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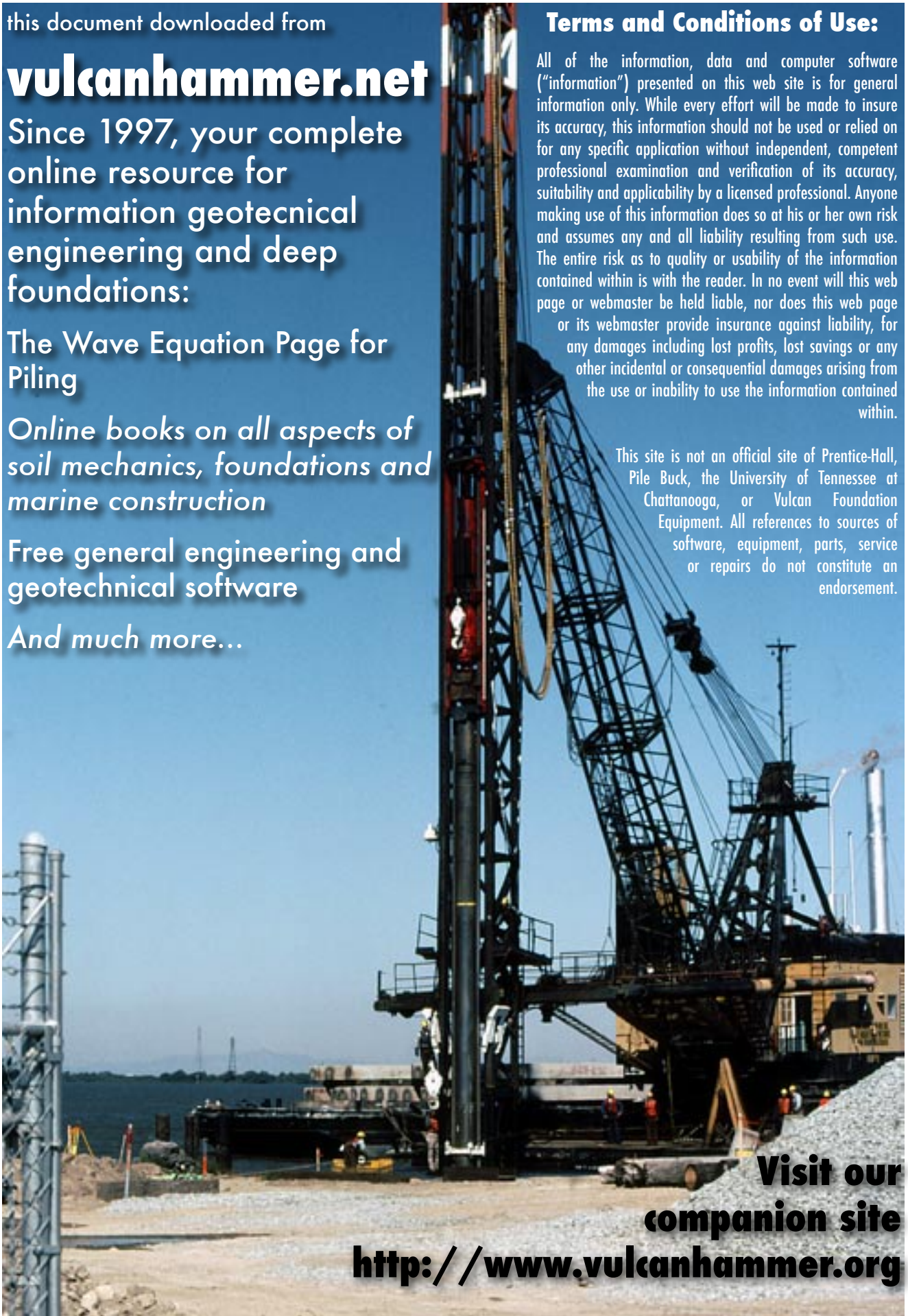
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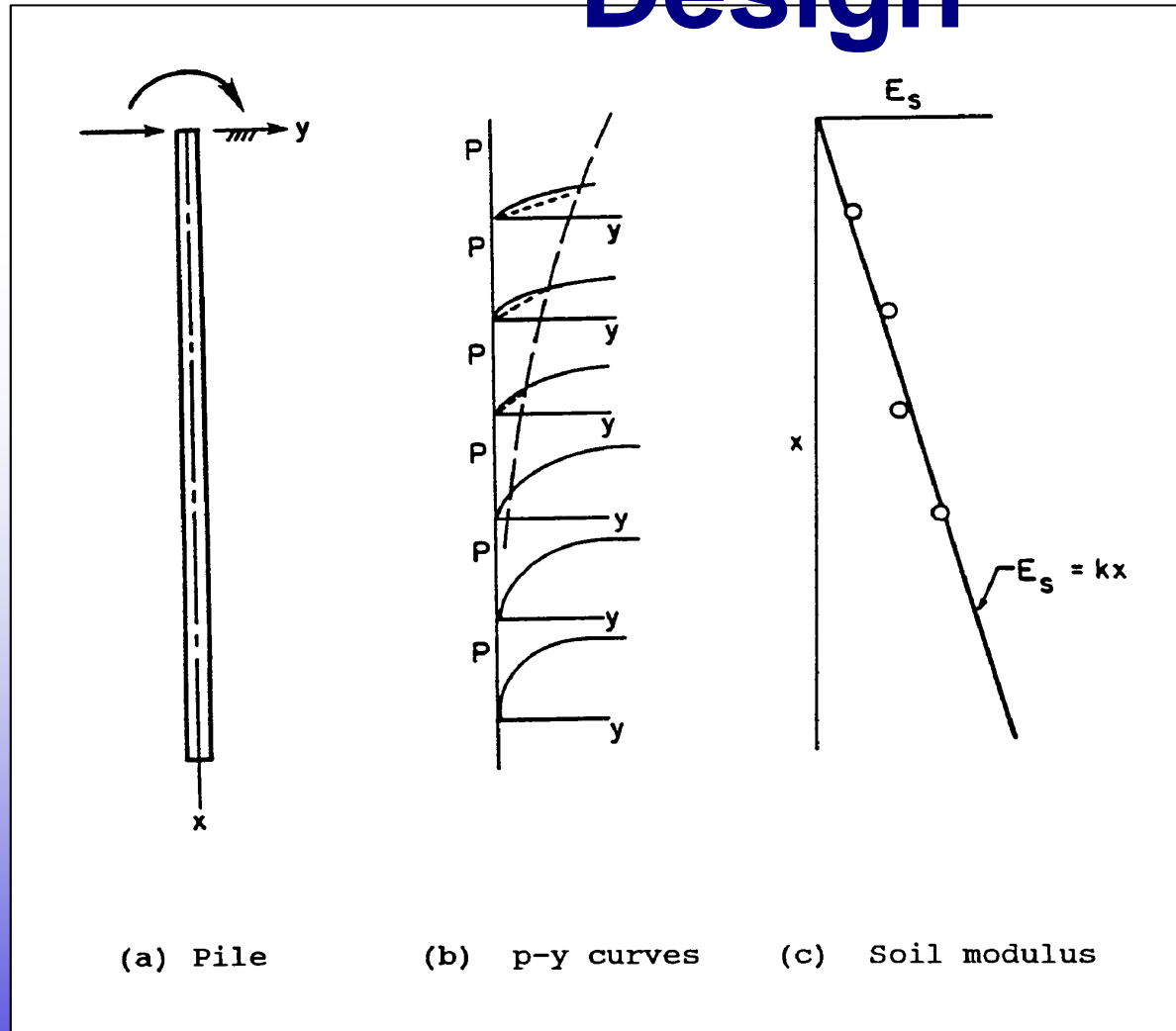
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ENCE 461

Foundation Analysis and Design



Lateral Loading of Piles
Design of Deep Foundations

Sources of Lateral Loading

- Earth pressures on retaining walls
- Wind Loads
- Seismic Loads
- Impact Loads from Ships (Berthing, Pier Collision, etc.)
- Eccentric Loads on Columns
- River current and mud movement loads in alluvial settings (foundations subject to scour)
- Ocean wave forces
- Slope movements
- Cable forces on transmission towers

Axial and Lateral Loads

VERTICAL LOAD, KIPS

$$Q < Q_u$$

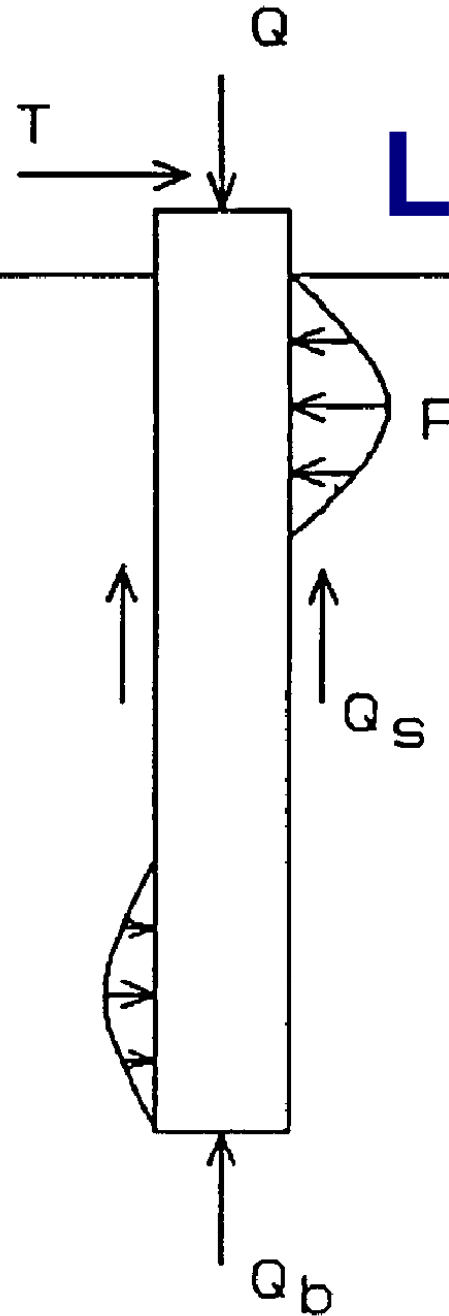
$$Q_u = Q_{bu} + Q_{su}$$

Q = APPLIED LOAD

Q_u = VERTICAL LOAD CAPACITY

Q_{bu} = BASE RESISTANCE CAPACITY

Q_{su} = SIDE FRICTION CAPACITY



LATERAL LOAD, KIPS

$$T < T_u$$

$$T_u = T_{us} + T_{up}$$

T = LATERAL LOAD

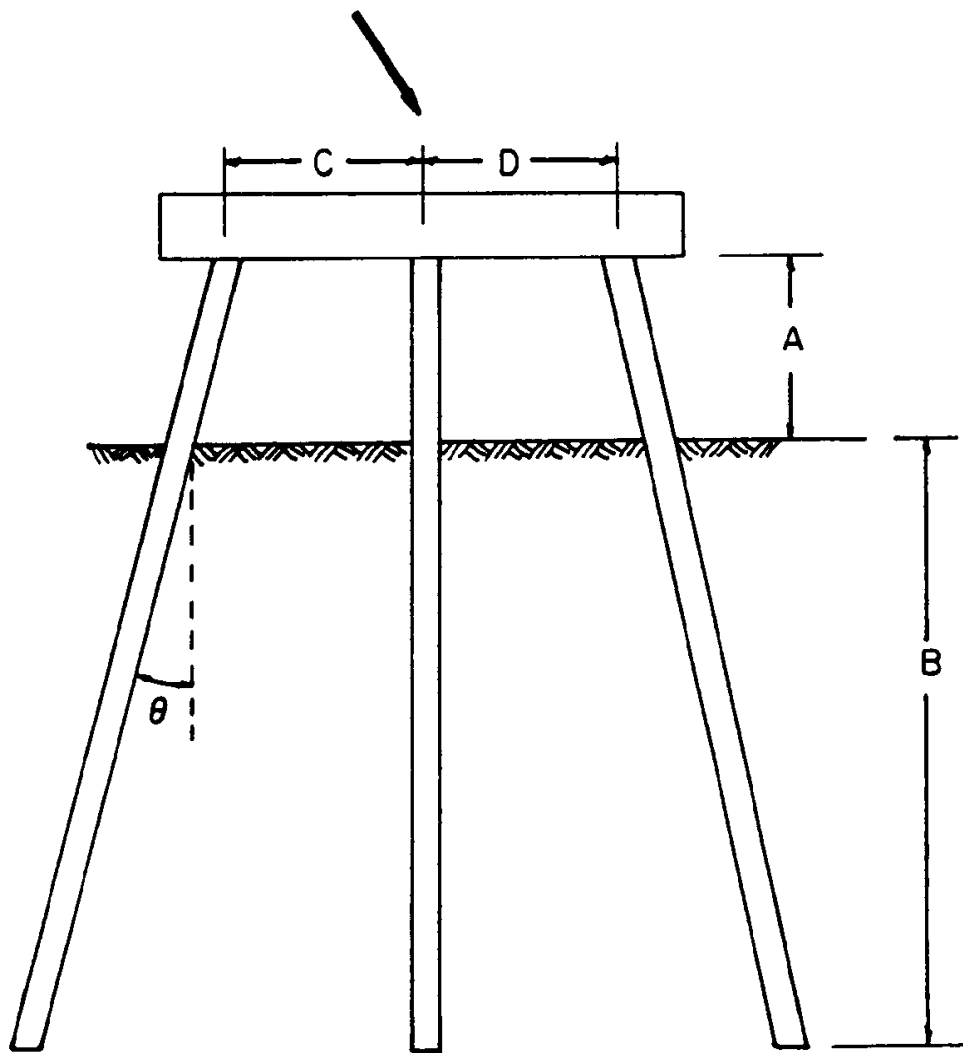
T_u = LATERAL RESISTANCE

T_{us} = LATERAL SOIL RESISTANCE

T_{up} = PILE SHEAR RESISTANCE

P = SOIL REACTION

Batter Piles



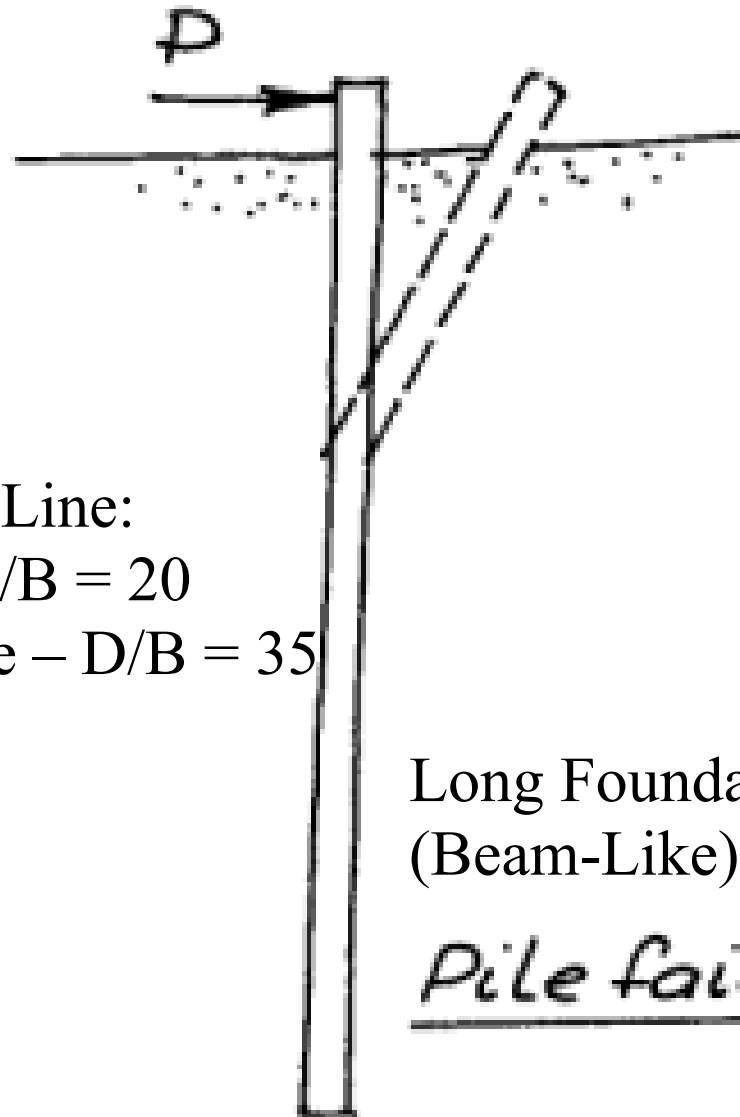
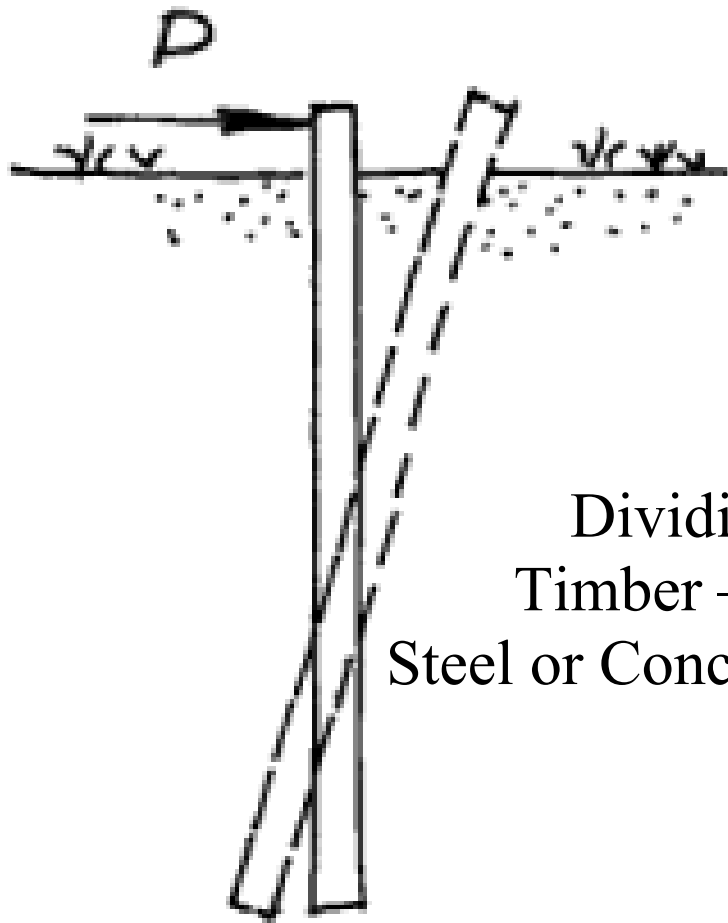
- Basically turn lateral loads into axial loads
- Present challenges in driving and testing
- Form a very stiff system than can pose problems in seismic situations
- Very common solution to lateral loading

Analytic Methods for Lateral Loading

- Rigid Methods (Broms)
 - Used for light weight « short » foundations
 - Same limitations as rigid methods for mat foundations
- Depth to Fixity Methods (Davisson)
 - Only considers a certain depth as flexible
 - Structural engineers could analyse the foundation as a structure once the depth of fixity was known
 - Too simplistic
- Finite Element Analysis
- p-y curves

Lateral Failure

Short vs. Long Foundations



Dividing Line:
Timber – $D/B = 20$
Steel or Concrete – $D/B = 35$

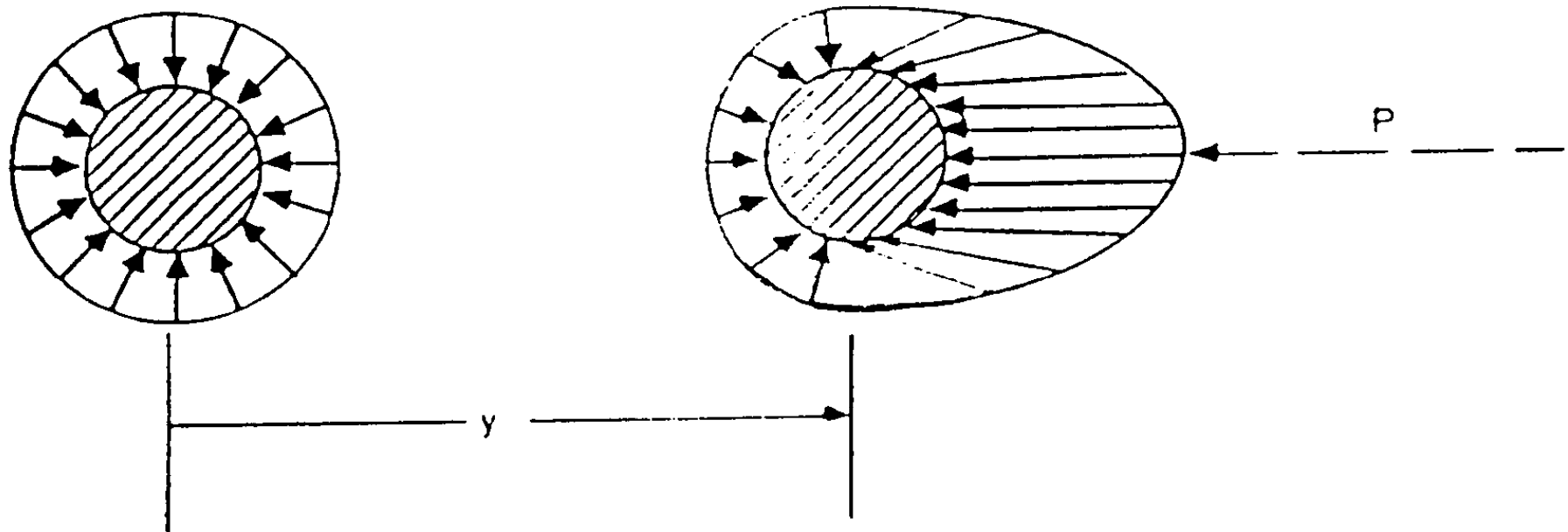
Long Foundations
(Beam-Like)

Soil failure

Pile failure

Short Foundations (Rigid)

Compression of Soil in Lateral Loading

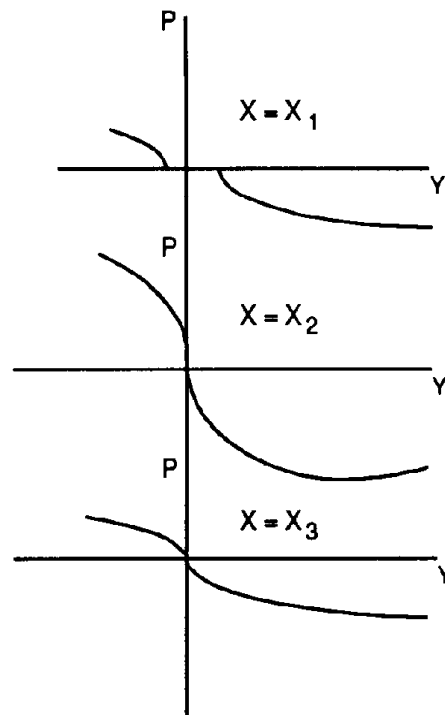
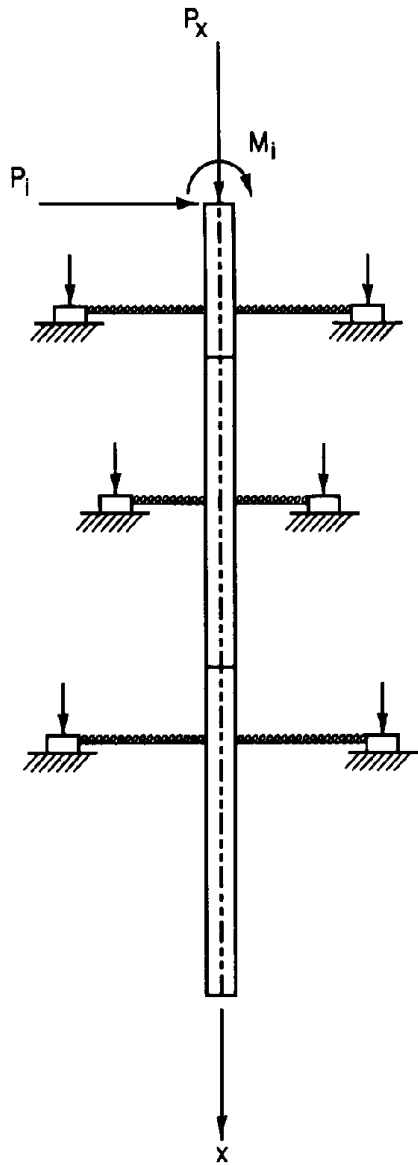


Suction on the load side
Additional stress on the far side

(a) Before bending

(b) After bending

p-y Curves

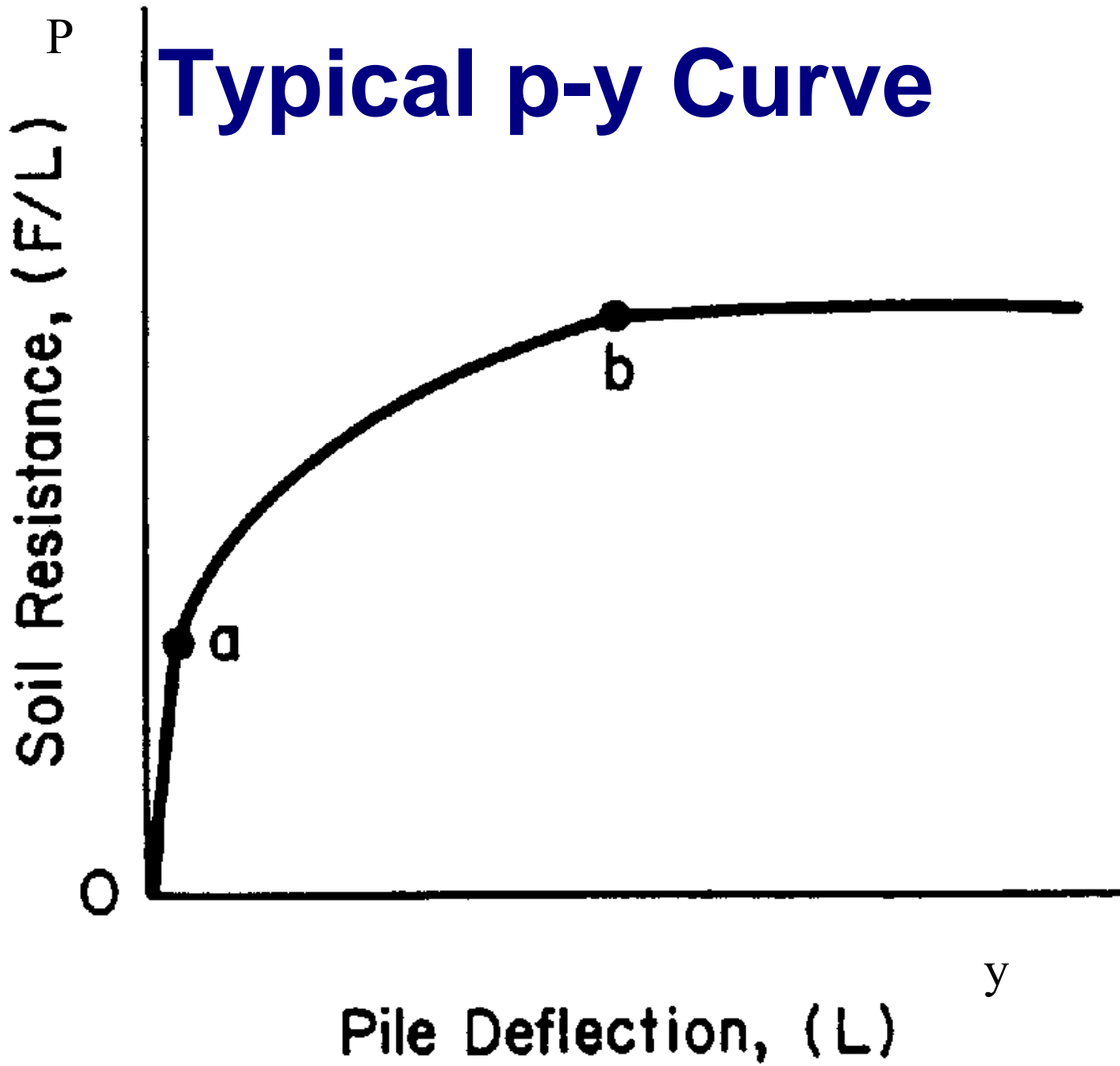


- Take into consideration nonlinear soil characteristics (as opposed to Winkler model)
- Properly require a finite-difference (COM624, LPILE) computer solution
- Non-dimensional solutions available for common problems

Development of p-y Curves

- Empirical Data
 - Based on actual lateral load tests, either on the job site itself or on controlled field tests
- Computer Programs
 - Model the lateral deflection of the pile as a function of depth
 - Take into consideration non-linear soil response
 - Can be difficult to use
- Non dimensional methods based on computer results or empirical data
 - Not as accurate as program, but suitable for estimates or smaller projects

Typical p-y Curve



Evans and Duncan Charts

- Based on the COM624G program
- Reduce the variables to nondimensional form
- Advantages
 - Analyses can be done quickly and simply
 - Can determine load-deflection characteristics directly
- Assumptions
 - Constant EI , s_u , or δ , and \tilde{a} for depth of pile
 - Foundation is long enough to be considered fixed at the toe ("long foundation" criterion)

Evans and Duncan Equations

- Characteristic shear and moment equations

$$V_c = \lambda B^2 ER_I \left(\frac{\sigma_p}{ER_I} \right)^m \varepsilon_{50}^n$$

$$M_c = \lambda B^3 ER_I \left(\frac{\sigma_p}{ER_I} \right)^m \varepsilon_{50}^n$$

Evans and Duncan Equations

- Stiffness ratio R_I
$$R_I = \frac{I}{\pi B^4}$$
$$64$$
 - $R_I = 1$ for circular cross-sections
 - $R_I = 1.7$ for solid square cross sections
- ε (based on soil's stress-strain behaviour)
 - 1 for plastic clay and sand
 - 0.14^n for brittle clay (residual strength \ll peak strength)

Evans and Duncan Equations

- V_c = characteristic shear load
- M_c = characteristic moment load
- B = diameter of foundation
- E = modulus of elasticity of foundation
- σ_p = representative passive pressure of soil

$$\sigma_p = 4.2 s_u (\text{clay})$$

$$\sigma_p = 2 C_{p\phi} \gamma B \tan^2 \left(45^\circ + \frac{\phi'}{2} \right) (\text{sand})$$

Evans and Duncan Equations

- ε_{50} = axial strain at which 50% of the soil strength is mobilised
 - Soft clay, 0.02
 - Medium clay, 0.01
 - Stiff clay, 0.005
 - Medium dense sand with little or no mica, 0.002
- I = moment of inertia of foundation
- s_u = undrained shear strength of soil
- φ' = effective friction angle (degrees)
 - Both s_u and φ' from ground surface to a depth of $8B$

Evans and Duncan Equations

- $C_{p\phi}$ = passive pressure factor = $\phi'/10$
- γ = unit weight of soil from ground surface to a depth of $8B$
 - Use a weighted average of both wet and buoyant weights
- m, n = exponents
 - V_c , clay: $m = 0.683, n = -0.22$
 - M_c , clay: $m = 0.46, n = -0.15$
 - V_c , sand: $m = 0.57, n = -0.22$
 - M_c , sand: $m = 0.40, n = -0.15$

Evans and Duncan Example

- Given

- Concrete Pile
 - Restrained head
 - 60' long, 12" square
 - $f'_c = 6000$ psi
- Shear load = 20 kips
- Soil: Sand, $\phi' = 36$ deg., $\gamma = 120$ pcf
- Groundwater table at depth of 40'

- Find

- Lateral deflection of the pile top
- Maximum moment at pile top

- Solution

- $\lambda = 1$ (sand); $R_I = 1.7$ (square pile)

- $C_{p\phi} = 36/10 = 3.6$

- $$\sigma_p = 2C_{p\phi}\gamma B \tan^2\left(45^\circ + \frac{\phi'}{2}\right) (\text{sand})$$

$$\sigma_p = 23.1 \text{ psi}$$

- $E = 4,400,000$ psi (concrete @ 6000 psi)

Evans and Duncan Example

- Compute characteristic shear force and moment

$$V_c = \lambda B^2 ER_I \left(\frac{\sigma_p}{ER_I} \right)^m \varepsilon_{50}^n$$

$$V_c = 1 \times 12^2 \times 4,400,000 \times 1.7 \times \left(\frac{23.1}{4,400,000 \times 1.7} \right)^{0.57} \times 0.002^{-0.22}$$

$$V_c = 3,056,000 \text{ lbs.}$$

$$\frac{V}{V_c} = \frac{20,000}{3,056,000} = 0.0065$$

Evans and Duncan Example

- Charts for Evans and Duncan Method
 - Shear Load vs. Lateral Deflection Curves
 - Clay, Free Head Condition
 - Clay, Restrained Head Condition
 - Sand, Free Head Condition
 - ~~Sand, Restrained Head Condition~~
 - Moment Load vs. Lateral Deflection Curves for Free Head Condition
 - Clay, Free Head Condition
 - Sand, Free Head Condition

Evans and Duncan Example

- Charts for Evans and Duncan Method
 - Shear Load vs. Maximum Moment Condition
 - Clay, Free Head Condition
 - Clay, Restrained Head Condition
 - Sand, Free Head Condition
 - ~~Sand, Restrained Head Condition~~

Evans and Duncan Example

- Using Shear Load vs. Lateral Deflection chart, compute pile head deflection

$$V/V_c = 0.0065$$

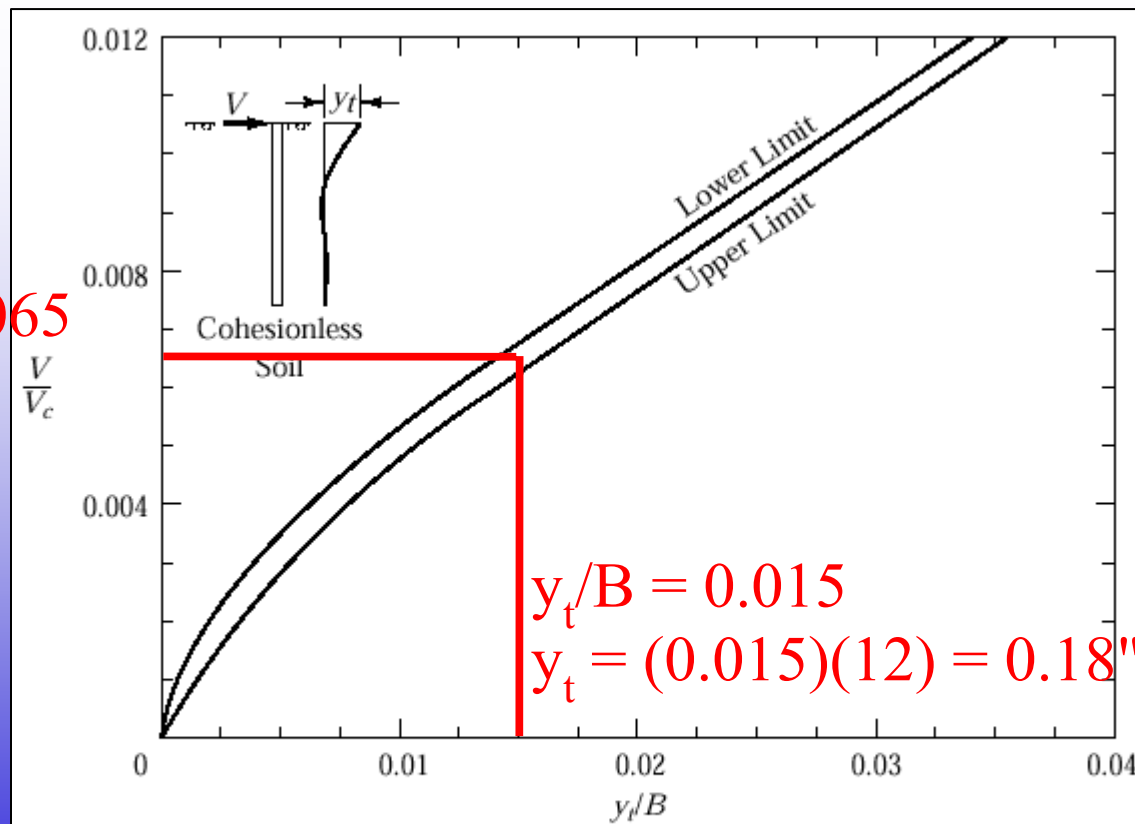


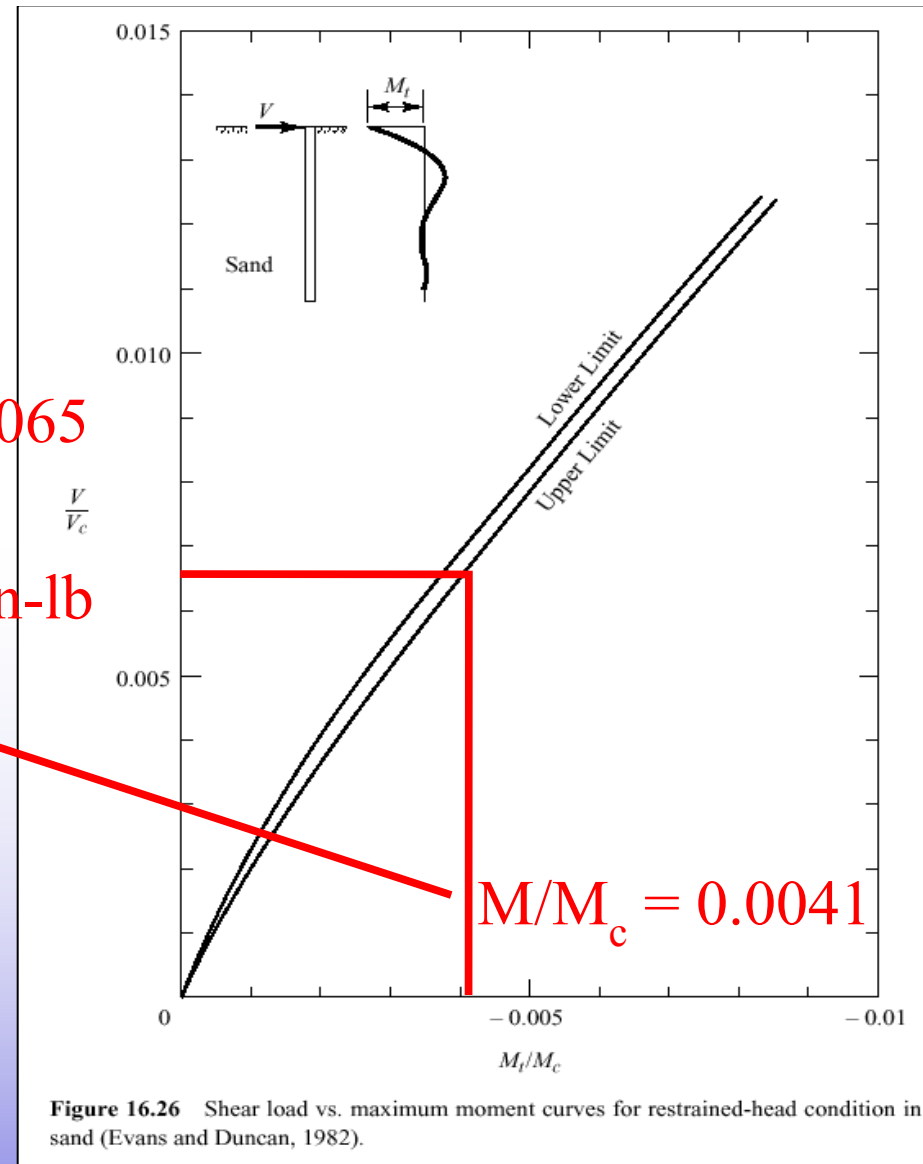
Figure 16.23 Shear load vs. lateral deflection curves for restrained-head condition in sand (Evans and Duncan, 1982).

Evans and Duncan Example

$$V/V_c = 0.0065$$

$$M = (0.0041)(205,200,000) = 841,000 \text{ in-lb}$$

- Compute characteristic pile head moment



$$M_c = \lambda B^3 ER_I \left(\frac{\sigma_p}{ER_I} \right)^m \epsilon_{50}^n$$

$$M_c = 1 \times 12^3 \times 4,400,000 \times 1.7 \times \left(\frac{23.1}{4,400,000 \times 1.7} \right)^{0.4} \times 0.002^{-0.15}$$

$$M_c = 205,200,000 \text{ in-lb}$$

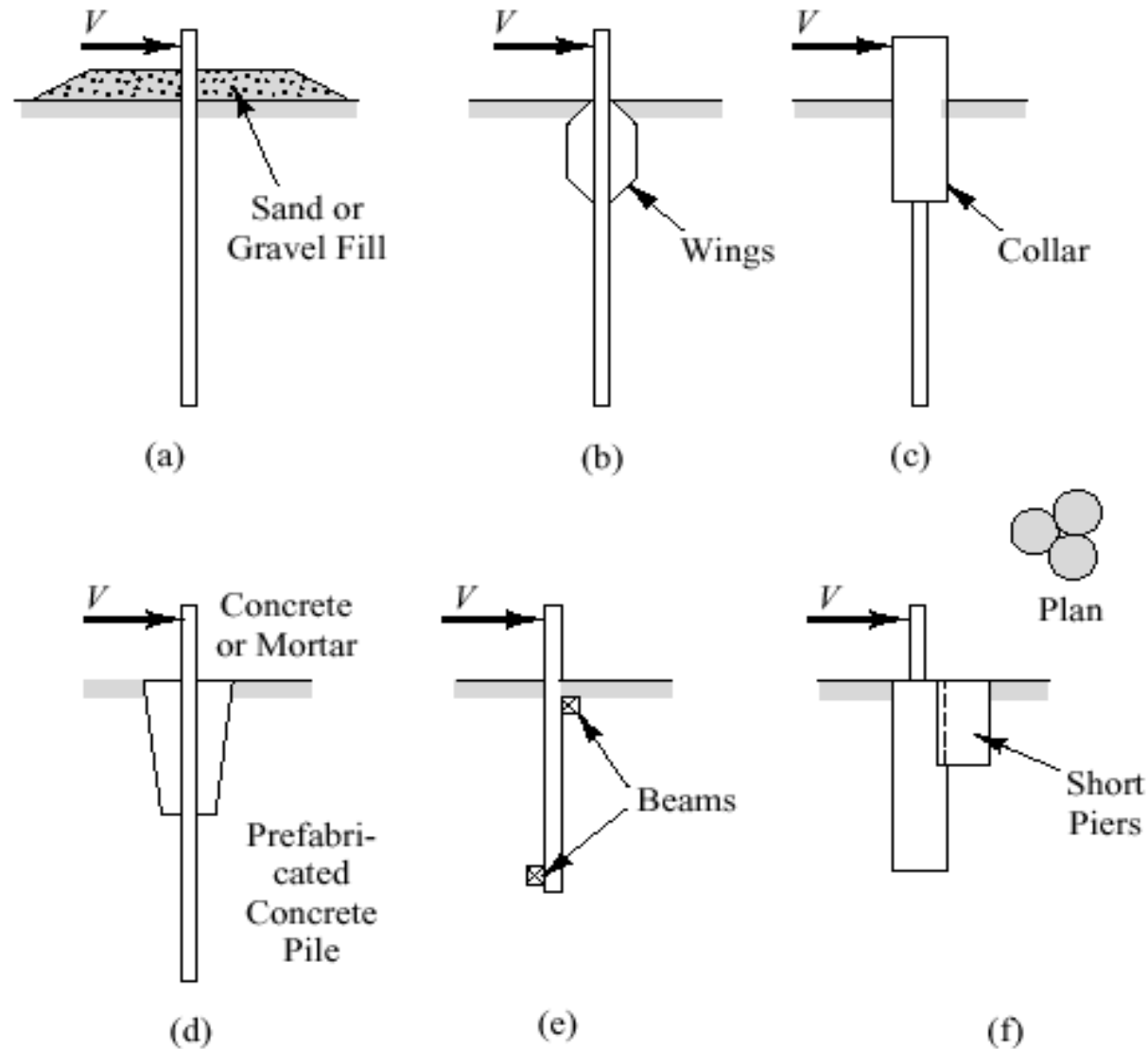
Group Effects with Lateral Piles

- Group effects are important with laterally loaded piles as they are with axial ones
- The effect is usually called the PSPI (pile-soil-pile-interaction), or shadow effect
 - The soil stress created by lateral loads around one pile will extend to the pile's neighbours, depending upon the distance between the piles and the level of stress
 - The lateral capacity of each pile is generally degraded by this effect
- Methods of solution use p-y curve methods and consider spacings and pile deflections

Lateral Load Verification

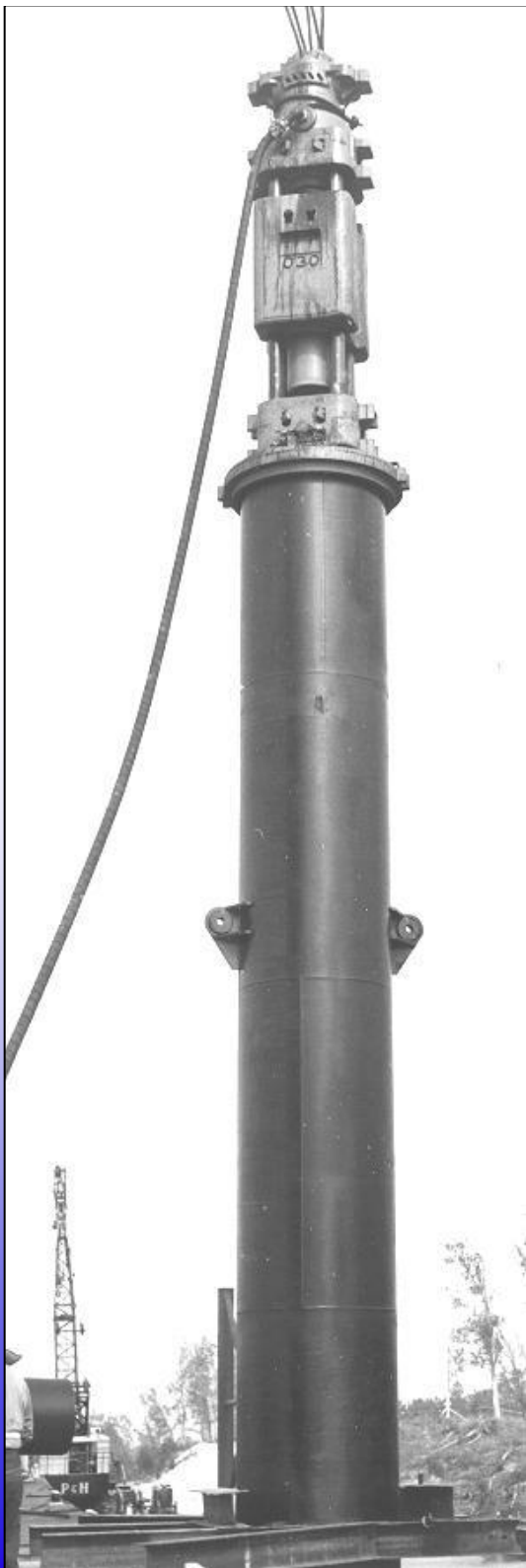
- Full-scale lateral load tests
 - As with axial tests, slow and expensive, but the best way to determine lateral load capacity
 - Always a reaction test
 - Can be used to back calculate p-y curves
- Model lateral load tests
 - Conditions are controlled, but extrapolation is difficult
- Lateral Static Tests
 - Only used as an impact load test

Improving Lateral Load Capacity



Design of Deep Foundations

- Service loads and allowable deformations
- Subsurface investigations
- Type of Foundation
- Lateral and Axial Load Capacity
- Driveability
- Structural Design
- Seismic Design
- Verification and Redesign
- Integrity Testing



Service loads and allowable deformations

- Most important step
- Loads can include
 - Axial loads (live or dead, tensile or compressive)
 - Lateral loads (live or dead)
 - Moment loads
- Should be combined both as unfactored loads (ASD) or factored loads (LRFD)
- Allowable settlements should be determined by structural engineer

Subsurface investigations

- For deep foundations, the subsurface investigations are generally more intensive and expensive
- Exploratory borings must extend well below the toe elevation, which may have to be altered after initial calculations
- Investigations assist in determining the type of foundation that should be used
- Use data from deep foundations that have already been installed in the vicinity (capacity and drivability)

Type of Foundation

- Type of Foundation is influenced by:
 - Design Loads
 - Subsurface Conditions
 - Constructibility
 - Reliability
 - Cost
 - Availability of materials, equipment and expertise
 - Local experience and precedent

Lateral and Axial Load Capacity

- Lateral Loads
 - Frequently dictate the diameter (section modulus) of the foundation, so should be considered first, if present
 - p-y curves are the best way of determining lateral capacity
 - Large diameter piles may also be necessary for scour resistance
 - Batter piles are also a typical way of dealing with lateral loads, but can pose rigidity problems in seismic situations
 - Seismic retrofits are a common application of laterally loaded piles

Lateral and Axial Load Capacity

- Axial loads
 - Analytic methods should be performed first, although their limitations should be understood
 - Analysis should include considerations of allowable load, allowable settlement, and group effects (including block failure)
 - Ideally, a static load test on test piles should be done; however, if economic or other factors make this impractical, other methods such as Osterberg Tests, CAPWAP, or Statnamic should be considered
 - Blow count specifications using a wave equation analysis are acceptable on smaller projects

Driveability

- Piles that cannot be driven cannot be used to support loads; thus, drivability is an important consideration with driven piles
- Wave equation methods are ideal to use for drivability studies
- Deep foundations must be designed and analysed to meet criteria for
 - Reasonable cost
 - Sufficient capacity
 - Possible drivability



Structural Design

- Once the geotechnical analysis is done, the structural engineer can proceed with the structural design
- Structural design involves both the structural capacity of the deep foundations themselves and the pile caps and connecting members that are above these members
- Plans and specifications presented for bid should be complete and unambiguous

Seismic Design

- In seismically active areas, earthquake occurrence must be taken into consideration
- Liquefaction of soils is a major cause of failure during seismic events
 - Deep foundations can be installed beyond liquefying soils in some cases
 - Soil improvement is necessary in others
- Most direct seismic loads on foundations are lateral ones so lateral load analysis is important for seismic resistance
- Batter piles tend to be too rigid for seismic loads

Special Considerations

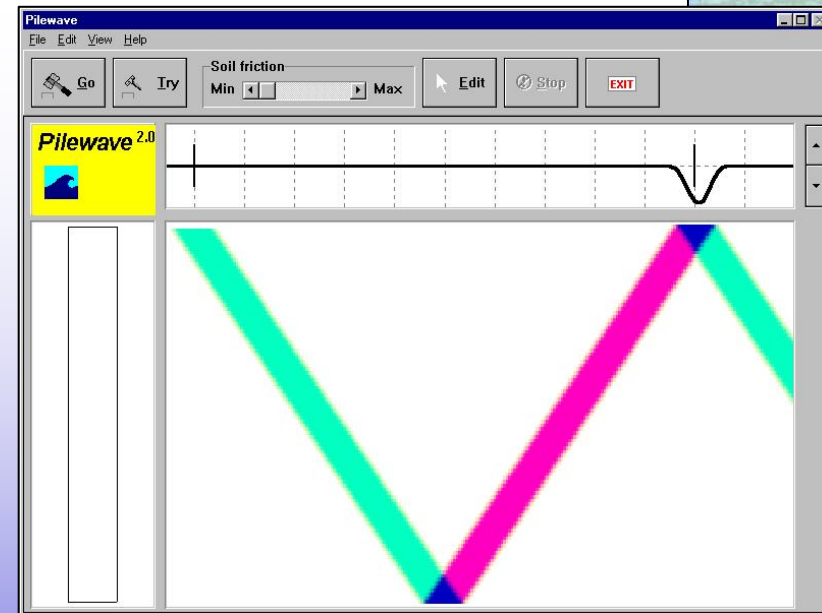
- Scour
 - Scour is an important consideration for bridges over rivers or other bodies of water with consistent currents
 - Loss of supporting soil at the head of the deep foundation must be considered when designing for scour
- Downdrag
 - Compression of soil by overburden around piles creates downdrag on piles
 - This is dealt with either by design or by treatment of the surface of the pile

Verification and Redesign

- Redesign during construction is to be avoided but is sometimes necessary due to differences in the subsurface conditions between what was estimated and what actually takes place
- Dynamic testing (Case Method, CAPWAP) is a useful tool to evaluate the need for redesign but must be used with good judgement
- Drilled shafts and the cuttings from boring should be inspected before and during the placement of concrete

Integrity Testing

- Integrity testing includes methods such as
 - Sonic logging
 - Nuclear logging
 - Vibration analysis
 - Stress-wave propagation (PIT)
 - Tomography
- Especially important with drilled shafts where quality control is critical



Questions

