Virginia Polytechnic Institute

And State University

The Charles E. Via, Jr.

Department of

Civil and Environmental Engineering

CENTER FOR

GEOTECHNICAL PRACTICE AND RESEARCH

Revision of the CLM Spreadsheet for Lateral

Load Analyses of Deep Foundations

by

Joseph A. Clarke

and

J. Michael Duncan

August 2001

Table of Contents

Introduction

The first version of the Characteristic Load Method (CLM) spreadsheet (Brettmann and Duncan, 1996) was based on the CLM method (Duncan, et al., 1994) for analysis of single piles, and the Group Amplification Method (Ooi and Duncan, 1994) for analysis of pile groups. That first version of the CLM spreadsheet was found to produce quite accurate results for single piles, but was found in many cases to overestimate deflections and bending moments for pile groups. The revised spreadsheet described in this report uses the same method of analysis as the original for single piles, but uses an improved method of analysis for pile groups.

Background

The characteristic load method (CLM) of analysis of laterally loaded piles (Duncan et al., 1994) was developed by performing nonlinear p-y analyses for a wide range of free-head and fixed-head piles and drilled shafts in clay and sand. The results of the analyses were used to develop nonlinear relationships between dimensionless measures of load and deflection. These relationships were found to be capable of representing the nonlinear behavior of single piles and drilled shafts quite accurately, producing essentially the same values of deflection and maximum moment as p-y analysis computer programs like COM624 and LpilePlus3.0. The principal limitation of the CLM method is that it is applicable only to uniform soil conditions.

The Group Amplification Method was developed by Ooi and Duncan (1994), to extend use of the CLM method to groups of piles and drilled shafts. Values of group amplification factors for deflection and moment were computed using the method developed by Focht and Koch (1973).

The original version of the CLM spreadsheet (Brettmann and Duncan, 1996) used the CLM method to calculate deflections and bending moments in single piles, and the Group Amplification Method to calculate deflections and moments for piles in pile groups. It was found that the original version of the spreadsheet resulted in accurate values of moment and deflection for single piles, but often over-estimated deflections and bending moments for the piles in pile groups, as judged by comparison with p-y analysis programs and the results of field load tests.

The revised spreadsheet uses p-y multipliers as the basis for improving the accuracy of pile group analyses. The p-y multiplier values used are those recommended by Mokwa and Duncan (2001) based on their field tests and review of recent literature.

p-y Multipliers

Piles or drilled shafts that are spaced close together respond to lateral loading differently than single isolated piles. Pile-soil-pile interaction or "shadowing" occurs when piles are close enough so that they transfer load to the same zone within the soil around the piles. As a result, the ground is more severely loaded, and pile deflections and moments are larger.

This phenomenon can be accounted for by reducing the soil resistance in p-y analyses (p is the soil resistance per unit length of pile, and y is the pile deflection). Multiplying the p-values by factors smaller than 1.0 reduces the resistance of the soil, and, by using appropriate values of p-multipliers, can account for "shadowing" within pile groups.

Mokwa and Duncan (2001) reviewed 37 experimental test results in which the effects of pile-soil-pile interaction were measured. These studies included full-scale lateral load tests, centrifuge tests and laboratory tests. They used these results, together with data from their tests at the Virginia Tech field test site, to develop p-y multipliers for use in design of pile groups. Their recommended values are shown in Figure 1, which shows the variation of p-multiplier values with pile spacing and row. These p-multipliers have been incorporated in the revised version of the CLM spreadsheet (CLM2.0) to account for pile group effects.

Figure 1 illustrates the values of the p-multipliers (f_m) decrease as the number of rows of piles increases, and as the spacing of the rows decreases. (The direction of load application is perpendicular to the axis of the rows.) The values of f_m shown in Figure 1 are proportional to the load carried by each row of piles, since the deflection of all piles is the same. The chart shows that the leading row (the one at the front of the pile group) takes the most load. The load drops off in the first, second, and third trailing rows, and remains constant for rows further back. The values of f_m decrease as the spacing of the rows decreases, indicating less efficient transfer of load to the ground. For piles spaced more than six diameters apart, the values of f_m are equal to 1.0, indicating that group interaction effects are negligible.
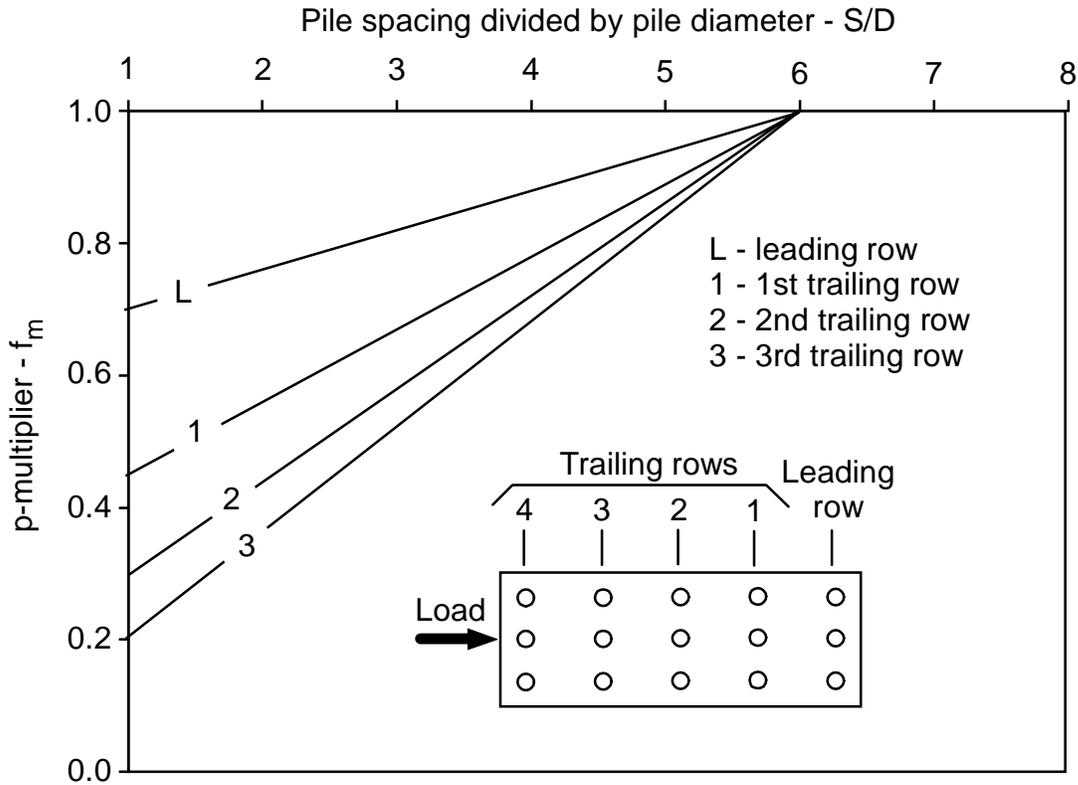
Notes:

1. The term row used in this chart refers to rows of piles aligned perpendicular to the direction of applied load.
2. Use the f_m values for the 3rd trailing row for all rows beyond the third trailing row.
3. Bending moments and shear forces computed for the leading row corner piles should be adjusted as follows:

Side-by-side spacing (within rows), expressed in pile diameters	Multiplier factor for corner piles (outside piles in the leading row)
3D	1.00
2D	1.20
1D	1.60

Figure 1 – p-multiplier design curves (after Mokwa and Duncan, 2001)

The experiments from which values of f_m were determined showed that the maximum bending moments in the piles in a group are nearly the same except for the corner piles (the outside piles in the leading row). For pile spacings smaller than three diameters (3D), the moments in the corner piles are larger, as shown in Figure 1. CLM2.0 computes values of maximum moment that are applicable to all except the corner piles. For piles spaced closer than 3D, the maximum moments in the corner piles should be increased by multiplying the moments computed by the spreadsheet by the corner pile factors shown in Figure 1.

Method of Including p-y Multipliers in CLM2.0

Because the value of f_m is a constant for each row, independent of depth, the value of f_m can be thought of as an efficiency factor for the piles in each row. The efficiency factor for the pile group (F_m) is the average of the efficiency factors for the rows in the group.

Pile group efficiency factors were incorporated in the Characteristic Load Method of analysis by reducing the soil resistance in the expressions for characteristic load (P_c) and characteristic moment (M_c). The undrained strength of clay (S_u), and the coefficient of passive earth pressure for sand (K_p) in those expressions were multiplied by F_m, leading to the following expressions for P_c and M_c.

For clay

$$P_c = 7.34D^2(E_pR_I)\left(\frac{S_uF_m}{E_pR_I}\right)^{0.68} \tag{1}$$

$$M_c = 3.86D^2(E_pR_I)\left(\frac{S_uF_m}{E_pR_I}\right)^{0.46} \tag{2}$$

For sand

$$P_c = 1.57D^2(E_pR_I)\left(\frac{\gamma'D\phi'K_pF_m}{E_pR_I}\right)^{0.57} \tag{3}$$

$$M_c = 1.33D^2(E_pR_I)\left(\frac{\gamma'D\phi'K_pF_m}{E_pR_I}\right)^{0.40} \tag{4}$$

where, P_c = characteristic load (force units, F), M_c = characteristic moment (force times length, FL), D = pile or shaft width or diameter (L), E_p = pile or drilled shaft modulus of elasticity (F/L^2), R_I = moment of inertia ratio (dimensionless), S_u = undrained shear strength for clay soil (F/L^2), F_m = pile or drilled shaft group efficiency based on pile spacing (dimensionless), γ' =

effective unit weight for sand (F/L^3), ϕ' = effective stress friction angle of sand (degrees), K_p = Rankine coefficient of passive earth pressure of sand (dimensionless). Any consistent set of units may be used.

The value of R_I is the ratio of the moment of inertia of the pile to the moment of inertia of a solid circular section of the same width, or diameter.

Soil Properties for CLM Analyses

The principal limitation of the CLM method is that it is applicable only to uniform soil conditions. For cases where soil conditions vary with depth, it is necessary to use an equivalent uniform soil profile. It has been found that only the soil within eight pile diameters of the ground surface is important for lateral load conditions, because almost all lateral load is transferred from the piles to the soil within eight diameters below the ground surface. Suitable soil properties for CLM analyses can be established by averaging soil properties within the upper eight diameters.

Comparisons of CLM2.0 with Field Load Tests and Other Software

The accuracy of CLM2.0 was examined by comparing results computed using it with the results of the following field load tests:

1. **Brown, et al. (1988)** conducted full-scale lateral load tests to determine the variation of soil resistance within a pile group. Ten steel pipe piles, consisting of one 3-by-3 group spaced 3 diameters center-to-center (c/c) and one isolated pile were subjected to two-way cyclic loading. The 10.75 inches in outside diameter (O.D.) and 10.00 inch in inner diameter (I.D.) piles were tested in submerged dense sand that was placed and compacted around the piles.

2. **Kim et al. (1979)** performed full-scale lateral load tests to relate the behavior of single piles to the behavior of pile groups in cohesive soils. Twenty 10BP42 steel piles, consisting of three six-pile groups and two isolated single piles were driven 40 feet to refusal into limestone. Two of the pile groups consisted of vertical piles, with one group spaced at 4-ft c/c and the other group spaced at 3-ft c/c. The third group consisted of 4 battered piles. This group was not used for comparison, because CLM2.0 does not account for battered piles.

3. **Rollins, et al. (1998)** performed full-scale lateral load tests to determine pile-soil-pile interaction within a group. Ten steel pipe piles, consisting of one 3-by-3 group spaced 3

diameters center-to-center (c/c) and one isolated pile were driven into soft to medium stiff clays and silts underlain by sand. The piles were 12.75 inches in outside diameter (O.D.) and 12.00 inches in inner diameter (I.D.).

Single Piles.   Comparisons of results computed using CLM2.0 for single piles with the results of field load tests and results computed using LpilePlus 3.0[©] (Reese and Wang, 1997) are shown in Figures 2, 3, and 4.   The actual soil profile and the averaged soil profile used in CLM2.0 are shown at the top of the figures.   Tabulated results are shown in the middle of each figure, and variations of deflection with applied load are shown at the bottom.

Because the load was applied above the ground surface for the load test shown in Figure 2, the "flagpole" analysis feature of CLM2.0 was used to compute the results shown in Figure 2.   It can be seen that the results computed using CLM2.0 are in close agreement with the results computed using LpilePlus 3.0[©], and that the measured deflections are about 30% smaller than the computed deflections.

In the load test shown in Figure 3, the single pile was attached to a "cap" to restrain rotation. Analyses performed using LpilePlus 3.0[©] and CLM2.0 were performed assuming fixed-head conditions at the top of the pile.   It can be seen that these analyses resulted in deflections that were smaller than those measured, indicating that the cap probably provided only partial restraint against rotation at the top of the pile.

In the case shown in Figure 4, the deflections computed using LpilePlus 3.0[©] and CLM2.0 are in close agreement with the field measurements.   As in the case shown in Figure 2, the load was applied above the ground surface, and the flagpole feature in CLM2.0 was used to represent this loading condition.

Pile Groups.   Comparisons of results computed using CLM2.0 pile groups with the results of field load tests and results computed using Group4.0[©] (Reese et al., 1996) are shown in Figures 5, 6, 7, and 8.

In the case shown in Figure 5, the piles were pinned to the cap, and the CLM2.0 and Group4.0[©] analyses were performed assuming free head conditions.   It can be seen that the computed results are in close agreement with the field measurements.

SOIL PROFILES

Top of Pile = −2.3 ft
Load Applied at −1.0 ft

Closed-end Steel
Pile Pile
O.D. = 10.75 in
I.D. = 10 in

Lpile Plus 3.0 Analysis

0

Clean Sand Fill γ_b = 66 pcf,
ϕ' = 39°

10

Stiff to Very Stiff Clay
γ_b = 63 pcf,
S_u = 3000 psf, ϕ_u = 0°

Depth - feet

35

CLM Analysis

Sand
γ_b = 66 pcf,
ϕ' = 39°
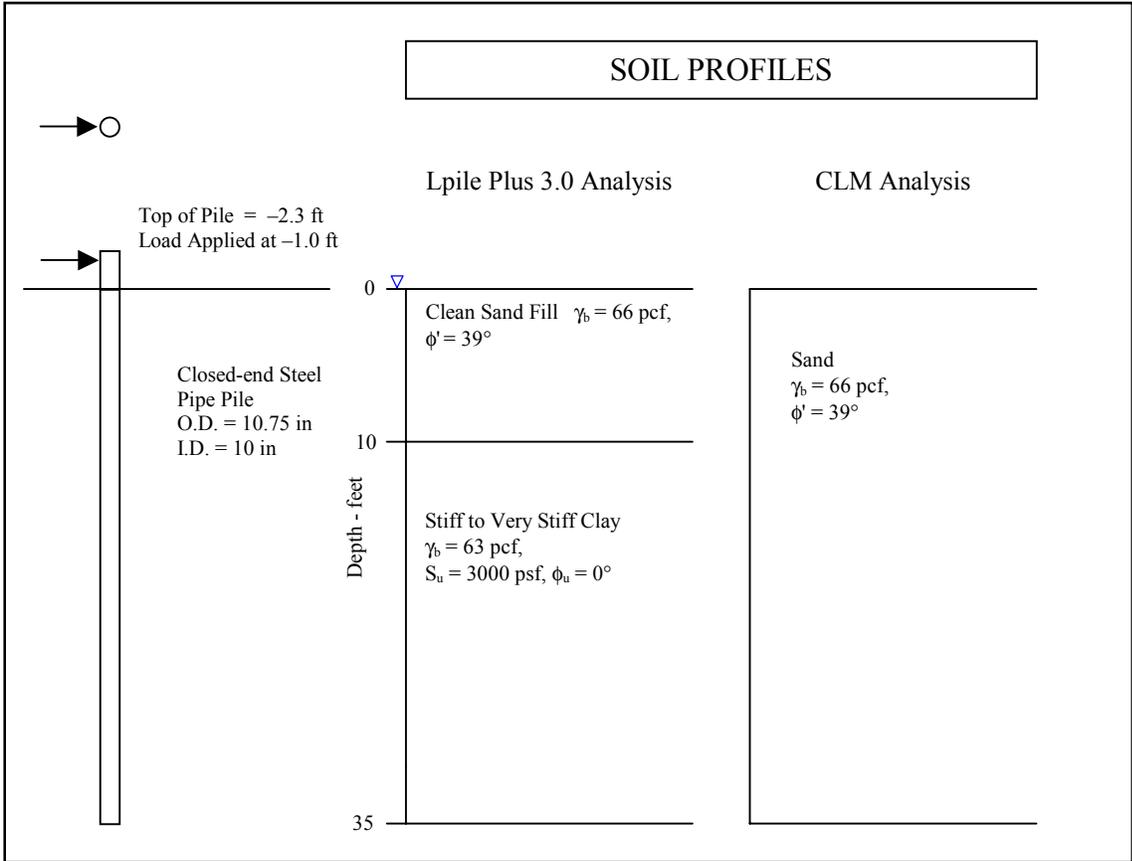
Load per Pile (kips)	Deflection		
	Measured (inches)	LpilePlus3.0 (inches)	CLM - Flagpole (inches)
13	0.5	0.77	0.77
23	1.0	1.83	1.79
30	1.5	2.83	2.67

Figure 2 – Single Pile Comparison (load test data from Brown et al., 1988)

SOIL PROFILES

CAP
Width = 3.5'
Length = 3.5'
Thickness = 4'

Lpile Plus 3.0 Analysis

CLM Analysis

10BP42 pile

Depth - feet

0

Silty Clay γ_m = 120 pcf, S_u = 1000psf, ϕ_u = 0°

7

Sandy Clay γ_m = 115 pcf, S_u = 1400psf, ϕ_u = 0°

13

Clay γ_m = 110 pcf, S_u = 500psf, ϕ_u = 0°

24

Clay Loam with Limestone Gravel Layers γ_m = 115 pcf, S_u = 2000psf, ϕ_u = 35°

35

Limestone, γ_m = 150 pcf, S_u = 5000psf, ϕ_u = 0°

40

Clay γ_m = 117 pcf, S_u = 1200 psf, ϕ_u = 0°
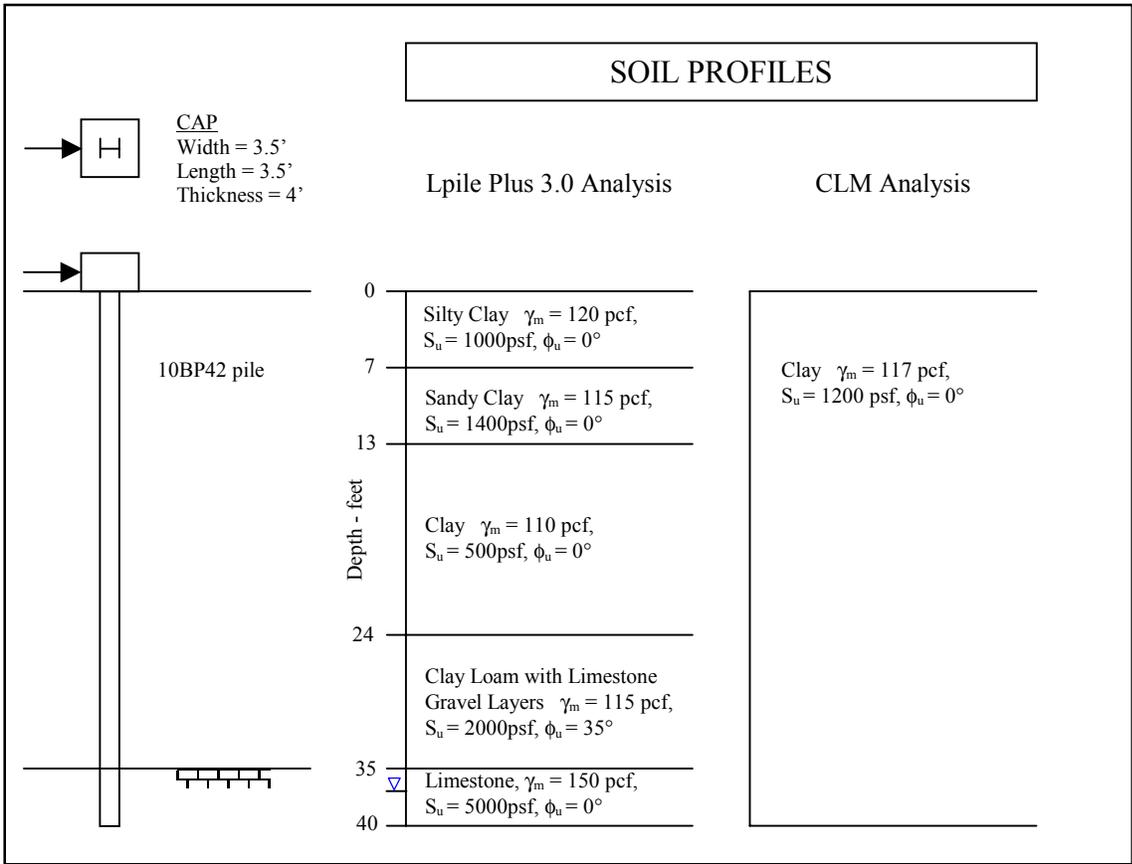
Load per Pile (kips)	Deflection		
	Measured (inches)	LpilePlus3.0 (inches)	CLM - Fixed-head (inches)
8.3	0.18	0.04	0.05
16.7	0.39	0.18	0.17
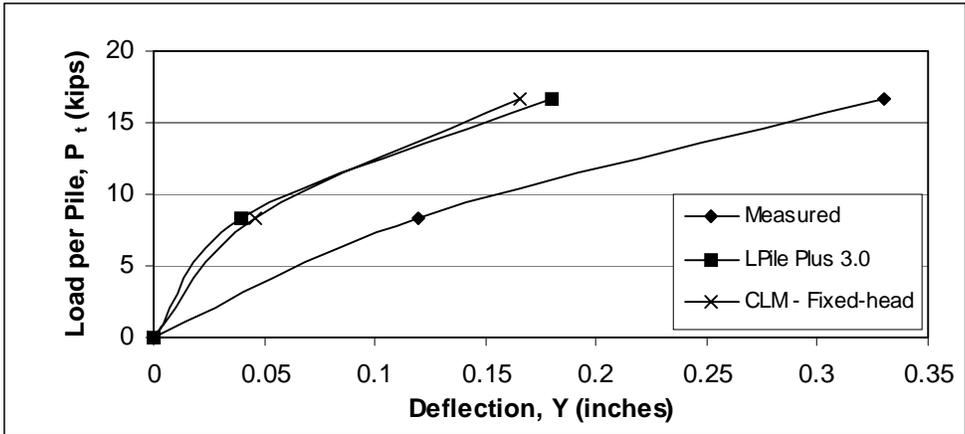
Figure 3 – Single Pile Comparison (load test data from Kim et al., 1979)

SOIL PROFILES

Lpile Plus 3.0 Analysis

Top of Pile = –2.0 ft
Load Applied at –1.5 ft

Closed-end Steel
Pipe Pile
O.D. = 12.75 in
I.D. = 12 in

Silt with Sand $\gamma_b = 58$ pcf, $S_u = 2100$ psf, $\phi_u = 0°$

Clay and Silt $\gamma_b = 53$ pcf, $S_u = 1000$ psf, $\phi_u = 0°$

Sand $\gamma_b = 58$ pcf, $S_u = 0$ psf, $\phi' = 36°$

Clay and Silt $\gamma_b = 53$ pcf, $S_u = 1000$ psf, $\phi_u = 0°$

Silty Sand, $\gamma_b = 58$ pcf, $S_u = 0$ psf, $\phi' = 36°$

Depth - feet: 0, 2, 9, 16, 23, 26

CLM Analysis

Clay $\gamma_b = 55$ pcf, $S_u = 1600$ psf, $\phi_u = 0$
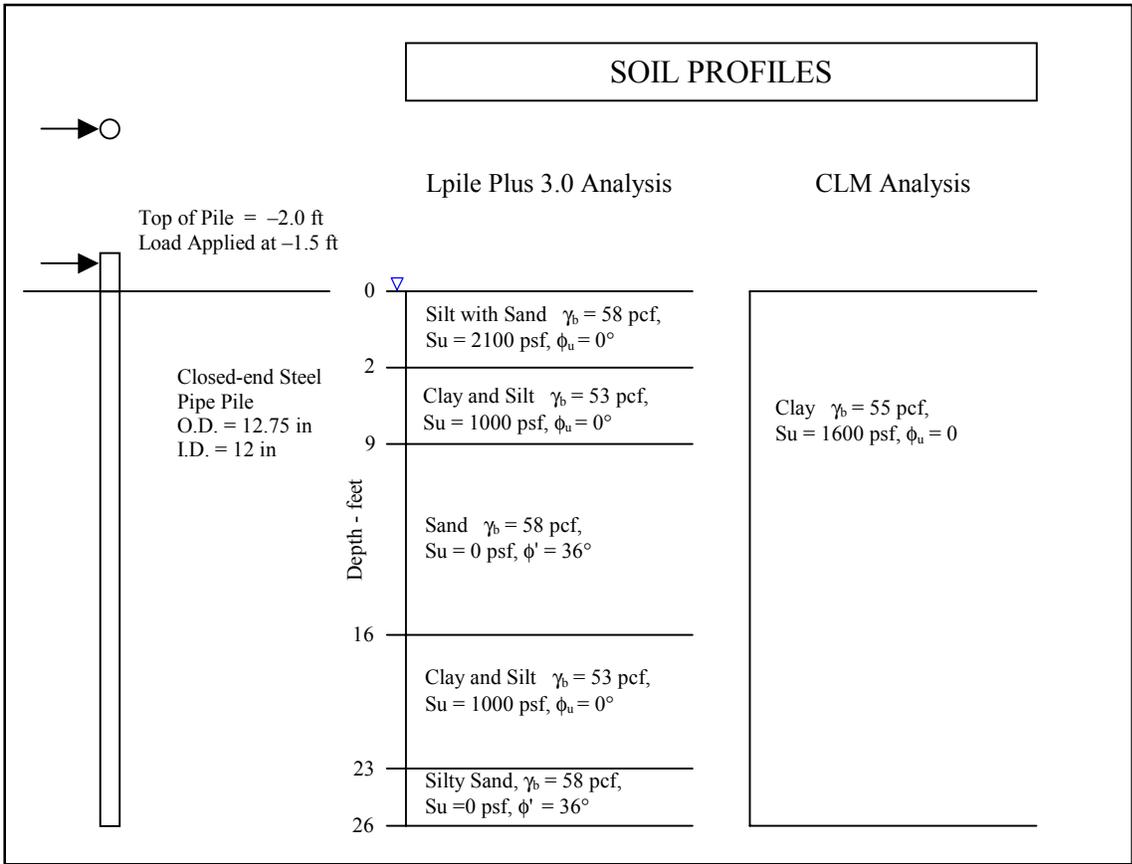
Load per Pile (kips)	Deflection		
	Measured – Flagpole (inches)	LpilePlus3.0 - Flagpole (inches)	CLM - Flagpole (inches)
20	0.79	0.86	0.92
30	1.57	1.63	1.82
40	2.36	2.97	3.06
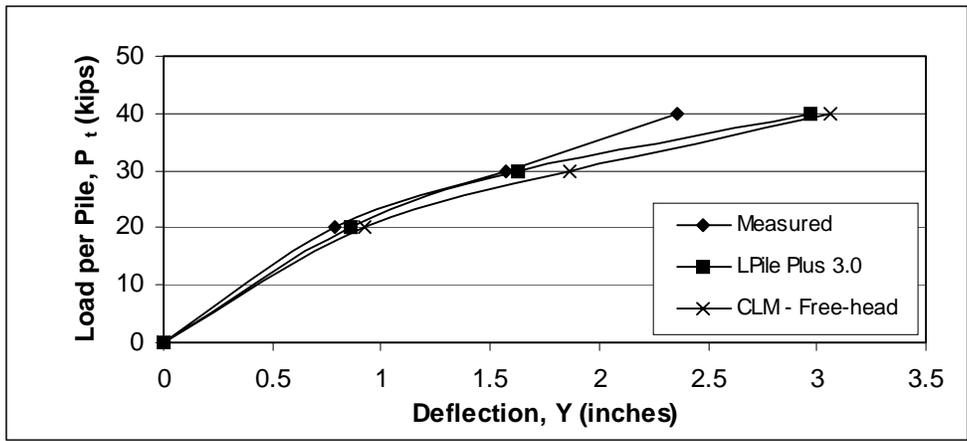
Figure 4 – Single Pile Comparison (load test data from Rollins et al., 1998)

SOIL PROFILES

No rotational restraint at top of piles.

Group 4.0 Analysis

CLM Analysis

Top of Pile = −2.3 ft
Load Applied at −1.0 ft

Clean Sand Fill γ_b = 66 pcf, ϕ' = 39°

Sand
γ_b = 66 pcf,
ϕ' = 39°

Closed-end Steel Pipe Piles
O.D. = 10.75 in
I.D. = 10 in
3x3 Group
3D spacing c/c

Stiff to Very Stiff Clay
γ_b = 63 pcf,
S_u = 3000 psf, ϕ_u = 0°

Depth - feet

0

10

35

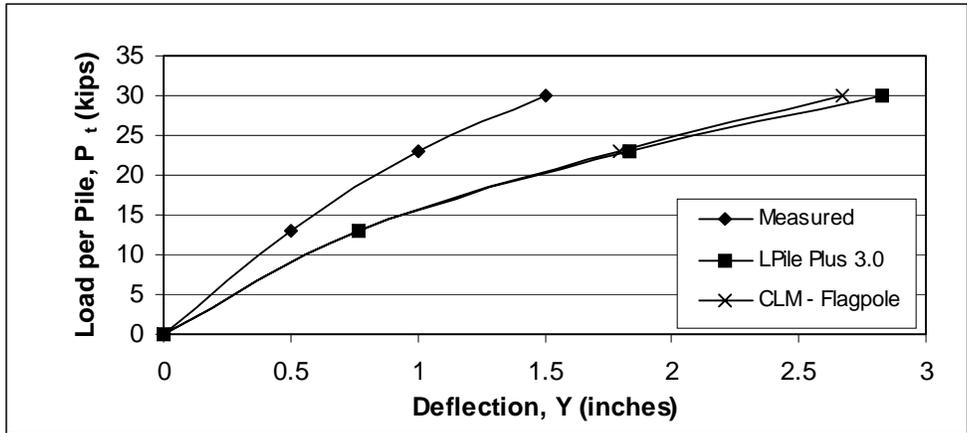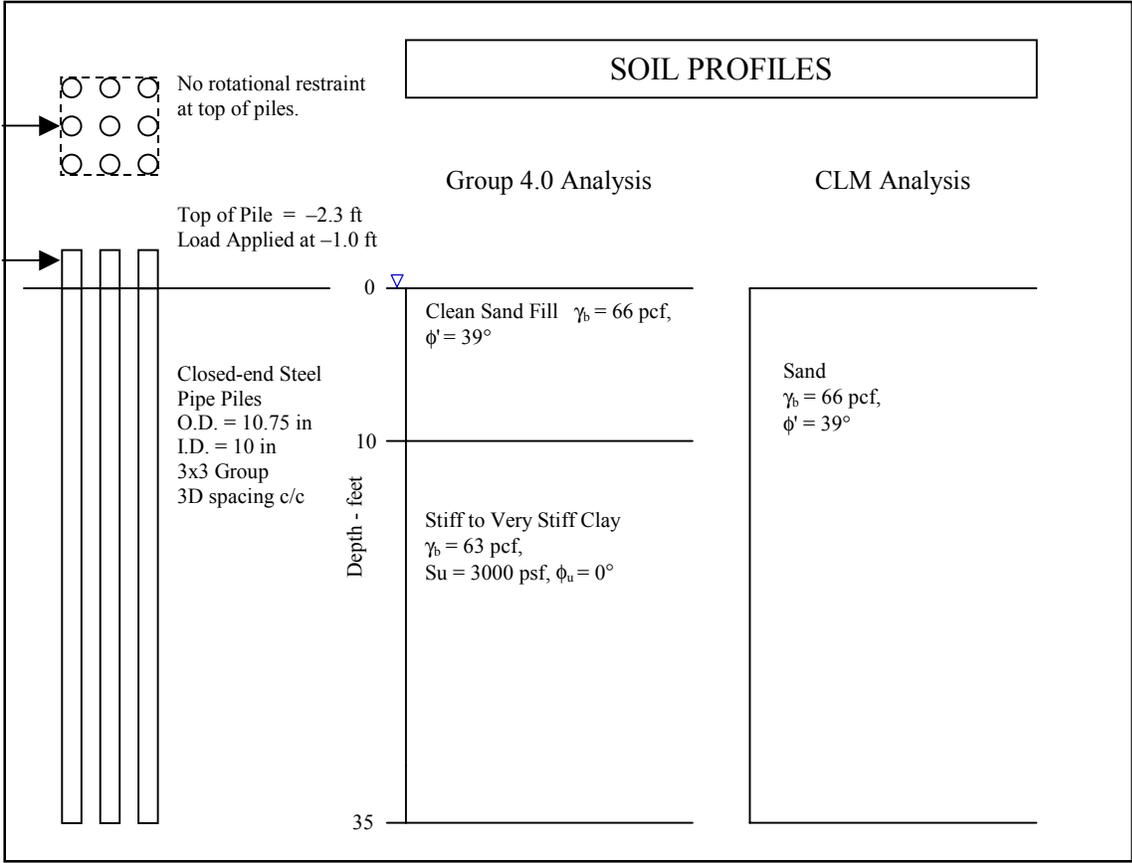| Load per Pile (kips)	Deflection		
	Measured (inches)	Group 4.0 (inches)	CLM - Free-head (inches)
10	0.5	0.65	0.56
15	1.0	1.13	1.04
20	1.5	1.76	1.61
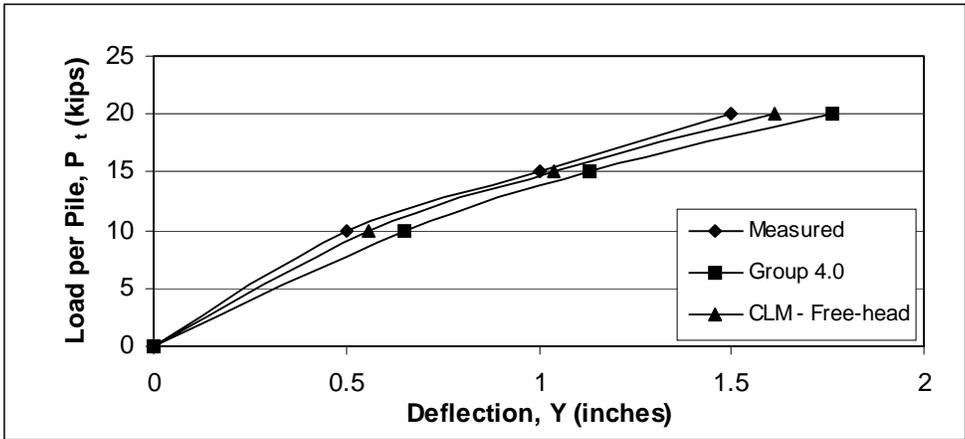
Figure 5 – Pile Group Comparison (load test data from Brown et al., 1988)

SOIL PROFILES

CAP
Width = 8'
Length = 12'
Thickness = 4'

Group 4.0 Analysis

CLM Analysis

10BP42 piles
2x3 Group
4-ft spacing c/c

Depth - feet

0

Silty Clay γ_m = 120 pcf,
S_u = 1000 psf, ϕ_u = 0°

7

Sandy Clay γ_m = 115 pcf,
S_u = 1400 psf, ϕ_u = 0°

13

Clay γ_m = 110 pcf,
S_u = 500 psf, ϕ_u = 0°

24

Clay Loam with Limestone
Gravel Layers γ_m = 115 pcf,
S_u = 2000 psf, ϕ_u = 0°

35

Limestone, γ_m = 150 pcf,
S_u = 5000 psf, ϕ_u = 0°

40

Clay γ_m = 117 pcf,
S_u = 1200 psf, ϕ_u = 0°
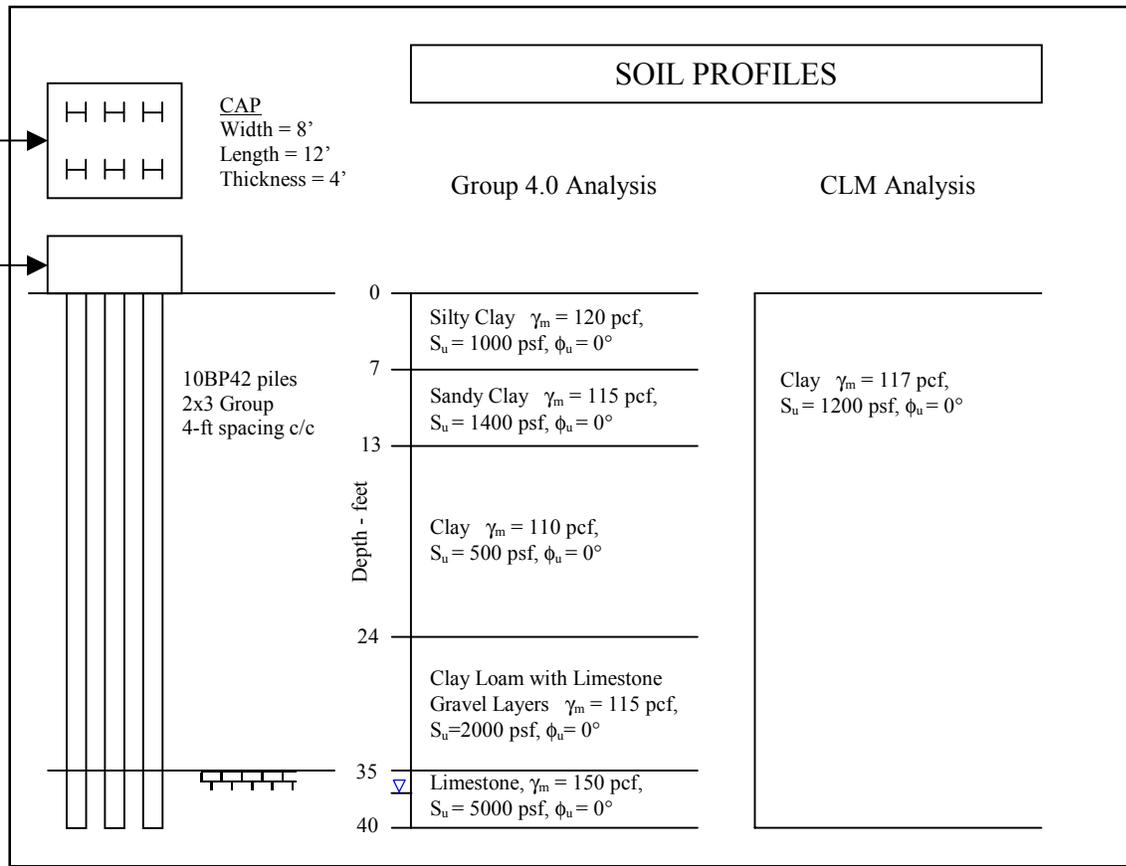
Load per Pile (kips)	Deflection		
	Measured (inches)	Group 4.0 (inches)	CLM - Fixed-head (inches)
8.3	0.05	0.06	0.06
16.7	0.12	0.25	0.23

Figure 6 – Pile Group Comparison (load test data from Kim et al., 1979)

SOIL PROFILES

CAP
Width = 7'
Length = 10'
Thickness = 4'

Group 4.0 Analysis

CLM Analysis

10BP42 piles
2x3 Group
3-ft spacing c/c

Depth - feet

0

Silty Clay γ_m = 120 pcf,
S_u = 1000psf, ϕ_u = 0°

7

Sandy Clay γ_m = 115 pcf,
S_u = 1400psf, ϕ_u = 0°

13

Clay γ_m = 110 pcf,
S_u = 500psf, ϕ_u = 0°

24

Clay Loam with Limestone
Gravel Layers γ_m = 115 pcf,
S_u = 2000psf, ϕ_u = 0°

35

Limestone, γ_m = 150 pcf,
S_u = 5000psf, ϕ_u = 0°

40

Clay γ_m = 117 pcf,
S_u = 1200 psf, ϕ_u = 0°

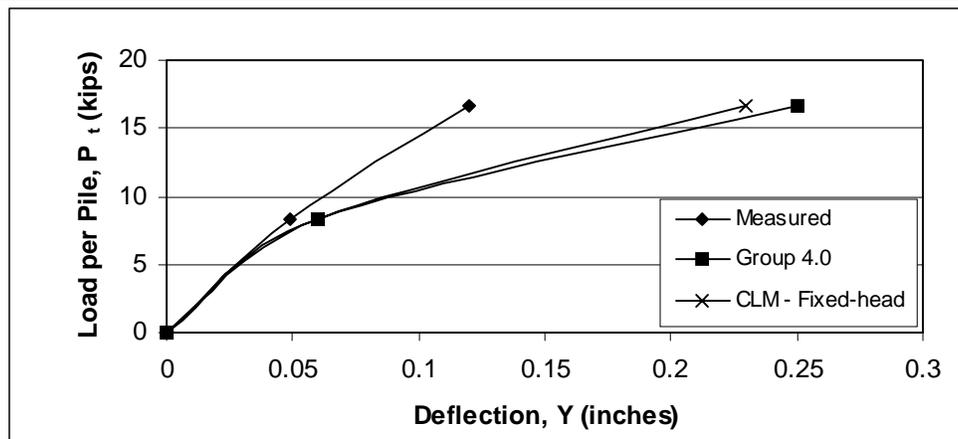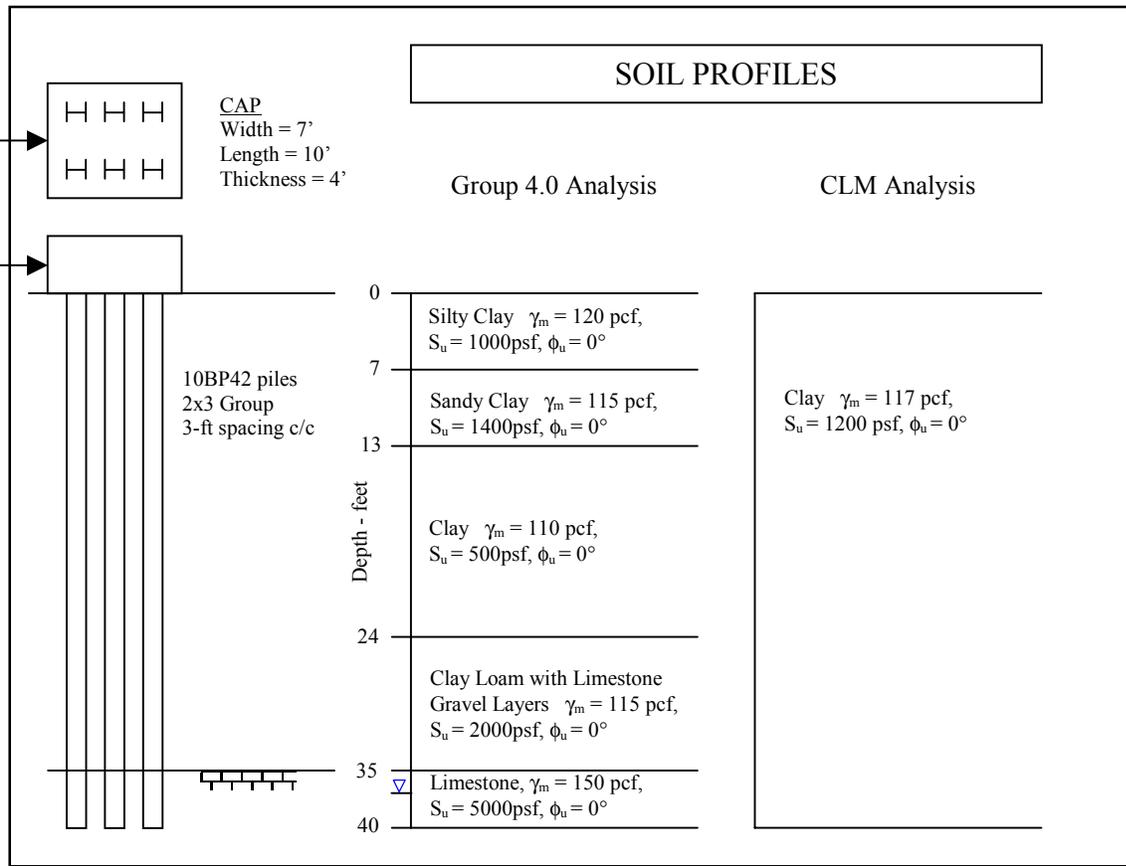| Load per Pile (kips)	Deflection		
	Measured (inches)	Group 4.0 (inches)	CLM - Fixed-head (inches)
8.3	0.1	0.08	0.07
16.7	0.24	0.32	0.27
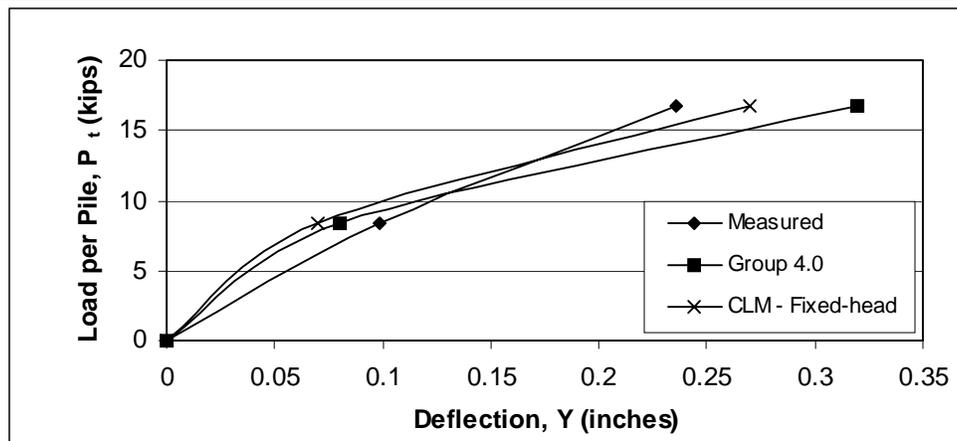
Figure 7 – Pile Group Comparison (load test data from Kim et al., 1979)

No rotational restraint at top of piles.

SOIL PROFILES

Group 4.0 Analysis

CLM Analysis

Top of Pile = −2.0 ft
Load Applied at −1.5 ft

Closed-end Steel
Pipe Piles
O.D. = 12.75 in
I.D. = 12 in
3x3 Group
3D spacing c/c

Depth - feet

0

Silt with Sand γ_b = 58 pcf,
S_u = 2100 psf, ϕ_u = 0°

2

Clay and Silt γ_b = 53 pcf,
S_u = 1000 psf, ϕ_u = 0°

9

Sand γ_b = 58 pcf,
ϕ' = 36°

16

Clay and Silt γ_b = 53 pcf, S_u = 1000 psf, ϕ' = 0°

23

Silty Sand, γ_b = 58 pcf,
ϕ' = 36°

26

Clay γ_b = 55 pcf,
S_u = 1600 psf, ϕ_u = 0
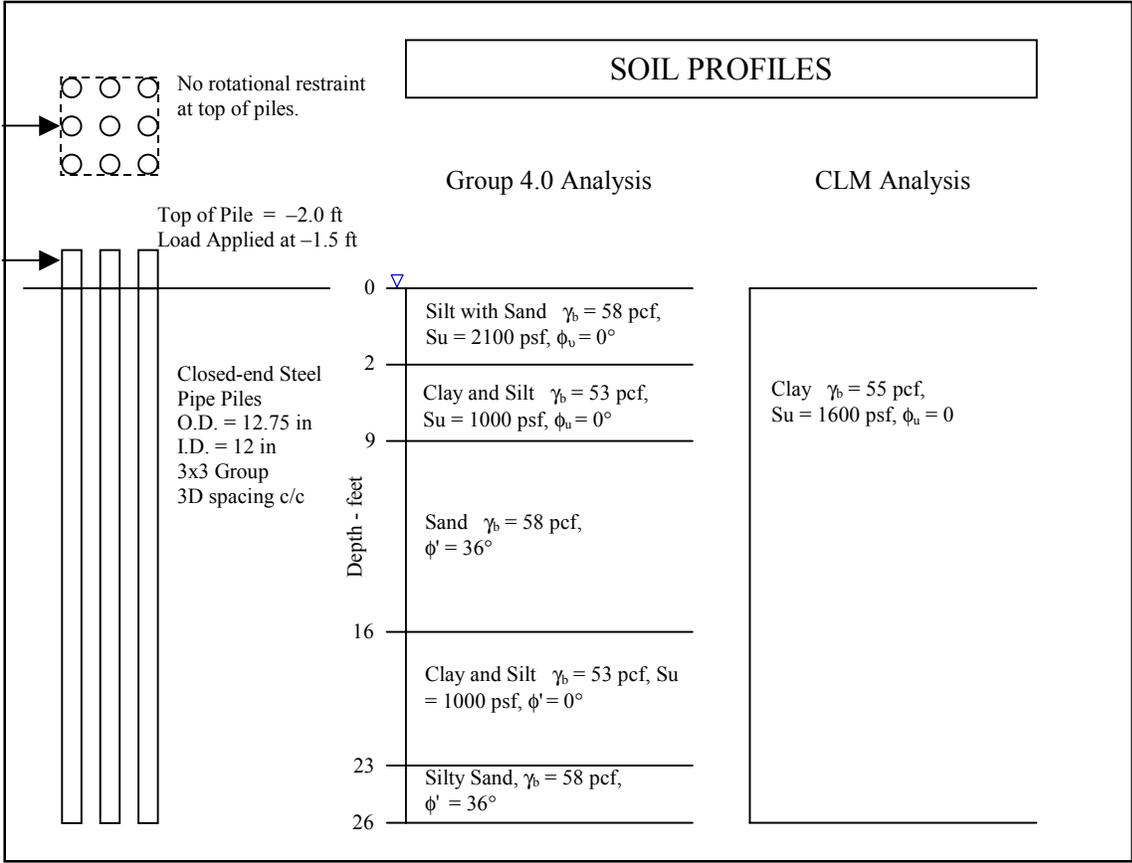
Load per Pile (kips)	Deflection		
	Measured (inches)	Group 4.0 (inches)	CLM - Free-head (inches)
14	0.79	0.66	0.50
20	1.57	1.12	0.97
23	2.36	1.44	1.25

Figure 8 – Pile Group Comparison (load test data from Rollins et al., 1998)

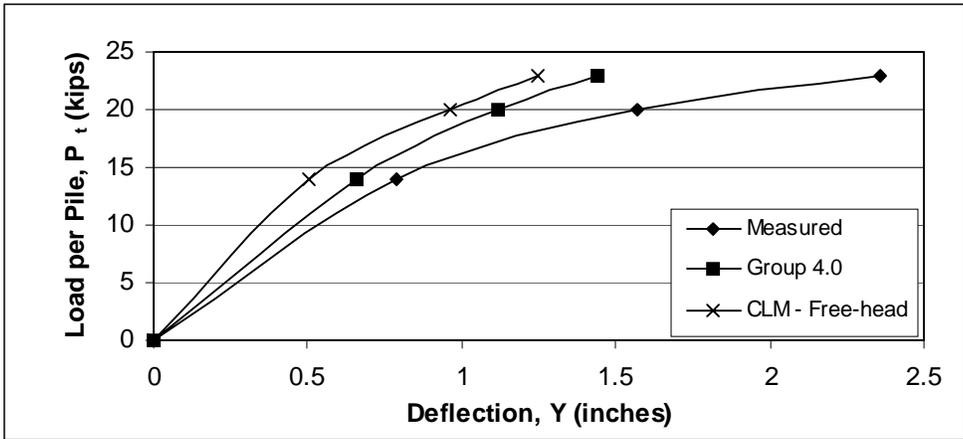In the case shown in Figure 6, it was assumed that the cap provided full restraint against rotation at the tops of the piles, and the CLM2.0 analyses were performed assuming fixed-head conditions. The results computed using CLM2.0 and Group4.0$^{©}$ agree well with the measured results for loads up to 8 kips per pile, but the computed deflections are larger than those measured for higher loads.

In the case shown in Figure 7, it was assumed that the cap provided complete restraint against rotation. The computed and measured results are in reasonable agreement overall, but the computed deflections are smaller than those measured for small loads, and larger than those measured for higher loads, indicating that the overall agreement may be somewhat fortuitous.

In the case shown in Figure 8, the soil profile contains sand, silt, and clay at shallow depth, making it difficult to determine what is a suitable average soil profile. It can be noted that for this case, the results computed using Group4.0$^{©}$ are in better agreement with the field measurements than those computed using CLM2.0. This case shows that the results computed using CLM2.0 are affected by the difficulty involved in representing the soil conditions around the top of the pile as uniform.

Using CLM2.0 – A Guide

The CLM2.0 workbook contains two spreadsheets, one for clay and one for sand. Examples are shown in Figures 9 and 10. Soil and pile properties are input in the block at the upper left in the sheets. Only the values shown in red on the spreadsheet can be changed. The explanatory text and the computed values shown in black are locked, and cannot be changed by the user. (Note that it is not possible to distinguish the "red" cells in Figures 9 and 10, which are shown entirely in black and white. The red cells are visible on the spreadsheet when it is opened in Excel.)

Units. The user enters the units of force and length to be used in the analysis. All of the soil and pile properties must be entered in consistent units, and the computed deflections and moments are also expressed in consistent units. For example, if the force unit is kips and the

CHARACTERISTIC LOAD METHOD OF ANALYSIS FOR LATERALLY LOADED PILES   08/15/01   PROJECT NO.:

LpileCLM2.0   Version 1, May 9, 2001   NAME:

Duncan, J. M., Evans, Jr., L. T. and Ooi, P. S. K. (1994) "Lateral Load Analysis of Single Piles and Drilled Shafts." J. Geot Div, ASCE, (120) No. 5,1018-1033.

Brettmann, T. and Duncan, J. M. (1996) "Computer Application of CLM Lateral Load Analysis to Piles and Drilled Shafts." J Geot Div ASCE (122) No. 6, 496-500

Mokwa, R. L. and Duncan, J. M. (2001) "Laterally Loaded Pile Group Effects and P-Y Multipliers."

SOIL TYPE: CLAY

INPUT PARAMETERS		INSTRUCTIONS AND DEFINITIONS	CALCULATED PILE PARAMETERS		
UNITS		Select either CLAY or SAND soil conditions worksheet.	Isirc=	1297.21 IN^4 (I for solid circle)	
FORCE =	KIPS	Input data in red cells only.	Ri =	0.22 (I / Isirc)	
LENGTH =	IN		EpRi =	6244.72 KIPS/IN^2	
		Su = Undrained shear strength for clay	EpRi/Su =	567,702	
SOIL PROPERTIES		ø = Effective friction angle for sand	L/D =	24	
Su =	0.011 KIPS/IN^2	γ = Effective unit weight for sand			
		Do = Outside pile diameter (circular) or width (noncircular)	**CHARACTERISTIC LOAD AND MOMENT**		
PILE PROPERTIES		Di = Inside diameter of pipe pile	Pc =	910.8 KIPS	
Do =	12.75 IN	[enter zero for solid section]	Mc =	112851.1 IN-KIPS	
Di =	12.00 IN	I = Moment of inertia for any noncircular section			
I =	0 IN^4	[enter zero for circular section]	**CALCULATED P-MULTIPLIER**		
Rcr =	1	Rcr = Ratio of cracked EI to uncracked EI	Fm =	0.69	
Ep =	29000 KIPS/IN^2	Ep = Modulus of elasticity of pile or drilled shaft			
L =	312 IN	L = Length of pile or drilled shaft	**MINIMUM REQUIRED L/D FOR CLM**		
PILE GROUP PROPERTIES		Nrow = Number of rows in pile group	EpRi/Su 100,000	300,000	1,000,000 3,000,000
Nrow =	3	S/D = Pile spacing to diameter ratio	L/D 6	10	14 18
S/D =	3	Fm = Group efficiency			

LOADING CONDITION: LOAD ONLY

FREE HEAD

			SINGLE PILE		GROUP	
Pt KIPS per Pile	Pt/Pc	Yt/D	Yp IN	Mmax IN-KIPS	Yp IN	Mmax IN-KIPS
14.0	0.0154	0.0248	0.317	444.8	0.504	519.9
20.0	0.0220	0.0476	0.607	704.2	0.965	823.0
23.0	0.0253	0.0614	0.782	843.1	1.245	965.4
8.0	0.0088	0.0090	0.114	216.3	0.182	252.9
10.0	0.0110	0.0135	0.172	288.4	0.273	337.1
12.0	0.0132	0.0188	0.239	364.7	0.381	426.3
14.0	0.0154	0.0248	0.317	444.8	0.504	519.9
16.0	0.0176	0.0317	0.404	528.3	0.643	617.5
18.0	0.0198	0.0393	0.501	614.8	0.797	718.6
20.0	0.0220	0.0476	0.607	704.2	0.965	823.0

FIXED HEAD

			SINGLE PILE		GROUP	
Pt KIPS per Pile	Pt/Pc	Yt/D	Yp IN	Mmax IN-KIPS	Yp IN	Mmax IN-KIPS
14.0	0.0154	0.0063	0.080	479.8	0.128	554.0
20.0	0.0220	0.0122	0.155	747.5	0.248	865.0
23.0	0.0253	0.0157	0.201	890.1	0.321	1030.0
8.0	0.0088	0.0022	0.029	238.0	0.046	275.4
10.0	0.0110	0.0034	0.043	314.5	0.069	363.9
12.0	0.0132	0.0047	0.060	394.9	0.097	457.0
14.0	0.0154	0.0063	0.080	479.8	0.128	554.0
16.0	0.0176	0.0081	0.103	565.7	0.164	654.6
18.0	0.0198	0.0100	0.128	655.3	0.204	758.3
20.0	0.0220	0.0122	0.155	747.5	0.248	865.0

LOADING CONDITION: MOMENT ONLY

FREE HEAD

Mt IN-KIPS	Mt/Mc	Ym/D	Ym IN
84.0	0.0007	0.0008	0.01
120.0	0.0011	0.0013	0.02
138.0	0.0012	0.0016	0.02
48.0	0.0004	0.0004	0.00
60.0	0.0005	0.0005	0.01
72.0	0.0006	0.0006	0.01
84.0	0.0007	0.0008	0.01
96.0	0.0009	0.0010	0.01
108.0	0.0010	0.0011	0.01
120.0	0.0011	0.0013	0.02

P-MULTIPLIER DESIGN CURVES

LOADING CONDITION: COMBINED LOAD AND MOMENT

FREE HEAD

Pt KIPS per Pile	Mt IN-KIPS	Pt/Pc	Yp/D	Mt/Mc	Ym/D	Per/Pc	Me/Mc	Σ Pt/Pc	Σ M/Mc	Σ Yp/D	Σ Ym/D	Yavg/D	Yavg IN
14.0	84.0	0.0154	0.0248	0.0007	0.0008	0.0023	0.0085	0.0177	0.0092	0.0322	0.0080	0.0301	0.38
20.0	120.0	0.0220	0.0476	0.0011	0.0013	0.0031	0.0134	0.0250	0.0145	0.0605	0.0530	0.0567	0.72
23.0	138.0	0.0253	0.0614	0.0012	0.0016	0.0034	0.0160	0.0287	0.0173	0.0775	0.0681	0.0728	0.93
9.0	49.0	0.0088	0.0090	0.0004	0.0004	0.0015	0.0041	0.0103	0.0045	0.0120	0.0103	0.0111	0.14
10.0	60.0	0.0110	0.0135	0.0005	0.0005	0.0018	0.0055	0.0128	0.0060	0.0178	0.0153	0.0165	0.21
12.0	72.0	0.0132	0.0188	0.0006	0.0006	0.0021	0.0069	0.0153	0.0076	0.0245	0.0212	0.0229	0.29
14.0	84.0	0.0154	0.0248	0.0007	0.0008	0.0023	0.0085	0.0177	0.0092	0.0322	0.0080	0.0301	0.38
16.0	96.0	0.0176	0.0317	0.0009	0.0010	0.0026	0.0100	0.0202	0.0109	0.0407	0.0356	0.0381	0.49
18.0	108.0	0.0198	0.0363	0.0010	0.0011	0.0028	0.0117	0.0226	0.0128	0.0502	0.0439	0.0470	0.60
20.0	120.0	0.0220	0.0476	0.0011	0.0013	0.0031	0.0134	0.0250	0.0145	0.0605	0.0530	0.0567	0.72
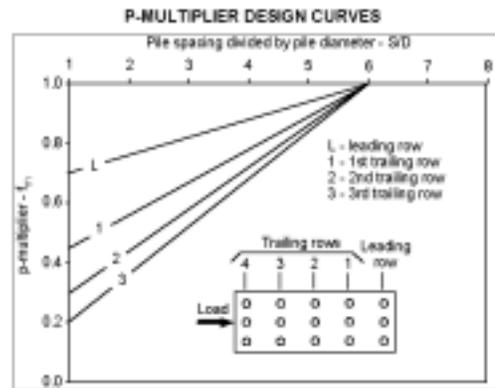
Figure 9 – CLM2.0 Spreadsheet for Clay

CHARACTERISTIC LOAD METHOD OF ANALYSIS FOR LATERALLY LOADED PILES   08/15/01   PROJECT NO.:
CLM2.0 August, 2001   NAME:
Duncan, J. M., Evans, Jr., L. T. and Ooi, P. S. K. (1994) "Lateral Load Analysis of Single Piles and Drilled Shafts." J. Geot Div, ASCE., (120) No. 5,1018-1033.
Breitmann, T. and Duncan, J. M. (1996) "Computer Application of CLM Lateral Load Analysis to Piles and Drilled Shafts." J Geot Div ASCE (122) No. 6, 496-500
Mokwa, R. L. and Duncan, J. M. (2001) "Laterally Loaded Pile Group Effects and P-Y Multipliers."

SOIL TYPE: SAND

INPUT PARAMETERS		INSTRUCTIONS AND DEFINITIONS	CALCULATED PILE PARAMETERS		
UNITS		Select either CLAY or SAND soil conditions worksheet.	Icirc =	IN^4 (I for solid circle)	
FORCE =	KIPS	Input data in red cells only.	Ri =	1.00 (I / Icirc)	
LENGTH =	IN		EpRi =	3600.00 KIPS/IN^2	
		Su = Undrained shear strength for clay	EpRi/γD φKp =	19,169	
SOIL PROPERTIES		φ = Effective friction angle for sand	L/D =	14	
φ =	30 DEGREES	γ = Effective unit weight for sand			
γ =	5.00E-05 KIPS/IN^3	Do = Outside pile diameter (circular) or width (noncircular)	CHARACTERISTIC LOAD AND MOMENT		
Kp =	3.00	Di = Inside diameter of pipe pile	Pc =	26529.5 KIPS	
PILE PROPERTIES		[enter zero for solid section]	Mc =	4325385.7 IN-KIPS	
Do =	36 IN	I = Moment of inertia for any noncircular section			
Di =	0 IN	[enter zero for circular section]	CALCULATED P-MULTIPLIER		
I =	0 IN^4	Rcr = Ratio of cracked EI to uncracked EI	Fm =	0.69	
Rcr =	1	Ep = Modulus of elasticity of pile or drilled shaft			
Ep =	3600 KIPS/IN^2	L = Length of pile or drilled shaft			
L =	500 IN	Nrow = Number of rows in pile group	MINIMUM REQUIRED L/D FOR CLM		
		S/D = Pile spacing to diameter ratio	EpRi/γD φKp =	10,000	40,000	200,000
PILE GROUP PROPERTIES		Fm = Group efficiency	L/D	8	11	14
Nrow =	3				
S/D =	3				

LOADING CONDITION: LOAD ONLY

FREE HEAD

			SINGLE PILE		GROUP	
Pt KIPS per Pile	Pt/Pc	Yt/D	Yp IN	Mmax IN-KIPS	Yp IN	Mmax IN-KIPS
10.0	0.0004	0.0007	0.026	338.1	0.036	391.2
20.0	0.0008	0.0021	0.075	882.4	0.104	1020.9
30.0	0.0011	0.0039	0.139	1546.5	0.193	1789.4
40.0	0.0015	0.0060	0.216	2302.9	0.296	2664.5
50.0	0.0019	0.0084	0.303	3136.2	0.420	3628.7
60.0	0.0023	0.0111	0.401	4036.3	0.555	4670.2
70.0	0.0026	0.0141	0.507	4986.2	0.701	5760.8
80.0	0.0030	0.0172	0.621	6010.4	0.860	6964.2
90.0	0.0034	0.0206	0.743	7074.5	1.029	8166.5
100.0	0.0038	0.0242	0.872	8185.2	1.208	9470.5

FIXED HEAD

			SINGLE PILE		GROUP	
Pt KIPS per Pile	Pt/Pc	Yt/D	Yp IN	Mmax IN-KIPS	Yp IN	Mmax IN-KIPS
10.0	0.0004	0.0002	0.008	404.4	0.010	459.5
20.0	0.0008	0.0006	0.021	995.7	0.030	1131.5
30.0	0.0011	0.0011	0.039	1686.7	0.054	1916.8
40.0	0.0015	0.0017	0.061	2451.6	0.084	2786.1
50.0	0.0019	0.0024	0.085	3276.7	0.117	3723.8
60.0	0.0023	0.0031	0.112	4153.1	0.154	4719.8
70.0	0.0026	0.0039	0.141	5074.7	0.194	5767.0
80.0	0.0030	0.0048	0.172	6038.7	0.237	6860.3
90.0	0.0034	0.0057	0.205	7035.5	0.282	7995.4
100.0	0.0038	0.0067	0.240	8066.3	0.331	9169.1

LOADING CONDITION: MOMENT ONLY

FREE HEAD

Mt IN-KIPS	Mt/Mc	Ym/D	Ym IN
600.0	0.0001	0.0003	0.01
1200.0	0.0003	0.0008	0.03
1800.0	0.0004	0.0014	0.05
2400.0	0.0006	0.0020	0.07
3000.0	0.0007	0.0027	0.10
3600.0	0.0008	0.0034	0.12
4200.0	0.0010	0.0041	0.15
4800.0	0.0011	0.0049	0.18
5400.0	0.0012	0.0057	0.21
6000.0	0.0014	0.0066	0.24

P-MULTIPLIERS

Pile spacing divided by pile diameter - S/D

L - leading row
1 - 1st trailing row
2 - 2nd trailing row
3 - 3rd trailing row

LOADING CONDITION: COMBINED LOAD AND MOMENT

FREE HEAD

| Pt KIPS per Pile	Mt IN-KIPS	Pt/Pc	Yp/D	Mt/Mc	Ym/D	Pe/Ps	Me/Ms	Σ P/Pc	Σ M/Mc	Σ Yp/D	Σ Ym/D	Yavg/D	Yavg IN
10.0	600.0	0.0004	0.0007	0.0001	0.0003	0.0002	0.0003	0.0006	0.0004	0.0015	0.0013	0.0014	0.05
20.0	1200.0	0.0008	0.0021	0.0003	0.0008	0.0004	0.0006	0.0012	0.0009	0.0040	0.0035	0.0037	0.13
30.0	1800.0	0.0011	0.0039	0.0004	0.0014	0.0006	0.0009	0.0017	0.0013	0.0072	0.0063	0.0067	0.24
40.0	2400.0	0.0015	0.0060	0.0006	0.0020	0.0007	0.0013	0.0022	0.0018	0.0109	0.0096	0.0103	0.37
50.0	3000.0	0.0019	0.0084	0.0007	0.0027	0.0009	0.0017	0.0028	0.0024	0.0151	0.0133	0.0142	0.51
60.0	3600.0	0.0023	0.0111	0.0008	0.0034	0.0010	0.0021	0.0033	0.0029	0.0197	0.0173	0.0185	0.67
70.0	4200.0	0.0026	0.0141	0.0010	0.0041	0.0012	0.0025	0.0038	0.0035	0.0247	0.0217	0.0232	0.83
80.0	4800.0	0.0030	0.0172	0.0011	0.0049	0.0013	0.0029	0.0043	0.0040	0.0300	0.0264	0.0282	1.01
90.0	5400.0	0.0034	0.0206	0.0012	0.0057	0.0015	0.0033	0.0049	0.0046	0.0356	0.0313	0.0335	1.20
100.0	6000.0	0.0038	0.0242	0.0014	0.0066	0.0016	0.0038	0.0054	0.0051	0.0415	0.0365	0.0390	1.41
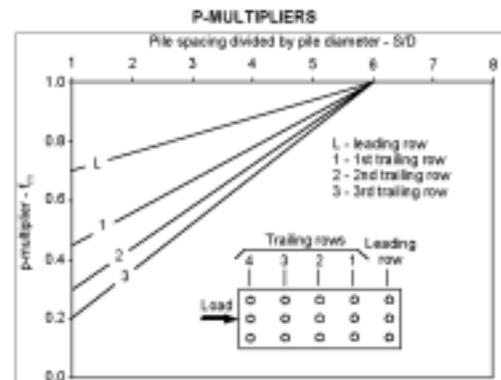
Figure 10 – CLM2.0 Spreadsheet for Sand

length unit is inches, the input shear strength must be expressed in kips per square inch, the pile diameter or width must be expressed in inches, the pile moment of inertia must be expressed in inches to the fourth power, and the pile length must be expressed in inches. With these input units, the computed values of pile deflection are expressed in inches, and bending moments are expressed in inch-kips. Any system of units can be used provided they are used consistently.

Soil Strength. In the clay spreadsheet the soil strength is characterized by undrained shear strength, S_u, and $\phi_u = 0$. In the sand spreadsheet the soil strength is characterized by a friction angle, ϕ', and $c' = 0$.

Unit weight. The unit weight of sand is also required. This is the moist unit weight above the water table, and the buoyant unit weight below the water table. Unit weight is not required for clay.

Pile Properties. The outside diameter of the pile (or the width of the pile for non-circular sections) is entered by the user.

For circular pipe piles the user also enters the inside diameter, and the spreadsheet computes the moment of inertia.

For drilled shafts the user enters zero for inside diameter. In this case the spreadsheet computes the moment of inertia, but the value is not displayed below the space for inside diameter. Instead, the value computed by the program is displayed in the top right section opposite I_{circ}.

For H-piles and other non-circular sections, the user leaves the inside diameter blank, and enters the moment of inertia value.

R_{cr} is the ratio of the EI after cracking to the EI before cracking. If a value smaller than 1.0 is entered, the spreadsheet reduces the moment of inertia used in computing deflections and moments. If it is likely that a reinforced concrete pile or drilled shaft will crack under the imposed loads, the user should calculate or estimate the value of R_{cr}, and enter it.

E_p is the modulus of elasticity of the pile material. For steel $E_p = 29,000$ ksi. The stiffness of reinforced concrete piles and drilled shafts depends on a number of factors including the amount of reinforcing, whether or not cracking will occur, and the magnitude of creep deflections under sustained loads. In many cases it is reasonable to simplify the analyses by using the modulus of

elasticity for the concrete and the moment of inertia of the uncracked section. This simple approximation ignores the compensating factors of the contribution of the steel to the moment of inertia, and cracking of the concrete. If no data are available, the modulus of elasticity of the concrete can be estimated using the following approximate correlation with compressive strength:

f'_c (psi)	3,000	4,000	5,000	6,000
E_c (psi)	3,000,000	3,600,000	4,000,000	4,400,000

Pile length is needed to determine if the CLM method is applicable to the piles analyzed. One of the simplifications used in deriving the CLM method is that the piles are infinitely long. This simplifies the theory by eliminating the need to examine the boundary condition at the bottom of the pile. While no real pile is infinitely long, the theory has been found to be accurate for real piles provided they exceed a certain length, expressed as a minimum number of pile diameters. CLM2.0 computes L/D (the ratio of length to diameter) and displays this in the box at the upper right in the sheet. CLM2.0 also computes the ratio E_pR_I/S_u for clay and the ratio $E_pR_I/\gamma'D \, \phi'K_P$ for sand. These ratios determine the minimum length for which the CLM method is applicable, as shown at the bottom of the box. Provided the value of L/D for the pile is larger than the minimum corresponding to the value of E_pR_I/S_u or $E_pR_I/\gamma'D \, \phi'K_P$ for the pile, the assumption that the pile is infinitely long will not introduce much inaccuracy. If the value of L/D for the pile is not larger than the minimum value shown, the computed deflections will tend to be too small, and the computed moments will tend to be too large.

Pile Group Geometry. The number of rows and the spacing between rows (expressed in pile diameters) are entered in the box at the upper left. These characterize the pile group for analysis. The number of piles per row is not needed.

Load Per Pile and Computed Results. The lower part of the spreadsheets contains four tables where the user enters applied loads and applied moments, and where results are displayed. The loads are specified per pile. Thus, if a four-pile group carries a horizontal load of 50 kips, the load would be entered as 12.5 kips per pile. For convenience, each table has 10 rows, making it possible to compute and view results for 10 load cases at the same time.

The upper two tables show results for single piles and pile groups where the horizontal load is applied at the ground surface. The table on the left gives results for free-head conditions, and the table at the right gives results for fixed-head conditions.

The table at the center of the page is for piles loaded by moment only, with zero horizontal load at the ground surface. This loading condition is unusual, and not frequently encountered.

The table at the bottom of the page is for single piles subjected to both load and moment at the ground surface, which is often called the "flagpole" loading condition. These results are computed using the nonlinear superposition technique developed by Duncan et al. (1994).

References

Brettmann, T. and Duncan, J. M. (1996) "Computer Application of CLM Lateral Load Analysis to Piles and Drilled Shafts," ASCE Journal of Geotechnical Engineering, Vol. 122, No. 6, pp. 496-500

Brown, D. A., Morrison, C., and Reese, L. C., (1988), "Lateral Load Behavior of Pile Group in Sand," ASCE Journal of Geotechnical Engineering, Vol. 114, No. 11, pp. 1261-1276.

Duncan, J. M., Evans, Jr., L. T. and Ooi, P. S. K. (1994) "Lateral Load Analysis of Single Piles and Drilled Shafts," ASCE Journal of Geotechnical Engineering, Vol. 120, No. 5, pp. 1018-1033.

Focht, J. A., and Koch, K. J., (1973), "Rational Analysis of the Lateral Performance of Offshore Pile Groups," Proceedings of the 5th Offshore Technology Conference, pp. 701-708.

Kim, J. B., L. P. Singh, and Brungraber, R. J. (1979), "Pile Cap Soil Interaction from Full-Scale Lateral Load Tests," ASCE Journal of Geotechnical Engineering, Vol. 105, No. 5, pp. 643-653.

Mokwa, R. L. and Duncan, J. M. (2001), "Laterally Loaded Pile Group Effects and p-y Multipliers," ASCE Geotechnical Special Publication No 113, pp. 728-742.

Ooi, P. S. K. and Duncan, J. M. (1994), "Lateral Load Analysis of Groups of Piles and Drilled Shafts,", ASCE Journal of Geotechnical Engineering, Vol. 120, No. 5, pp. 1034-1050.

Reese, L. C., Wang, S. T., Arrellaga, J. A., and Hendrix, J. (1996), "Group4.0: A Program for the Analysis of a Group of Piles Subjected to Axial and Lateral Loading," Ensoft, Inc., P. O. Box 180348, Austin, Texas, 78718.

Reese, L. C. and Wang, S. T. (1997), "LpilePlus3.0: A Program for the Analysis of Piles and Drilled Shafts under Lateral Loading," Ensoft, Inc, P. O. Box 180348, Austin, Texas, 78718.

Rollins, K. M., Peterson, K. T., and Weaver, T. J. (1998), "Lateral Load Behavior of Full-Scale Pile Group in Clay," ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol. 124, No. 6, pp. 468-478.