The following pages of *Bridge Design Aids*, Section 12, have been reviewed in February 1990 and found to be valid and appropriate for continued use:

Pages	*Date*	*Title*
12-30 thru 12-49	September 1986	Pile Shaft Design

These pages will be updated from time-to-time when significant changes in the technology occur.

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PILE SHAFT DESIGN

GENERAL

This pile shaft material (12-30 thru 12-49) replaces previously distributed literature concerning pile shaft design. The two design charts which estimate the depth to the point of effective fixity based on the Kocsis procedure, contained in the memorandum dated November 1984, have been replaced. These charts are no longer to be used.

After obtaining input from representatives of both design and research, new charts have been developed based on Professor Reeses research efforts. The new charts more accurately estimate the point of effective fixity.

The drilled shaft foundation is generally cheaper than other foundation types and permits the location of columns in tight locations with a minimum of disturbance to existing facilities. The use of this foundation is generally limited to areas where soil conditions permit economical excavation for the shaft and where ground water is not encountered. The presence of ground water does not prohibit the use of the drilled shaft, however the cost becomes considerably higher in this case. Lined and slurry displacement shafts require special considerations and should be cleared with the columns and piles committee.

The design problems involved with the use of the pile shaft are slightly different from those of ordinary pile and spread footing foundations. The pile shaft has a smaller lateral stiffness and therefore requires more refined foundation data at an earlier stage in the design process. This smaller lateral stiffness must also be considered in the design and analysis of the superstructure as well as the substructure components.

Engineering Geology Translab should be consulted where foundations are composed of rock or rock like material in order to determine weakness due to jointing and fracture planes.

The following memo describes the recommended procedure for the design and analysis of large diameter pile shafts. The procedure is divided into a number of distinct steps. It is a simplified method in which an equivalent column technique is used. An example problem is included. It is suggested that first-time users study the various steps before using the procedure.

Any comments or questions concerning pile shaft design should be directed to SASA 5-1439.

PILE SHAFT DESIGN PROCEDURE

1. Determine an equivalent column length using the rigorous or simplified procedure.

2.-4. Run the BDS, BENT, and STRUDL programs using the equivalent column lengths to determine column service loads to be used in programs YIELD and PILE. The superstructure may be designed using these listings.

5. Design the TOP of column reinforcement for all load groups I thru VII using the YIELD program and the equivalent column length.

6. Using the PILE program, determine the maximum service moments in the pile shaft for the components of group loads I thru VII. Detailed soil data from Engineering Geology is required for use of the PILE program.

7.-8. Using the YIELD program, determine the amount of vertical reinforcement required to resist the maximum moment in the pile shaft. The plastic moment capacity of the column and shaft is also determined at this time.

9. Using the PILE program, analyze the pile shaft for the plastic condition. The plastic moment, the associated axial load, and the assumed plastic shear are applied at the top of the column. The program is then run interactively by incrementing the shear until a plastic hinge forms in the pile shaft.

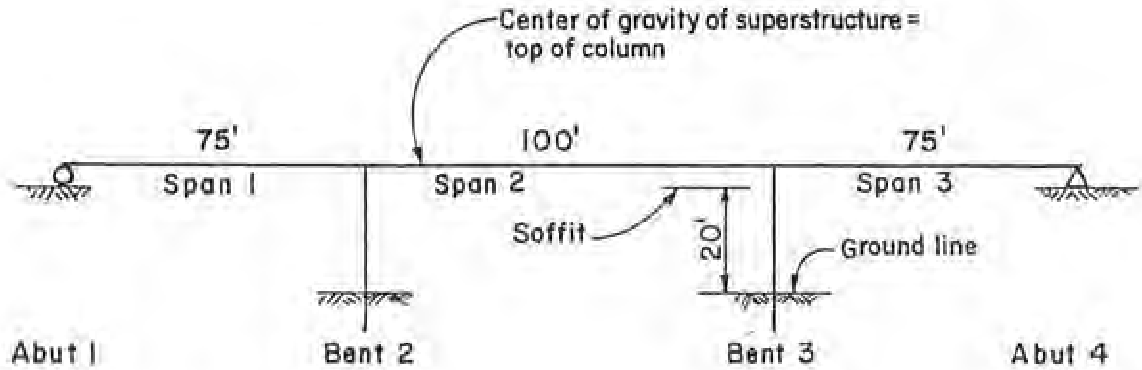
   The shear reinforcement is then designed for the lesser of the shears resulting from seismic plastic hinging or group loads I to VI and ARS unreduced seismic group load VII.

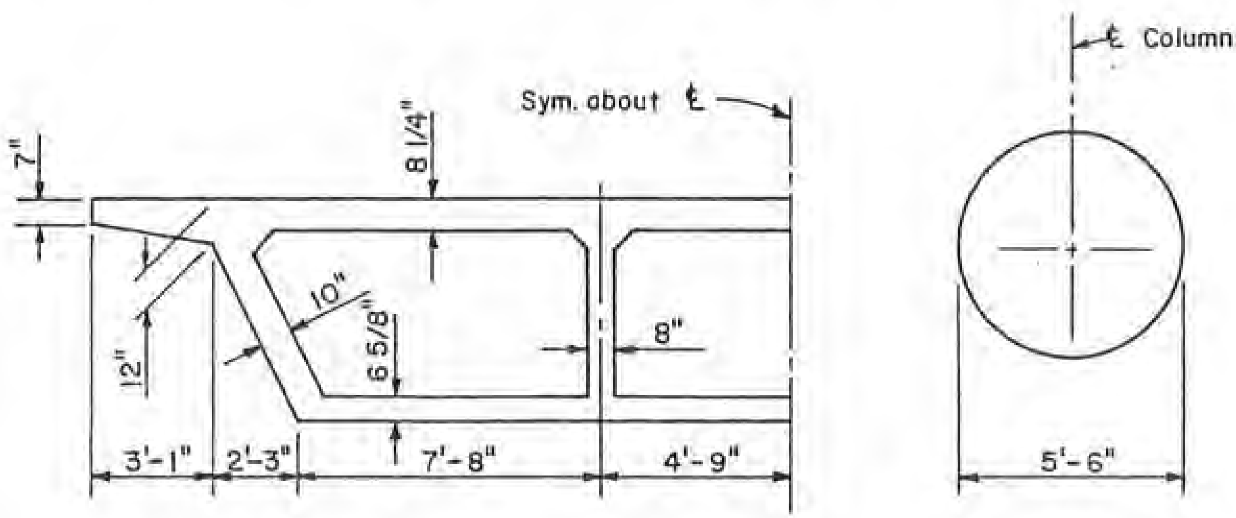
10. Perform a final check of the overall stability of the pile shaft using the PILE program.

Knowledge on the use of the PILE and YIELD programs in addition to BDS, BENT and STRUDL are required for successful application of this procedure.

PILE SHAFT DESIGN EXAMPLE PROBLEM

(Reference: Bridge Design Practice Manual 2-3)





COLUMN/SHAFT DATA:

Dia = 5.5 Ft   A = 23.8 Ft   I = 44.9 Ft   F'c = 3250 Psi

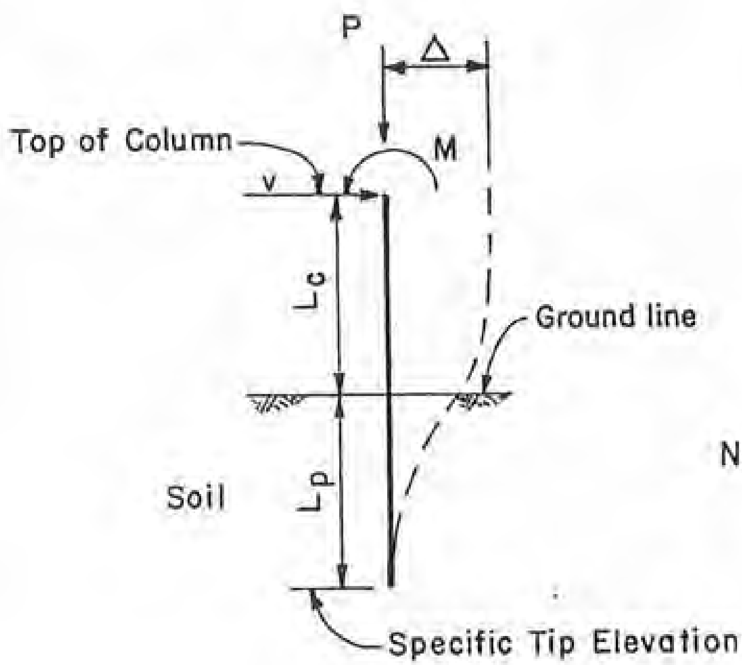
Lc = 20 Ft   Lp = 60 Ft   Ec = 468000 Ksf

SOIL DATA: Sand Above The Water Table

Layer	Class	Unit Wt (Kcf)	Thickness (Ft)	Blow Count (Blows/Ft)	Friction Angle (Degrees)
1	Loose	.13	10	10	28
2	Dense	.14	50	45	40

Peak Rock acceleration = 0.3 G   Depth of Alluvium = 70 Ft

1. Determine an equivalent column length. The equivalent length (Le) of a column/pile shaft member is defined as that length of column (Lc) plus pile shaft (Lp) which when fixed at the bottom will produce the same deflections at the top of the column for a given load as the actual column plus shaft surrounded by soil. The equivalent column has the same EI as the actual column. The analysis of the bridge supported by columns in the soil can be carried out if the columns of the bridge are adjusted to the equivalent length, thus eliminating the soil from the problem.



SIMPLIFIED METHOD

Often detailed soil information lags the bridge preliminary report and it is desired to proceed with the design. Therefore, a 'Simplified Method' may be used to determine the equivalent length. The designer must obtain the soils general classification (sand or clay) and the standard penetration index (N) or an estimate of the soils relative density (loose, compact, dense etc.).

Assume the top of the column is at the C.G. of the superstructure, (3 feet above the soffit).

Lc = 20' + 3' = 23'

The charts are based on a single layer of soil. For this example, assume a single layer of dense sand 55 feet thick and neglect the first 5 feet of loose sand.

Lc (Adjusted) = 23' + 5' = 28'

Enter Figure 1. on page 16 with the blow count (N=45) and determine the number of pile diameters (No=3) from the ground line to the point of effective fixity.

Le = Lc + (No x Dia) = 28' + (3 x 5.5') = 44.5' (use 45')

There are some sites where the 'Simplified Method' should not be used:

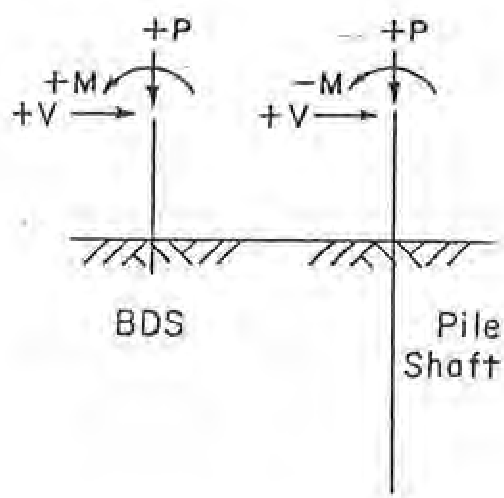
(1) Sites with large variations in soil stiffness with depth.
(2) Sites with soft intermediate layers.

For these cases, use the "Rigorous Method' to determine the equivalent length as described on page 12-45.

2. Run programs BDS and BENT (with or without sidesway) at the service level using the equivalent column length (Le). Determine the necessary service column loads to be used in programs YEILD and PILE at the TOP of the column. The shears at the top of the column are obtained by summing moments about the bottom of the column and dividing by the equivalent length. The moments at the bottom of the column are used only to obtain the shear forces and in no case are to be used to design the shaft.

<u>BENT OUTPUT - TOP of Column Loads: (Service)</u>

		:---- LL + IMPACT ----:		
		1	2	3
	DEAD LOAD	TRANS MY-MAX	LONG MX-MAX	AXIAL N-MAX
MY	0	1367	65	117
MX	-225	-80	-672	-108
N	1122	226	170	305
PMY		3944	2368	3944
PMX		-175	-933	-175
PN		459	276	459



BENT OUTPUT - Bottom of Column Loads: (Service)

	DEAD LOAD	LL + IMPACT 1 TRANS MY-MAX	2 LONG MX-MAX	3 AXIAL N-MAX
MY	0	1367	65	117
MX	112	40	337	54
N	1277	226	170	305
PMY		3944	2358	3944
PMX		88	468	88
PN		459	276	459

Calculated Top of Column Shear Forces: (Service)

	DEAD LOAD	LL + IMPACT 1 TRANS MY-MAX	2 LONG MX-MAX	3 AXIAL N-MAX
VX	0	0	0	0
VY	-7.5	-2.7	-22.4	-3.6
PVX	-	0	-	0
PVY	-	-5.8	-31.1	-5.8

Example calculation:

The shear is equal to the sum of the moments about the bottom of the column divided by the column length (Le):

(933 ft-k + 468 ft-k) / 45 = 31.1

3. Run STRUDL (or SEISAB) using the equivalent column length and obtain the unreduced elastic ARS seismic loads at the top of the column. The loads are RMS values and thus do not have a sign.

STRUDL OUTPUT - TOP of Column Loads: (Unreduced ARS)

	CASE I	CASE II
MY	3667	1100
MZ	5543	18475
N	41	138
VZ	193	58
VY	252	841

4. Determine Wind, WL, LF, CF, and T loads at the top of the column using STRUDL or hand procedures. Use the equivalent column length in these analyses. The loads at the bottom of the columns produced in the STRUDL analysis are fictitious and in no case are to be used to design the shaft.

STRUDL OUTPUT - TOP of Column Loads: (Service)

	Wind	WL	LF	CF-MY	TEMP
MY	175	14	0	0	0
MZ	289	107	86	0	420
N	2	1	1	0	1
VZ	10	2	0	0	0
VY	13	5	4	0	22

5. Using the YIELD program, design the top of the column for group loads I thru VII (moments and axial loads). Use the equivalent length as the column length and appropriate fixities. This will allow the correct moment magnification factors to be calculated.

YIELD INPUT - Top of Column Service Loads (Groups I - VII):

		:---- LL + IMPACT ----:							
		1	2	3					
	DEAD LOAD	TRANS MY-MAX	LONG MX-MAX	AXIAL N-MAX	WIND	WL	LF	CF	TEMP
MY	0	1367	65	117	175	14	0	0	0
MX	225	80	672	108	289	107	86	0	420
N	1122	226	170	305	2	1	1	0	1
PMY		3944	2368	3944					
PMX		175	933	175					
PN		459	276	459					

(ARS) UNREDUCED SEISMIC (Ductility Factor Z = 6)

	CASE 1	CASE 2
MY	3667	1100
MX	5543	18475
N	41	138

YIELD RESULTS:

Column Diameter = 5.5 ft.
Controlling Group Loading = IP Case 1
Percent Steel Required = 1.43
Total Area of Steel Required = 47.2 sq. in.
Number of bars Required = 37.2 @ 1.27 sq. in.

* Use 38 - #10 bars

6. Using the PILE program, apply the components of the group loads I to VII at the top of the column, and determine the corresponding maximum moments below the ground line in the shaft for each component. The moments and lateral loads are the moments and shears obtained from step 2. Case VII loads are reduced before input into program PILE. This is done to avoid excessive deflections which occur beyond the yield point. No axial loads are applied the because program YIELD considers slenderness by applying moment magnification factors. Obtain from the Engineering Geology and Technical Services Branch at Translab the soil classifications, thickness of soil layers, soil densities, pile shaft length (Lp based on maximum vertical loads) and the internal friction angles for a sand or the undrained shear strengths for a clay. Frequently the number of load cases can be reduced by inspection.

PILE INPUT - TOP of Column Component Loads (Groups I - VII):

LONGITUDINAL LOADS (Mx): (Service)

LOAD NO	AXIAL LOAD (k)	LATERAL LOAD (k)	MOMENT (k-ft)	LOAD COMPONENT
1	0.0	-7.5	225.00	DL
2	0.0	-2.7	80.00	IH-1
3	0.0	-22.4	672.00	IH-2
4	0.0	-3.6	108.00	IH-3
5	0.0	-5.8	175.00	IP-1,3
6	0.0	-31.1	933.00	IP-2
7	0.0	-13.0	289.00	W
8	0.0	-5.0	107.00	WL
9	0.0	-4.0	86.00	LF
10	0.0	-21.8	420.00	T
11	0.0	-42.1	924.00	VII-1 (reduced)
12	0.0	-140.2	3080.00	VII-2 (reduced)

LATERAL LOADS (My): (Service)

LOAD NO	AXIAL LOAD (k)	LATERAL LOAD (k)	MOMENT (k-ft)	LOAD COMPONENT
1	0.0	0.0	1367.00	IH-1
2	0.0	0.0	65.00	IH-2
3	0.0	0.0	117.00	IH-3
4	0.0	0.0	3944.00	IP-1,3
5	0.0	0.0	2358.00	IP-2
6	0.0	-10.0	175.00	W
7	0.0	-2.0	14.00	WL
8	0.0	-32.1	612.00	VII-1 (reduced)
9	0.0	-9.6	184.00	VII-2 (reduced)

PILE OUTPUT - Moments in Shaft below ground line:

LONGITUDINAL MOMENTS (Mx): (Service)

LOAD NO	MAX Mx MOMENT (k-ft)	LOAD COMPONENT
1	67	DL
2	15	IH-1
3	134	IH-2
4	22	IH-3
5	36	IP-1,3
6	187	IP-2
7	-161	W
8	-61	WL
9	-48	LF
10	-305	T
11	-490	VII-1 (reduced)
12	-1717	VII-2 (reduced)

LATERAL MOMENTS (My): (Service)

LOAD NO	MAX My MOMENT (k-ft)	LOAD COMPONENT
1	1370	IH-1
2	65	IH-2
3	117	IH-3
4	3940	IP-1,3
5	2370	IP-2
6	-159	W
7	-34	WL
8	-457	VII-1 (reduced)
9	-137	VII-2 (reduced)

7. Using the YIELD program, design the pile shaft below the ground line for group loads I - VII (moments and axial loads). To obtain the unreduced seismic moments for Group VII loads, multiply the reduced seismic moments in the pile shaft below the ground line, from step 6, by the ductility factor (Z). Use the equivalent column length and appropriate end fixities in the input.

YIELD INPUT - Service Loads in Shaft (Groups Loads I - VII):

		:---- LL + IMPACT ----:							
		1	2	3					
	DEAD LOAD	TRANS MY-MAX	LONG MX-MAX	AXIAL N-MAX	WIND	WL	LF	CF	TEMP
MY	0	1370	65	117	159	34	0	0	0
MX	67	15	134	22	161	61	48	0	305
N	1277	226	170	305	2	1	1	0	1
PMY		3940	2370	3940					
PMX		36	187	36					
PN		459	275	459					

UNREDUCED SEISMIC (Ductility Factor Z = 6)

	CASE 1	CASE 2
MY	2742	822
MX	2940	10302
N	41	138

YIELD RESULTS:

Column Diameter	= 5.5 ft.
Controlling Group Loading	= IP Case 1
Percent Steel Required	= 1.25
Total Area of Steel Required	= 42.75 sq. in.
Number of bars Required	= 33.6 @ 1.27 sq. in.

* Use 38 - #10 bars (same as at top of column)

Top of column moments govern the design.

8. Run program YIELD in the check mode and determine the probable plastic moment and plastic shear at the top and bottom of the column. Assume the length of column is equal to the equivalent column length.

   Note: The plastic moment capacity of the shaft may be different than the plastic moment capacity of the top of the column (ie. different diameter, percent steel, or axial load).

<u>YIELD OUTPUT - Plastic Moment Capacity of Column/Pile Shaft</u>

Pp(top) = 1122 K
Mp(top) = 9699 K-Ft
Vp(top) = 436 K

Pp(bot) = 1277 K
Mp(bot) = 9921 K-Ft

9. Using program PILE, apply at the top of the column the associated probable plastic moment (Mp) and axial load (Pp) while incrementing the plastic shear until a second plastic hinge forms in the pile shaft.

a. If the plastic shear (Vp) is less than the unreduced elastic ARS (seismic) + dead load shear, design the shear reinforcement for the plastic shear (Vp).

c. If the plastic shear (Vp) is greater than the unreduced elastic ARS (seismic) + dead load shear, design the shear reinforcement for group loads I to VI and unreduced elastic group loads VII.

PILE INPUT/OUTPUT:

LOAD NO	TOP AXIAL P (k)	TOP SHEAR V (k)	TOP MOMENT M (k-ft)	MAX. M IN SHAFT (k-ft)	LOCATION FROM TOP (ft)
1	1122	-450	9699	5600	37
2	1122	-500	9699	7310	37
3	1122	-550	9699	8950	37
4	1122	-560	9699	9280	37
5	1122	-570	9699	9610	37
* 6	1122	-580	9699	9940	37
7	1122	-590	9699	10300	37
8	1122	-600	9699	10600	37

* The plastic hinge forms in the shaft.

Vp (580 K) < Vars (849 K)

Design the shear reinforcement for the plastic shear.

From YIELD in the CHECK mode:

Use #5 bars at max. pitch = 3 5/8 in.

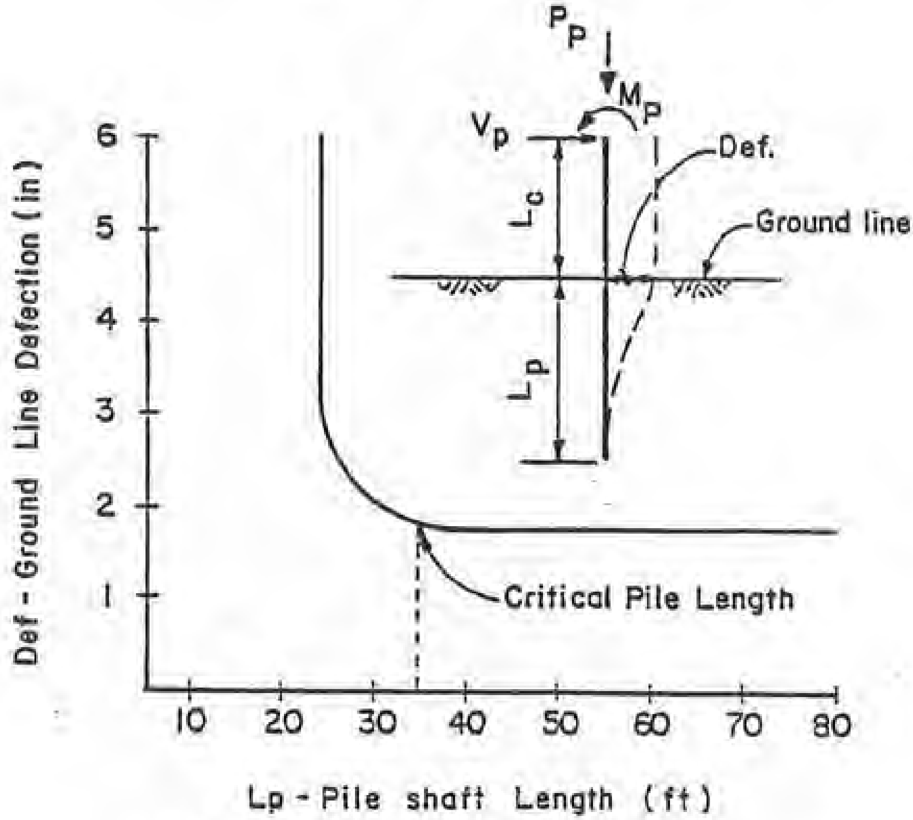
Shear Capacity of #5 bars = Vu (731 K) > Vp (580 K) OK

Note: The Pastic Hinge occured at 37 feet from the top of the column. The YIELD program calculated the plastic moment capacity of the shaft at 45 feet from the top of the column. In this example the decrease in plastic moment capacity due to a lower axial load at 37 feet as opposed to 45 feet is small and is ignored.

10. The pile shaft is considered stable when a substantial decrease in pile shaft length does not result in excessive deflection. The amount of reserve shaft length is an indication of the factor of safety against overturning. A stability ratio greater than 1.0 is mandatory. A good rule of thumb is; the greater the uncertainty of the soil, then the greater the stability ratio. A stability ratio below 1.5 is not recommended without reliable soil data.

P = 1122 K V = -580 K Mp = 9699 K-Ft

Column Length (Lc) = 23'



CRITICAL PILE LENGTH = 35 feet

STABILITY RATIO = 60/35 = 1.7

Pile Shaft Length (Lp) vs. Deflection (Def)
Graph 1.

RIGOROUS METHOD

This procedure should be used at the following sites:

(1) Sites with large variations in soil stiffness with depth.
(2) Sites with soft intermediate layers.

1. Obtain detailed soil information from Engineering Geology at Translab.

   SOIL DATA:

   Sand Above The Water Table

Layer	Class	Unit Wt (Kcf)	Thickness (Ft)	Friction Angle (Phi) (Degrees)
1	Loose	.13	10	28
2	Dense	.14	50	40

2. Apply approximate service level loads to the top of the column using the program PILE. Apply the shear and the moment as separate load cases to isolate them and their results. Note both the deflections and the rotations at the top of the column.

   PILE INPUT/OUTPUT:

LOAD NO	APPLIED SHEAR V (k)	APPLIED MOMENT M (k-ft)	DEFLECTIONS (in)	ROTATIONS (rad)
1	100		1.5353	0.00439
2		500	0.2635	0.00102

3. Solve for the equivalent length using the following equations. These four equations should result in approximately equal lengths. Average the results to determine the equivalent length.

$$L(Dv) = \left| \frac{3DvEI}{V} \right|^{1/3} \qquad L(Rv) = \left| \frac{2RvEI}{V} \right|^{1/2}$$

$$L(Dm) = \left| \frac{2DmEI}{M} \right|^{1/2} \qquad L(Rm) = \left| \frac{RmEI}{M} \right|$$

Dv = Top of column deflection due to applied shear (V).
Dm = Top of column deflection due to applied moment (M).
Rv = Top of column rotation due to applied shear (V).
Rm = Top of column rotation due to applied moment (M).

$$L(Dv) = \left| \frac{3*(1.5353/12)*468000*44.9}{100} \right|^{1/3} = 43.2 \text{ ft}$$

$$L(Rv) = \left| \frac{2*(0.00439)*468000*44.9}{100} \right|^{1/2} = 43.0 \text{ ft}$$

$$L(Dm) = \left| \frac{2*(0.2635/12)*468000*44.9}{500} \right|^{1/2} = 43.0 \text{ ft}$$

$$L(Rm) = \left| \frac{(0.00102)*468000*44.9}{500} \right| = 42.9 \text{ ft}$$

Le = (43.2 + 43.0 + 43.0 + 42.9) / 4 = 43.0 Ft

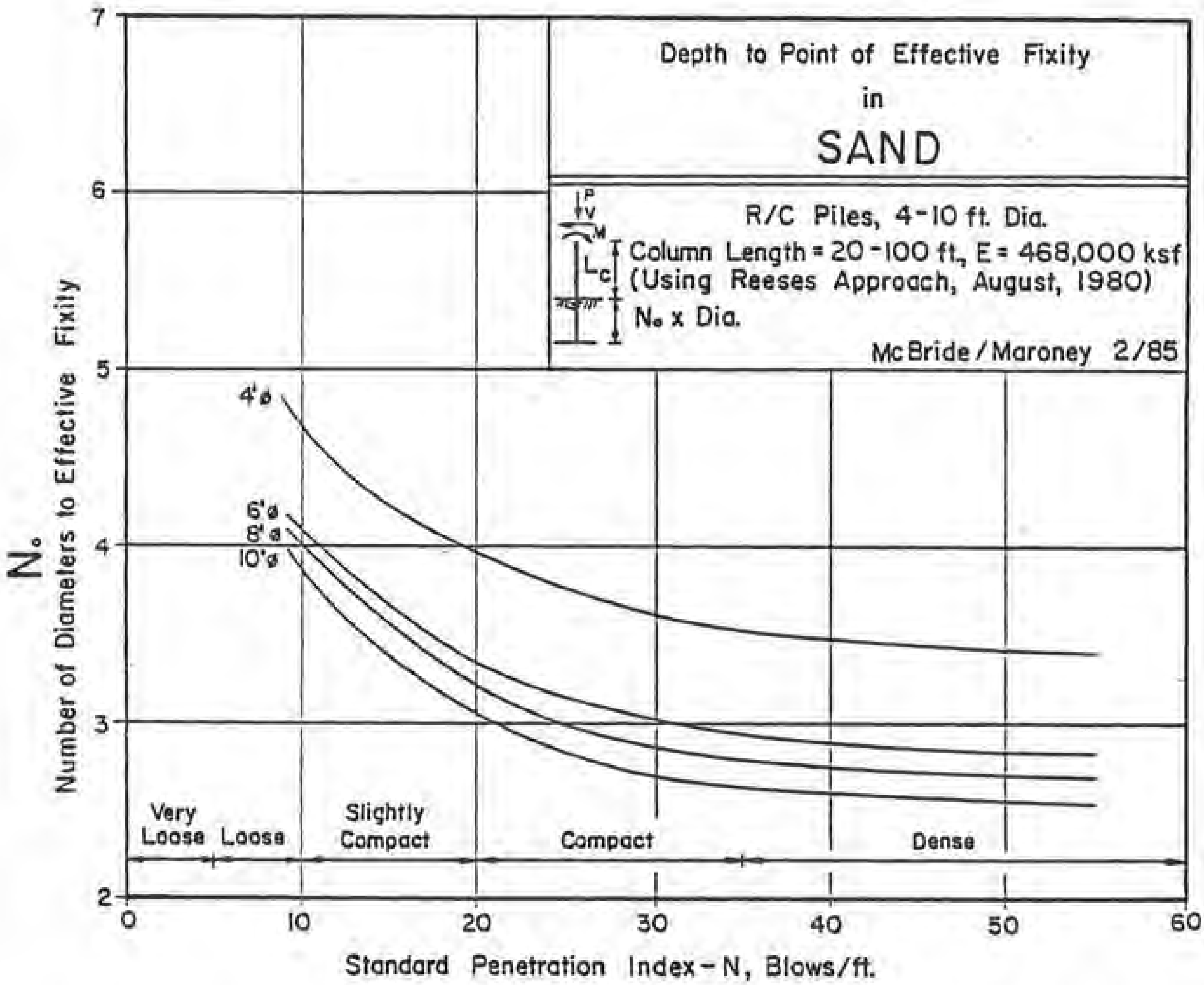
Note: 'Simplified' procedure gave an Le = 45.0 Ft.

Two observations should be noted with this example.

(1) Equivalent column lengths are used to design the superstructure and substructure. It is conservative to assume a longer equivalent column length for the design of the superstructure. However, this will produce unconservative top of column loads.

(2) A more accurate equivalent column length is produced with the additional effort displayed above, but for normal conditions the additional accuracy is not worth the required additional time and effort.

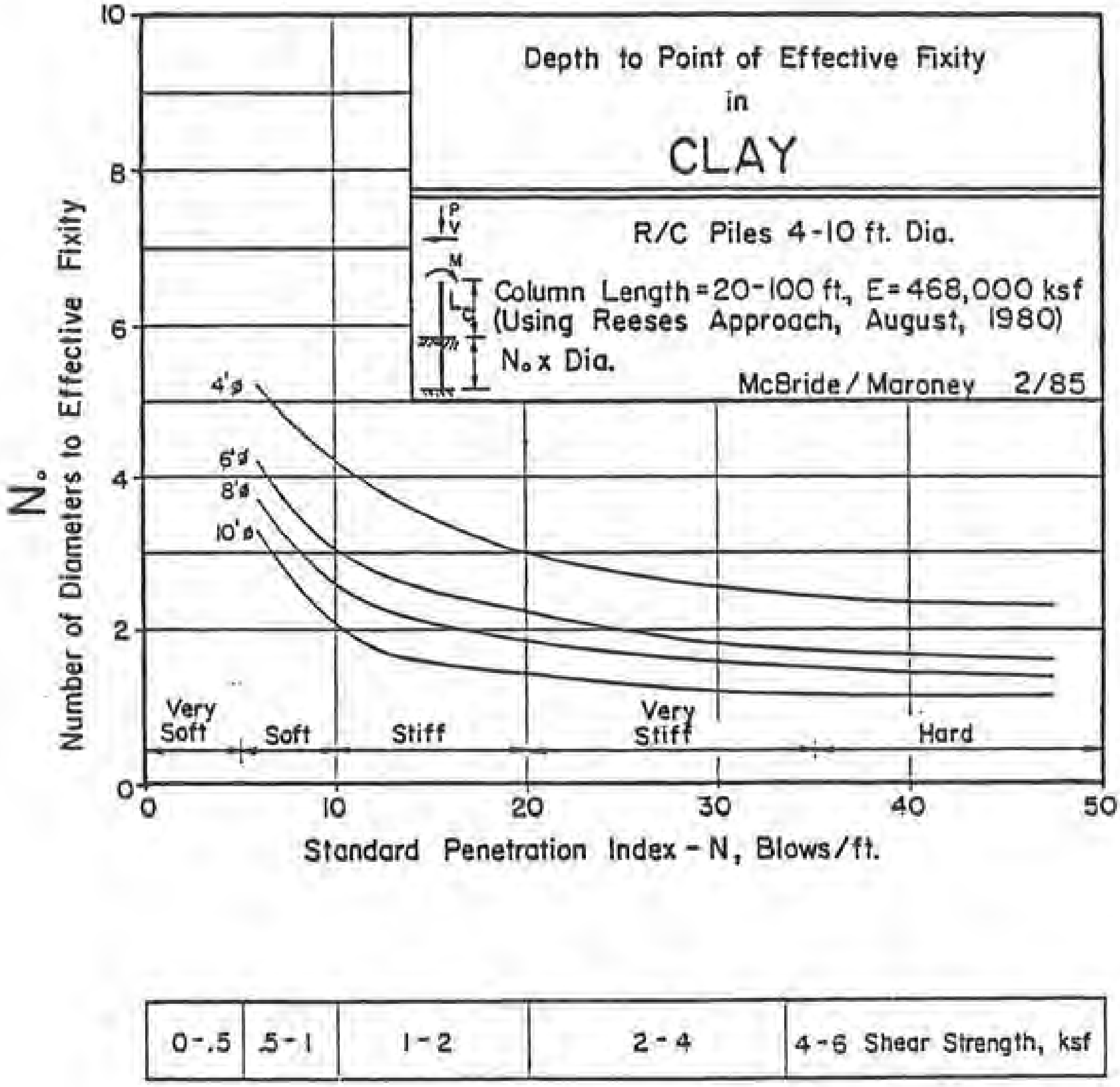
With the equivalent column modeling technique the bridge superstructure design, substructure design and the detailed geotechnical report may be completed simultaneously. Since the pile shaft design is dependent on the detailed soil information, the initial assumptions should be compared to the soil information included in the final geotechnical report.



0-28	28-30	30-36	36-41	Approximate ø in degrees

Depth to Point of Effective Fixity in Sand

Figure 1.



Depth to Point of Effective Fixity in Clay

Figure 2.