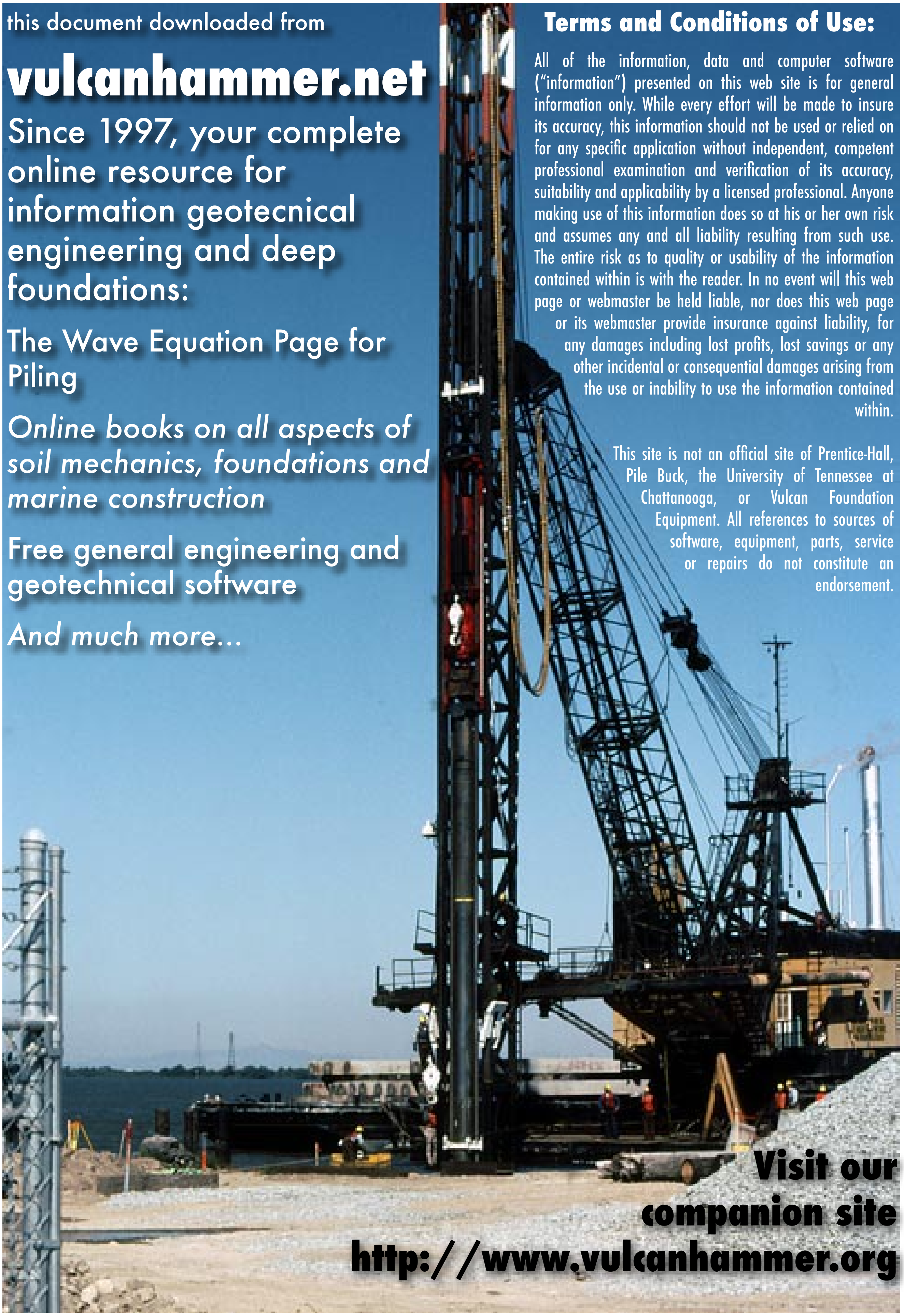
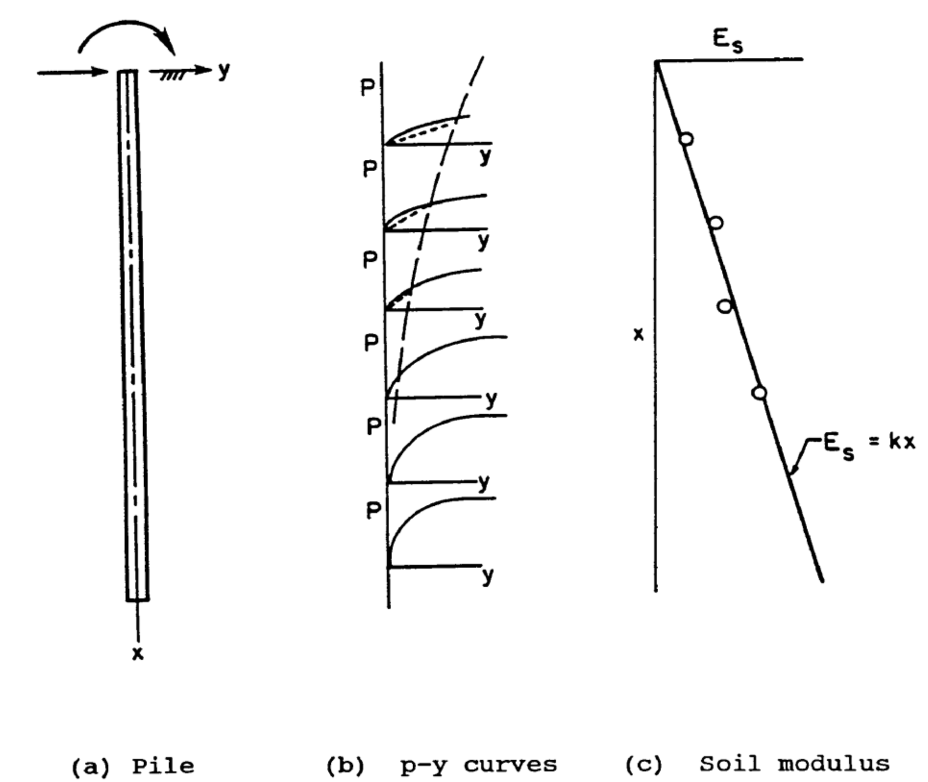


ENCE 4610
Foundation Analysis and Design

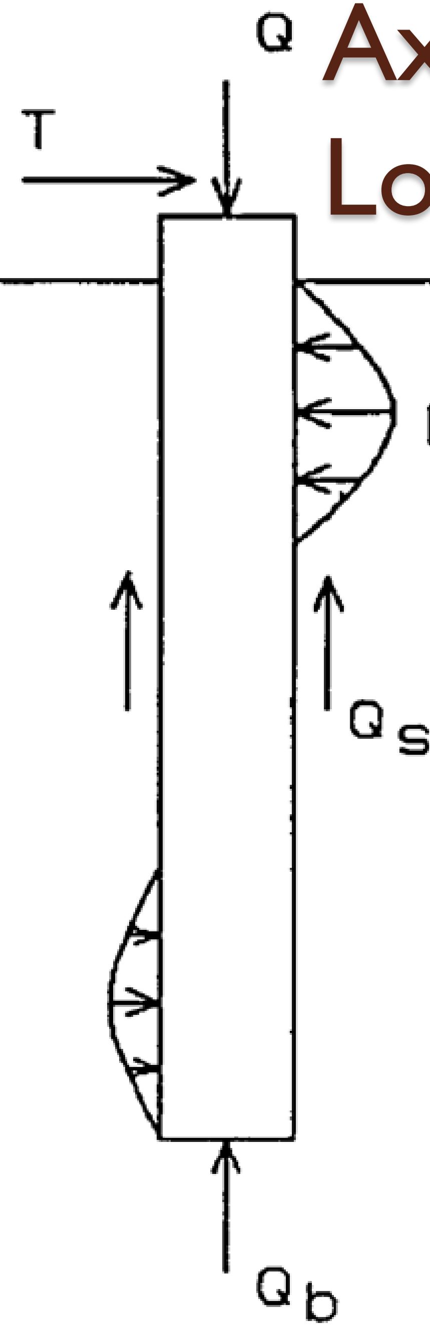
Lateral Loading of Piles
Design of Deep Foundations



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

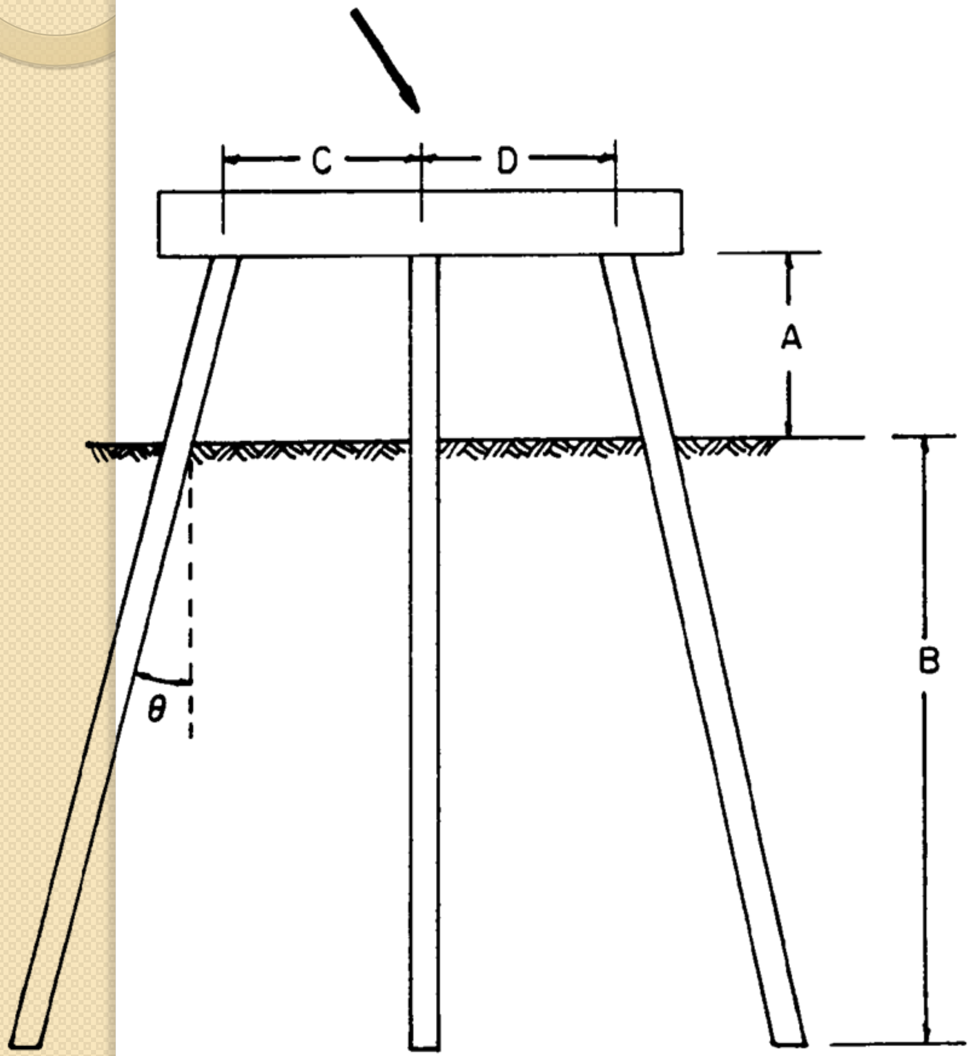
T_u = LATERAL RESISTANCE

T_{us} = LATERAL SOIL RESISTANCE

T_{up} = PILE SHEAR RESISTANCE

P = SOIL REACTION

Batter Piles

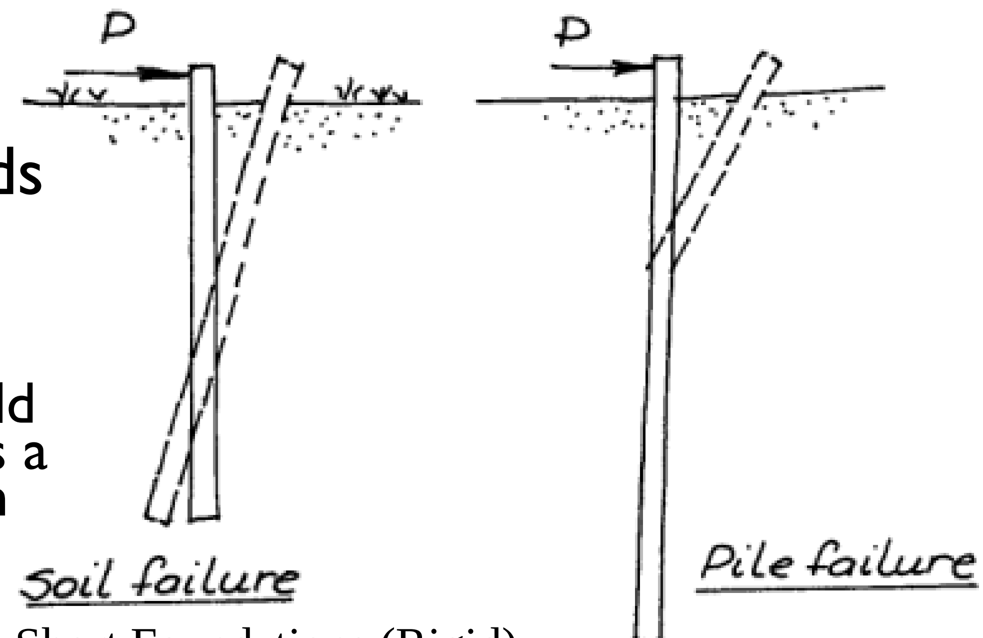


- Basically turn lateral loads into axial loads
- Present challenges in driving and testing
- Form a very stiff system than can pose problems in seismic situations
- Very common solution to lateral loading

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

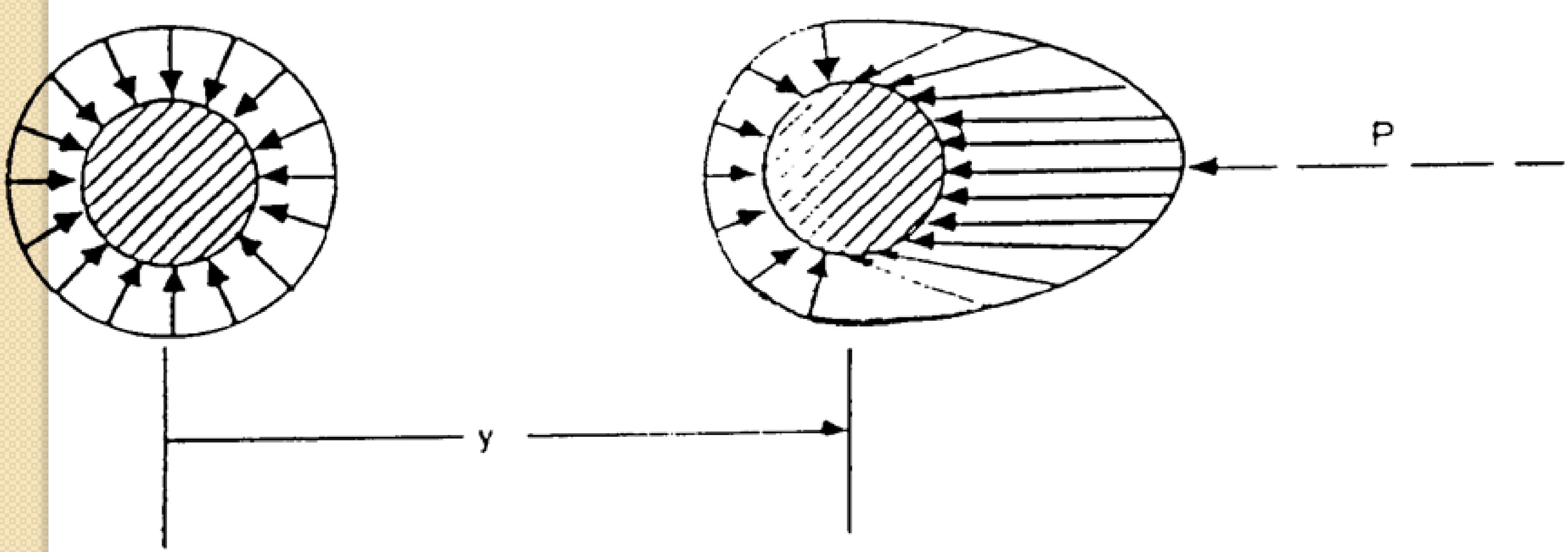
Dividing Line:
Timber – D/B = 20
Steel or Concrete – D/B = 35



Short Foundations (Rigid)

Long Foundations (Beam-Like)

Compression of Soil in Lateral Loading

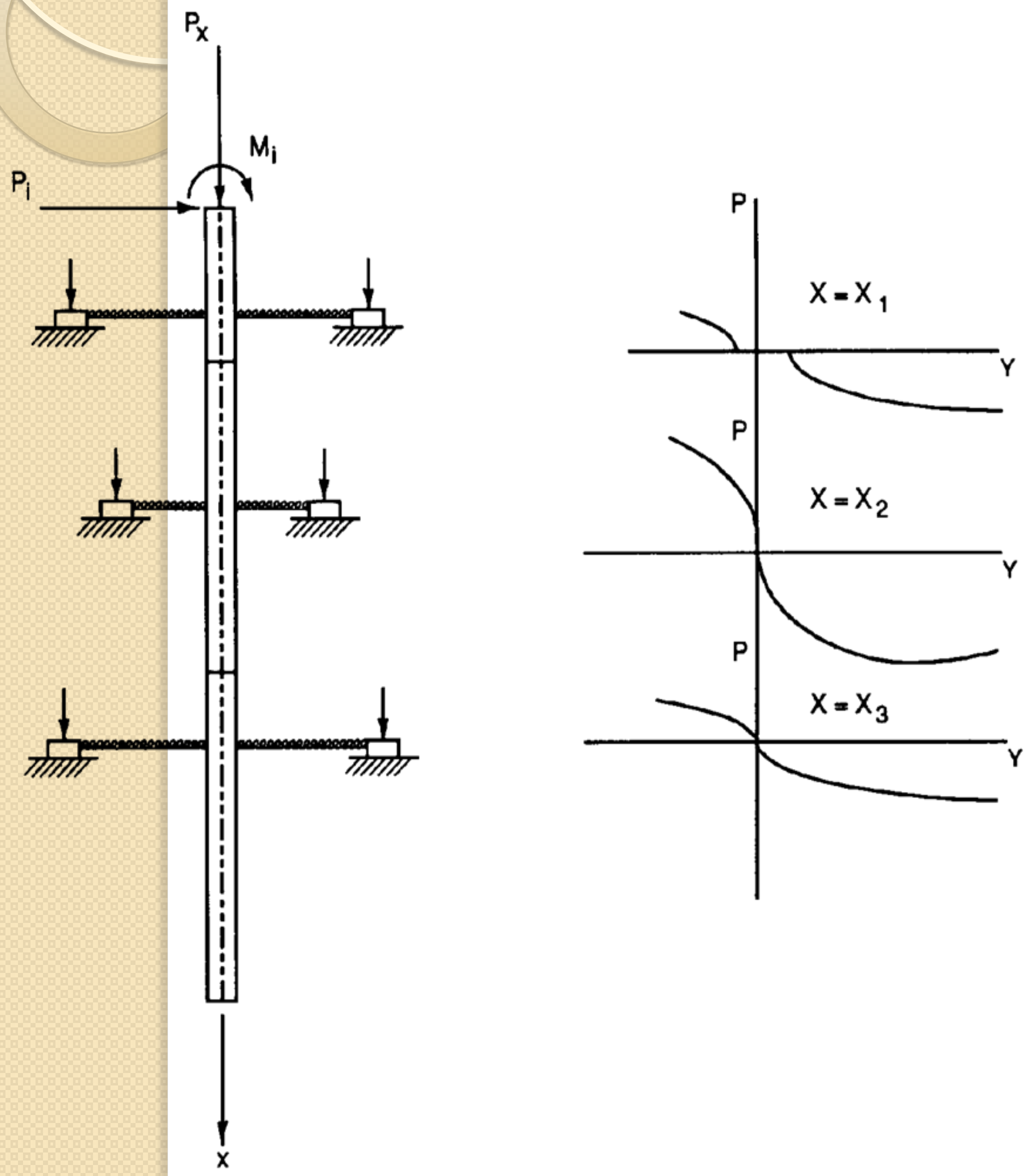


Suction on the load side
Additional stress on the far side

(a) Before bending

(b) After bending

p-y Curves

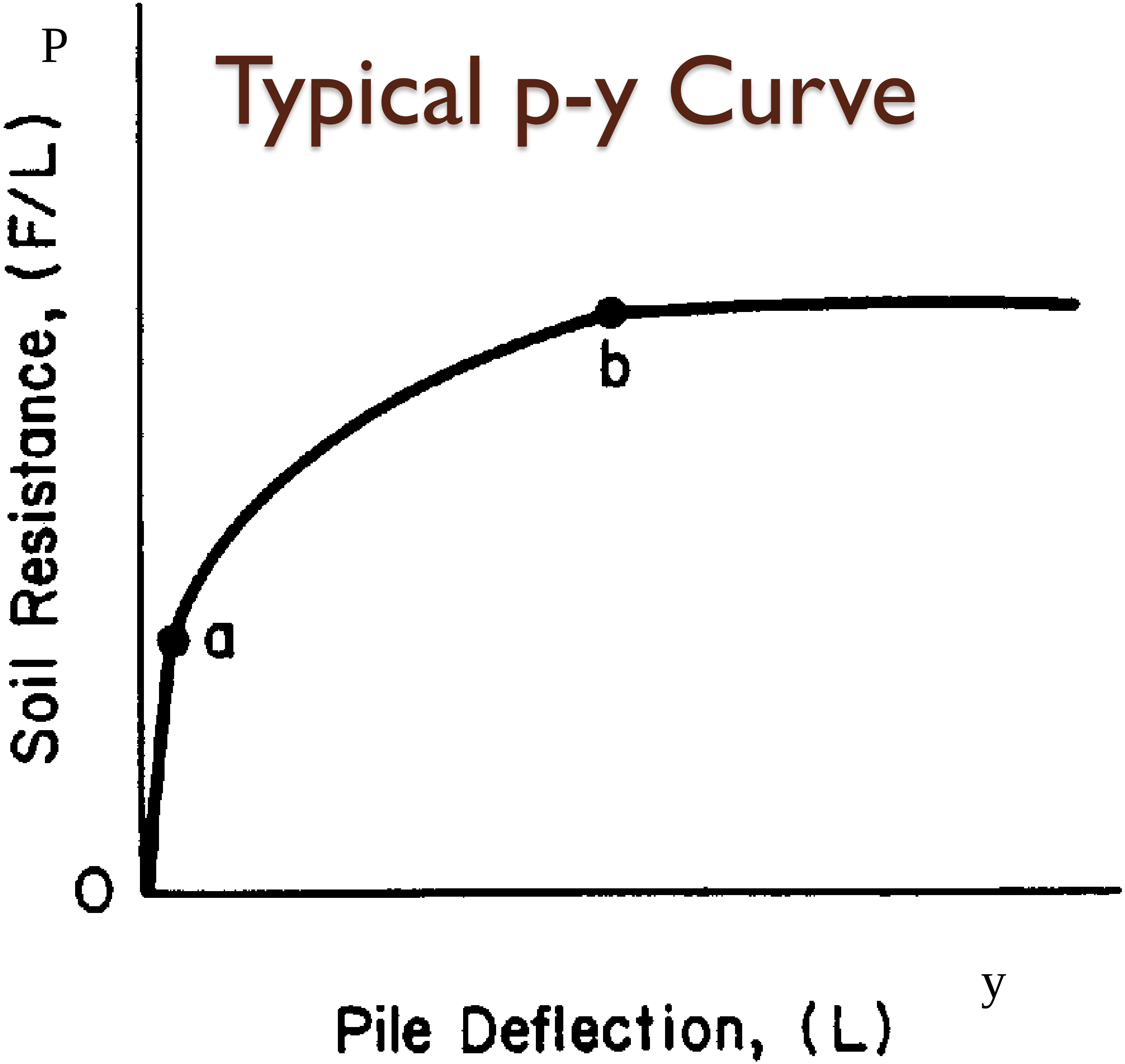


- Take into consideration nonlinear soil characteristics (as opposed to Winkler model)
- Properly require a finite-difference (COM624, LPILE) computer solution
- Non-dimensional and spreadsheet solutions available for common problems

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 φ, and γ for depth of pile
  - Foundation is long enough to be considered fixed at the toe ("long foundation" criterion)
- Method also embodied in CLM2 spreadsheet

Evans and Duncan Equations

- Characteristic shear and moment equations

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

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

- Stiffness ratio R_I

$$R_I = \frac{I}{\frac{\pi B^4}{64}}$$

  - 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 << 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

$$\sigma_p = 4.2 s_u (clay)$$

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

- 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
- $C_{p\phi}$ = passive pressure factor = ϕ'/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, ϕ' = 36 deg., γ = 120 pcf
  - Groundwater table at depth of 40'
- Find
  - Lateral deflection of the pile top
  - Maximum moment at pile top

- Solution
  - λ = 1 (sand); R_I = 1.7 (square pile)
  - $C_{p\phi}$ = 36/10 = 3.6
  -

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

$$\sigma_p = 23.1 psi$$

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

Evans and Duncan Example

- Compute characteristic shear force and moment

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

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

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

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

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

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

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

- Compute characteristic pile head moment

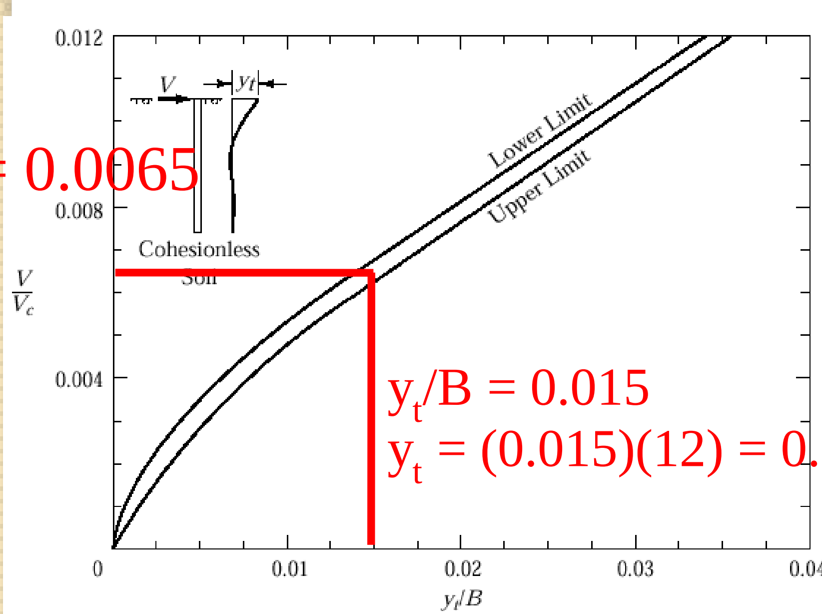
Evans and Duncan Example

- 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
- 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
- Using Shear Load vs. Maximum Moment chart, compute maximum moment

$V/V_c = 0.0065$

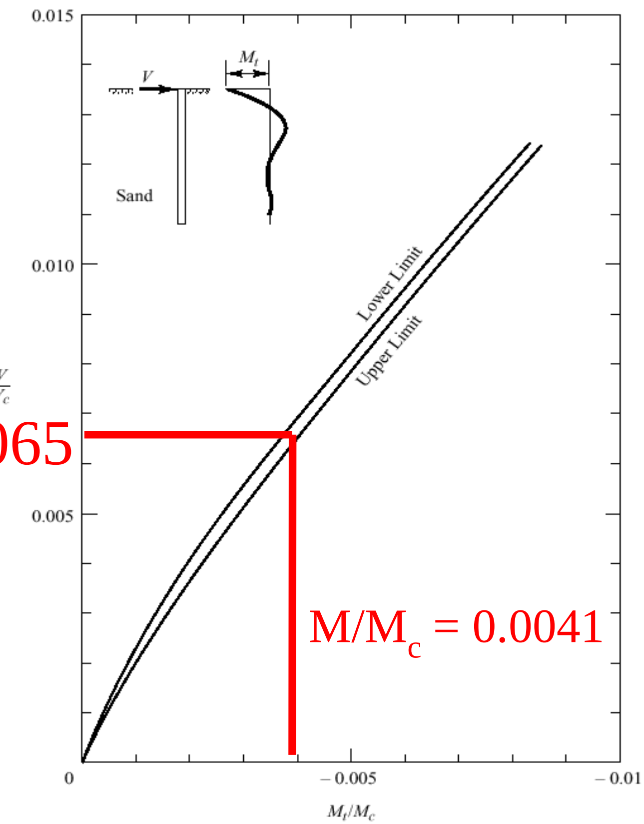


$y_t/B = 0.015$

$y_t = (0.015)(12) = 0.18''$

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

$V/V_c = 0.0065$



$M/M_c = 0.0041$

Figure 16.26 Shear load vs. maximum moment curves for restrained-head condition in sand (Evans and Duncan, 1982).

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

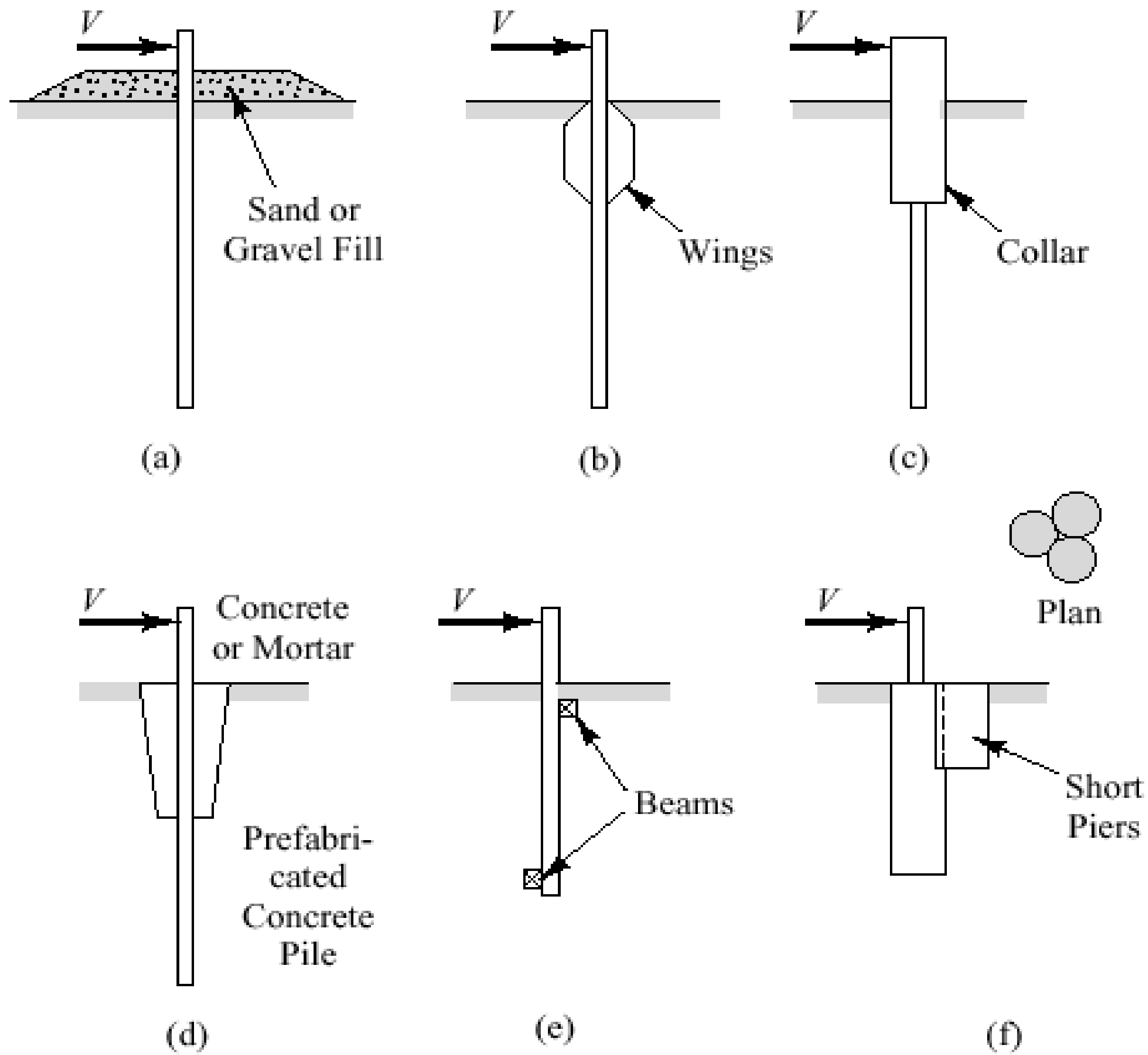
Group Effects with Lateral Piles

- 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 Statnamic 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

Design of Deep Foundations

- 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
- 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 and Seismic Design

- 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

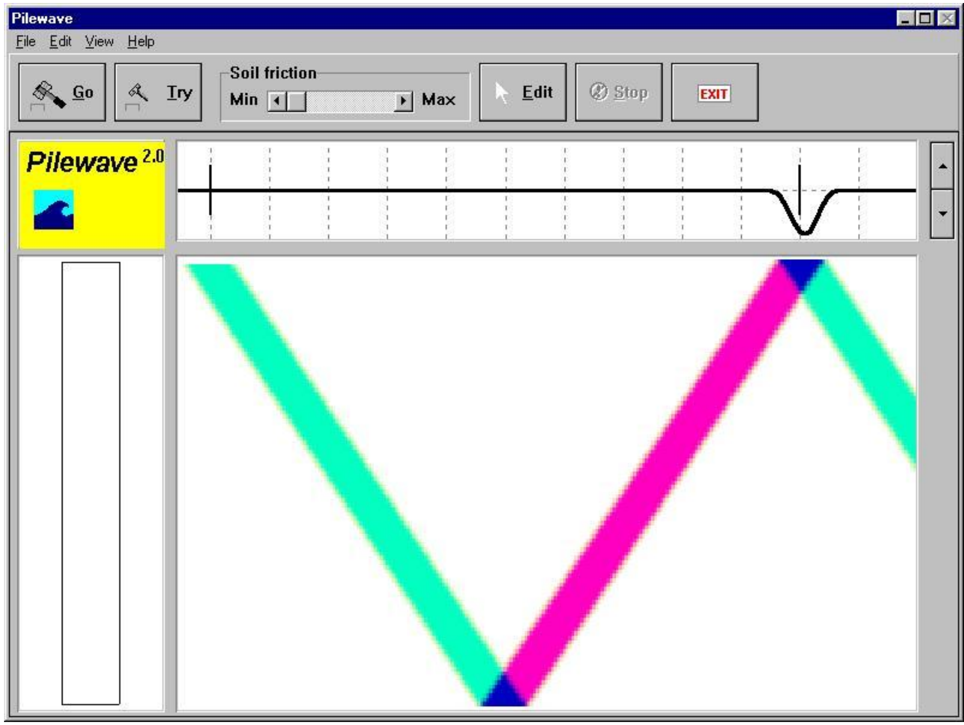
- Scour
  - Scour is an important consideration for bridges over rivers or other bodies of water with consistent currents
  - Loss of supporting soil at the head of the deep foundation must be considered when designing for scour
- Downdrag
  - Compression of soil by overburden around piles creates downdrag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