INTRODUCTION TO STATIC ANALYSIS

STATIC ANALYSIS

- Single pile design issues
- Group design issues
- Special design considerations
- Additional design and construction considerations

STATIC ANALYSIS METHODS

Static analysis methods and computer solutions are used to:

- Calculate pile length for loads
- Determine number of piles
- Determine most cost effective pile type
- Calculate foundation settlement
- Calculate performance under uplift and lateral loads

STATIC ANALYSIS METHODS

Static analysis methods and computer solutions are an integral part of the design process.

Static analysis methods are necessary to determine the most cost effective pile type.

For a given pile type:

- calculate capacity
- determine pile length
- determine number of piles

} Bid Quantity

STATIC ANALYSIS METHODS

Foundation designer <u>must</u> know design loads and performance requirements.

Many static analysis methods are available.

- methods in manual are relatively simple
- methods provide reasonable agreement with full scale tests
- other more sophisticated methods could be used

<u>Designer should fully know the basis for, limitations of, and applicability of a chosen method.</u>

BASICS OF STATIC ANALYSIS

Static capacity is the sum of the soil/rock resistances along the pile shaft and at the pile toe.

Static analyses are performed to determine ultimate pile capacity and the pile group response to applied loads.

The ultimate capacity of a pile and pile group is the smaller of the soil rock medium to support the pile loads or the structural capacity of the piles.

ULTIMATE CAPACITY

Qu = (Design Load x FS) + “other”

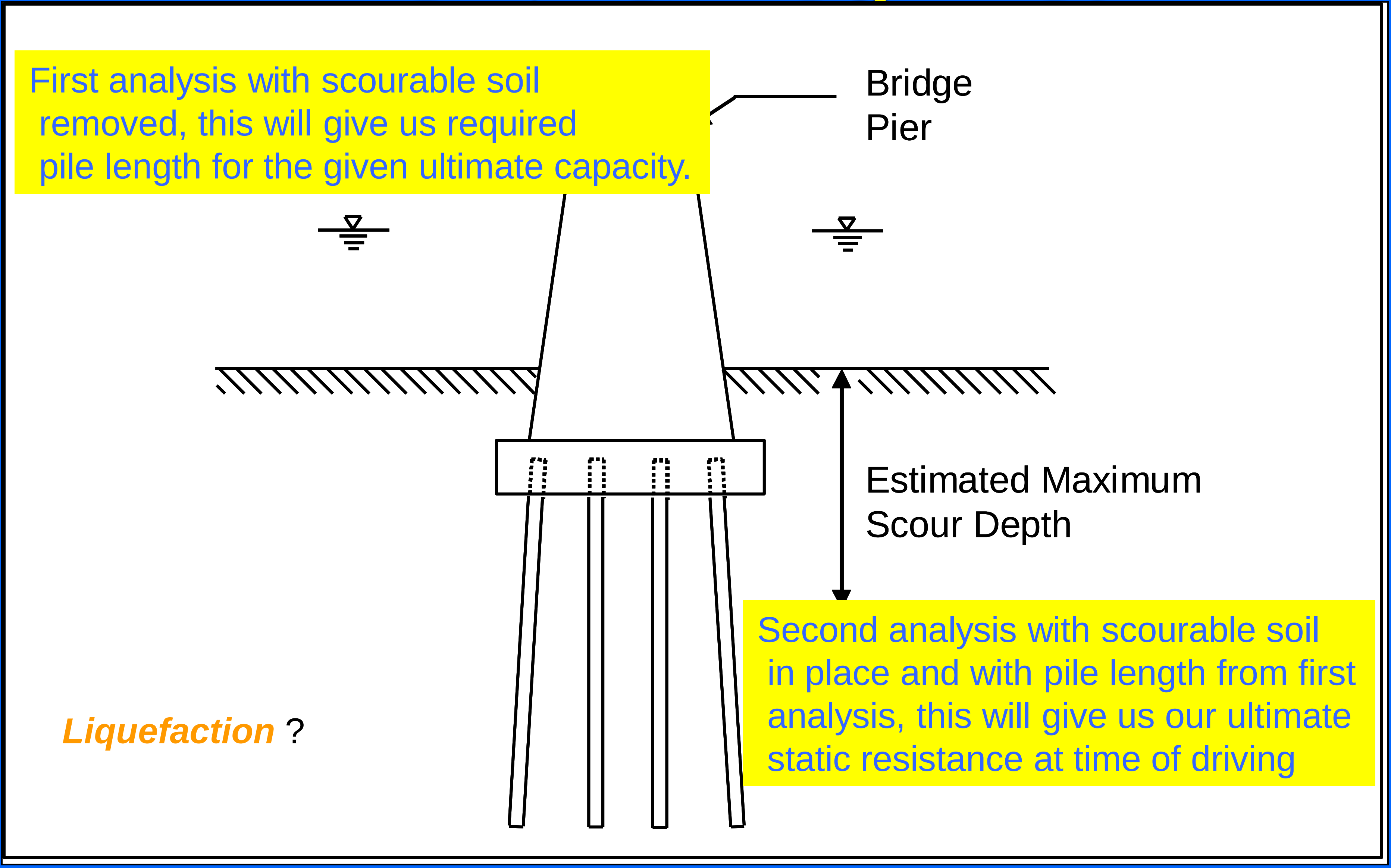
“Other” could be the resistance provided by scourable soil

“Other” could be the resistance provided by Liquefiable soil

“Other” is soil resistance at the time of driving

not present later during the design life of the pile

TWO STATIC ANALYSIS ARE OFTEN REQUIRED



LOAD TRANSFER

The ultimate pile capacity is typically expressed as the sum of the shaft and toe resistances:

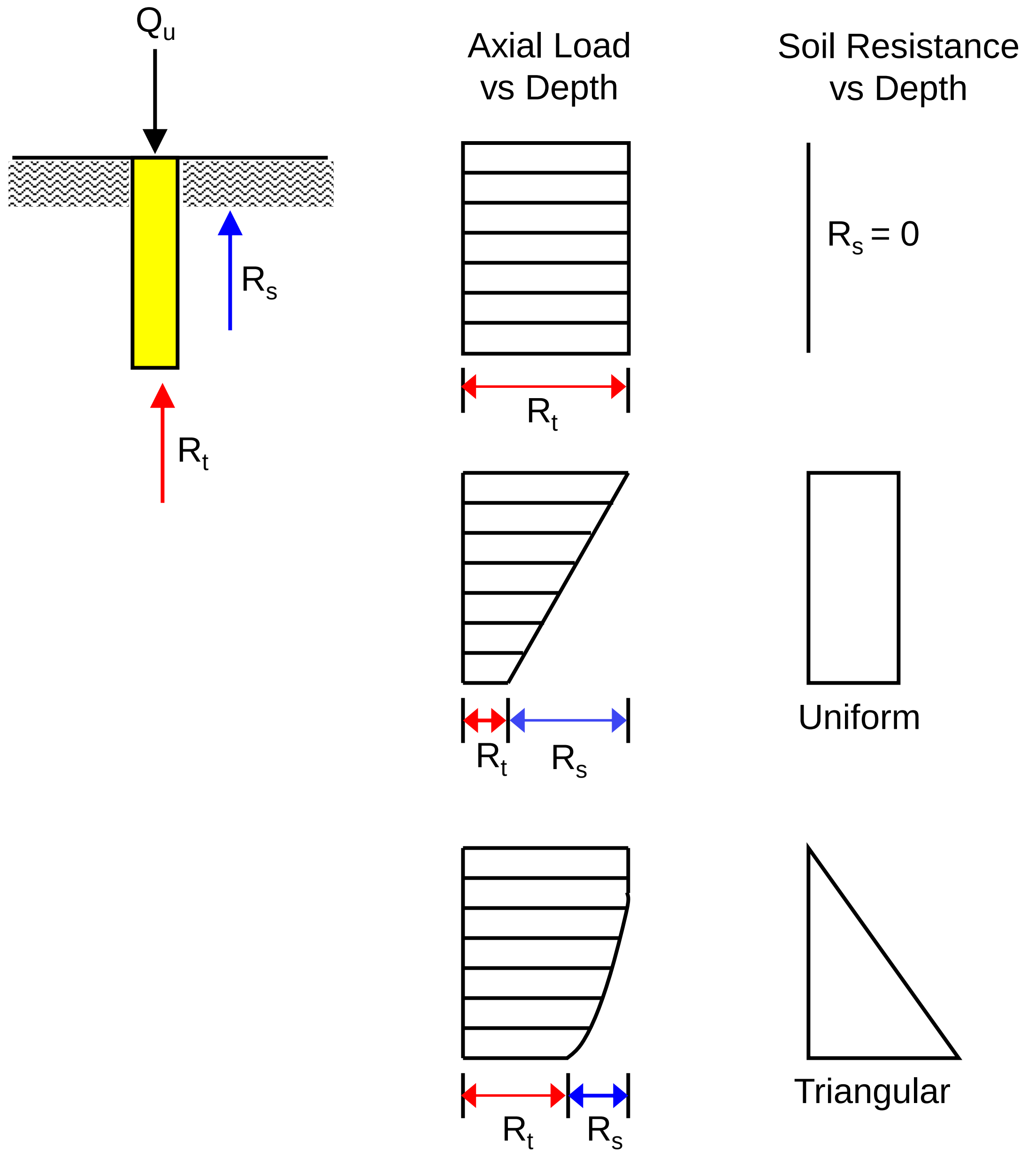
$$Q_u = R_s + R_t$$

This may also be expressed in terms of unit resistances:

$$Q_u = f_s A_s + q_t A_t$$

The above equations assume that the ultimate shaft and toe resistances are simultaneously developed.

LOAD TRANSFER



STUDENT EXERCISE #1

Figure 9.7 on page 12 shows the effect of water table location on effective stresses. Low water table results in higher effective stresses, higher shear strength, and therefore higher driving resistances

DESIGN SOIL STRENGTH PARAMETERS

Most of the static analysis methods in cohesionless soils use the soil friction angle determined from laboratory tests or SPT N values.

In coarse granular deposits, the soil friction angle should be chosen conservatively.

What does this mean ??

DESIGN SOIL STRENGTH PARAMETERS

For a cost effective design with any static analysis method, the foundation designer <u>**must**</u> consider time dependent soil strength changes.

FACTOR OF SAFETY SELECTION

Historically, the range in factor of safety has depended upon the reliability of a particular static analysis method with consideration of :

- Level of confidence in the input parameters
- Variability of soil and rock
- Method of static analysis
- Effects of, and consistency of proposed pile installation method
- Level of construction monitoring

FACTORS OF SAFETY

The factor of safety used in a static analysis should be based on the construction control method specified.

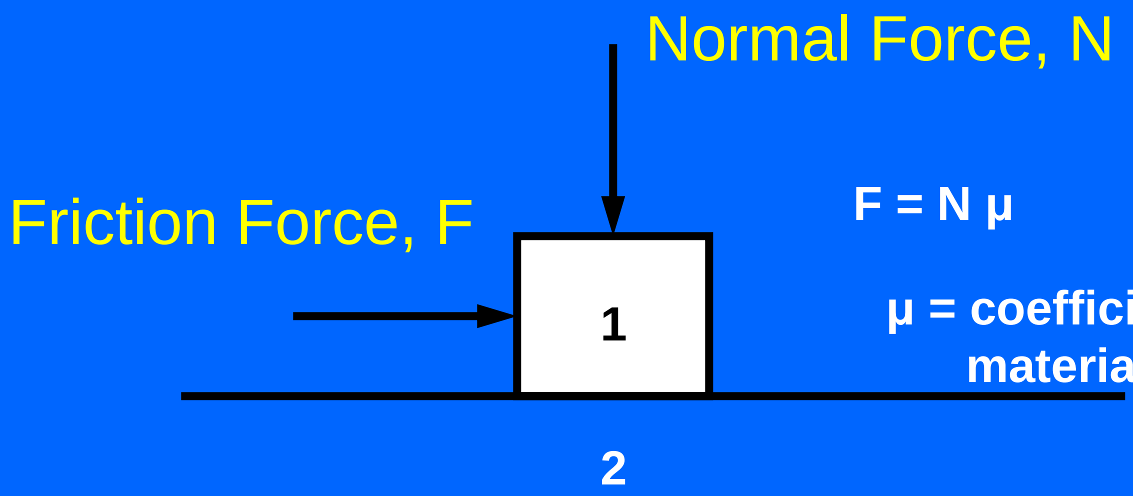
Construction Control Method	Factor of Safety
Static load test with wave equation analysis	2.00
Dynamic testing with wave equation analysis	2.25
Indicator piles with wave equation analysis	2.50
Wave equation analysis	2.75
Gates dynamic formula	3.50

Static Analysis - Single Piles

Methods for estimating static resistance of soils

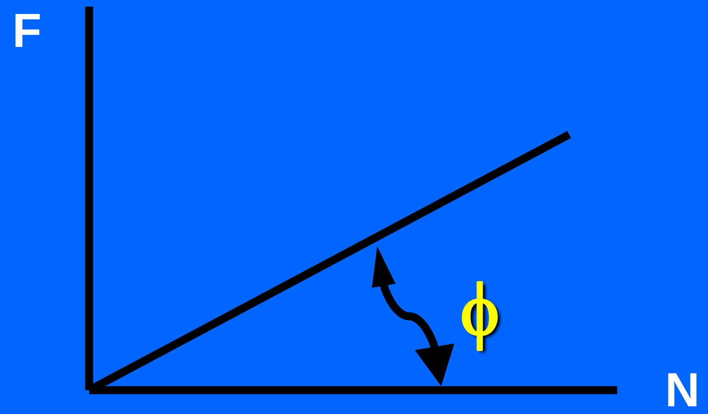
STATIC CAPACITY OF PILES IN COHESIONLESS SOILS

Cohesionless Soils, Drained Strength



F = N μ

μ = coefficient of friction between material 1 and material 2



Tan (ϕ) = F/N

F = N TAN (ϕ)

Soil on Soil, we use ϕ

Soil on Pile, we use δ

phi = angle such that TAN (ϕ) is coefficient of friction between material 1 and material 2

METHODS OF STATIC ANALYSIS FOR PILES IN COHESIONLESS SOILS

Method	Approach	Design Parameters	Advantages	Disadvantages	Remarks
Meyerhof Method	Empirical Experience	Results of SPT tests. N	Widespread use of SPT test and input data availability. Simple method to use.	Non reproducibility of N values. Not as reliable as the other methods presented in this chapter.	Due to non reproducibility of N values and simplifying assumptions, use should be limited to preliminary estimating purposes.
Brown Method	Empirical	Results of SPT tests based of N_{60} values.	Widespread use of SPT test and input data availability. Simple method to use.	N_{60} values not always available.	Simple method based on correlations with 71 static load test results. Details provided in Section 9.7.1.1b.
Nordlund Method. FHWA	Semi-empirical Part Theory Part Experience	Charts provided by Nordlund. Estimate of soil friction angle is needed.	Allows for increased shaft resistance of tapered piles and includes effects of pile-soil friction coefficient for different pile materials.	No limiting value on unit shaft resistance is recommended by Nordlund. Soil friction angle often estimated from SPT data.	Good approach to design that is widely used. Method is based on field observations. Details provided in Section 9.7.1.1c.

METHODS OF STATIC ANALYSIS FOR PILES IN COHESIONLESS SOILS					
Method	Approach	Design Parameters	Advantages	Disadvantages	Remarks
Effective Stress Method.	Semi-empirical	Soil classification and estimated friction angle for β and N_t selection.	β value considers pile-soil friction coefficient for different pile materials. Soil resistance related to effective overburden pressure.	Results effected by range in β values and in particular by range in N_t chosen.	Good approach for design. Details provided in Section 9.7.1.3.
Methods based on Cone Penetration Test (CPT) data.	Empirical	Results of CPT tests.	Testing analogy between CPT and pile. Reliable correlations and reproducible test data.	Limitations on pushing cone into dense strata.	Good approach for design. Details provided in Section 9.7.1.7.

Nordlund Data Base

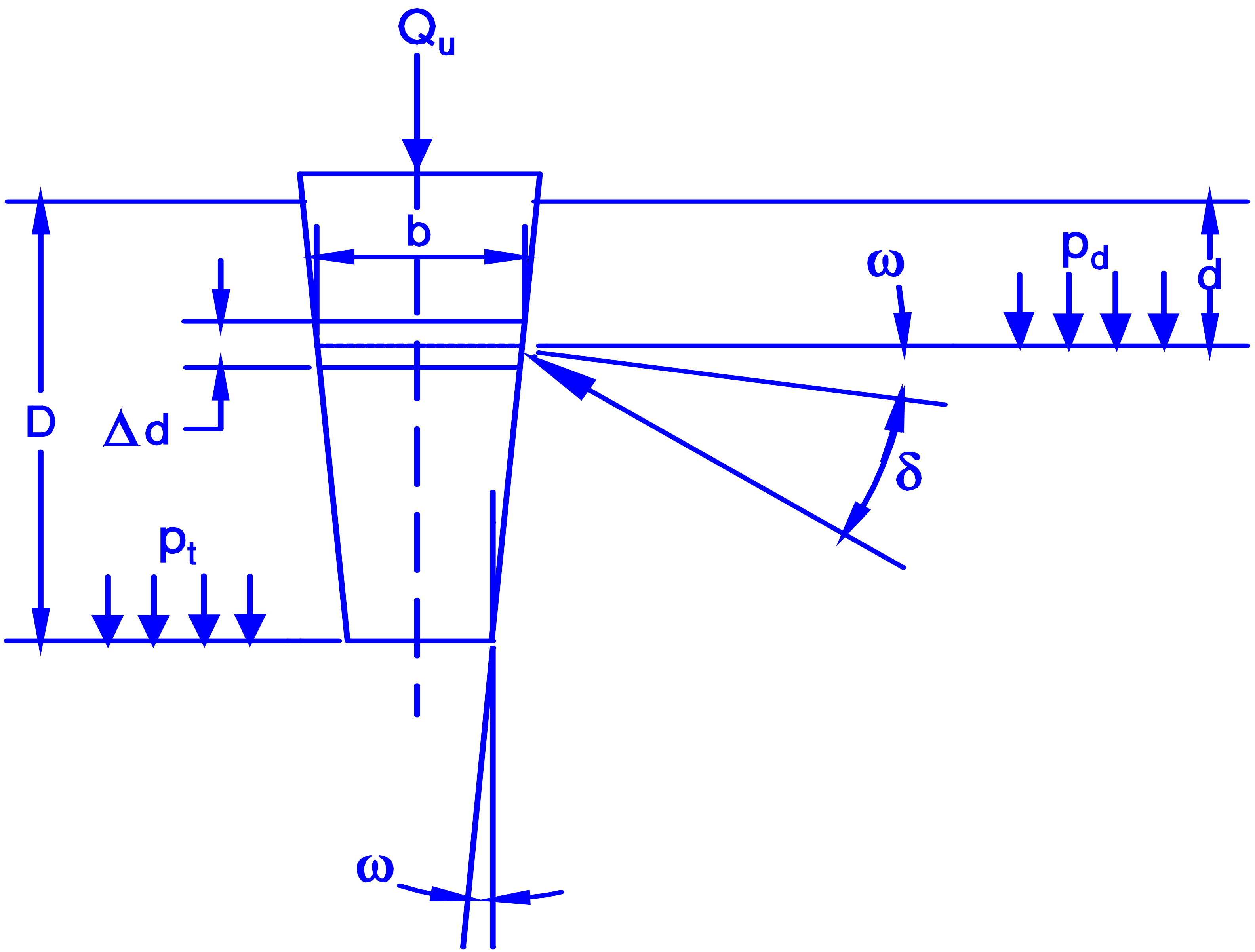
Pile Types	Timber, H-piles, Closed-end Pipe, Monotube, Raymond Step-Taper
Pile Sizes	Pile widths of 250 – 500 mm (10 - 20 in)
Pile Loads	Ultimate pile capacities of 350 -2700 kN (40 -300 tons)

Nordlund Method tends to overpredict capacity of piles greater than 600 mm (24 in)

Nordlund Method

Considers:

1. The friction angle of the soil.
2. The friction angle of the sliding surface.
3. The taper of the pile.
4. The effective unit weight of the soil.
5. The pile length.
6. The minimum pile perimeter.
7. The volume of soil displaced.



$$Q_u = \sum_{d=0}^{d=D} K_\delta \, C_F \, p_d \frac{\sin(\delta + \omega)}{\cos \omega} C_d \, \Delta d + \alpha_t \, N'_q \, A_t \, p_t$$

Nordlund Method

For a <u>pile of uniform cross section</u> (ω=0) and embedded length D, driven in soil layers of the same effective unit weight and friction angle, the Nordlund equation becomes:

$$Qu = \underbrace{(K_\delta C_F p_d (\sin\delta) C_d D)}_{R_S} + \underbrace{(\alpha_t N'_q A_t p_t)}_{R_T}$$

Nordlund Shaft Resistance

$$R_s = K_\delta \, C_F \, p_d \, \sin\delta \, C_d \, D$$

K_δ = coefficient of lateral earth pressure Figures 9.11 - 9.14

C_F = correction factor for K_δ when $\delta \neq \phi$ Figure 9.15

p_d = effective overburden pressure at center of layer

δ = friction angle between pile and soil Figure 9.10

C_d = pile perimeter

D = embedded pile length

Nordlund Toe Resistance

$$R_T = \alpha_T N'_q p_T A_T$$

Lesser of

$$R_T = q_L A_T$$

α_T = dimensionless factor Figure 9.16a

N'_q = bearing capacity factor Figure 9.16b

A_T = pile toe area

p_T = effective overburden pressure at pile toe ≤ 150 kPa

q_L = limiting unit toe resistance Figure 9.17

Nordlund Method

$$R_u = R_S + R_T$$

and

$$Q_a = R_U / FS$$

FS based on construction control method as in 9-14

Nordlund Method Procedure

Steps 1 through 6 are for computing shaft resistance and steps 7 through 9 are for computing the pile toe resistance

STEP 1 Delineate the soil profile into layers and determine the ϕ angle for each layer

a. Construct p_o diagram using procedure described in Section 9.4.

b. Correct SPT field N values for overburden pressure using Figure 4.4 from Chapter 4 and obtain corrected SPT N' values. Delineate soil profile into layers based on corrected SPT N' values.

c. Determine ϕ angle for each layer from laboratory tests or in-situ data.

d. In the absence of laboratory or in-situ test data, determine the average corrected SPT N' value, $\overline{N}'$, for each soil layer and estimate ϕ angle from Table 4-5 in Chapter 4.

STATIC CAPACITY OF PILES IN COHESIVE SOILS

Cohesive Soils, Undrained Strength

F = Friction resistance ; N = Normal force (stress)

C is independent of overburden pressures

c = cohesion, stickiness, soil / soil

a = adhesion, stickiness, soil / pile

METHODS OF STATIC ANALYSIS FOR PILES IN COHESIVE SOILS					
Method	Approach	Method of Obtaining Design Parameters	Advantages	Disadvantages	Remarks
α-Method (Tomlinson Method). **FHWA**	Empirical, total stress analysis.	Undrained shear strength estimate of soil is needed. Adhesion calculated from Figures 9.18 and 9.19.	Simple calculation from laboratory undrained shear strength values to adhesion.	Wide scatter in adhesion versus undrained shear strengths in literature.	Widely used method described in Section 9.7.1.2a.
Effective Stress Method.	Semi-Empirical, based on effective stress at failure.	β and N_t values are selected from Table 9-6 based on drained soil strength estimates.	Ranges in β and N_t values for most cohesive soils are relatively small.	Range in N_t values for hard cohesive soils such as glacial tills can be large.	Good design approach theoretically better than undrained analysis. Details in Section 9.7.1.3.
Methods based on Cone Penetration Test data.	Empirical.	Results of CPT tests.	Testing analogy between CPT and pile. Reproducible test data.	Cone can be difficult to advance in very hard cohesive soils such as glacial tills.	Good approach for design. Details in Section 9.7.1.7.

Tomlinson or α-Method

Unit Shaft Resistance, f_s:

$$f_s = c_a = \alpha c_u$$

Where:

c_a = adhesion (Figure 9.18)

α = empirical adhesion factor (Figure 9.19)

Tomlinson or α-Method

Shaft Resistance, R_s:

$$R_s = f_s\,A_s$$

Where:

A_s = pile surface area in layer
(pile perimeter x length)

H piles use “box” area – 4 sides, pg 45

Tomlinson or α-Method (US)

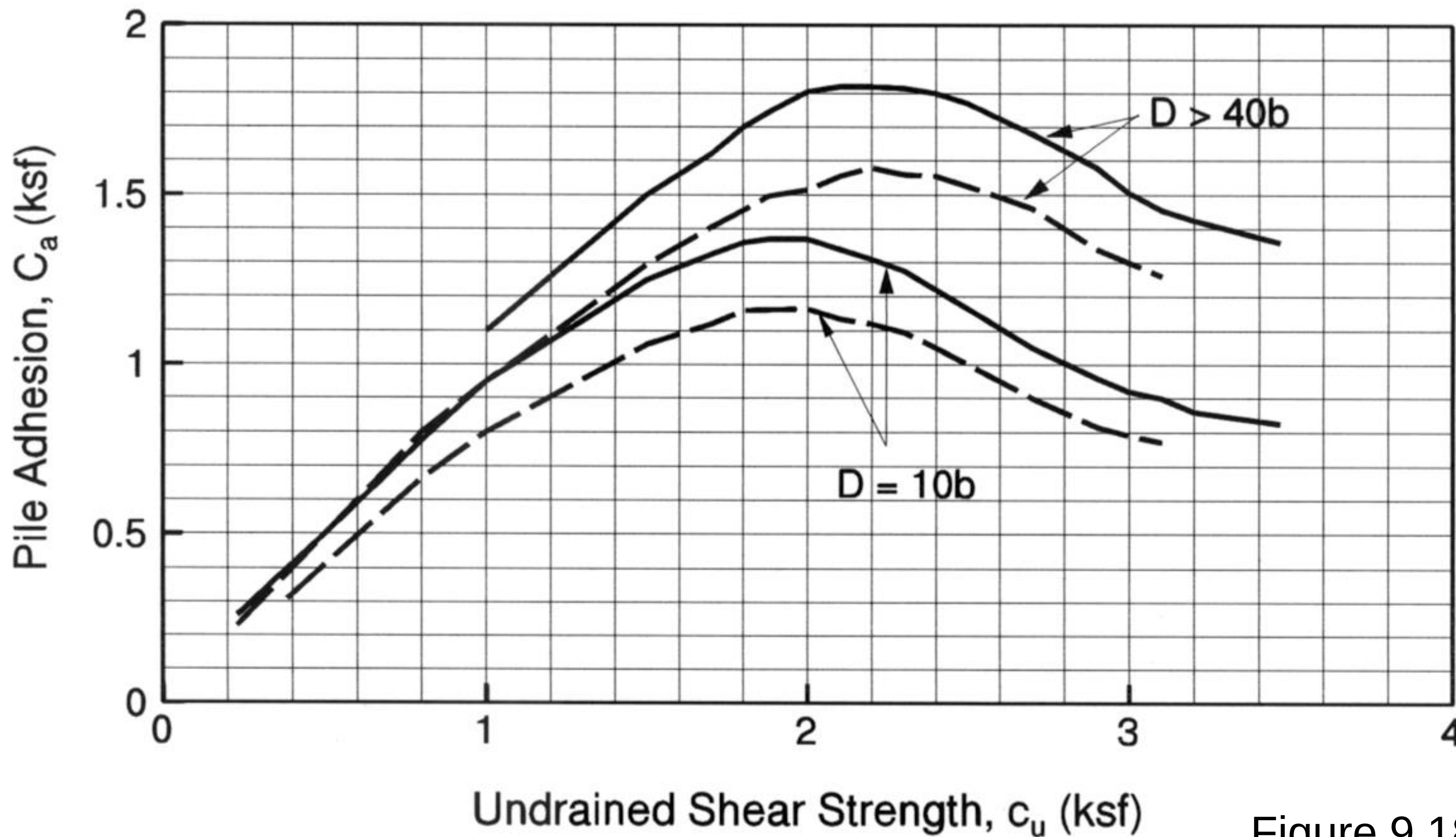
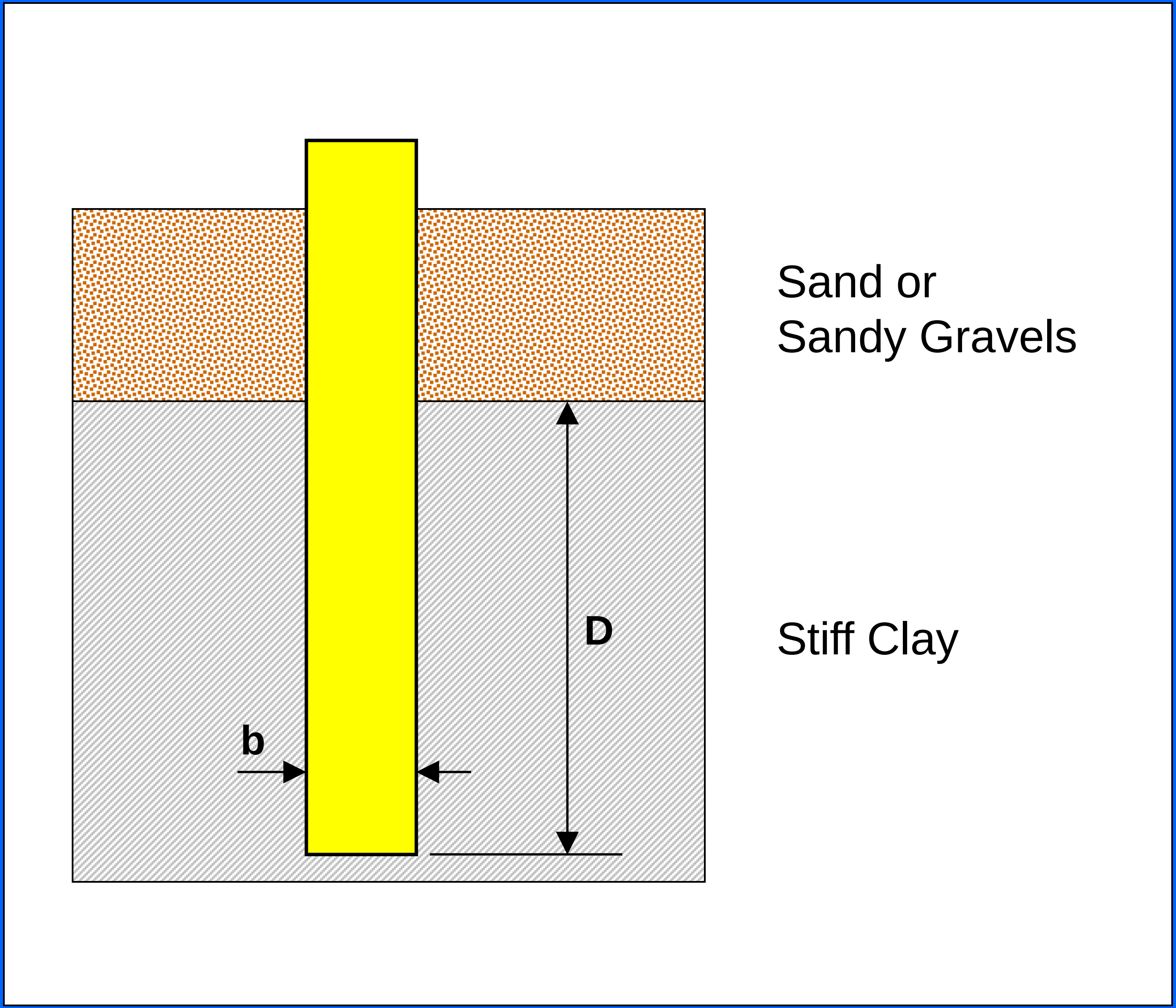


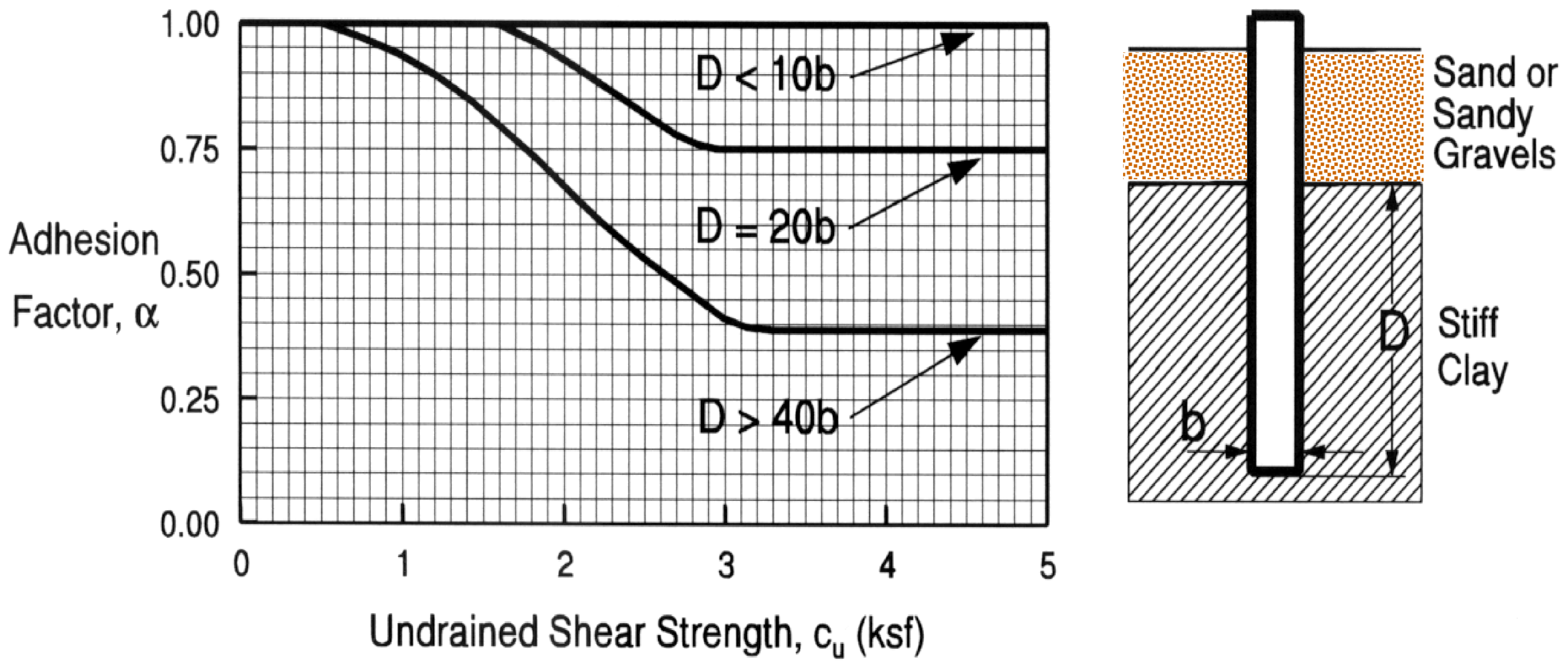
Figure 9.18

———— Concrete, Timber, Corrugated Steel Piles	D = distance from ground surface to bottom of clay layer or pile toe, whichever is less
— — — - Smooth Steel Piles	b = Pile Diameter

Tomlinson or α-Method



Tomlinson or α-Method (US)

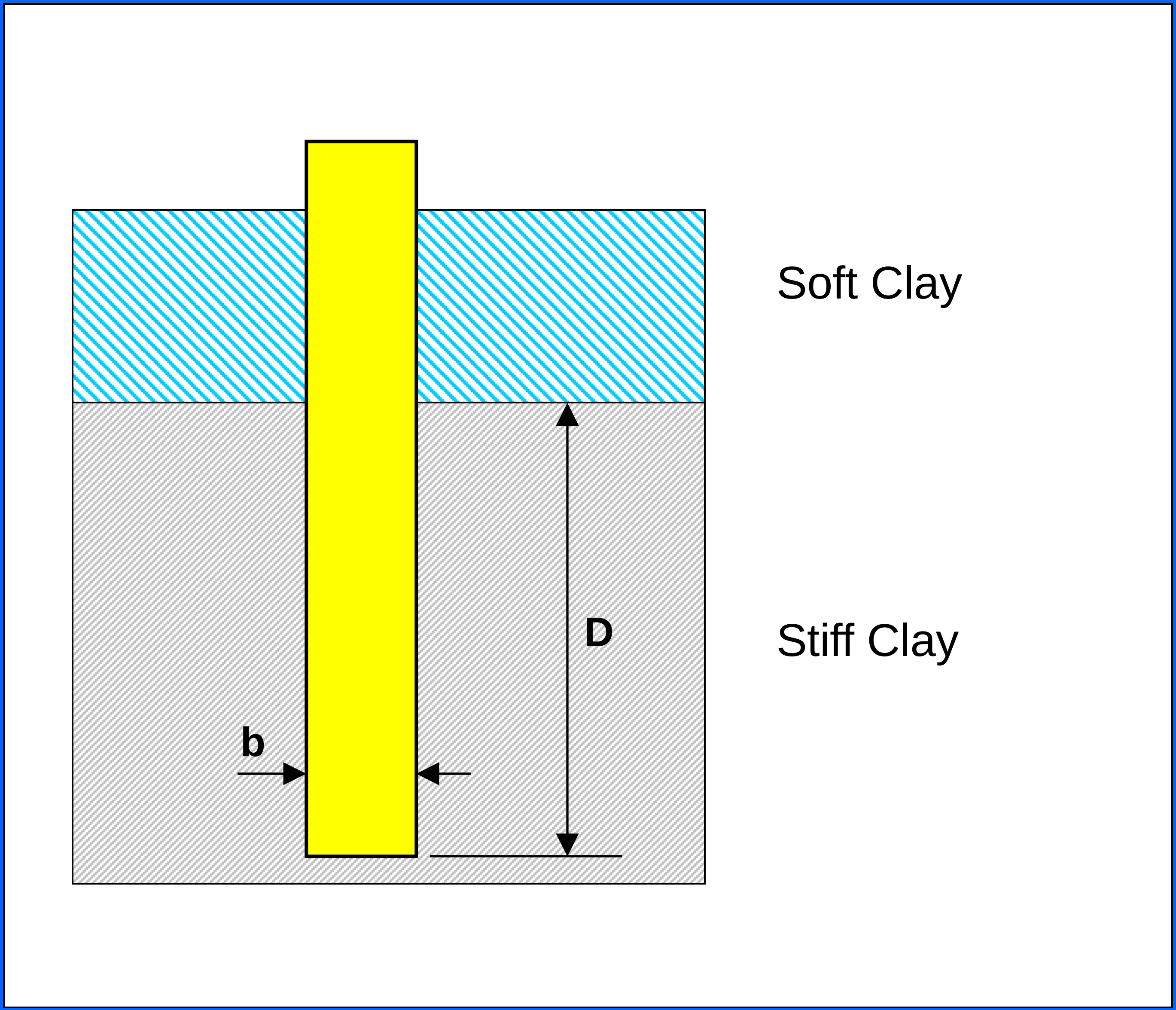


D = distance into stiff clay layer

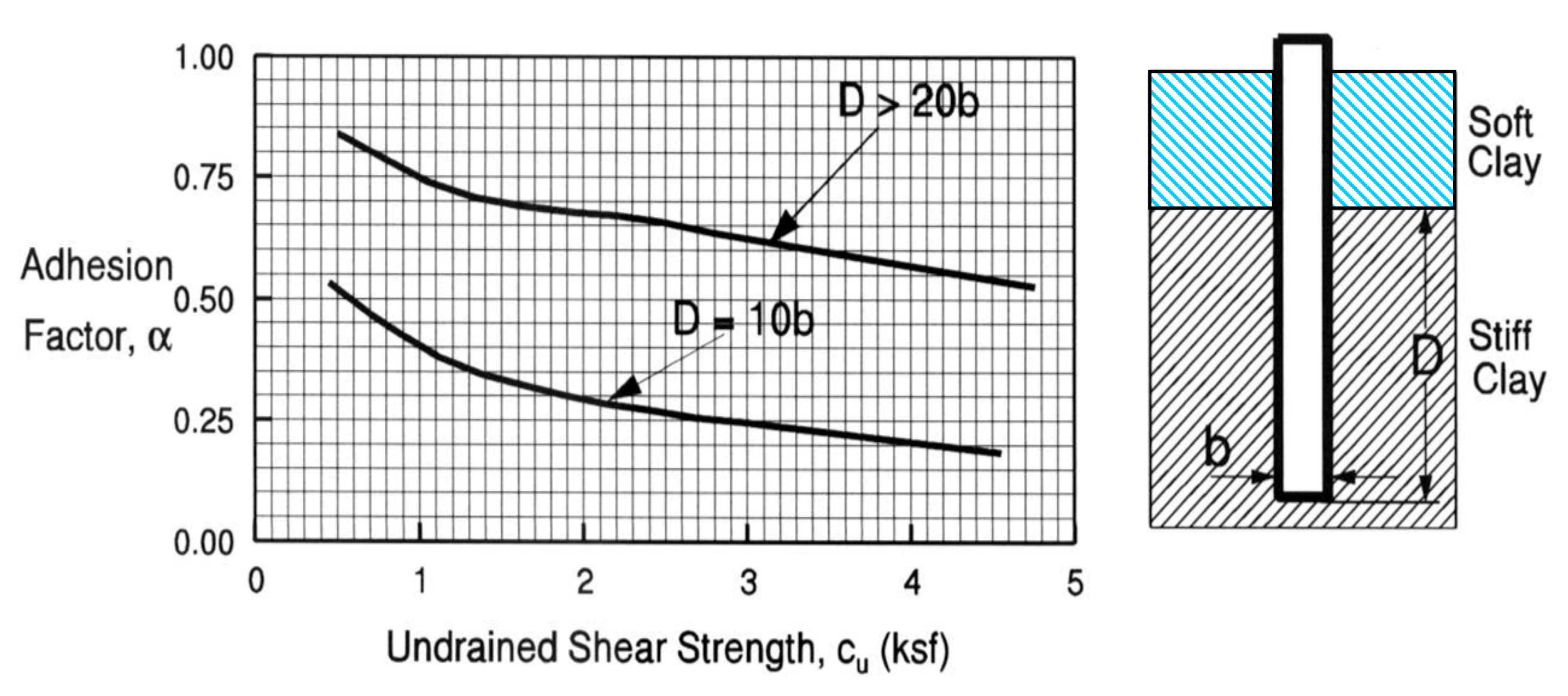
b = Pile Diameter

Figure 9.19b

Tomlinson or α-Method



Tomlinson or α-Method (US)

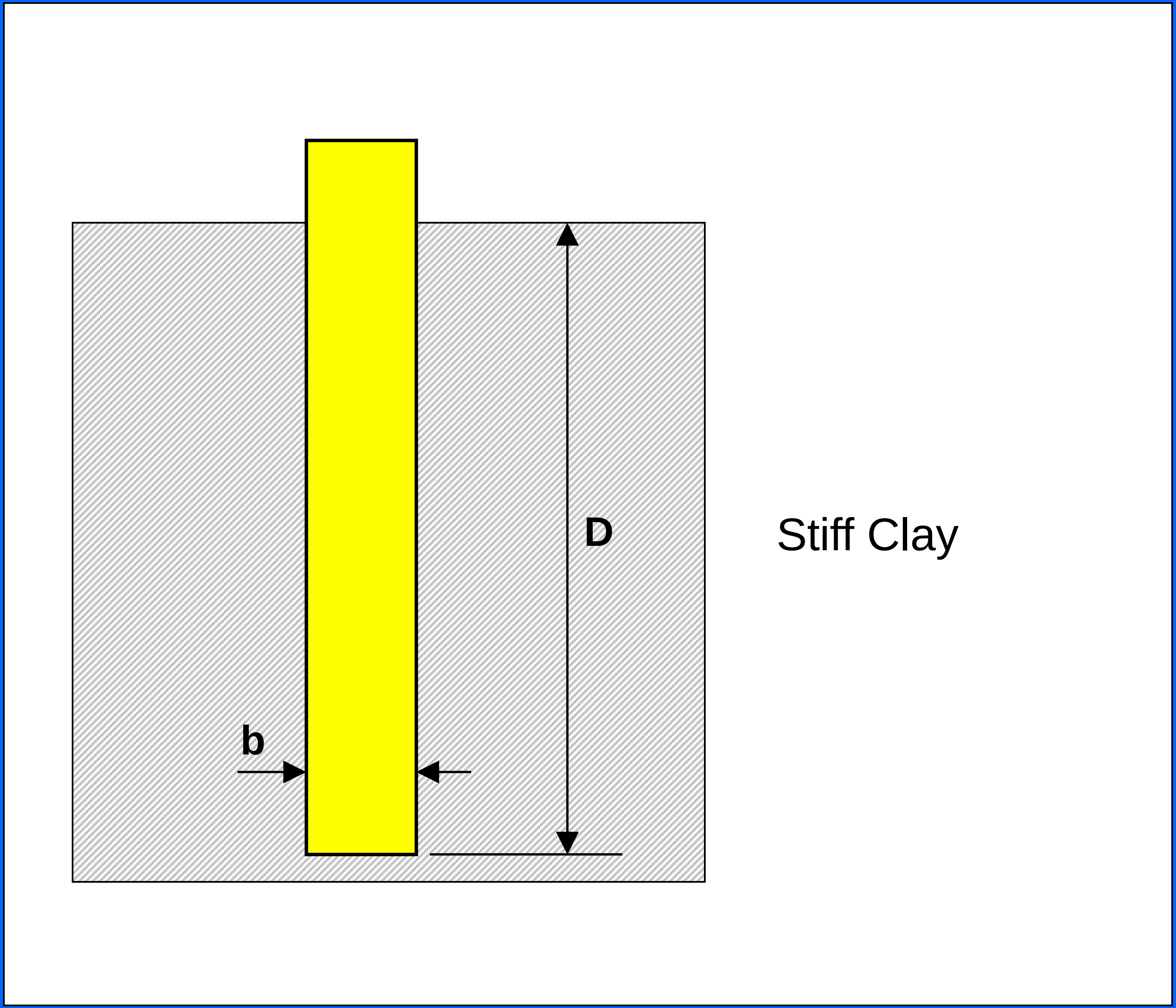


D = distance into stiff clay layer

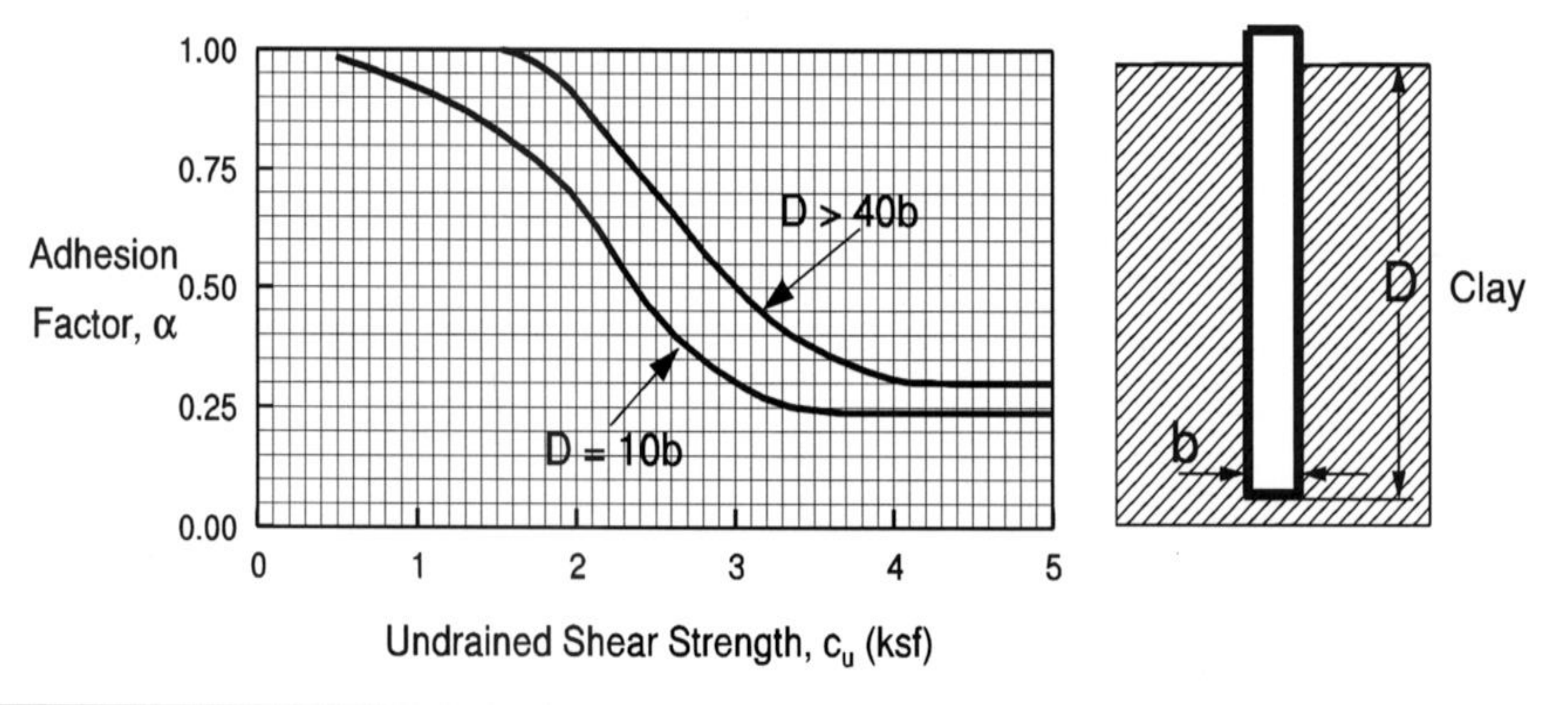
b = Pile Diameter

Figure 9.19b

Tomlinson or α-Method



Tomlinson or α-Method (US)



D = distance into stiff clay layer

b = Pile Diameter

Figure 9.19b

Tomlinson or α-Method

Unit Toe Resistance, q_t:

$$q_t = c_u N_c$$

Where:

c_u = undrained shear strength of the soil at pile toe

N_c = dimensionless bearing capacity factor (9 for deep foundations)

Tomlinson or α-Method

Toe Resistance, R_t:

$$R_t = q_t A_t$$

The toe resistance in cohesive soils is sometimes ignored since the movement required to mobilize the toe resistance is several times greater than the movement required to mobilize the shaft resistance.

Tomlinson or α-Method

$$R_u = R_S + R_T$$

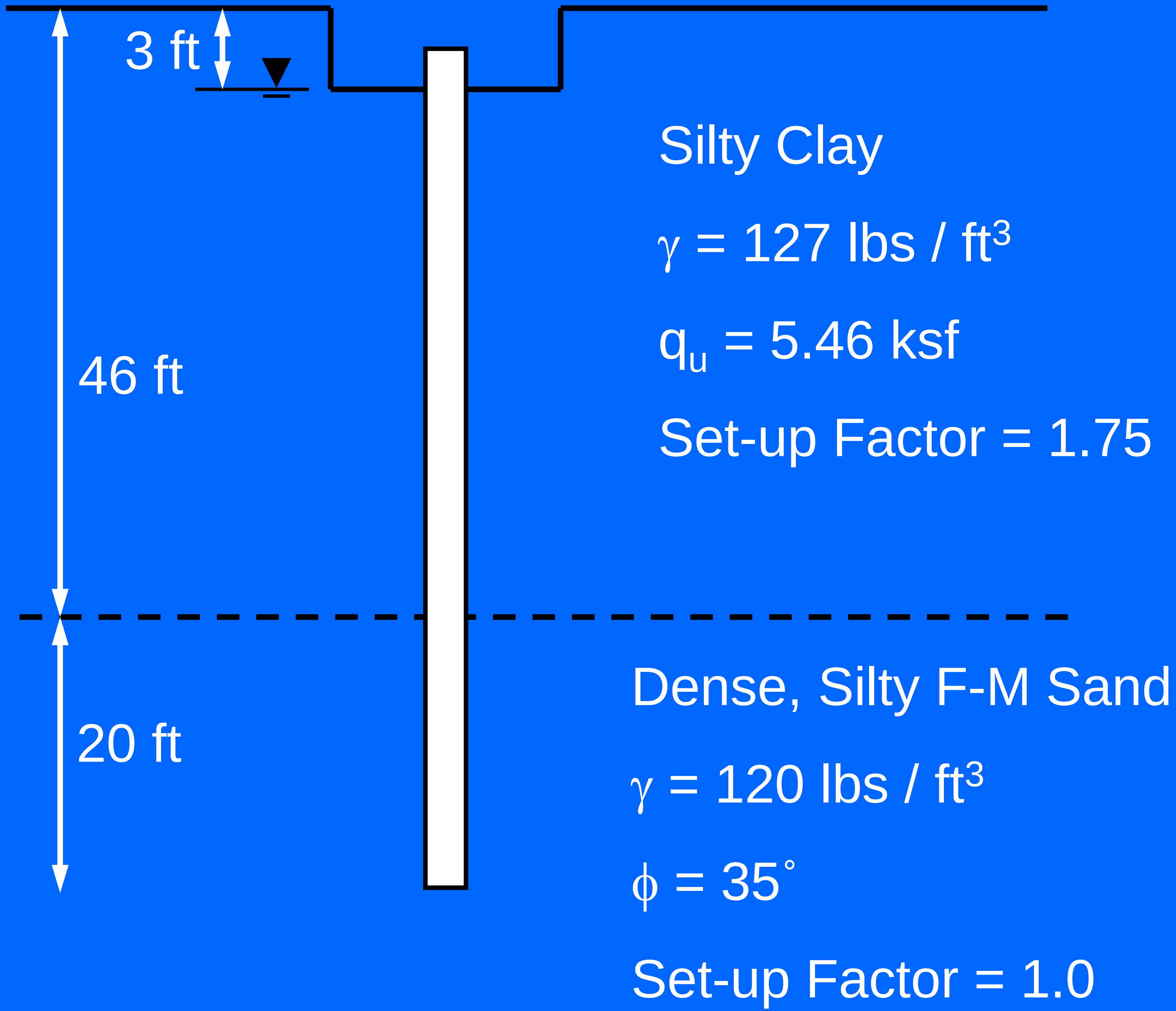
and

$$Q_a = R_U / FS$$

STUDENT EXERCISE #2

Use the α-Method described in Section 9.7.1.2a and the Nordlund Method described in Section 9.7.1.1c to calculate the ultimate pile capacity and the allowable design load for a 12.75 inch O.D. closed end pipe pile driven into the soil profile described below. The trial pile length for the calculation is 63 feet below the bottom of pile cap excavation which extends 3 feet below grade. The pipe pile has a pile-soil surface area of 3.38 ft^2/ft and a pile toe area of 0.89 ft^2. Use Figure 9.18 to calculate the shaft resistance in the clay layer. The pile volume is 0.89 ft^3/ft. The effective overburden at 56 feet, the midpoint of the pile shaft in the sand layer is 3.73 ksf, and the effective overburden pressure at the pile toe is 4.31 ksf. Remember, the soil strengths provided are unconfined compression test results ($c_u = q_u / 2$).

Soil Profile



Solution

- We will discuss this solution during the DRIVEN workshop (ie steps 1-9)

STEP 10

$Q_u = R_s + R_t$ = 1465 + 410 = 1875 kN

METHODS BASED ON CPT DATA

Pages 9-65 through 9-80

Nottingham and Schmertmann

Laboratoire des Ponts et Chaussees (LPC)

Elsami and Fellenius

UPLIFT CAPACITY OF SINGLE PILES

pg 9-81

Increasingly important design consideration

Sources of uplift loads include seismic events, vessel impact, debris loading and cofferdam dewatering.

The design uplift load may be taken as 1/3 the ultimate shaft resistance from a static analysis.

STATIC ANALYSIS – SINGLE PILES LATERAL CAPACITY METHODS

Reference Manual Chapter 9.7.3

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.

Lateral Capacity of Single Piles

- Historically, prescription values were used for lateral capacity of vertical piles, or battered (inclined) piles were added.
- Modern design methods are readily available which allow load-deflection behavior to be rationally evaluated.

Lateral Capacity of Single Piles

Soil, 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**
  - **FB-PIER**

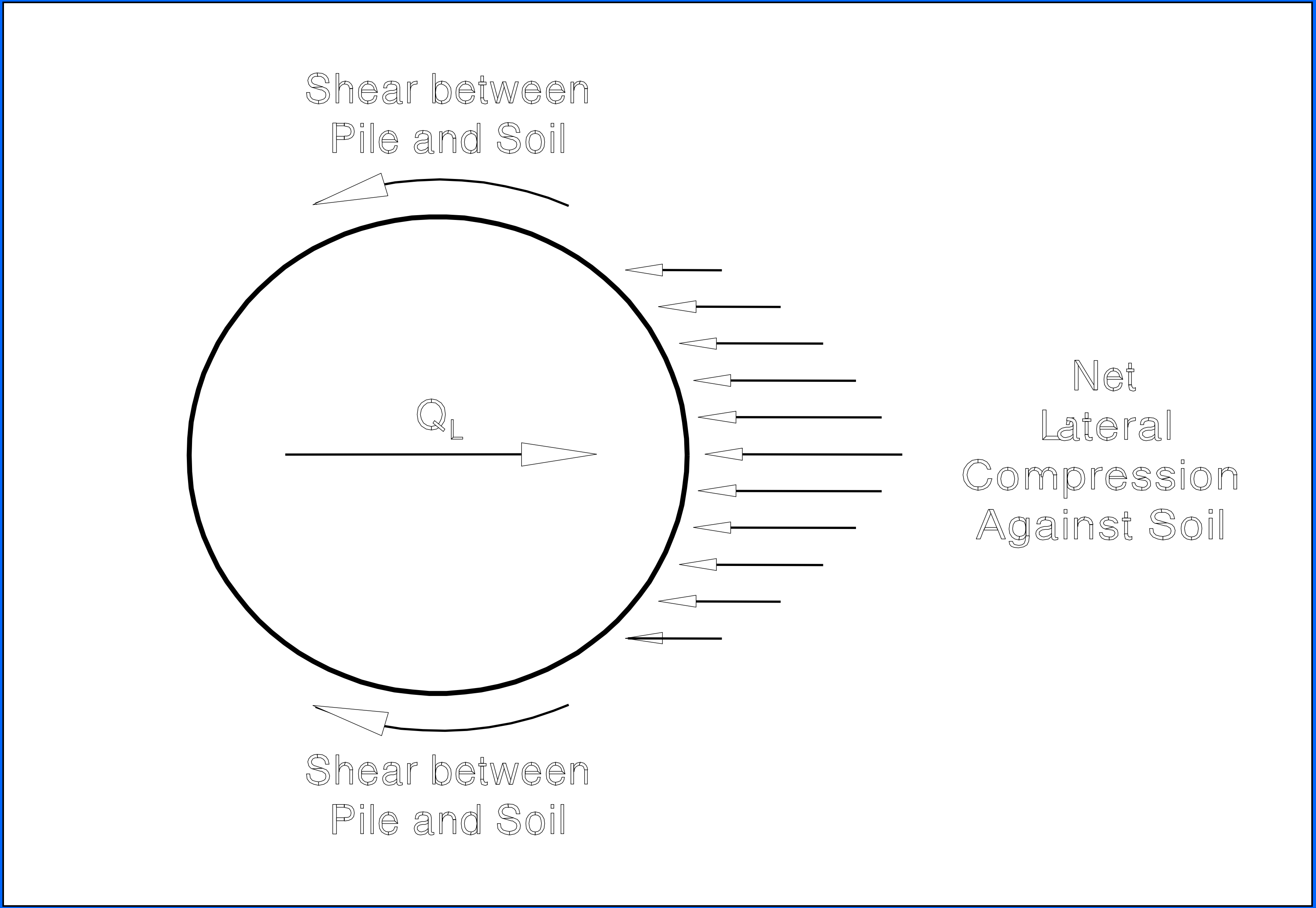


Figure 9.36 Soil Resistance to a Lateral Pile Load (adapted from Smith, 1989)

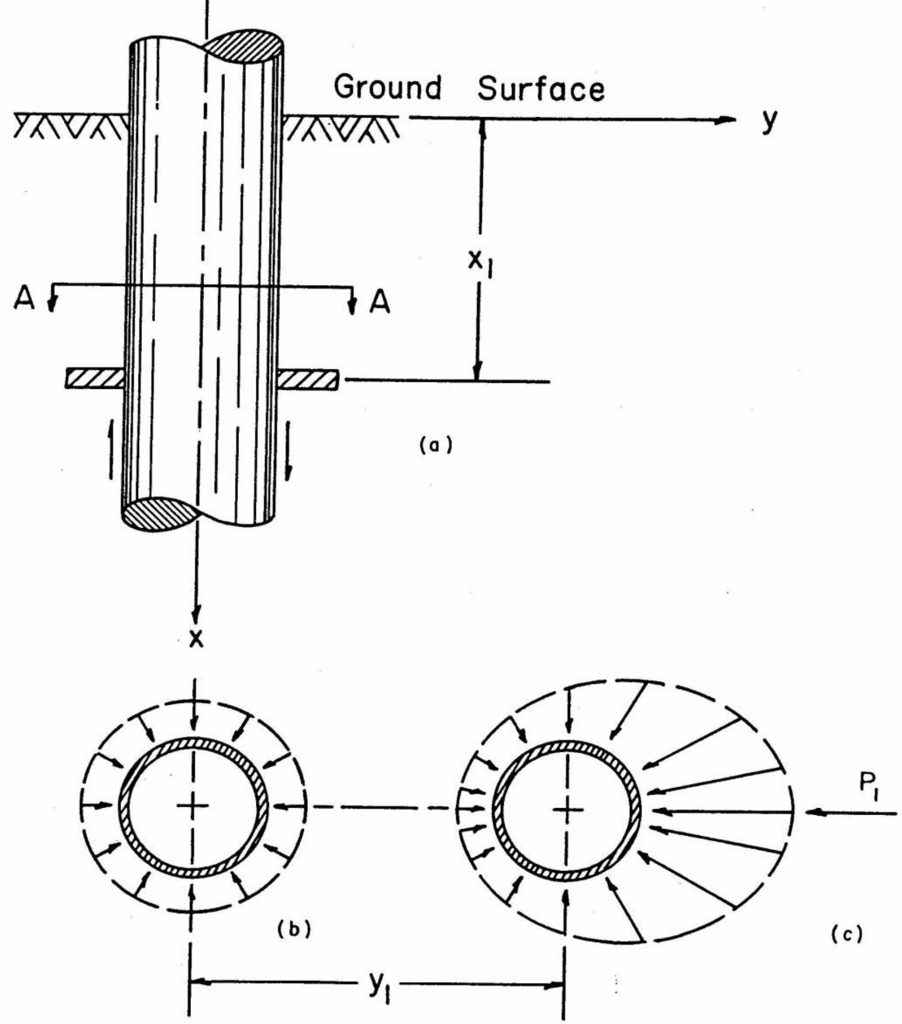


Fig. 3.1. Graphical definition of p and y
(a) view of elevation of section of pile
(b) view A-A - earth pressure distribution prior to lateral loading
(c) view A-A - earth pressure distribution after lateral loading.

NIM

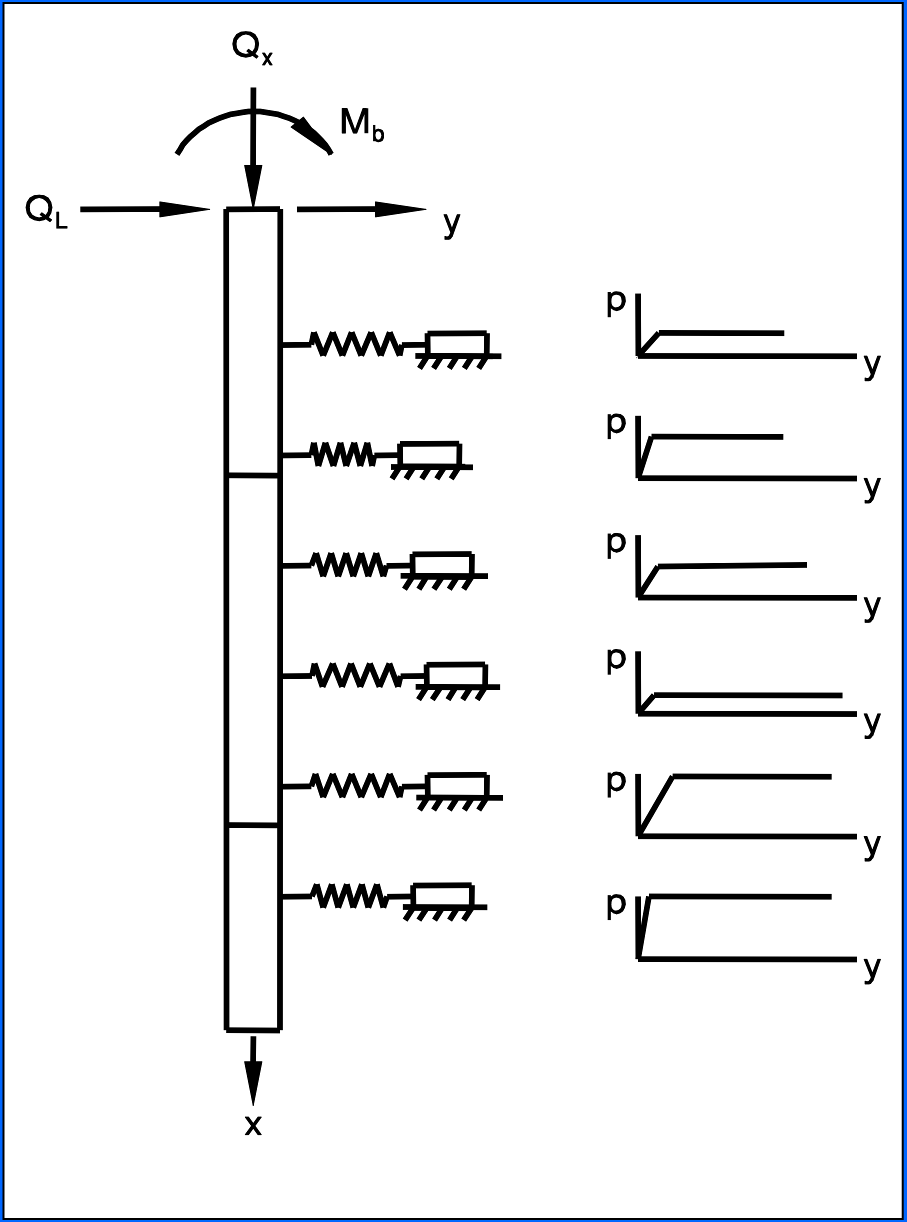
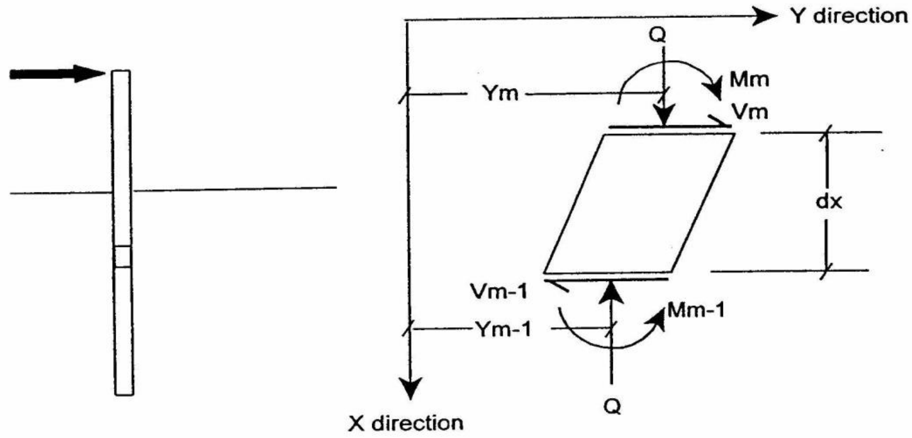


Figure 9.44 LPILE Pile-Soil Model

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:

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

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

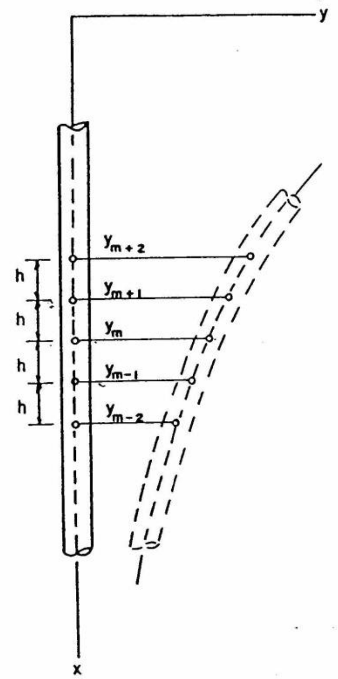


Fig. 5.1. Representation of deflected pile.

In a similar manner

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

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

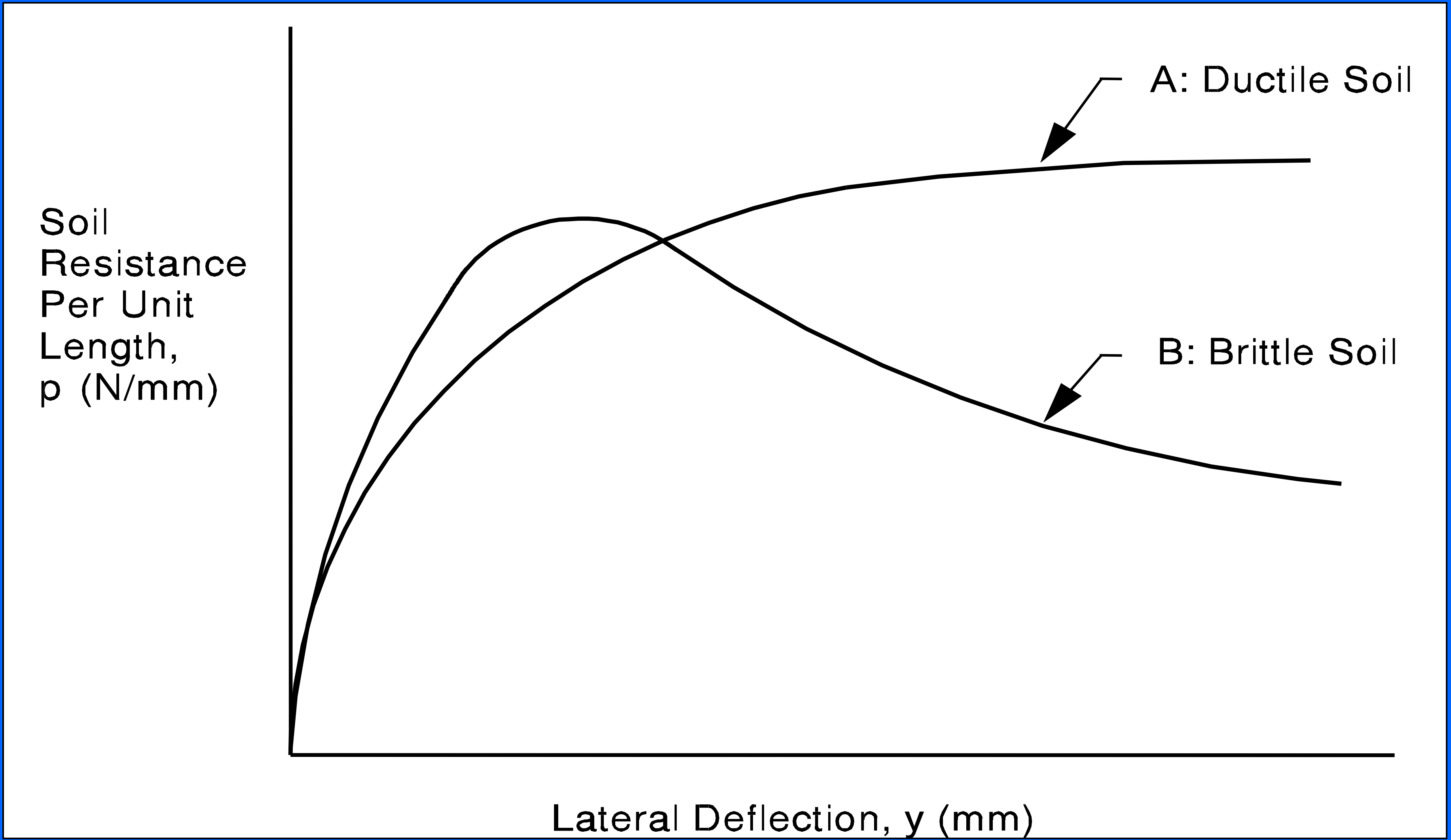


Figure 9.45 Typical p-y Curves for Ductile and Brittle Soil (after Coduto, 1994)

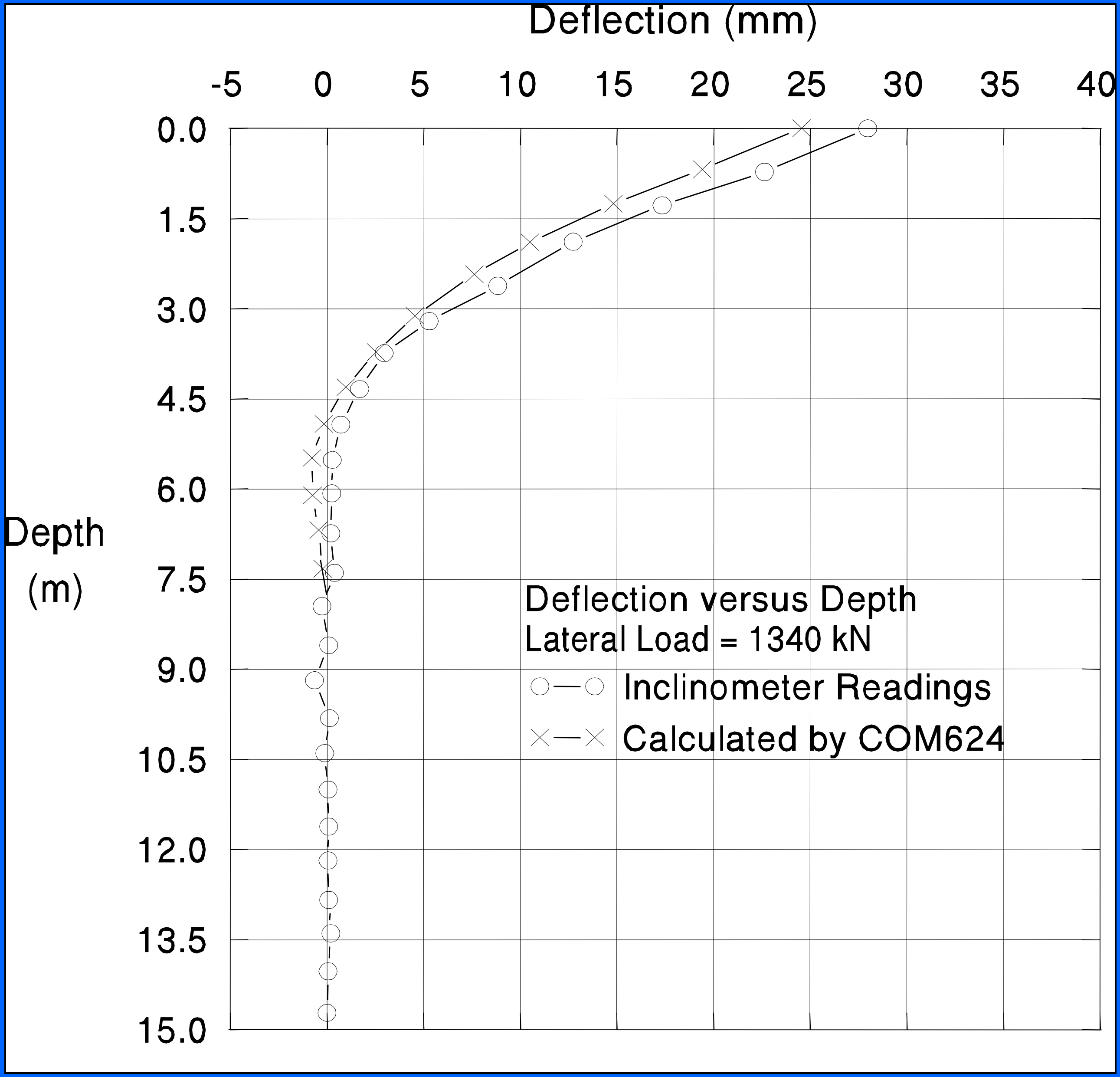


Figure 9.47 Comparison of Measured and COM624P Predicted Load-Deflection Behavior versus Depth (after Kyfor *et al.* 1992)

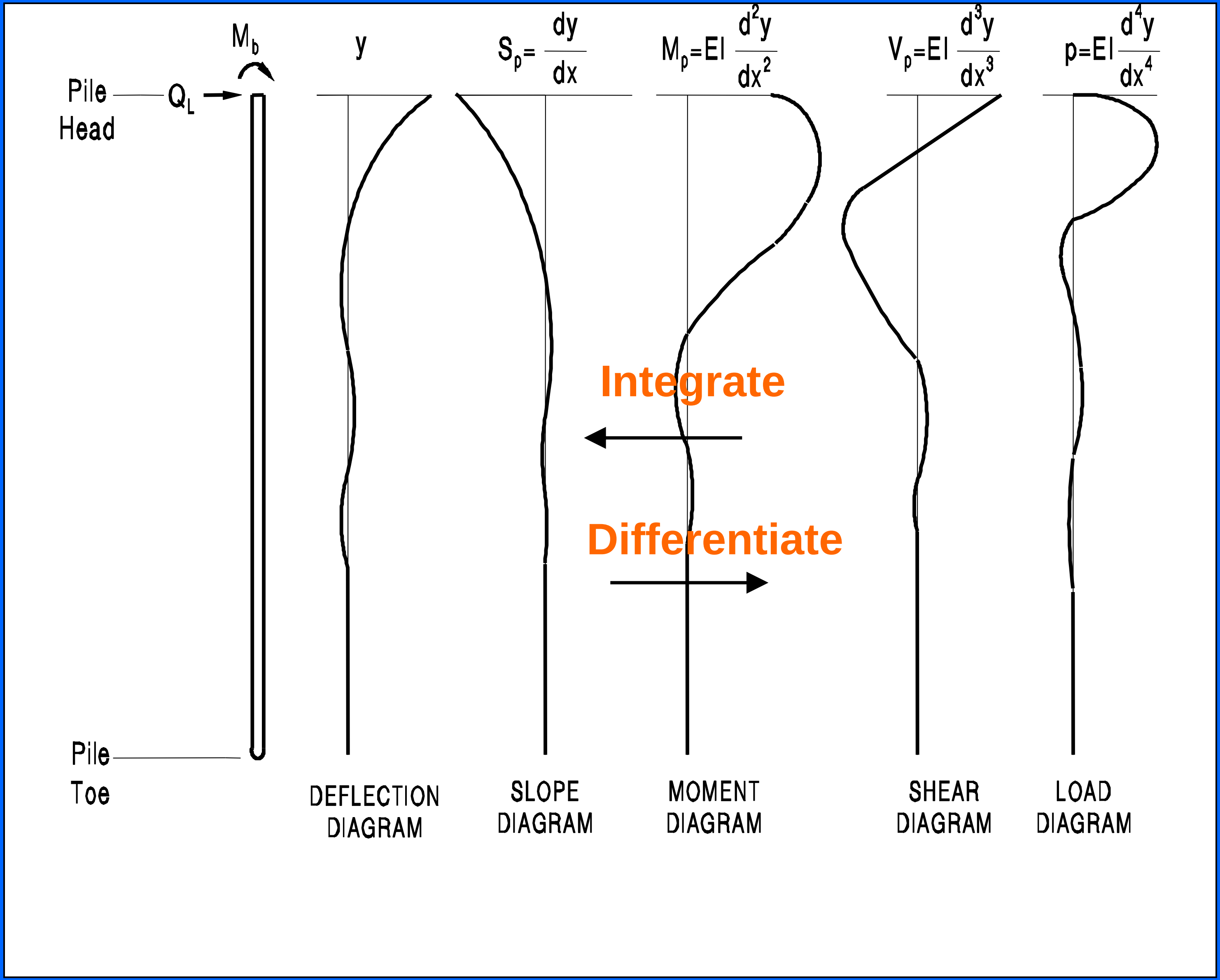


Figure 9.36 Graphical Presentation of LPILE Results (Reese, *et al.* 2000)

ANY QUESTIONS ?