PDPI 2015
STATIC ANALYSIS – LATERALLY LOADED PILE DESIGN

Chapter 9

PDCA
PILE DRIVING CONTRACTORS ASSOCIATION

Lateral Capacity of Single Piles

- Potential sources of lateral loads include vehicle acceleration & braking, wind loads, wave loading, debris loading, ice forces, vessel impact, lateral earth pressures, slope movements, and seismic events.
- These loads can be of the same magnitude as axial compression loads.

SOURCES of LATERAL LOADS

- Ship Impact
- Ice
- Debris
- Earthquake
- Traffic Loads

Lateral Capacity of Single Piles

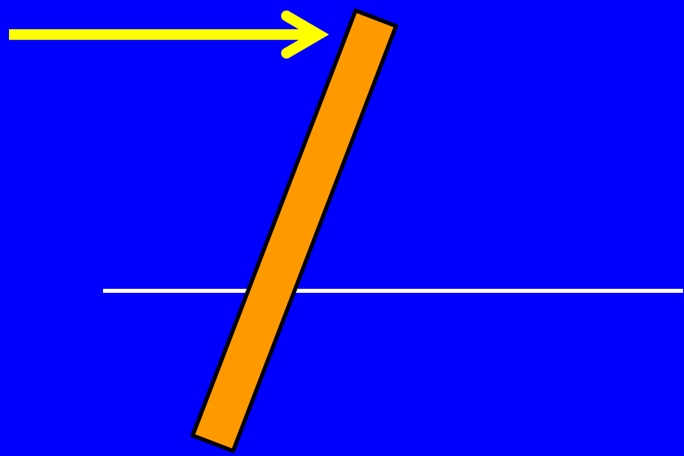
pile, and load parameters significantly affect lateral capacity.

- Soil Parameters
  - Soil type & strength
  - Horizontal subgrade reaction
- Pile Parameters
  - Pile properties
  - Pile head condition
  - Method of installation
  - Group action
- Lateral Load Parameters
  - Static or Dynamic
  - Eccentricity

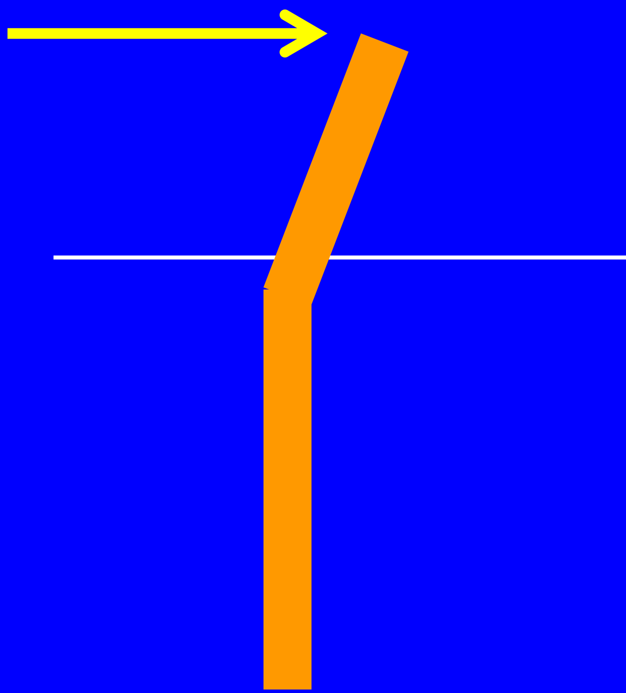
Lateral Capacity of Single Piles

Design Methods

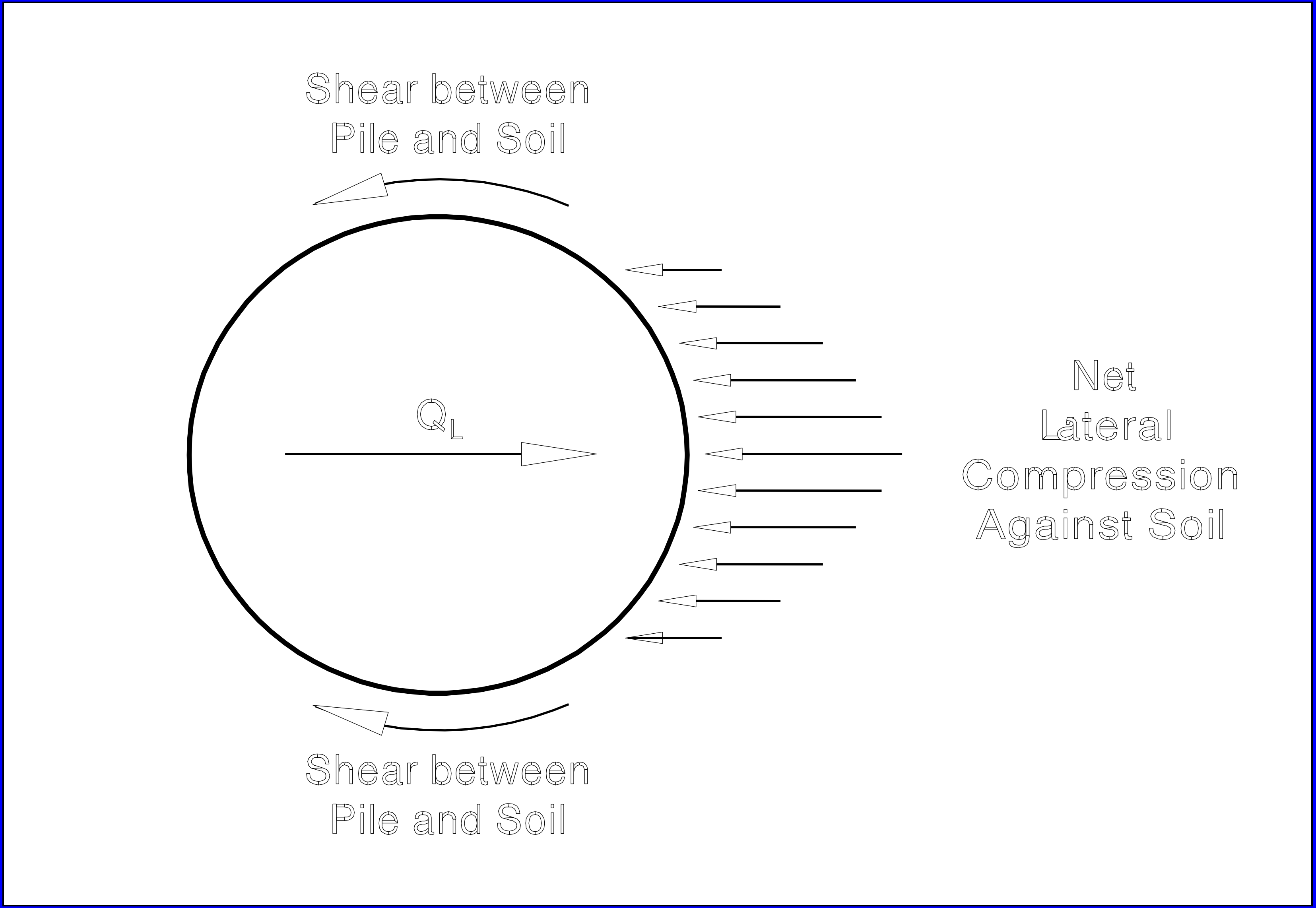
- Lateral load tests
- Analytical methods
  - Broms' method 9-86 (long pile, short pile)
  - Reese's COM624P method
  - LPILE program 9-100



Short pile – soil fails



Long pile – pile fails



Lateral Pile Load (adapted from Smith, 1989)

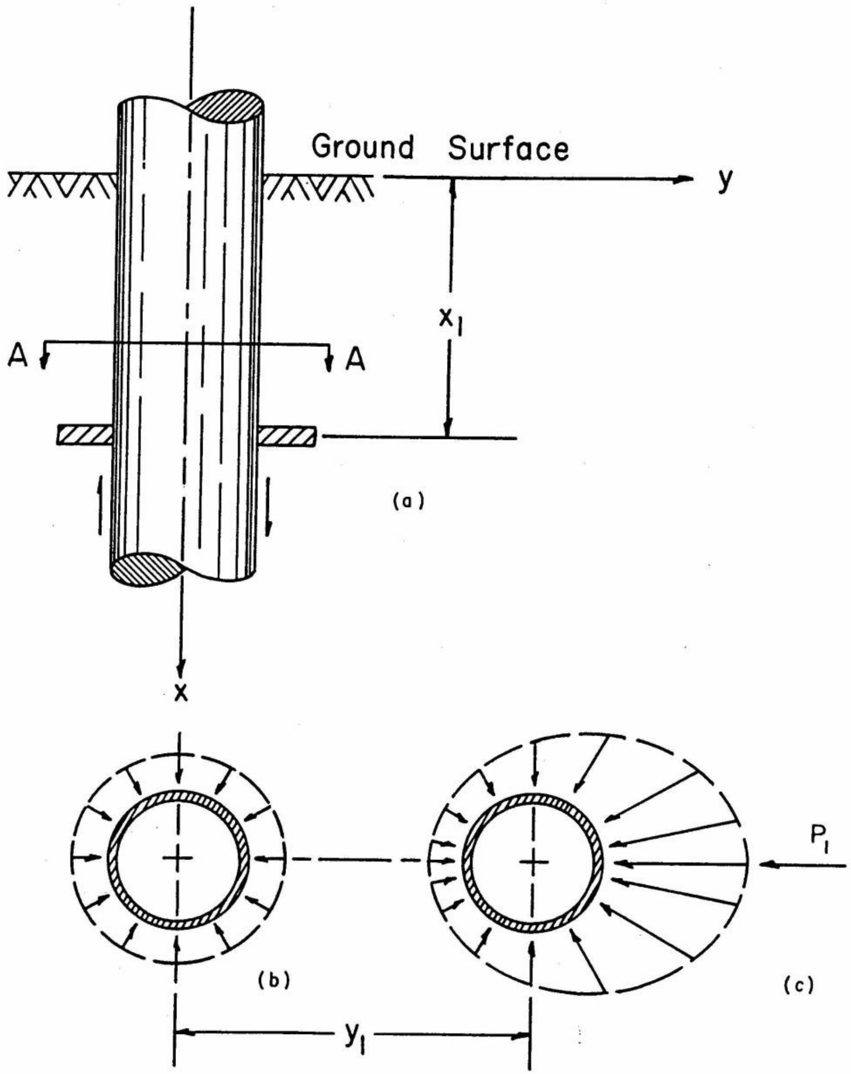
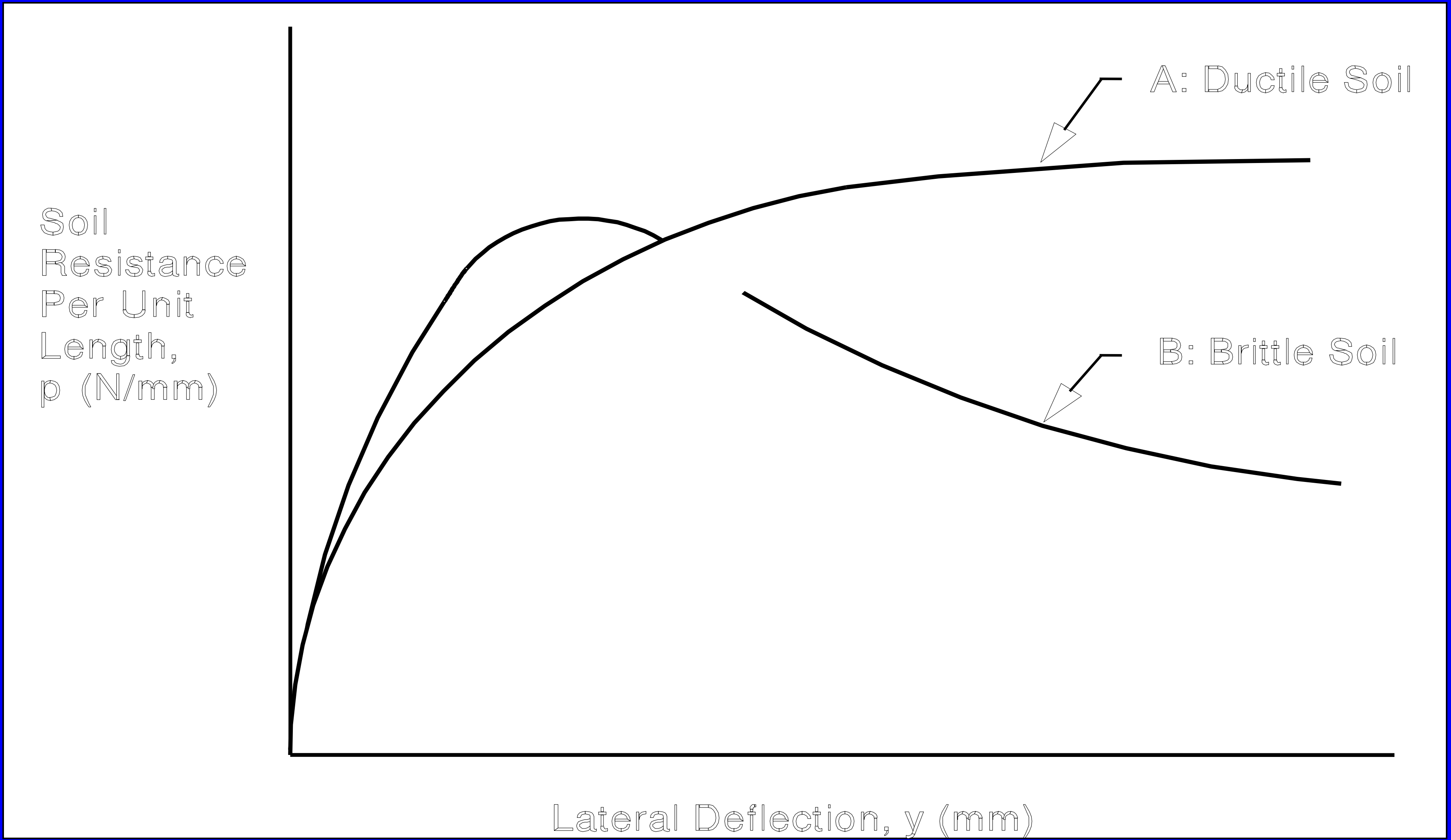
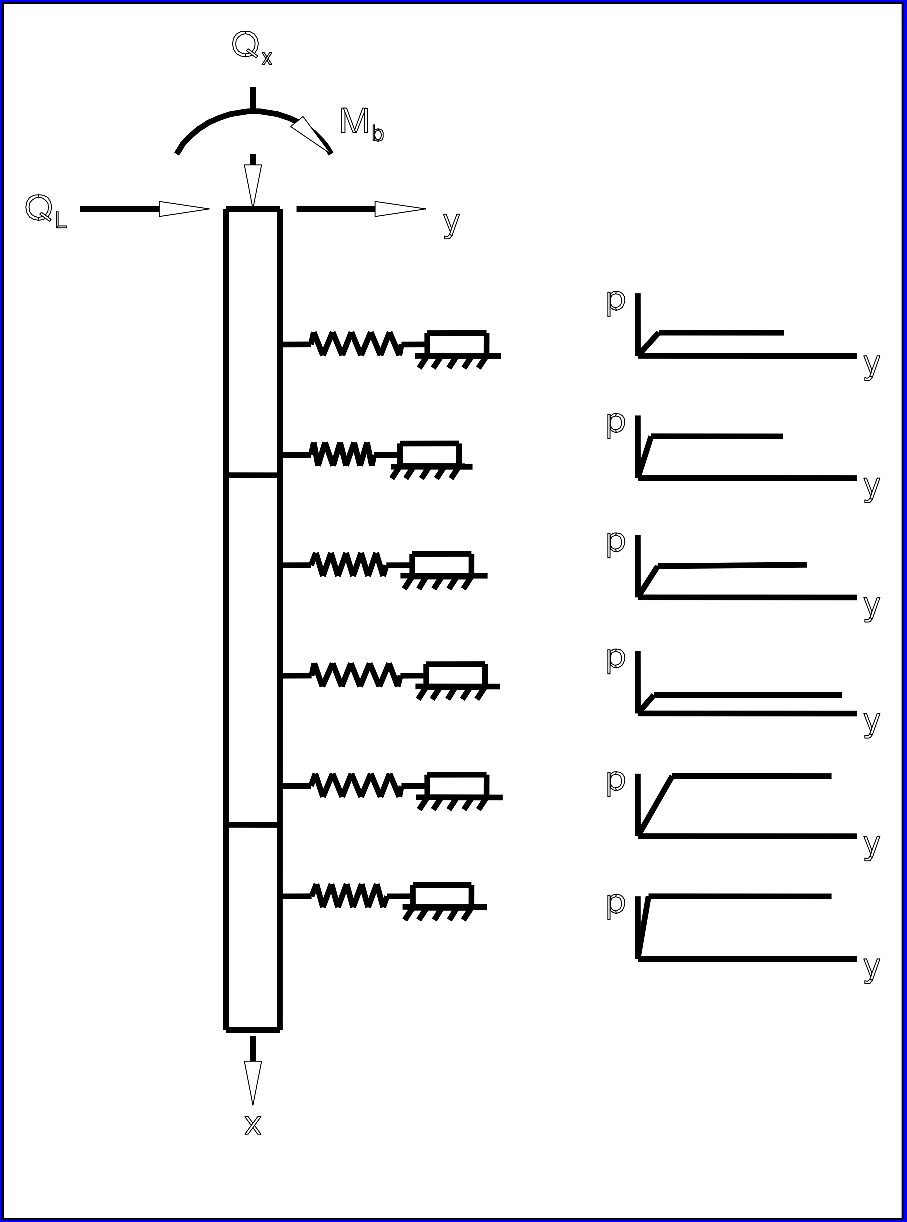


Fig. 3.1. Graphical definition of p and y
(a) view of elevation of section of pile
(b) view A-A - earth pressure distribution prior to lateral loading
(c) view A-A - earth pressure distribution after lateral loading.

NIM

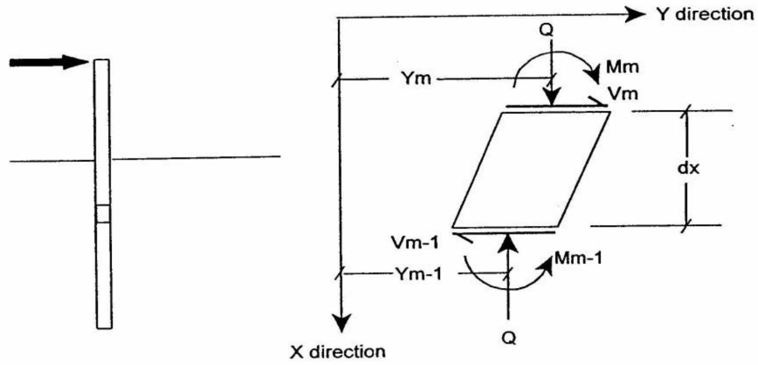


Ductile and Britle Soil (after Coduto, 1994)



9.44 LPILE Pile-Soil Model

Development of general equation for laterally loaded pile



y_m = deflection at top

y_{m+1}= deflection at bottom

M_m = moment at top

M_{m+1}= moment at bottom

p = soil response (force/length)

Q_m = axial load (top and bottom)

x = direction along pile length

y = deflection at some distance, x

Take moments about lower left on x axis:

$$M_{m-1} - M_m + Q(y_{m-1}) - Q(y_m) - V_m(dx) = 0$$

$$M_{m-1} - M_m - Q(y_m - y_{m-1}) - V_m(dx) = 0$$

$$\Delta M + Q(\Delta y) - Vdx = 0$$

$$dM/dx + Q\, dy/dx - V = 0$$

differentiate with respect to x:

$$d^2M/dx^2 + Q\, d^2y/dx^2 - dV/dx = 0$$

recall that dV/dx = p (distributed load)
Recall that M = EI d^2y/dx^2

$$EI\, d^4y/dx4 + Q\, d^2y/dx^2 - p = 0$$

<----- This is the equation that is solved by means of finite differences in most software packages (COM624P, LPILE etc.)

NIM

5.2 RELATIONSHIPS IN DIFFERENCE FORM

Figure 5.1 shows a portion of the elastic curve of a pile. Relationships in difference form are as follows:

$$\left(\frac{dy}{dx}\right)_{x=m} \cong \frac{y_{m-1} - y_{m+1}}{2h} \tag{5.2}$$

$$\left(\frac{d^2y}{dx^2}\right)_{x=m} \cong \frac{\frac{y_{m-1} - y_m}{h} - \frac{y_m - y_{m+1}}{h}}{h} \cong \frac{y_{m-1} - 2y_m + y_{m+1}}{h^2} . \tag{5.3}$$

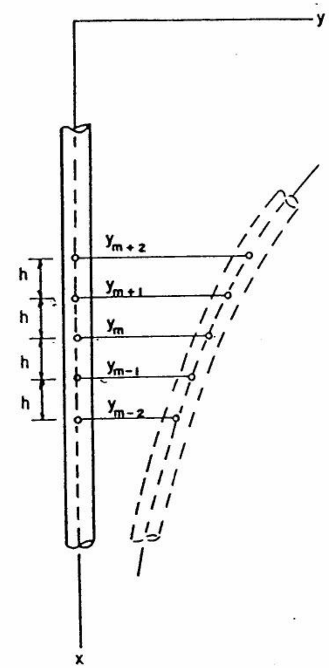


Fig. 5.1. Representation of deflected pile.

In a similar manner

$$\left(\frac{d^3y}{dx^3}\right)_{x=m} \cong \frac{y_{m-2} - 2y_{m-1} + 2y_{m+1} - y_{m+2}}{2h^3} \tag{5.4}$$

$$\left(\frac{d^4y}{dx^4}\right)_{x=m} \cong \frac{y_{m-2} - 4y_{m-1} + 6y_m - 4y_{m+1} + y_{m+2}}{h^4} . \tag{5.5}$$

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We have n equations and (n+4) unknowns

BOUNDARY CONDITIONS *(long pile)*

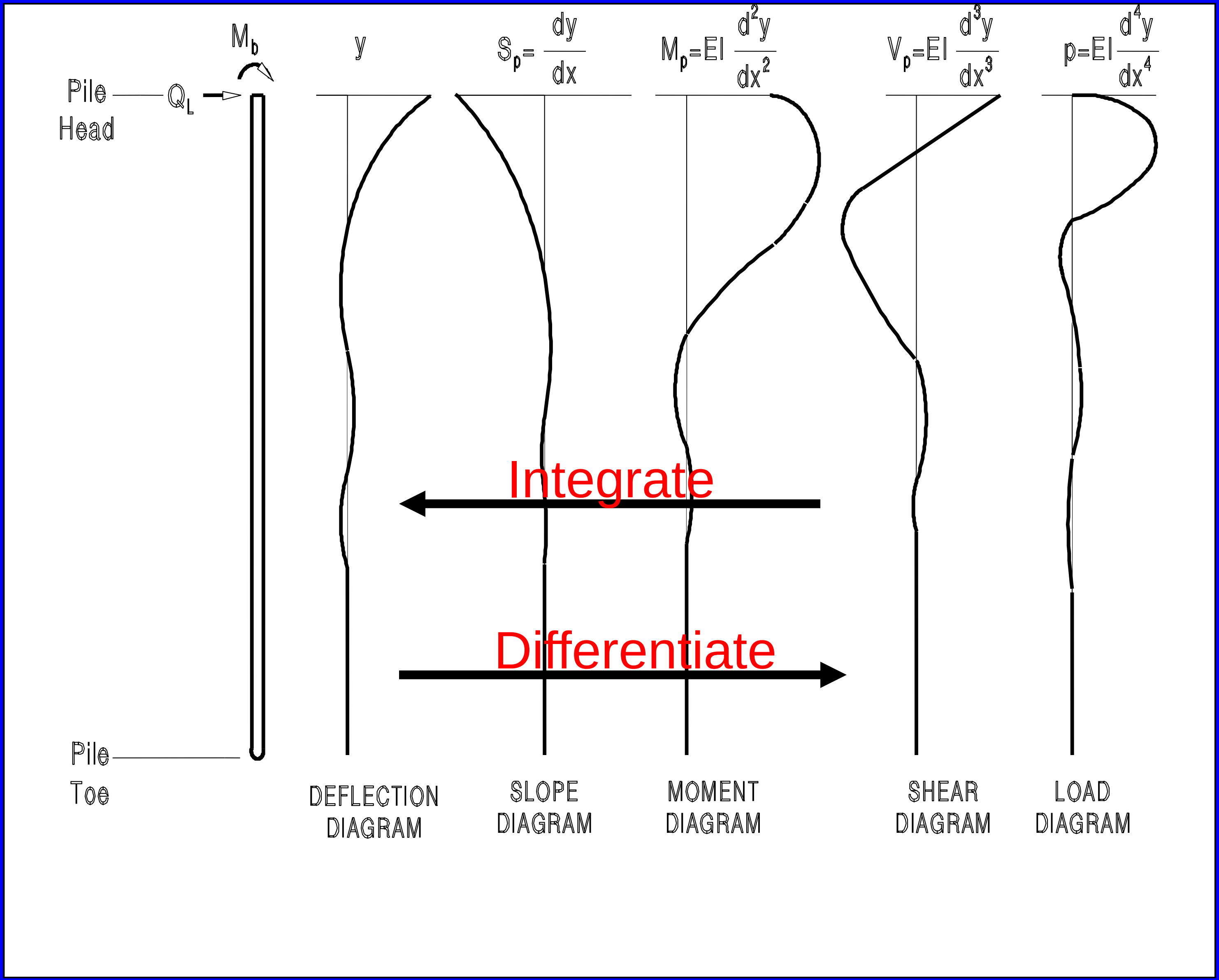
@ Pile Bottom

Moment = 0

Shear = 0

@ Pile Top

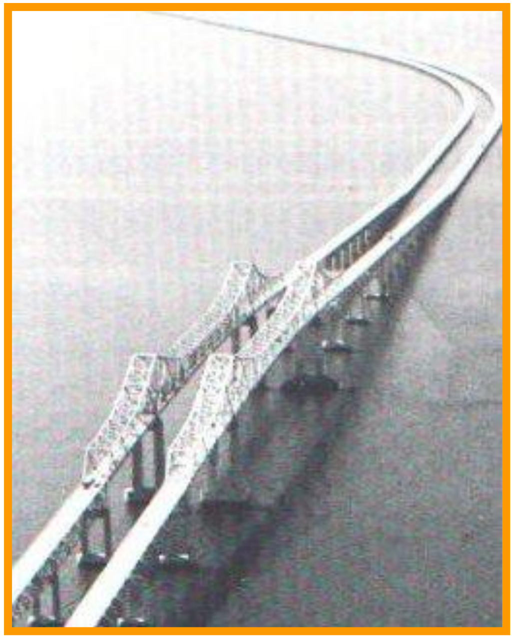
??

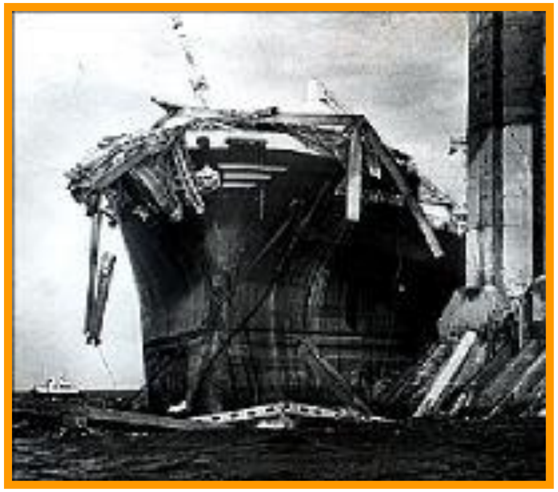


9.46 Graphical Presentation of LPILE Results (Reese, *et al.* 2000)

Lateral Capacity of Pile Groups

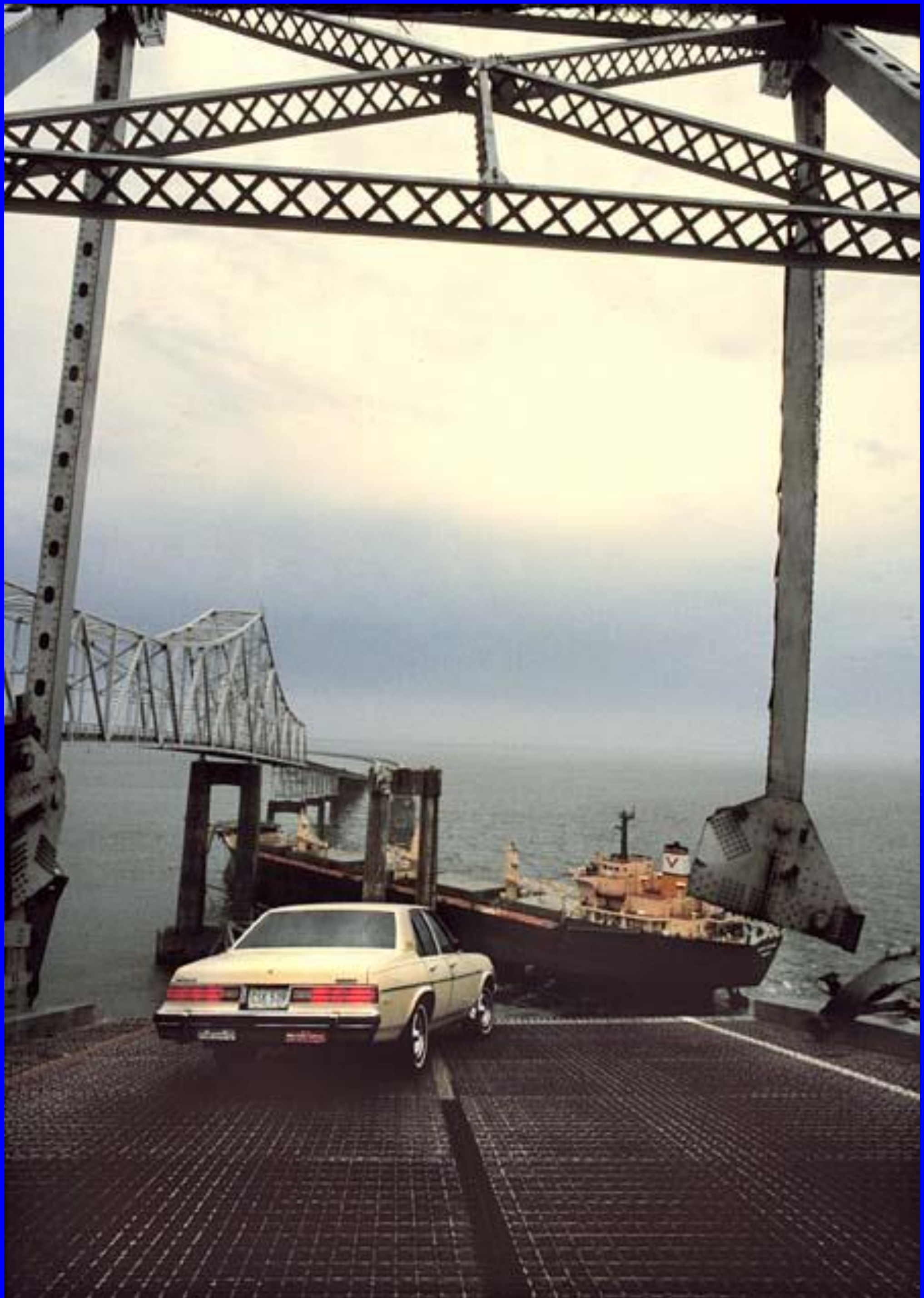
Why Worry?



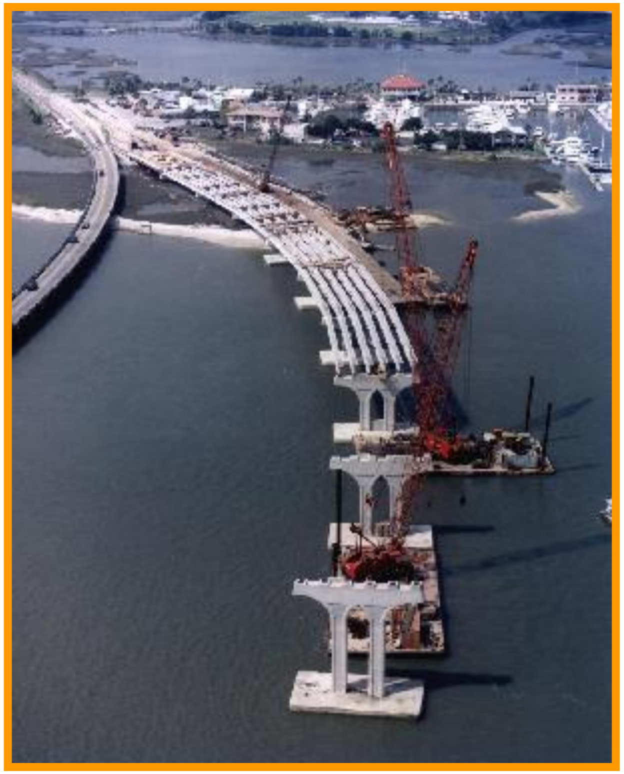


Sunshine Skyway bridge disaster, May 1980

- 35 souls plunged to their deaths
- Including Greyhound bus - 26 deaths
- Summit Venture – 20,000 ton barge riding high in the water
- Winds of 60 mph



Laterally Loaded Deep Foundations



UNIVERSITY OF FLORIDA

GATOR Engineering


New Sunshine Skyway Bridge

LATERAL CAPACITY OF PILE GROUPS

The lateral deflection of a pile group is typically 2 to 3 times larger than the deflection of a single pile.

Piles in trailing rows of pile groups have significantly less lateral load resistance than piles in the lead row.

Laterally loaded pile groups have a group efficiency less than 1.

LATERAL CAPACITY OF PILE GROUPS

The lateral capacity of an individual pile in a group is a function of its position (row) in the group, and the c-t-c pile spacing.

A p-multiplier, is used to modify p-y curve

Laterally loaded pile groups have a group efficiency less than 1.

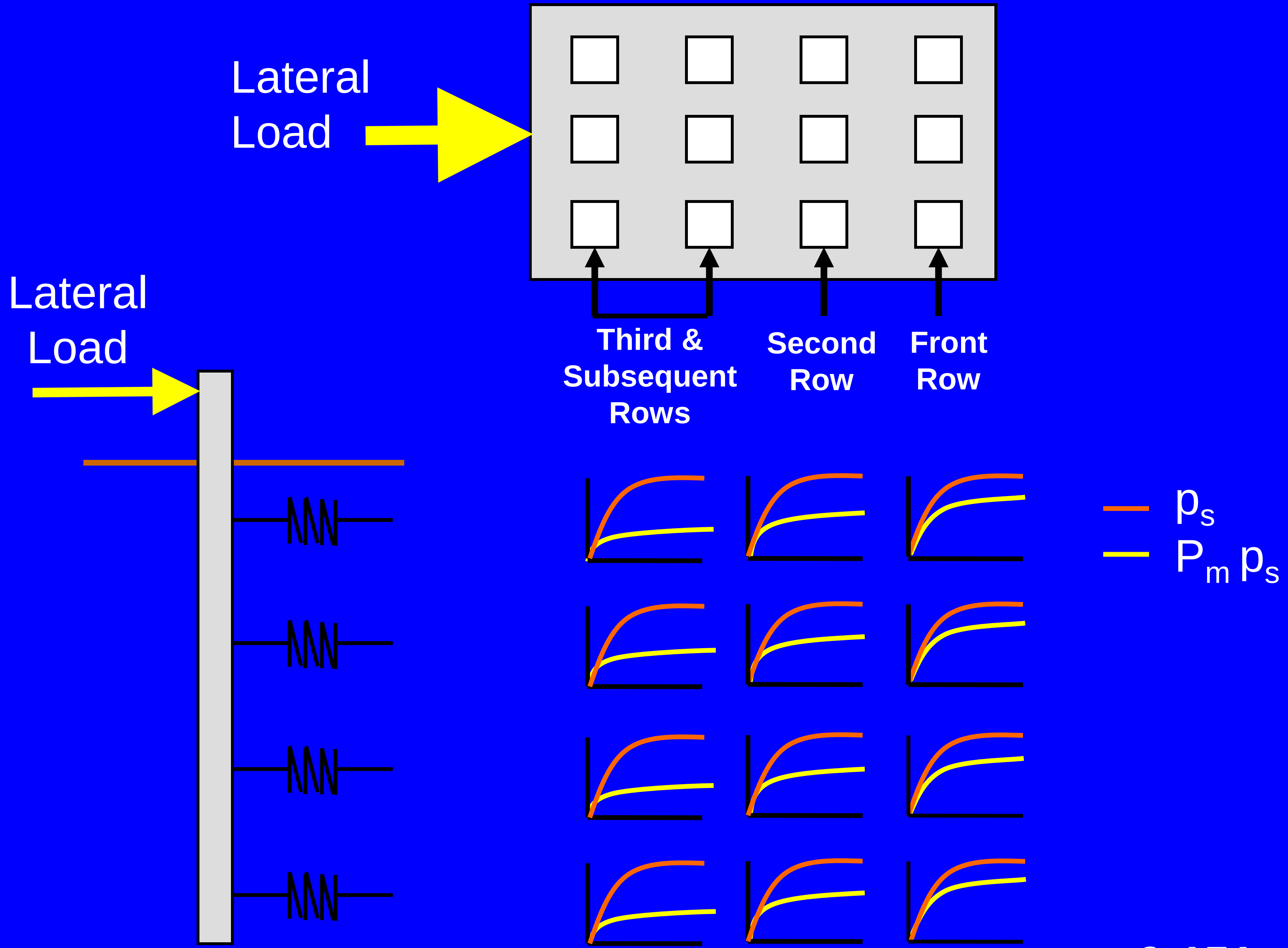
LATERAL CAPACITY OF PILE GROUPS

The lateral capacity of an individual pile in a group is a function of its position (row) in the group, and the c-t-c pile spacing.

A p-multiplier: 0.8, 0.4, & 0.3 (thereafter)

TABLE 9-19 LATERALLY LOADED PILE GROUPS STUDIES

Soil Type	Test Type	Center to Center Pile Spacing	Calculated p-Multipliers, P_m For Rows 1, 2, & 3+	Deflection in mm (in)	Reference
Stiff Clay	Field Study	3b	.70, .50, .40	51 (2)	Brown *et al*, (1987)
Stiff Clay	Field Study	3b	.70, .60, .50,	30 (1.2)	Brown *et al*, (1987)
Medium Clay	Scale Model-Cyclic Load	3b	.60, .45, .40	600 at 50 cycles (2.4)	Moss (1997)
Clayey Silt	Field Study	3b	.60, .40, .40	25-60 (1.0 - 2.4)	Rollins *et al*, (1998)
V. Dense Sand	Field Study	3b	.80, .40, .30	25 (1)	Brown *et al*, (1988)
M. Dense Sand	Centrifuge Model	3b	.80, .40, .30	76 (3)	McVay *et al*, (1995)
M. Dense Sand	Centrifuge Model	5b	1.0, .85, .70	76 (3)	McVay *et al*, (1995)
Loose M. Sand	Centrifuge Model	3b	.65, .45, .35	76 (3)	McVay *et al*, (1995)
Loose M. Sand	Centrifuge Model	5b	1.0, .85, .70	76 (3)	McVay *et al*, (1995)
Loose F. Sand	Field Study	3b	.80, .70, .30	25-75 (1-3)	Ruesta *et al*, (1997)

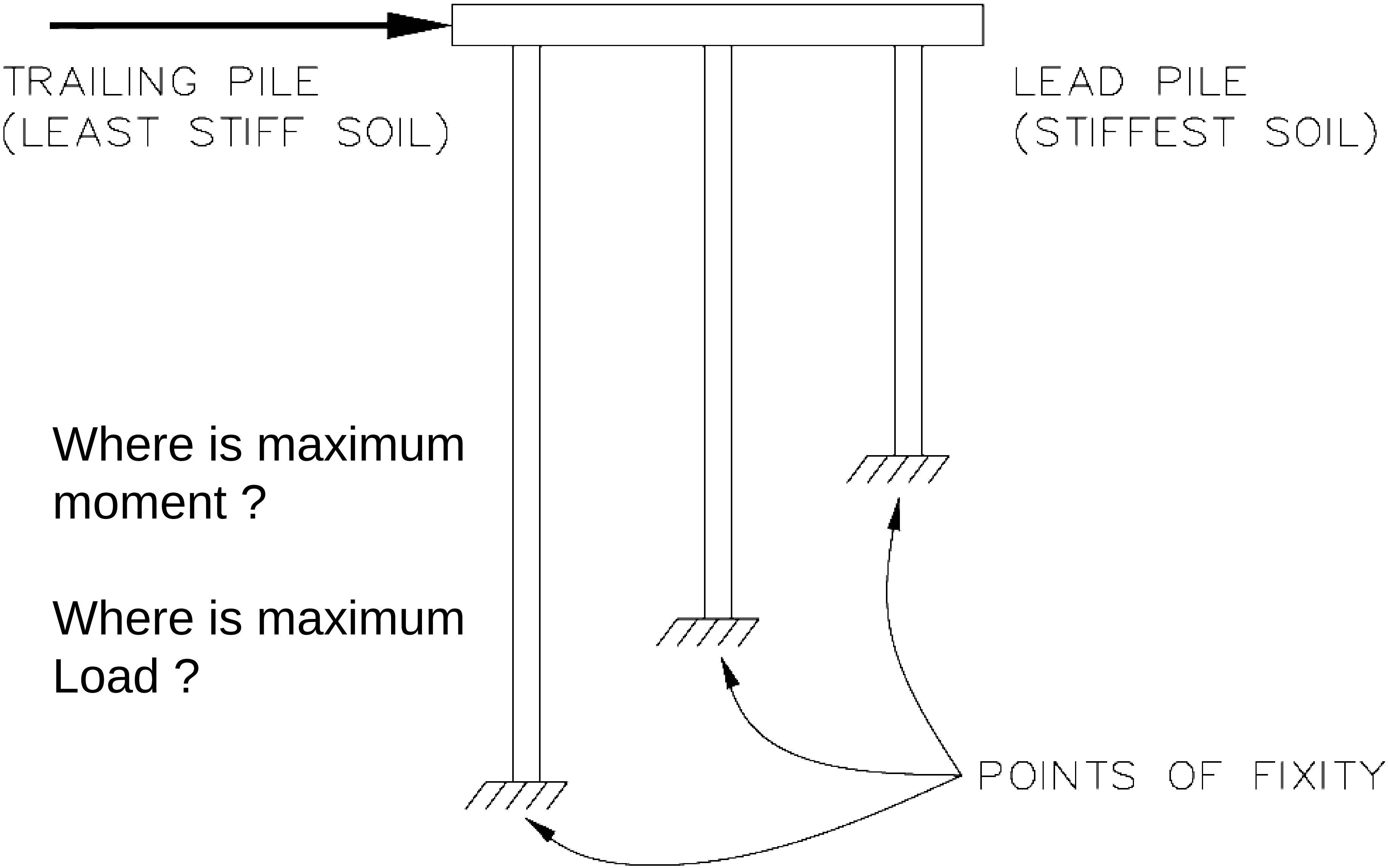


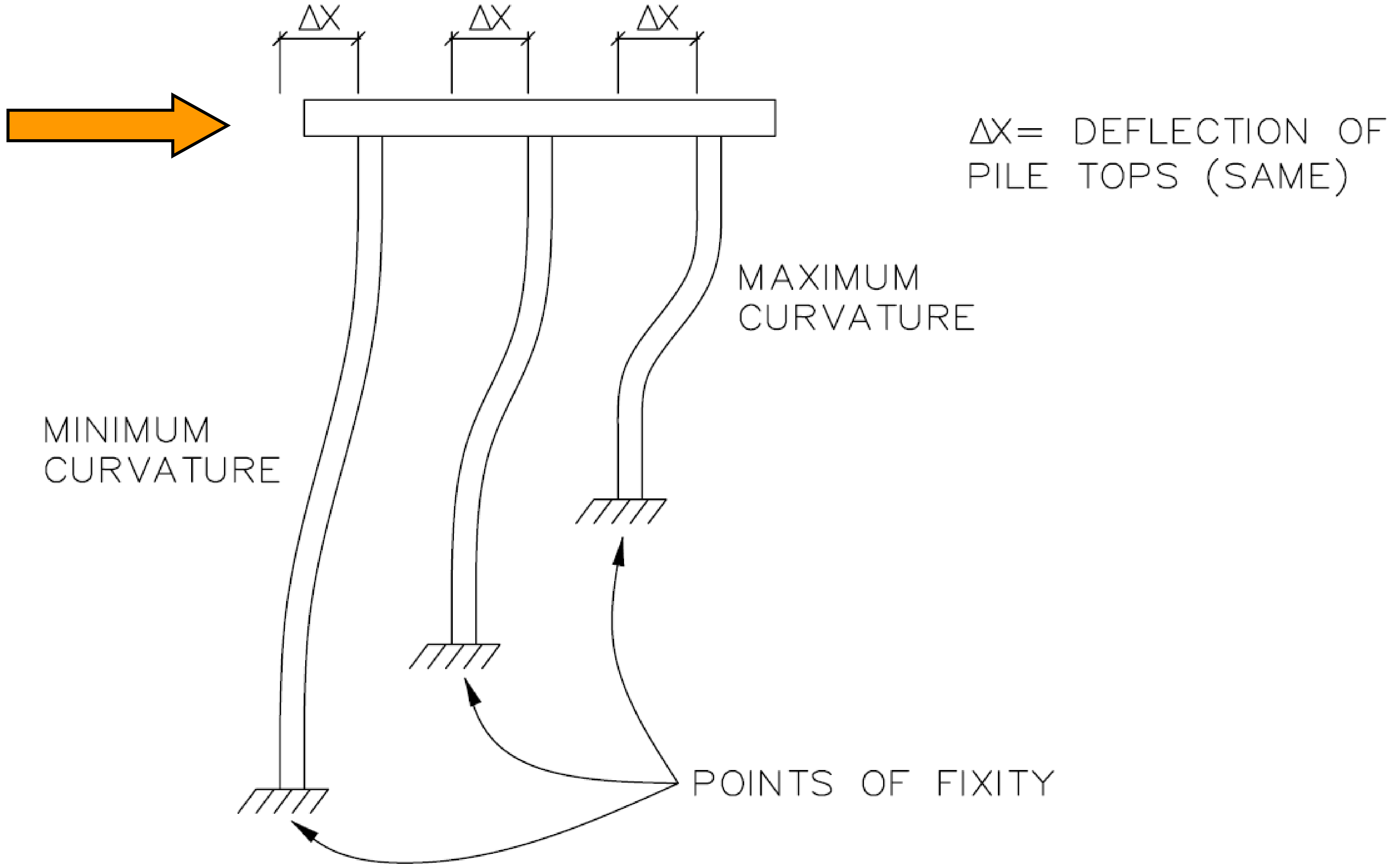
Single Pile Model

p-y Curves for Group

Where is maximum moment ?

Where is maximum Load ?




ΔX
ΔX
ΔX
ΔX= DEFLECTION OF PILE TOPS (SAME)
MAXIMUM CURVATURE
MINIMUM CURVATURE
POINTS OF FIXITY

STEP BY STEP DESIGN PROCEDURE FOR LATERALLY LOADED PILE GROUPS

STEP 1 : Obtain Lateral Loads.

STEP 2 : Develop p-y curves for single pile.

a. Obtain site specific single pile p-y curves from instrumented lateral pile load test at site.

b. Use p-y curves based on published correlations with soil properties.

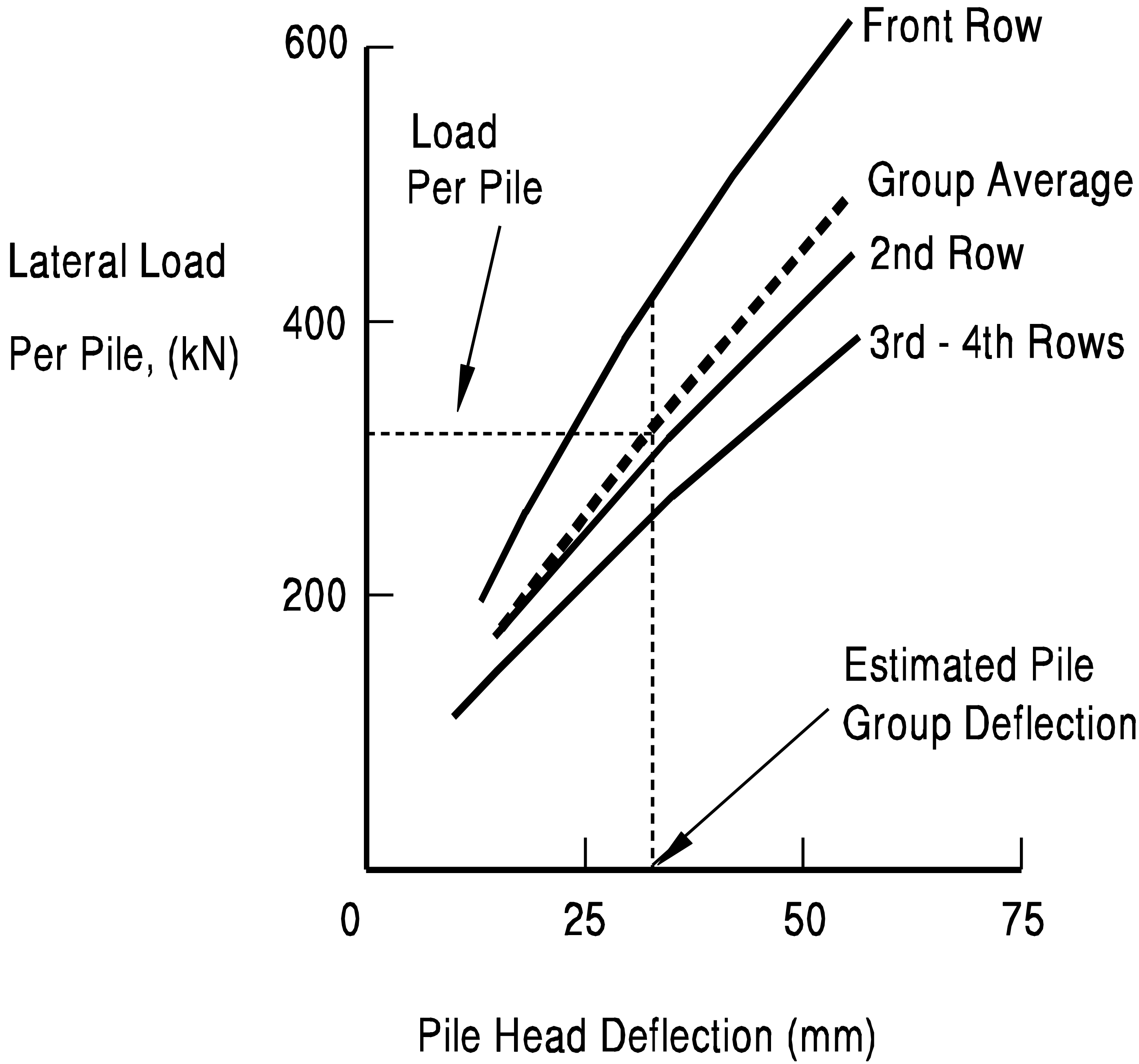
c. Develop site specific p-y curves based on in-situ test data.

STEP 3 : Perform LPILE Analyses.

a. Perform LPILE analyses using the P_m value for each row position to develop load-deflection and load-moment data.

b. Based on current data, it is suggested that P_m values of 0.8 be used for the lead row, 0.4 for the second row, and 0.3 for the third and subsequent rows. These recommendations are considered reasonable for center to center pile spacing of 3b and pile deflections at the ground surface of .10 to .15b. For larger c-t-c spacings or smaller deflections, these Pm values should be conservative.

c. Determine shear load versus deflection behavior for piles in each row. Plot load versus pile head deflection results similar to as shown in Figure 9.69(a).

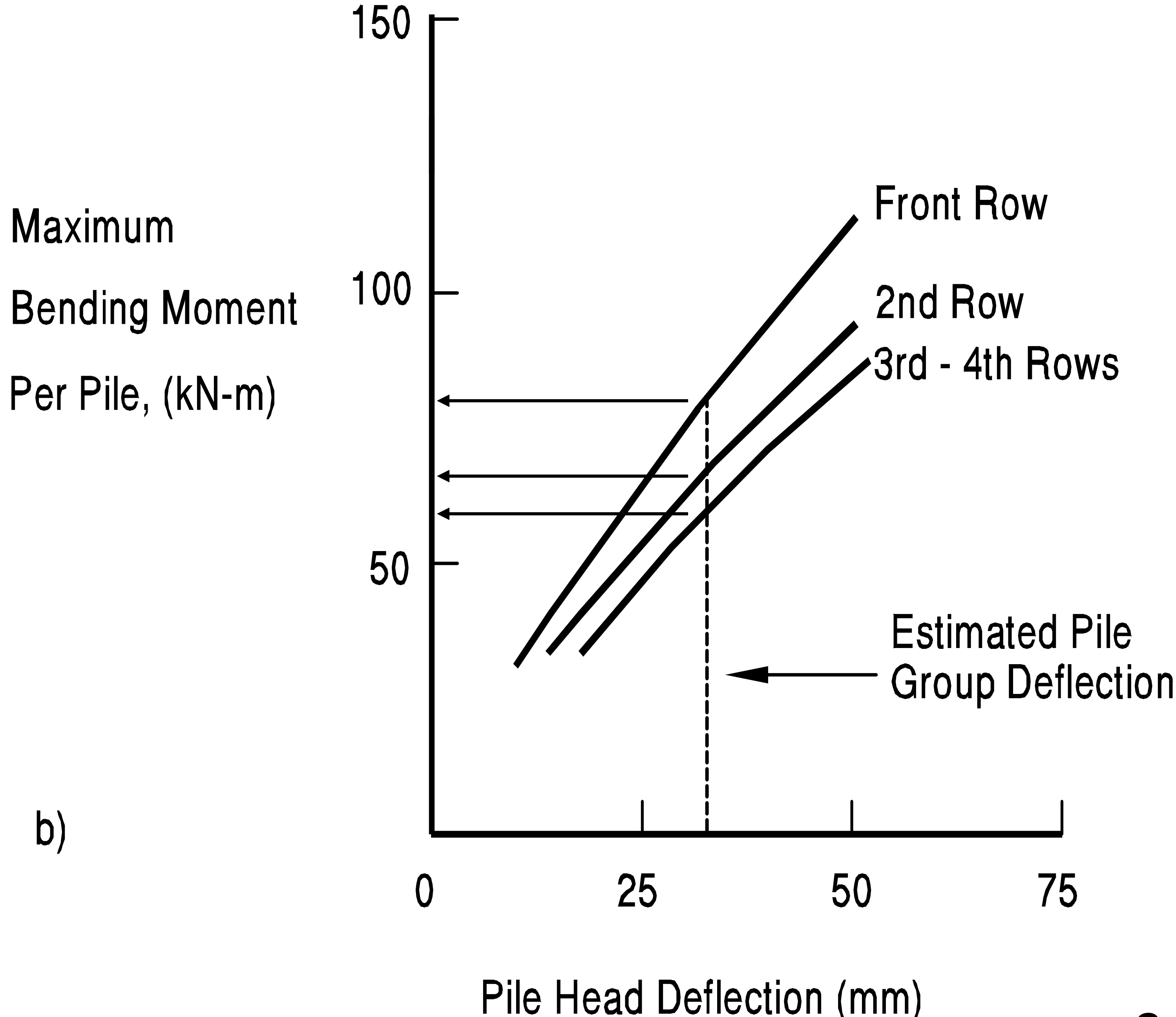

Front Row
Group Average
2nd Row
3rd - 4th Rows
Load
Per Pile
Lateral Load
Per Pile, (kN)
600
400
200
0
25
50
75
Estimated Pile
Group Deflection
Pile Head Deflection (mm)

STEP 4: Estimate group deflection under lateral load.

a. Average the load for a given deflection from all piles in the group (i.e., each of the four rows) to determine the average group response to a lateral load as shown in Figure 9.69(a).

b. Divide the lateral load to be resisted by the pile group by the number of piles in the group to determine the average lateral load resisted per pile.

c. Enter load-deflection graph similar to Figure 9.69(a) with the average load per pile to estimate group deflection using the group average load deflection curve.



150
100
50
Maximum
Bending Moment
Per Pile, (kN-m)
Front Row
2nd Row
3rd - 4th Rows
Estimated Pile
Group Deflection
b)
0
25
50
75
Pile Head Deflection (mm)

STEP 5: Evaluate pile structural acceptability.

a. Plot the maximum bending moment determined from LPILE analyses versus deflection for each row of piles as illustrated in Figure 9.69(b).

b. Check the pile structural adequacy for each row of piles. Use the estimated group deflection under the lateral load per pile to determine the maximum bending moment for an individual pile in each row.

c. Determine maximum pile stress from LPILE output associated with the maximum bending moment.

d. Compare maximum pile stress with pile yield stress.

STEP 6: **Perform refined pile group evaluation that considers superstructure substructure interaction.**

SEE HANDOUT FOR

USU HW PROBLEM

Lateral Load Test Setup

16 in. x 0.5 in wall CEP

14 in. x 0.375 in wall CEP

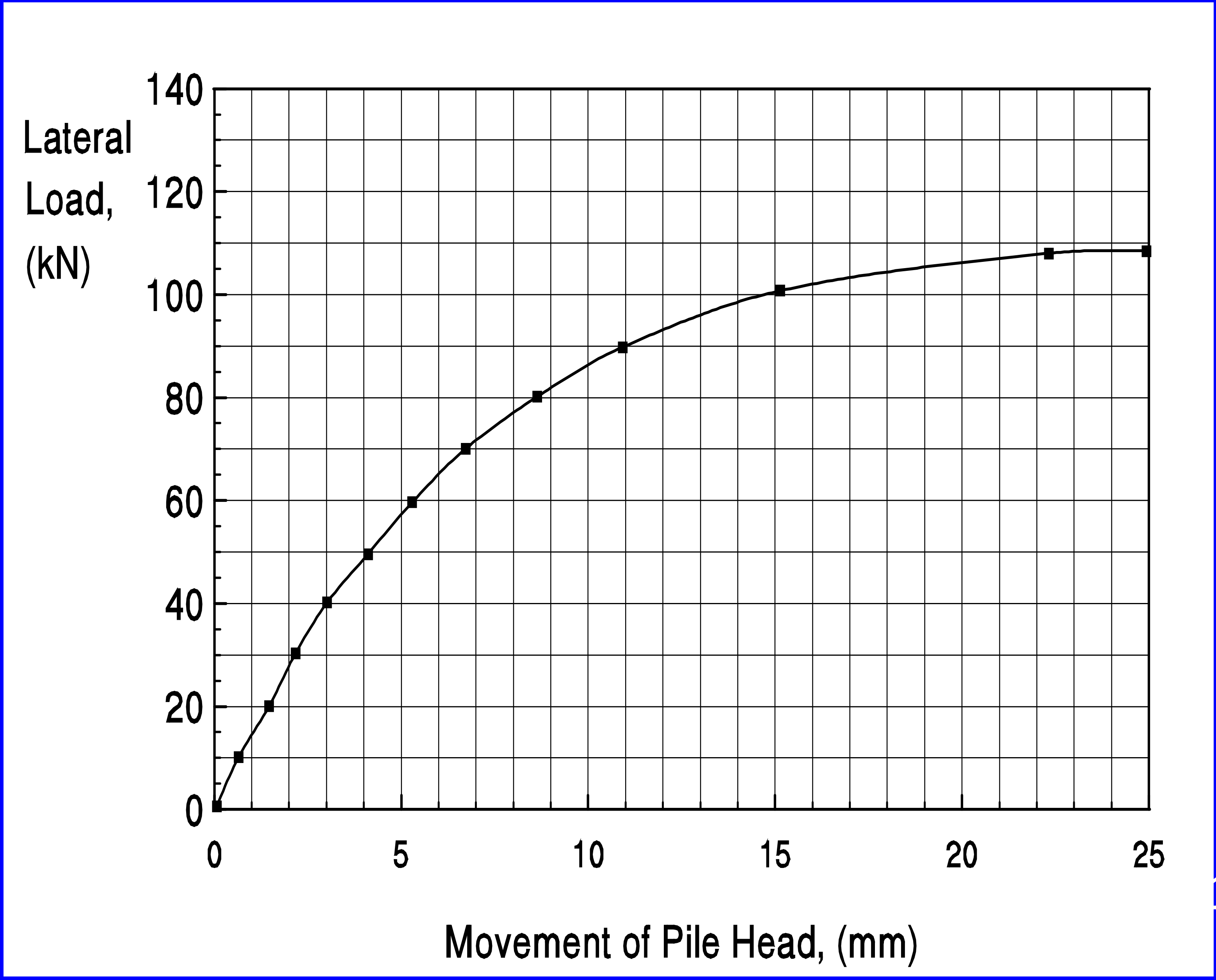
Load Cell and Spherical Bearing Plates

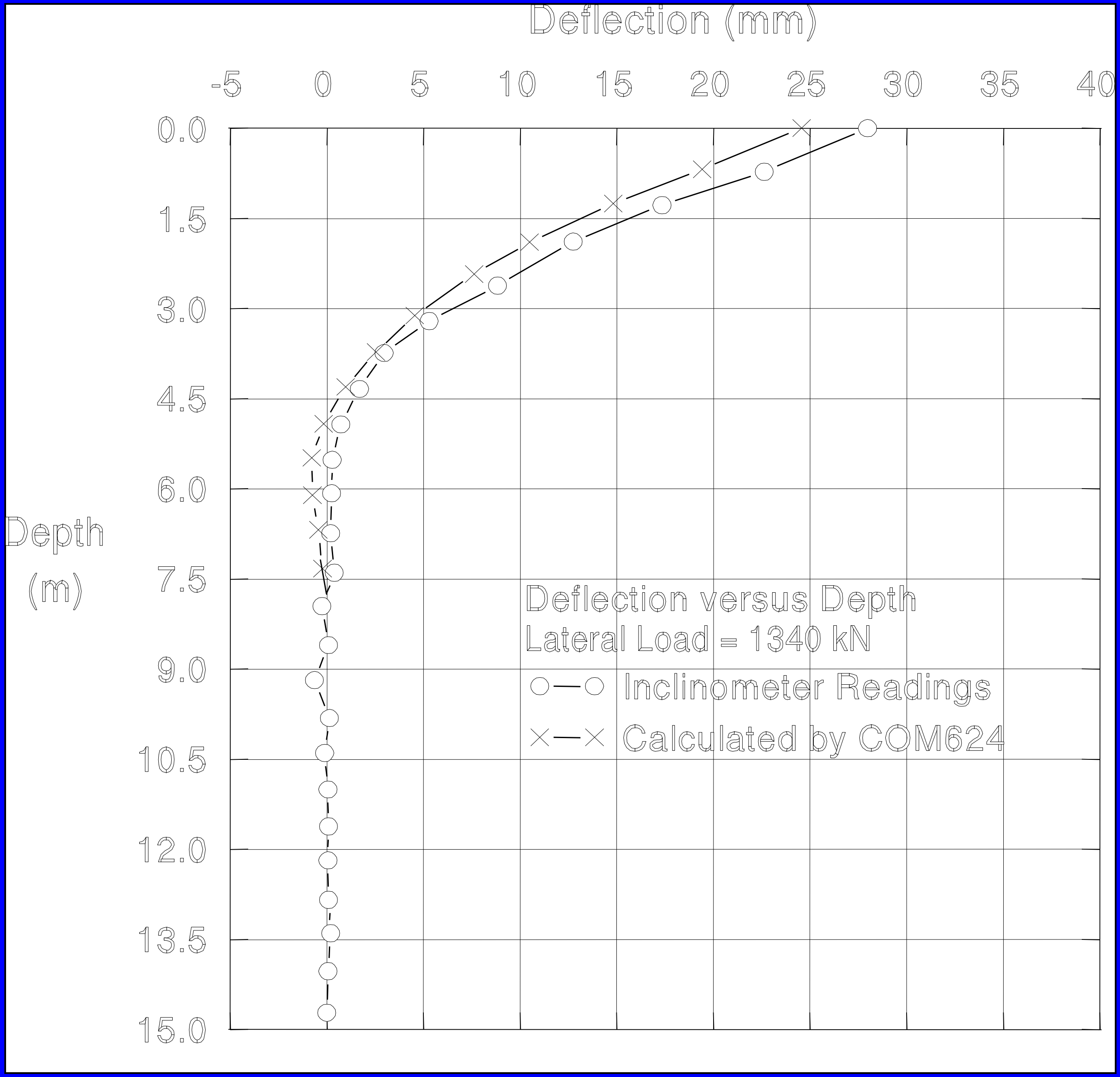
Hydraulic Jack

Load Cell and Spherical Bearing Plates

Hydraulic Jack

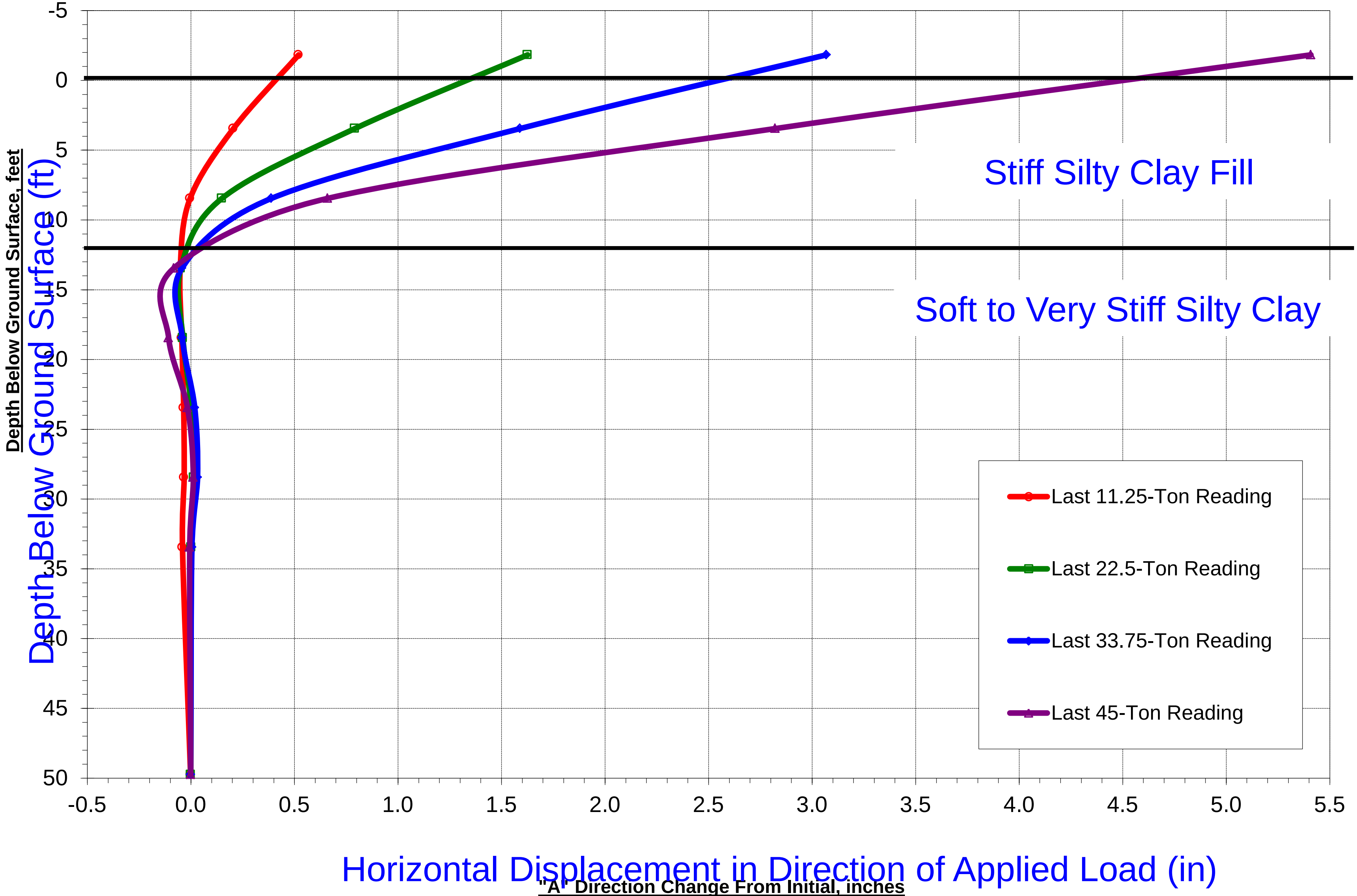
Pile Head Movement Versus Lateral Load





Depth (after Kyfor *et al.* 1992)


Inclinometer
s
Wheel Assembly
Extensions



Stiff Silty Clay Fill
Soft to Very Stiff Silty Clay
Last 11.25-Ton Reading
Last 22.5-Ton Reading
Last 33.75-Ton Reading
Last 45-Ton Reading
Depth Below Ground Surface (ft)
Depth Below Ground Surface, feet
-5
0
5
10
15
20
25
30
35
40
45
50
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
Horizontal Displacement in Direction of Applied Load (in)
"A" Direction Change From Initial, inches


DO NOT ENTER


CAUTION DO NOT ENTER
CAUTION DO NOT ENTER


CAUTION DO NOT ENTER
CAUTION DO NO


DO NOT ENTER

ANY QUESTIONS ?