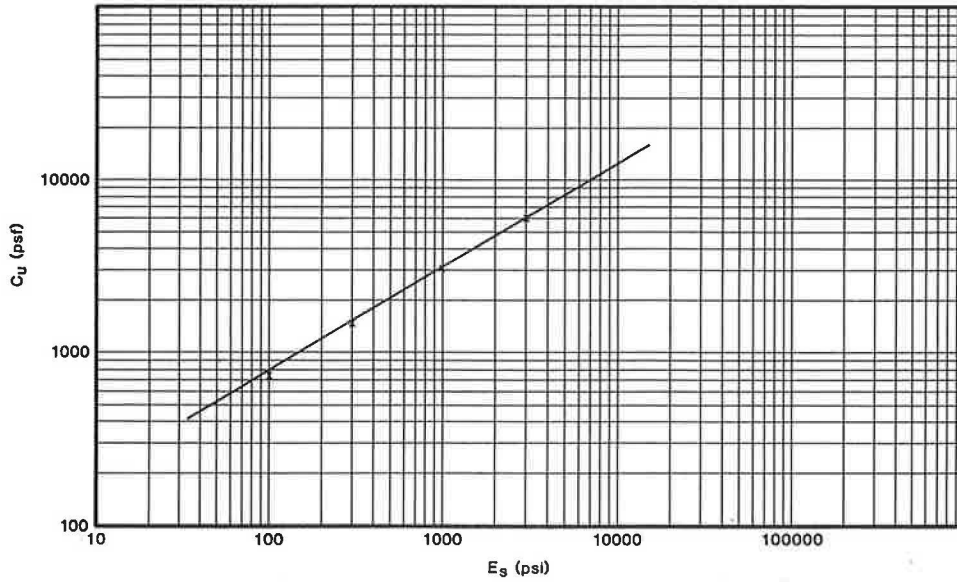6. Calculate the maximum moment from Equation 8.

FIGURE 6 Relationship between C_u and E_s (1 psf = 47.9 N/m²; 1 psi = 6.89 kN/m²).

TABLE 4   PARAMETERS REQUIRED TO GENERATE p-y CURVES FOR SUBMERGED STIFF CLAYS

Pile Dia. B (in) (Control Parameter)	Soil Stiffness k (pci)	Cohesion c^u (psf) (Figure 2)	e_{50}	Soil Modulus E$_S$ (psi) Figure 7	K_R (X10$_{-8}$) (Eq 17)	y_{50} (Eq 16)
12	300	1500	0.007	300	1.9	0.126
36					15.5	0.061
12	1000	3000	0.005	1000	0.6	0.259
36					4.7	0.124
12	3000	6000	0.004	3000	0.2	0.541
36					1.5	0.260

Note: 1 in = 2.54 cm; 1 pci = 271.7 kN/m³;
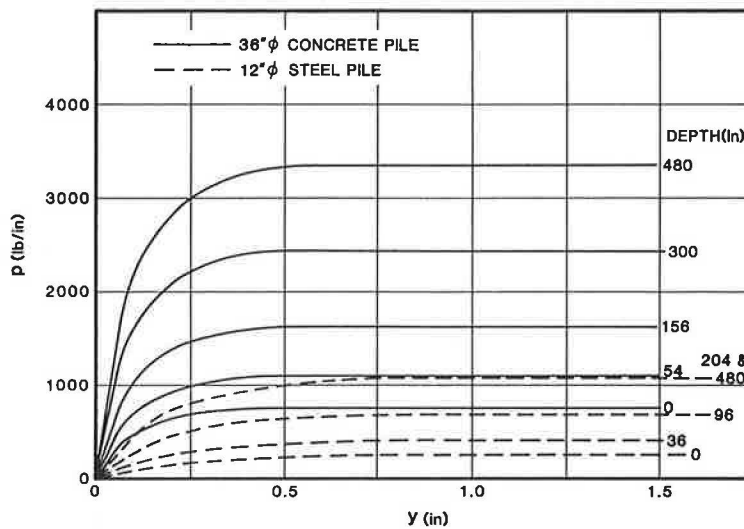   1 psi = 6.89 kN/m²; 1 psf = 47.9 N/m²

FIGURE 7 p-y Curves generated for submerged stiff clay: $k = 300$ pci (1 in. = 2.54 cm; 1 pci = 271.7 kN/m³; 1 lb/in. = 175.2 N/m).
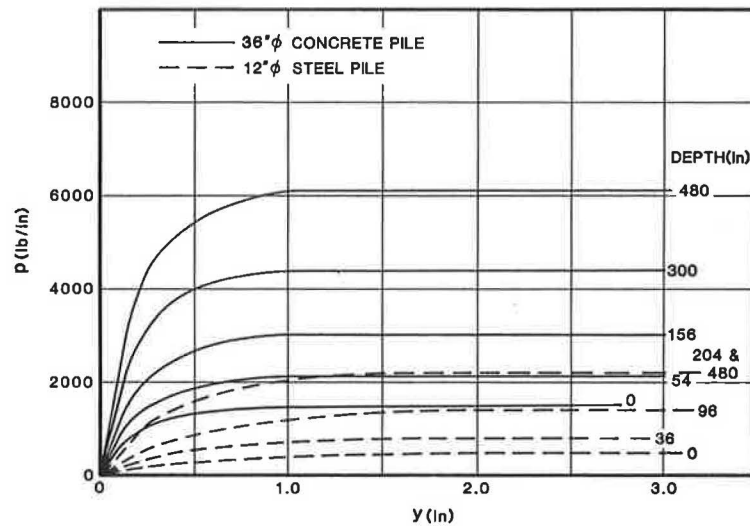
FIGURE 8 p-y Curves generated for submerged stiff clay: $k =$ 1,000 pci (1 in. = 2.54 cm; 1 pci = 271.7 kN/m³; 1 lb/in. = 175.2 N/m).
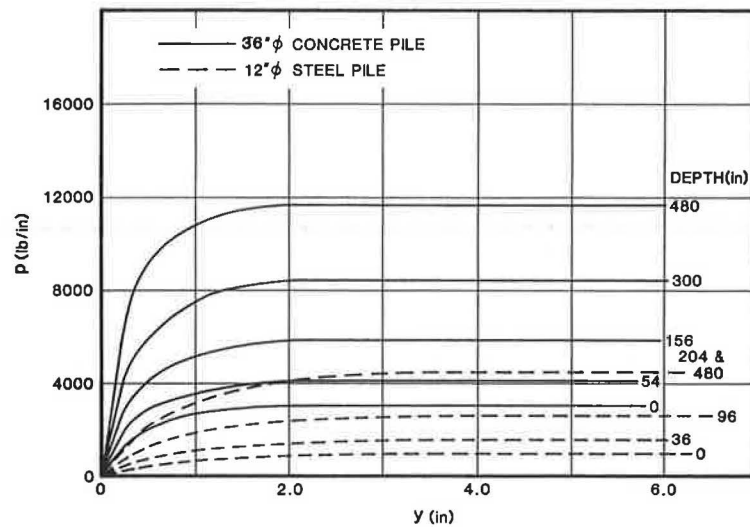

FIGURE 9 p-y Curves generated for submerged stiff clay: $k =$ 3,000 pci (1 in. = 2.54 cm; 1 pci = 271.7 kN/m³; 1 lb/in. = 175.2 N/m).

The maximum deflection can also be estimated from Equation 7 using the nondimensional method. However, it is shown later that the prediction is not as good as that by Broms's equation.

In order to examine its effectiveness, the design procedure is used to predict the published field test data. Table 5 summarizes the parameters derived by the proposed procedure for load-deflection prediction. As an example to demonstrate the proposed step-by-step design procedure, the published data for stiff clay above the water table (3) (Table 5) were used. English units as from the published data were used for this example. For C_u of 2,200 psf, k was found to be about 600 pci from Figure 1 according to Step 1. The coefficient β in Step 2 was calculated to be 0.0139 from Equation 2. The dimensionless lateral load factor shown in Step 3 was found to be 0.0618 assuming a lateral load of 80 kips and using B of 30 in. From Figure 12 according to Step 4, k_{eq} was taken

as 160 pci. The maximum deflection for an 80-kip load was calculated to be 0.463 in. according to Step 5 (Equation 3) as shown in Table 6. Maximum moment can also be found using E and I from Table 5 and Equations 6 and 8.

Table 6 presents the predicted and published maximum deflections and moments for the criterion of stiff clay above the water table. These data show a relatively poor prediction of maximum deflections at large lateral loads by the nondimensional solutions (Equations 6 and 7) by substituting k_{eq} for k_n in Equation 6. It is speculated that the error is possibly due to a deeper depth influence under larger lateral load, which may imply a smaller actual k_{eq}, as indicated in Equation 6a.

Table 7 presents the predicted values corresponding to the published data available for the soft clay and submerged stiff clay criteria. Only Broms's equation (Equation 3) was used to predict the maximum deflection.
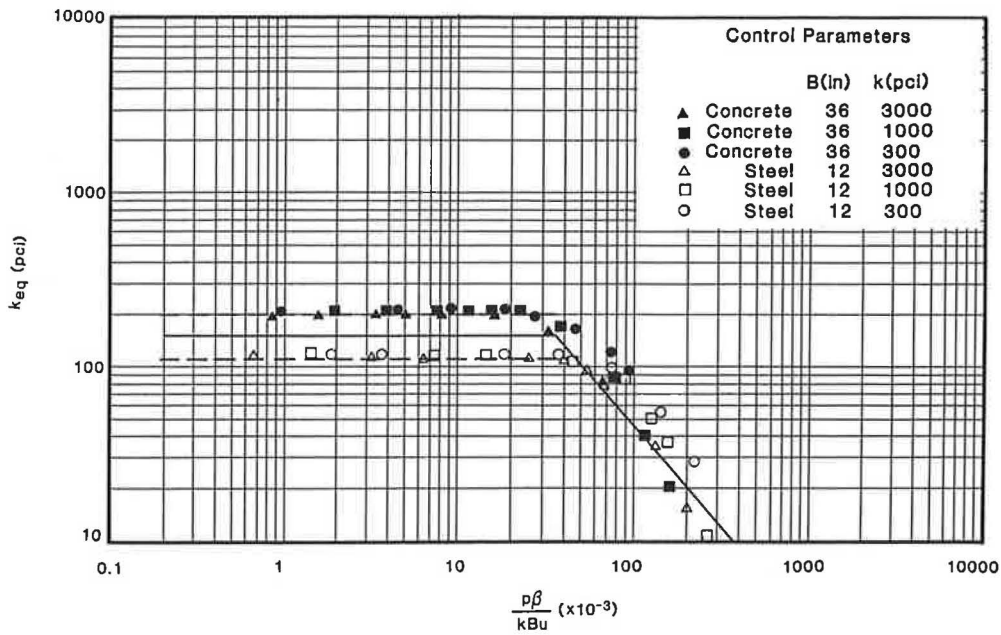
FIGURE 10 Equivalent subgrade modulus versus dimensionless lateral load factor for stiff clay below water: free-head conditions (1 in. = 2.54 cm; 1 pci = 271.7 kN/m³).
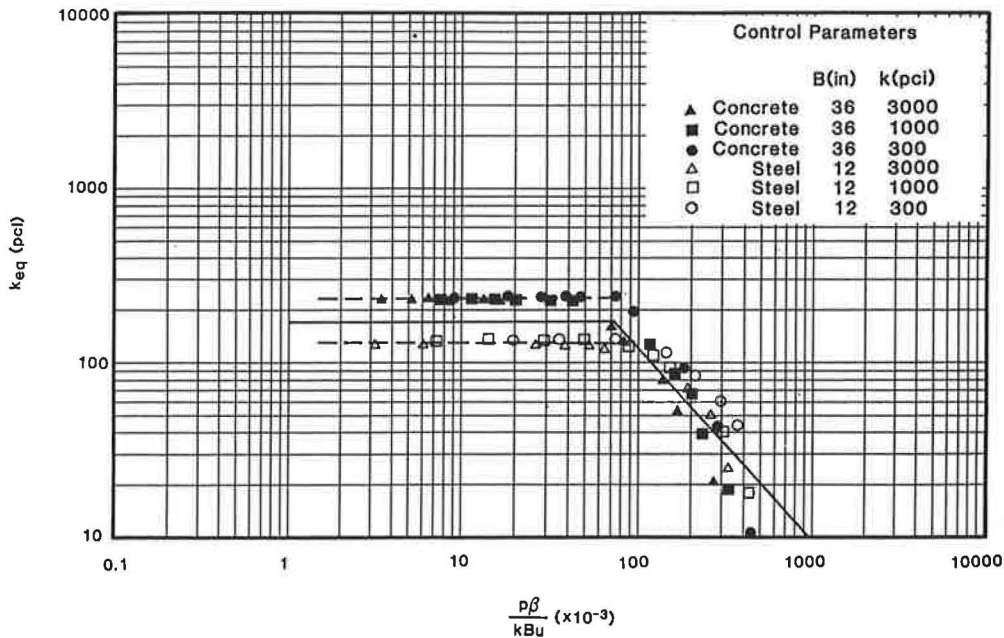

FIGURE 11 Equivalent subgrade modulus versus dimensionless lateral load factor for stiff clay below water: restrained-head conditions (1 in. = 2.54 cm; 1 pci = 271.7 kN/m³).

The overall comparison between predicted and published values in Tables 6 and 7 is favorable.

CONCLUSIONS

The concept of equivalent subgrade modulus for laterally loaded piles in clays was developed to represent nonlinear pile-soil behavior within a simplified analytical procedure involving linear modeling. The modulus is shown to be a simple function of the dimensionless lateral load factor and can be easily determined provided pile properties and undrained cohesion of soils are known. Maximum deflection and maximum moment of laterally loaded piles in clays can be readily predicted using the design curves for equivalent subgrade modulus versus dimensionless lateral load factor for free-head and restrained-head conditions. An efficient and easy-to-follow design procedure is also proposed. The procedure was tested by predicting published field test data and judged to yield reasonable and useful results.
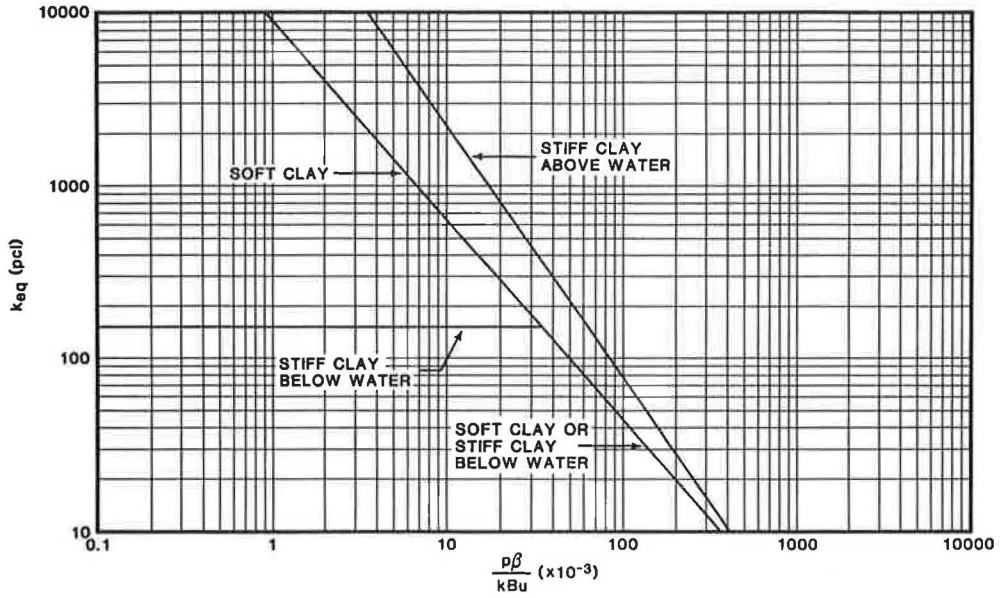
FIGURE 12 Design curves of equivalent subgrade modulus versus dimensionless lateral load factor: free-head conditions (1 pci = 271.7 kN/m³).
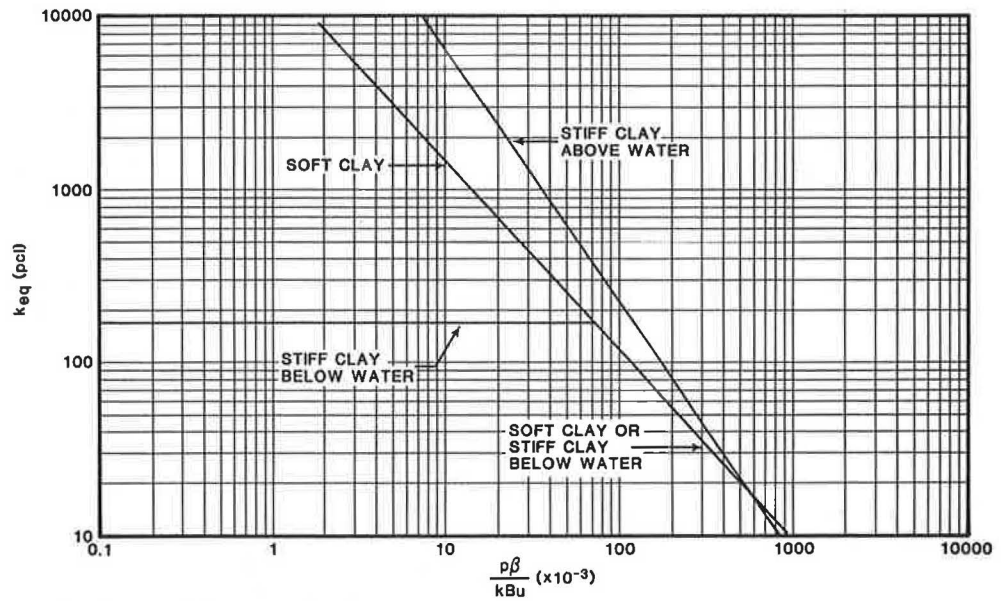

FIGURE 13 Design curves of equivalent subgrade modulus versus dimensionless lateral load factor: restrained-head conditions (1 pci = 271.7 kN/m³).

TABLE 5   PARAMETERS USED TO PREDICT PUBLISHED FIELD
DATA

Criteria	Published Data		Calculated Data			
	B (in)	Cu (psf)	E^4 (psi)	I (in^4)	k^5(pci)	β^6
Soft Clay[1]	12.75	300	3×10^7	155	25	0.0114
Stiff Clay Above Water[2]	30	2200	3×10^6	39761	600	0.0139
Stiff Clay Below Water[3]	48	1671	3×10^7	26302	350	0.0086

Note: 1 in = 2.54 cm; 1 psf = 47.9 N/m^2
      1 psi = 6.89 kN/m^2; 1 pci = 271.7 kN/M^3

1. Matlock (2)
2. Reese & Welch (3)
3. Pile 2, Dunnavant & O'Neill (5)
4. Assume 3×10^7 psi for steel and 3×10^6 psi for concrete
5. From Figure 1
6. From Eq. 2

TABLE 6   PREDICTED AND PUBLISHED MAXIMUM DEFLECTIONS
AND MOMENTS FOR STIFF CLAY ABOVE THE WATER TABLE (3)

Lateral Load (kip)	Maximum Deflection (in)				Maximum Moment (in-lb)x 10^6		
	Measured	Computed[1]	Predicted (Eq. 3)	Predicted (Eq. 7)	Measured	Computed[1]	Predicted (Eq. 8)
	(Published Data)				(Published Data)		
20	0.020	0.027	0.015	0.026	0.583	0.539	0.618
40	0.090	0.114	0.088	0.096	1.33	1.62	1.51
60	0.254	0.282	0.222	0.193	2.39	2.81	2.50
80	0.586	0.540	0.463	0.335	3.88	4.04	3.64
100	1.160	0.875	0.840	0.540	5.55	5.53	4.94

Note: 1 in = 2.54 cm; 1 in-lb = 113 mm-N; 1 kip = 4.45 kN

[1]Published data which were computed using the p-y relationship.

TABLE 7   COMPARISON OF PREDICTED AND PUBLISHED DATA
FOR SOFT CLAY (2) AND SUBMERGED STIFF CLAY (5)

Lateral Load (kip)	Maximum Deflection (in)		Maximum Moment (in-lb)x10^6	
	Measured (Dunnavant et al., 1989)	Predicted (Eq. 3)	Measured (Matlock, 1970)	Predicted
4	-	-	0.168	0.134
8	-	-	0.395	0.317
16	-	-	0.992	0.741
50	0.13	0.12	-	-
75	0.25	0.21	-	-
150	0.70	0.76	-	-
195	1.50	1.54	-	-
240	1.96	2.34	-	-

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