SALLOP: Simple Approach for Lateral Loads on Piles

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Abstract: The problem of a pile subjected to lateral loading is often solved by assuming that the pile is an elastic member and that the soil can be represented by a series of nonlinear horizontal springs. The *P-y* curves describe the nonlinear behavior of the soil springs. Previously, a method was developed at Texas A&M University to obtain the *P-y* curve directly from the pressuremeter curve. This method gave good predictions but was complicated and time consuming. Simple approach for lateral load on piles (SALLOP) is a simplification of the complicated method; it makes use of the pressuremeter limit pressure and the pressuremeter modulus. It is a semitheoretical or semiempirical method in that the framework is theoretical but the factors in the theoretical equations are adjusted by comparison to 20 full-scale load tests. The accuracy of SALLOP is very reasonable as shown by comparing measured and predicted behavior for the 20 full-scale pile load tests used to develop the method.

THE IDEA

Previously, Smith (1983) and Briaud et al. (1985) developed a pressuremeter method to solve the problem of a pile subjected to a lateral load. The basis of the method was the use of the complete pressuremeter test (PMT) curve to characterize the soil resistance. The beam column and *P-y* curve approach pioneered by Matlock (1970) and Reese (1977) was then used to predict the pile response. The transformation of the PMT curve into a *P-y* curve combined with the beam-column approach, while giving very good results, was very cumbersome and time consuming. In that regard, Einstein said: "Everything should be made as simple as possible, but not one bit simpler than that" (Safir and Safire 1982). Developing a much simpler method while maintaining accuracy and precision in the predictions has been the impetus leading to a new approach, hereafter termed Simple Approach for Lateral Load On Piles (SALLOP). This simple method fits in the same category as the methods proposed by Broms (1964), Davisson (1970), and Evans and Duncan (1982).

The following observation is the basis for the simplification. A conceptual plot of the soil resistance P per unit length of pile as a function of depth z is shown in Fig. 1. The sinusoidal nature of the *P-z* profile (Baguelin et al. 1978; Briaud 1992) is such that the soil resistance P alternates direction and essentially cancels itself out except for a shallow zone close to the surface, which contributes most to the lateral resistance. More specifically, there is a depth close to the ground surface where the shear force in the pile is zero (Fig. 2). This depth is called the zero-shear depth D_v. The horizontal equilibrium of this relatively shallow segment of pile is the basis for SALLOP. One key element then is to find out the depth of this shallow segment of pile, as discussed in the next section.

ZERO-SHEAR DEPTH

The zero-shear depth D_v is the shallowest depth where the shear force in the pile is zero (Fig. 2). To calculate D_v, two theoretical solutions were used: (1) the solution for an infinitely long pile in a Winkler uniform soil; and (2) the solution for a short rigid pile in a Winkler uniform soil. A Winkler soil refers here to a soil characterized by linear independent springs at discrete locations. Furthermore, the soil is assumed to be uniform with depth.

In the case of an infinitely long pile in a Winkler uniform soil, the pile deflection y, the pile slope y', the moment in the pile M, the shear in the pile V, and the soil resistance P can be obtained easily as a function of the depth z (Hetenyi 1946; Baguelin et al. 1978; Briaud 1992). An example of those profiles is shown in Fig. 3. The expression for the shear force V in the pile is

$$V = H_o e^{-(z/l_o)} \left(\cos \frac{z}{l_o} - \sin \frac{z}{l_o}\right) - \frac{2M_o}{l_o} e^{-(z/l_o)} \sin \frac{z}{l_o} \quad (1)$$

where V = shear force in the pile at depth z (kN); H_o = horizontal force applied at $z = 0$ (kN); z = depth along the pile (m); l_o = transfer length as defined next (m); and M_o = moment applied at $z = 0$ (kN·m). The transfer length l_o is a function of the relative stiffness of the pile and of the soil

$$l_o = \left(\frac{4EI}{K}\right)^{1/4} \quad (2)$$

where E = modulus of elasticity for the pile material (kN/m²); I = moment of inertia for the pile (m⁴); and K = soil spring constant (kN/m²). The spring constant K is the ratio of the soil

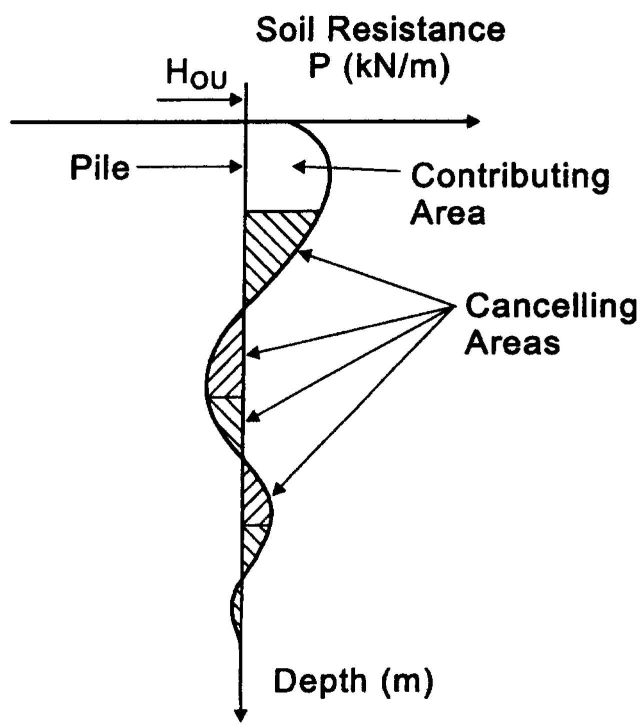

FIG. 1. Conceptual Soil Resistance versus Depth Profile

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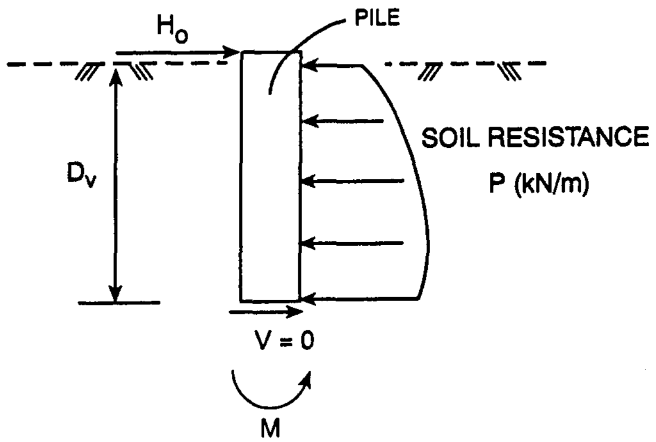

FIG. 2. Free Body Diagram of Pile Down to Zero-Shear Depth D_v

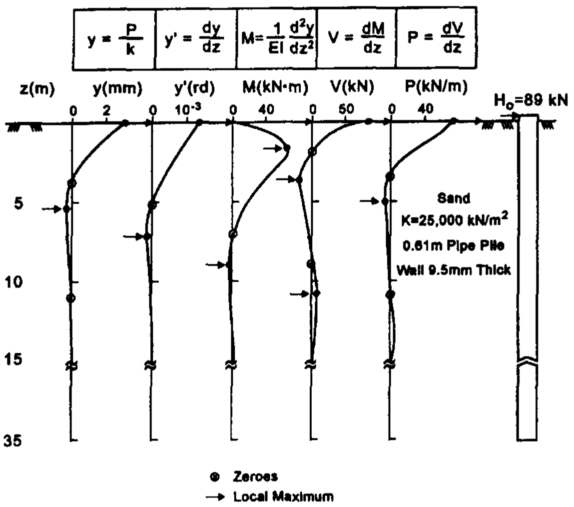

FIG. 3. Example of Profiles at Working Load

resistance P (kN/m) at a depth z to the horizontal pile displacement $y(m)$ at the same depth.

The zero-shear depth D_v is obtained by setting $V = 0$

$$D_v = l_o \tan^{-1}\left(\frac{1}{1 + \frac{2M_o}{l_o H_o}}\right) \tag{3}$$

where the argument of the arctan function is in radians. If $M_o = 0$ then

$$D_v = \frac{\pi}{4} l_o \tag{4}$$

In the case of a short rigid pile in a Winkler uniform soil, the shear force V in the pile is given by (Baguelin et al. 1978; Briaud 1992)

$$V = H_o + \frac{6(H_oL + 2M_o)}{L^3}\frac{z^2}{2} - \frac{2(2H_oL + 3M_o)}{L^2} z \tag{5}$$

where L = embedded pile length. When $V = 0$, the smallest of the two roots gives D_v

$$D_v = \frac{H_oL^2}{3(H_oL + 2M_o)} \tag{6}$$

and if $M_o = 0$ then

$$D_v = \frac{L}{3} \tag{7}$$

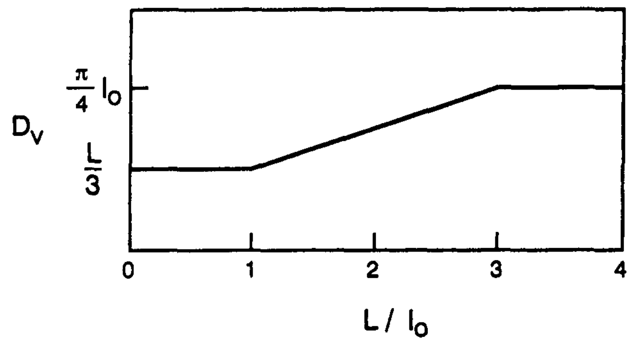

FIG. 4. Linear Interpolation for Zero-Shear Depth D_v

Eq. (1) is based on the assumption that the pile is infinitely long while (5) is based on the assumption that the pile is rigid. It can be shown by comparison with the general solution (Hetenyi 1946) that (1) is applicable if the pile length L is larger than $3l_o$. In the same way it can be shown that (5) is applicable if the pile length L is smaller than l_o. Therefore, in SALLOP, D_v will be calculated as

$$D_v = \frac{\pi}{4} l_o \quad \text{if} \quad L \geq 3l_o \tag{8}$$

$$D_v = \frac{L}{3} \quad \text{if} \quad L \leq l_o \tag{9}$$

A linear interpolation between the two values will be used if the pile length is between l_o and $3l_o$ (Fig. 4). As will be seen later, most piles satisfy $L \geq 3l_o$.

PREDICTING LATERAL PILE CAPACITY

The result of a vertical load test is a load-settlement curve from which a reference vertical capacity is often defined as the load corresponding to a settlement equal to one-tenth of the pile diameter plus the compression of the pile as if it was a free standing column. The result of a horizontal load test is a load-displacement curve. The reference lateral pile capacity H_{ou} for the pile-soil system is defined here as the load corresponding to a horizontal displacement equal to one-tenth of the pile diameter or width. The lateral capacity of the pile H_{ou} is meant to be a reference soil capacity. If the pile breaks structurally or develops a plastic hinge before a displacement of $0.1B$ is reached, the SALLOP method will give lateral capacity predictions, which will likely be too high.

The horizontal equilibrium of the segment of pile shown in Fig. 2 at the lateral capacity H_{ou} gives

$$H_{ou} = \int_o^{D_v} P_u \, dz \tag{10}$$

where D_v = zero-shear depth (m); and P_u = soil resistance (kN/m) corresponding to the reference lateral capacity of the pile. In SALLOP, the lateral capacity H_{ou} is calculated as

$$H_{ou} = \frac{3}{4} p_L B D_v \tag{11}$$

where B = pile diameter or width; D_v = zero-shear depth given by (8) or (9); and p_L = preboring pressuremeter limit pressure within D_v; p_L is the pressure against the soil when the pressuremeter probe reaches a volume corresponding to a cavity volume equal to twice the initial cavity volume (Briaud 1992). If the SPT blow count N, the CPT point resistance q_c, or the undrained shear strength S_u are available instead of p_L, the correlations between N, q_c, S_u, and p_L proposed by Briaud (1992) can be used to estimate p_L. However the reliability of the predictions is decreased because of the scatter in the correlations.

Eq. (11) implies that the pressure on the pile within the critical depth averages $0.75p_L$. This was determined empirically by using a database of lateral load tests where pressuremeter data were available and by optimizing the comparison between the predicted and measured lateral capacities H_{ou}. This database and the comparison are presented in the next section.

PREDICTED VERSUS MEASURED LATERAL CAPACITIES

A database of 47 full-scale horizontal pile load tests with corresponding pressuremeter tests was assembled (Donthireddy and Briaud 1995). Out of those 47 tests, 27 tests could not be used because the pile was not pushed to a displacement of $0.1B$ necessary to obtain the measured value of H_{ou} or because the pile broke during the load test. The remaining 20 cases were used to evaluate the reliability of (11). The references for the tests are shown in Table 1. The pile and soil properties are in Table 2. Note that the pressuremeter used in most cases was the TEXAM pressuremeter (Smith 1983). The predicted and measured values of H_{ou} for each pile are in Table 3.

The profiles of the pressuremeter limit pressure p_L and of the pressuremeter first load modulus E_o were obtained for each load test location. An example for a drilled shaft in stiff clay is given in Fig. 5. The soil spring constant K was obtained from

TABLE 1. References for SALLOP Database

Pile identification number (1)	Reference (2)
1–7	Donthireddy and Briaud (1995)
8, 9	Little and Briaud (1988)
10	Matlock and Tucker (1961); Smith (1983)
11	Matlock et al. (1956); Smith (1983)
12	Kasch et al. (1977); Smith (1983)
13	Holloway et al. (1978); Smith (1983)
14	O'Neill and Dunnavant (1984); Makarim and Briaud (1986)
15, 16	Briaud et al. (1984)
17, 18	Woodward Clyde Consultants (1979); Smith (1983)
19	Soil Mechanics, Inc. (1982); Smith (1983)
20	Baguelin and Jezequel (1972)

$$K = 2.3E_o \tag{12}$$

The factor 2.3 was determined empirically by optimizing the comparison between the predicted deflections and the measured deflections, as will be shown later. Note that in (12), E_o is the average PMT modulus within the zero-shear depth D_v. Finding the average E_o requires an iteration because D_v depends on E_o. The average K value within D_v was used to calculate the transfer length l_o using (2). Then D_v was obtained using (8) or (9). At this time the calculated D_v was compared to the D_v used to find the average E_o and an iteration was performed if necessary. The lateral capacity $H_{ou(pred)}$ predicted by SALLOP was then calculated by using (11) (Table 3).

The lateral capacity measured in the load test $H_{ou(meas)}$ was obtained from the load displacement curve at a horizontal displacement equal to one tenth of the pile diameter (Table 3). Fig. 6 is a comparison between $H_{ou(meas)}$ and $H_{ou(pred)}$ by SALLOP. Overall the comparison is very good ($r^2 = 0.977$) and much better than similar comparisons for vertical loads (Briaud and Tucker 1988). One must caution the SALLOP user however that the scatter in Fig. 6 is the lowest that can be expected for this method since it is a comparison of $H_{ou(pred)}$ versus $H_{ou(meas)}$ for the database used to develop the method in the first place. Generally, the cases where a method overpredicts the pile capacity are more undesirable than cases of underpredictions. In this database the worst overprediction with SALLOP is for pile number 20 when $H_{ou(pred)}$ over $H_{ou(meas)}$ is equal to 1.42. A factor of safety of 3 on $H_{ou(pred)}$ for a working stress design seems to be appropriate to obtain a safe lateral load.

PREDICTING DEFLECTION AT WORKING LOADS

The load-deflection curves for a number of piles in the database were plotted on a normalized graph with H_o/H_{ou} on the vertical axis and $y/0.1B$ on the horizontal one. Fig. 7 shows the load test curves. It is observed in Fig. 7 that at H_o equal to $H_{ou}/3$, the deflection averages $0.017B$ and varies from $0.009B$ to $0.034B$. Therefore it is proposed for SALLOP that the deflection y_o under the reference load $H_{ow} = H_{ou}/3$ be estimated by $0.02B$ to be somewhat conservative

$$y_o = 0.02B \tag{13}$$

Taking $H_{ou} = H_{ou}/3$ is simply used to give an example of the reliability of the method at small deflections. The engineer can select a factor different from 3 if desired and look at Fig. 7 in

TABLE 2. Soil and Pile Properties for SALLOP Database

Pile number (1)	Site/pile (2)	Soil type (3)	p_L (kN/m²) (4)	E_o (kN/m²) (5)	Pile type (6)	B (m) (7)	L (m) (8)	E (kN/m²) (9)	I (m⁴) (10)	EI (kN/m²) (11)
1	Edmonton/U_4	Sand fill over clay	180	3,700	Driven steel pipe piles, closed end, filled	0.324	24.0	2.0 E+8	9.3 E-5	1.87 E+4
2	Edmonton/C_1	Sand fill over clay	180	3,700	with concrete, 9.5-mm-thick wall	0.324	24.0	2.0 E+8	9.3 E-5	1.87 E+4
3	Edmonton/C_2	Sand fill over clay	180	3,700		0.324	24.0	2.0 E+8	9.3 E-5	1.87 E+4
4	Edmonton/C_3	Sand fill over clay	180	3,700		0.324	24.0	2.0 E+8	9.3 E-5	1.87 E+4
5	New Orleans/TPU	Sand fill over clay	430	3,300	Timber	0.356	21.0	1.4 E+7	7.88 E-4	1.10 E+4
6	New Orleans/CPI	Sand fill over clay	440	3,600	Driven prestressed concrete	0.356	21.0	2.1 E+7	1.34 E-3	2.81 E+4
7	New Orleans/SP3	Sand fill over clay	450	3,800	Steel pipe, closed end, 10-mm-thick wall	0.324	21.0	2.0 E+8	1.22 E-4	2.44 E+4
8	Baytown/pile 2	Sand	720	6,000	Steel pipe, open end, 16-mm-thick wall	0.610	36.6	2.0 E+8	1.30 E-3	2.60 E+5
9	Baytown/pile 3	Sand	680	5,500	Driven prestressed concrete	0.510	29.6	2.1 E+7	2.19 E-3	4.59 E+4
10	Sabine	Clay	100	1,000	Steel pipe, open end, 16-mm-thick wall	0.324	11.0	2.0 E+8	1.84 E-4	3.68 E+4
11	Lake Austin	Clay	200	2,600	Steel pipe, closed end, 15-mm-thick wall	0.324	12.2	2.0 E+8	1.75 E-4	3.50 E+4
12	Texas A&M 1977	Clay	500	7,250	Bored reinforced concrete	0.915	6.1	2.1 E+7	3.44 E-2	7.22 E+5
13	Texas A&M 1978	Clay	500	7,250	Bored reinforced concrete	0.915	4.6	2.1 E+7	3.44 E-2	7.22 E+5
14	U. of Houston	Clay	260	3,600	Steel pipe, open end, 9.3-mm-thick wall	0.273	11.8	2.0 E+8	6.70 E-5	1.34 E+4
15	Lock & Dam 26 (83)	Sand	450	3,800	H pile 14 × 73	0.356	20.4	2.0 E+8	3.05 E-4	6.10 E+4
16	Lock & Dam 26 (83)	Sand	450	3,800	H pile 14 × 73	0.356	20.4	2.0 E+8	3.05 E-4	6.10 E+4
17	Lock & Dam 26 (78)	Sand	730	6,160	H pile 14 × 73	0.356	15.2	2.0 E+8	3.05 E-4	6.10 E+4
18	Lock & Dam 26 (78)	Sand	730	6,160	Steel pipe, open end, 9.5-mm-thick wall	0.356	15.2	2.0 E+8	1.55 E-4	3.10 E+4
19	Baytown	Clay	280	3,200	Bored reinforced concrete	0.610	11.9	2.1 E+7	6.79 E-3	1.43 E+5
20	Plancoet	Silt/clay	155	2,500	H pile	0.280	6.1	2.0 E+8	1.37 E-4	2.74 E+4
Mean			390	4,216		0.426	18	1.7 E+8	4.16 E-3	1.18 E+5
High			730	7,250		0.915	36.6	2.0 E+8	3.44 E-2	7.22 E+5
Low			100	1,000		0.273	4.6	1.4 E+7	6.70 E-5	1.10 E+4

TABLE 3. Predicted and Measured Values for Piles in SALLOP Database

Pile number (1)	K (kN/m²) (2)	l_o (m) (3)	D_v (m) (4)	$H_{ou(pred)}$ (kN) (5)	$H_{ou(meas)}$ (kN) (6)	$y_{(pred)}$ (0.02B) (mm) (7)	$y_{(pred)}$ (K) (mm) (8)	$y_{(meas)}$ (mm) (9)	Flexible or rigid (10)
1	8,510	1.72	1.35	59	90	6.5	2.7	3.0	f
2	8,510	1.72	1.35	59	97	6.5	2.7	3.0	f
3	8,510	1.72	1.35	59	93	6.5	2.7	3.0	f
4	8,510	1.72	1.35	59	93	6.5	2.7	2.5	f
5	7,590	1.55	1.22	140	104	7.1	7.9	8.0	f
6	8,280	1.92	1.51	177	137	7.1	7.4	9.5	f
7	8,740	1.83	1.44	157	145	6.5	6.5	12.1	f
8	13,800	2.95	2.31	762	712	12.2	12.5	10.4	f
9	12,650	1.95	1.53	399	422	10.2	10.8	5.1	f
10	2,300	2.83	2.22	54	55	6.5	5.5	4.4	f
11	5,980	2.20	1.73	84	77	6.5	4.3	9.3	f
12	16,675	3.63	2.31	792	756	18.3	9.8	9.7	r/f
13	16,675	3.63	1.71	586	556	18.3	9.7	6.6	r/f
14	8,280	1.59	1.25	67	73	5.5	3.4	3.3	f
15	8,740	2.30	1.80	217	245	7.1	7.2	4.2	f
16	8,740	2.30	1.80	217	272	7.1	7.2	5.5	f
17	14,168	2.04	1.60	312	258	7.1	7.2	9.2	f
18	14,168	1.72	1.35	263	192	7.1	7.2	11.2	f
19	7,360	2.97	2.33	299	260	12.2	9.1	14.2	f
20	5,750	2.09	1.66	54	38	5.6	3.1	10.5	f/r
Mean	9,700	2.22	1.63	241	234	8.5	6.5	7.6	—
High	16,675	3.62	2.33	792	756	18.3	12.5	16.5	—
Low	2,300	1.55	1.22	54	38	5.5	2.7	3.1	—

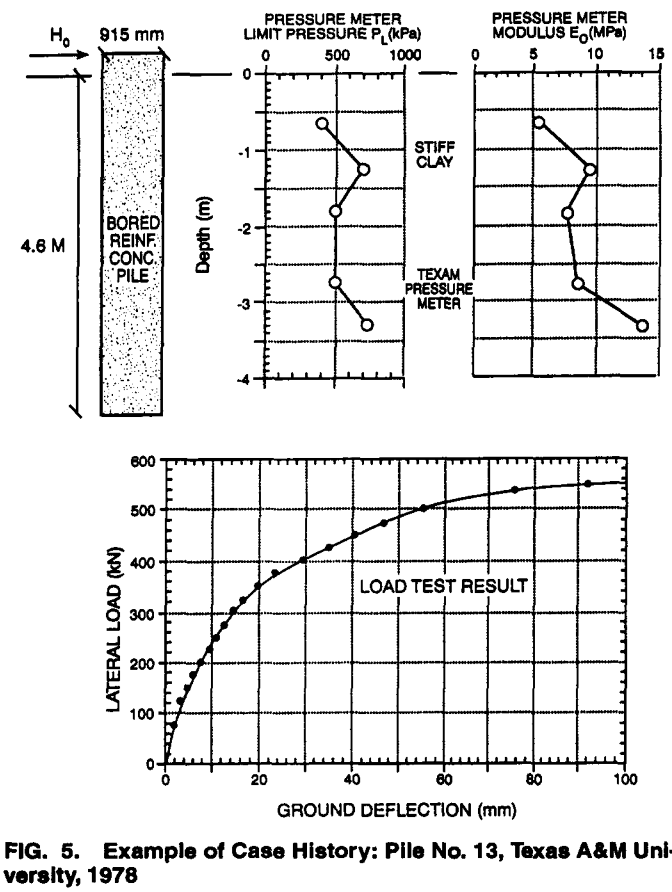

FIG. 5. Example of Case History: Pile No. 13, Texas A&M University, 1978

order to develop another equation like (13) for his or her load level. Fig. 8 shows a comparison of y_o predicted by (13) and y_o measured at the predicted reference load H_{ow} for the load tests in the database. The predicted reference load H_{ow} was taken as one-third of the lateral capacity H_{ou} predicted by (11). There is more scatter for the deflection predictions ($r^2 = 0.082$) (Fig. 8) than for the lateral capacity predictions (Fig. 6). The reasons include that soil movement is always more difficult to

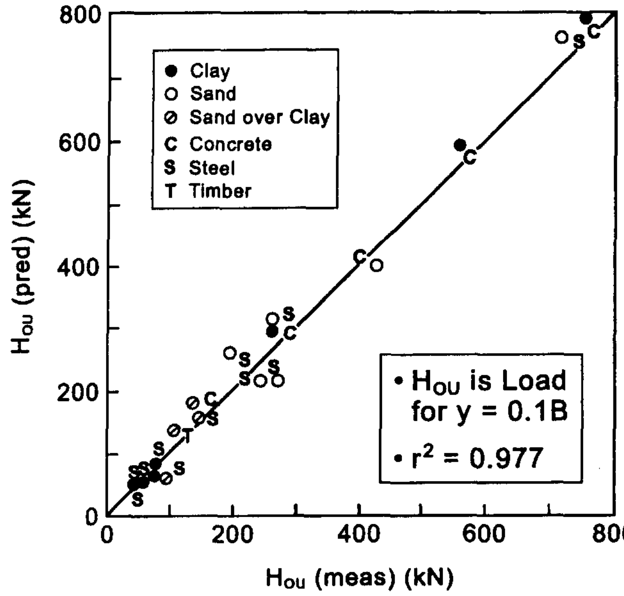

FIG. 6. Predicted versus Measured Lateral Capacity

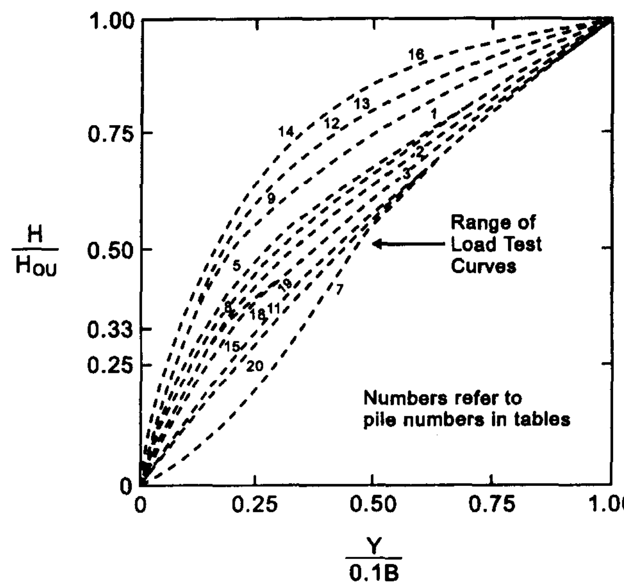

FIG. 7. Normalized Load Deflection Curves

predict than soil capacity, that the error on y_o includes the error on H_o plus the error to go from $H_{ou}/3$ to y_o, and that (13) is very simplistic. Generally, the cases where a method underpredicts the deflection at working loads are more undesirable than cases of overprediction. Fig. 8 shows a worst underprediction with SALLOP for pile number 20 when y_o measured over y_o predicted is equal to 1.87.

An alternative way to calculate y_o was sought to improve the drastic scatter, and it was decided to use the spring constant approach. The spring constant K can be obtained from the preboring pressuremeter as follows:

$$K = 2.3E_o \tag{14}$$

where E_o = preboring first load pressuremeter modulus within a depth D_v [(8) or (9)] from the ground surface. If the SPT blow count N, the CPT point resistance q_c, or the undrained shear strength S_u are available instead of E_o, the correlations between N, q_c, S_u, and E_o proposed by Briaud (1992) can be used to estimate E_o; however the reliability of the predictions is decreased because of the scatter in the correlations.

The factor 2.3 in (14) was obtained empirically by optimiz-

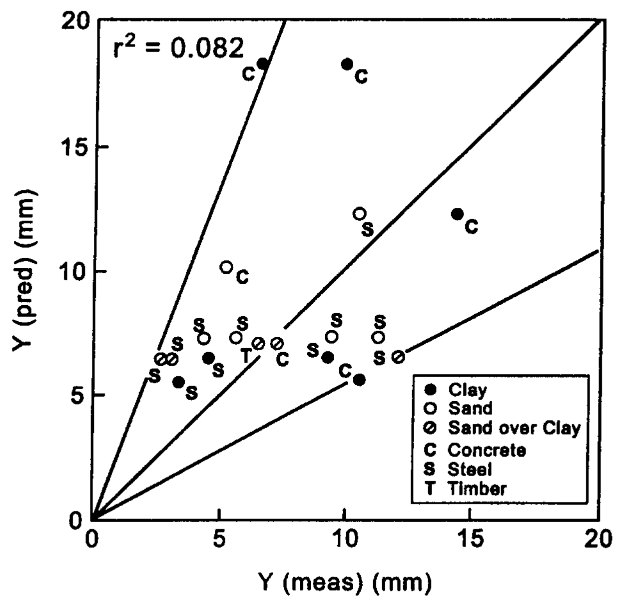

FIG. 8. Predicted versus Measured Deflections at One-Third of Predicted Lateral Capacity (0.02 *B* Method)

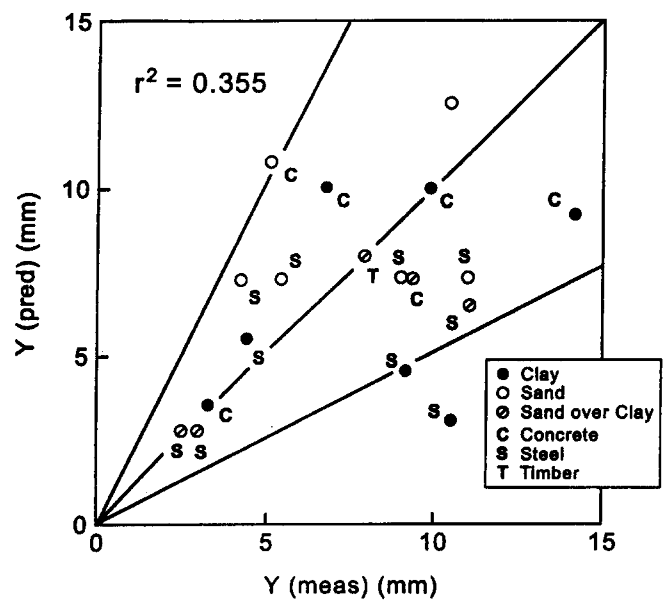

FIG. 9. Predicted versus Measured Deflections at One-Third of Predicted Lateral Capacity (*K* Method)

ing the comparison (Fig. 9) between the deflections predicted by this spring constant method and the deflections measured in the load test at one-third of the lateral capacity predicted by (11).

For long flexible piles ($L > 3l_o$), the pile deflection y_o is (Baguelin et al. 1978; Briaud 1992)

$$y_o = \frac{2H_o}{l_oK} + \frac{2M_o}{l_o^2K} \tag{15}$$

and for short rigid piles ($L < l_o$)

$$y_o = \frac{2(2H_oL + 3M_o)}{KL^2} \tag{16}$$

A linear interpolation between the two values will be used if the pile length is between l_o and $3l_o$ (Fig. 10). Fig. 9 shows a comparison of y_o predicted by (15) or (16) depending on L and l_o, and y_o measured at the predicted reference load H_{ow} for the load tests in the database. The predicted load H_{ow} was taken

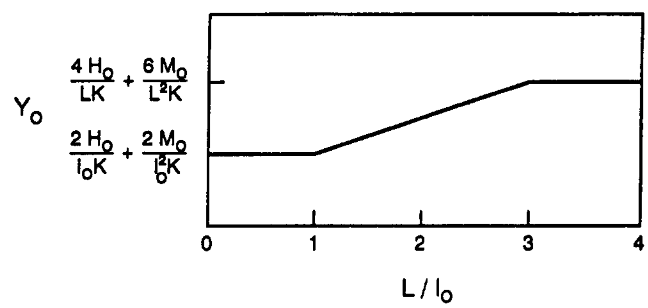

FIG. 10. Linear Interpolation for Pile Deflection y_o

as one-third of the lateral capacity H_{ou} predicted by (11). The scatter is significantly reduced compared to Fig. 8 except for pile number 20. The coefficient of determination r^2 is 0.355 when pile 20 is excluded. Pile 20 is an H pile tested at Plancoet (Baguelin and Jezequel 1972) where a 1.2-m-thick stiff crust existed at the surface; in that crust the E_o values are about three times higher than in the soft underlying silty clay. Using the E_o value for the underlying clay brings the prediction very close to the measurement. The next worst prediction is for pile number 11, a steel pipe pile at Lake Austin where the measured overprediction ratio is 2.16.

One must recognize that two identical piles located a few meters from each other and loaded under identical conditions may give significantly different values for the measured value of y_o. This is the case of the two H piles at lock and dam 26 (piles number 15 and 16) where the difference in y_o measured is 31%. Similar variations in results between closely spaced load tests were found for spread footings (Briaud and Gibbens 1994) and for axially loaded piles (Tucker and Briaud 1988).

CASE OF COMBINED LOADING

For all the load tests in the database, the horizontal load was acting either at the ground surface or close to it so that the moment applied at the ground surface M_o was very small. Eq. (11) predicts the lateral capacity at the ground surface H_{ou} with no moment on the pile; (13), (15), and (16) predict the deflection at $H_{ou}/3$, also when there is no moment on the pile. In the case of combined loading the pile is subjected to a combination of H_o and M_o at the ground surface. In this case an interaction diagram can be used as follows.

In a proper design, the reference load $H_{ow} = H_{ou}/3$ leads to an allowable deflection y_{oa} if the moment M_o is zero. On the other hand y_{oa} can be generated by a working moment M_{ow} when the horizontal load is zero. Eqs. (15) and (16) give such a moment as

$$M_{ow} = \frac{1}{2} y_{oa}l_o^2K \quad \text{for long flexible piles} \tag{17}$$

and

$$M_{ow} = \frac{1}{6} y_{oa}L^2K \quad \text{for short rigid piles} \tag{18}$$

Furthermore, (15) and (16) show that there is a linear relationship between y_o, H_o, and M_o; therefore it is reasonable to propose linear interaction diagrams as shown in Fig. 11. Any combination of H_{ow} and M_{ow} given by a point on the interaction diagram will generate the allowable deflection y_{oa}.

MAXIMUM BENDING MOMENT AND GROUNDLINE SLOPE

The maximum bending moment in the pile M_{max} must be checked against the moment that can be resisted by the pile. The value of M_{max} can be obtained from the linear Winkler-

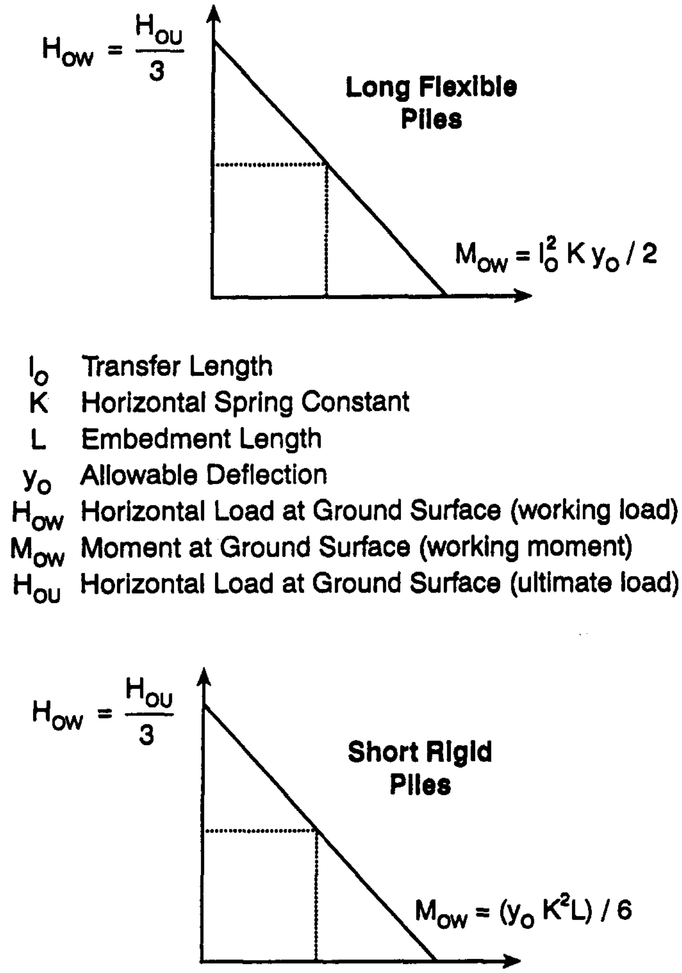

FIG. 11. Interaction Diagram for Load and Moment

Spring solution (Baguelin et al. 1978; Briaud 1992) for long flexible piles ($L > 3l_o$)

$$M_{max} = H_o l_o e^{-(z_{max}/l_o)} \sin \frac{z_{max}}{l_o} + M_o e^{-(z_{max}/l_o)} \left(\cos \frac{z_{max}}{l_o} + \sin \frac{z_{max}}{l_o} \right) \tag{19}$$

with

$$z_{max} = l_o \tan^{-1} \left(\frac{1}{1 + \frac{2M_o}{l_o H_o}} \right) \tag{20}$$

Note that the argument of the arctan function is in radians. For short rigid piles ($L < l_o$)

$$M_{max} = M_o + H_o z_{max} + \left(\frac{H_o L + 2M_o}{L^3} \right) z_{max}^3 - \left(\frac{2H_o L + 3M_o}{L^2} \right) z_{max}^2 \tag{21}$$

with

$$z_{max} = \frac{H_o L^2}{3(H_o L + 2M_o)} \tag{22}$$

Similarly, if necessary, the slope of the pile at the ground surface y'_o can be obtained from the same solution for long flexible piles ($L > 3l_o$)

$$y'_o = \frac{2H_o}{l_o^2 K} + \frac{4M_o}{l_o^3 K} \tag{23}$$

and for short rigid piles ($L < l_o$)

$$y'_o = \frac{6(H_o L + 2M_o)}{K L^3} \tag{24}$$

SALLOP METHOD

This simple method can be summarized in the following steps:

1. Perform preboring pressuremeter tests at the site with a higher concentration of tests near the surface. A typical sequence might be to perform PMT tests at the following depths: 0.5, 1, 1.5, 2, 3, 4.5, and 6 m. This represents approximately one days work and often only requires a hand auger as was the case for many of the test holes for the database. Note that the pressuremeter used in this study was primarily the TEXAM pressuremeter (Smith 1983).
2. Reduce the data and obtain the profiles of limit pressure p_L, and first loading modulus E_o as a function of depth (Briaud 1992). Select the average p_L and E_o values within an assumed zero-shear depth D_v (1.5 m is a good first guess). If PMT data are not available, correlations between PMT data and other test data (SPT, CPT, S_u) (Briaud 1992) can be used to estimate p_L and E_o at the cost of decreased reliability.
3. Calculate the zero-shear depth D_v by using (8) or/and (9) depending on L and l_o. If the pile length L is between l_o and $3l_o$ use linear interpolation.
4. If the D_v value from step 3 is not close to the assumed value in step 2, iterate steps 2 and 3 until the assumed and calculated D_v values are within a chosen tolerance (say 5%).
5. Calculate the lateral capacity H_{ou} by using (11) for the case where no moment M_o is applied.
6. Calculate the deflection y_o under the reference load $H_{ou}/3$ using (13), (15), and (16).
7. In the case of combined horizontal load and overturning moment, modify the results using the interaction diagram of Fig. 11.
8. Calculate the maximum bending moment by using (19) for long flexible piles or (21) for short rigid piles, and ensure that it can be safely resisted by the pile.
9. If necessary calculate the slope y'_o of the pile at the ground surface using (23) for long flexible piles and (24) for short rigid piles.

Besides its simplicity, the advantage of SALLOP is that it is based on a test that can be performed in almost any soil and that the method is the same whether the soil is cohesive or cohesionless. The limitations of the method are as follows. The method has been checked against a database with pile lengths from 4.6 to 36.6 m, pile widths from 0.273 to 0.915 m, for steel, concrete, and timber piles, for sand, clay, and sand over clay. These limits represent limits of verification for SALLOP. SALLOP does not seem to give as good a prediction when the soil strength profile varies significantly versus depth; such a case occurs when a stiff clay crust occurs at the surface. In this case it may be prudent to ignore the beneficial effect of the stiff layer. The accuracy of deflection predictions is not as good as that of lateral capacity predictions. SALLOP uses the assumption that the pile is linear elastic, that is to say that the stiffness EI is a constant independent of the bending moment M. Caution should be exercised when using SALLOP for concrete piles, especially nonprestressed or bored piles; for these piles, the cross section may gradually crack and lead to excessive deflections or pile failure before soil failure. For such piles the cracking bending moment must be checked and if it occurs before $H_{ou}/3$, a more sophisticated method must be used to allow nonlinearity in the relationship from *EI* to *M*. Alternatively SALLOP can be used with a reduced value of *EI*.

CONCLUSIONS

A simple method named SALLOP for the design of piles subjected to horizontal loads is presented. It is a semitheoretical or semiempirical method in that the framework is theoretical but the factors in the theoretical equations are adjusted by comparison to 20 full-scale load tests. In that sense, the use of this method is limited to cases similar to those of the database. SALLOP makes use of preboring pressuremeter test results and is very economical because in many cases it only requires a hand augered hole down to 5 or 6 m. The calculations can be essentially done on the "back of an envelope" and follow the step by step procedure outlined in the previous section. The reliability of the method can be judged by inspection of the graphs showing the predicted versus measured lateral capacity (Fig. 6) and the predicted versus measured lateral deflection under a reference load taken as one-third of the predicted lateral capacity (Figs. 8 and 9).

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