

SOIL MECHANICS II
CIVL 311
COURSE NOTES
2012

Module 8 – Segment C
Design of Deep Foundations

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Module 8

Design of Deep Foundations

Overall Learning Objectives

- Introduction – Deep Foundations (Book 2 pp. 274 - 280)
- Ultimate Limit State – load capacity of single piles (Book 2 pp. 280 – 297, 313 - 316)
- Serviceability Limit State – settlement of piles and pile groups (Book 2 pp. 298 – 313)
- Lateral Loading of Piles (Book 2 pp. 317 – 323)
- Design Issues and Procedures (Book 2 pp. 324 – 332)

SOIL MECHANICS II

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COURSE NOTES

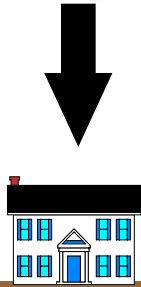
Load Capacity of Pile Groups



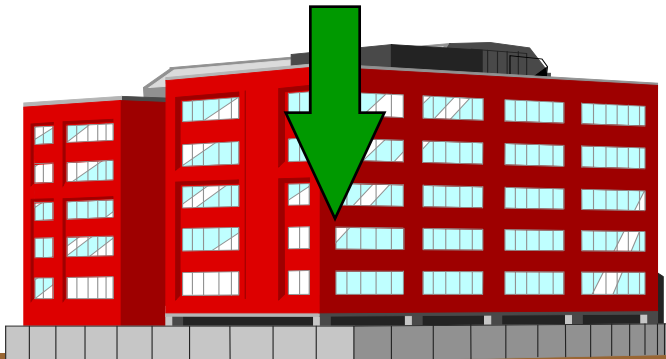
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Selection of foundation scheme

Low Weight



Large Distributed Weight



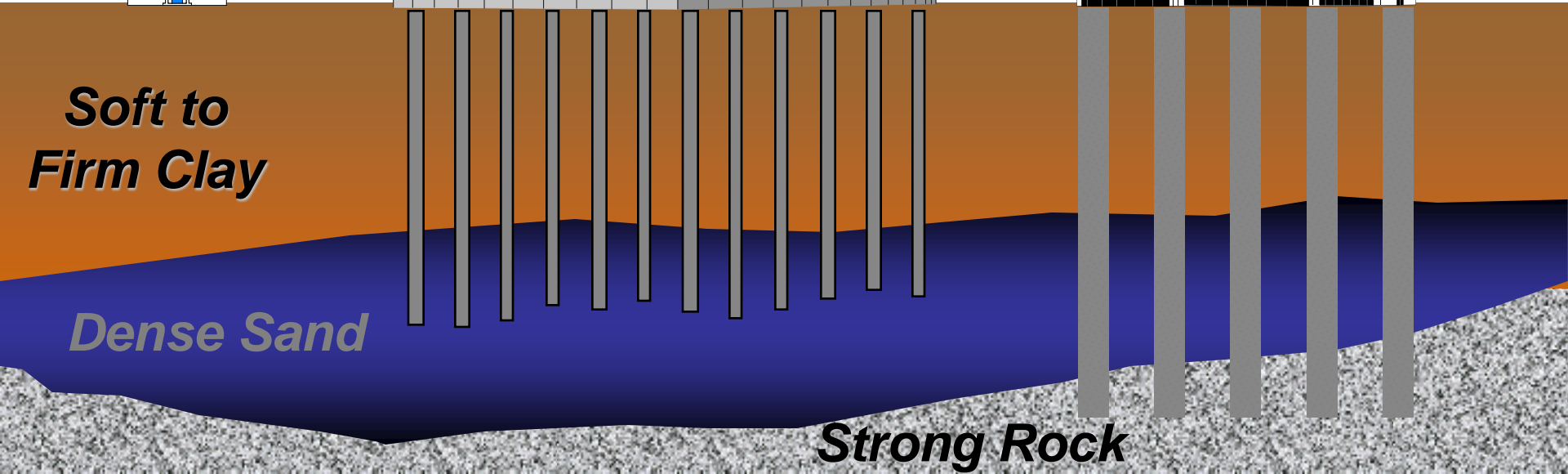
Very Large Concentrated Weight



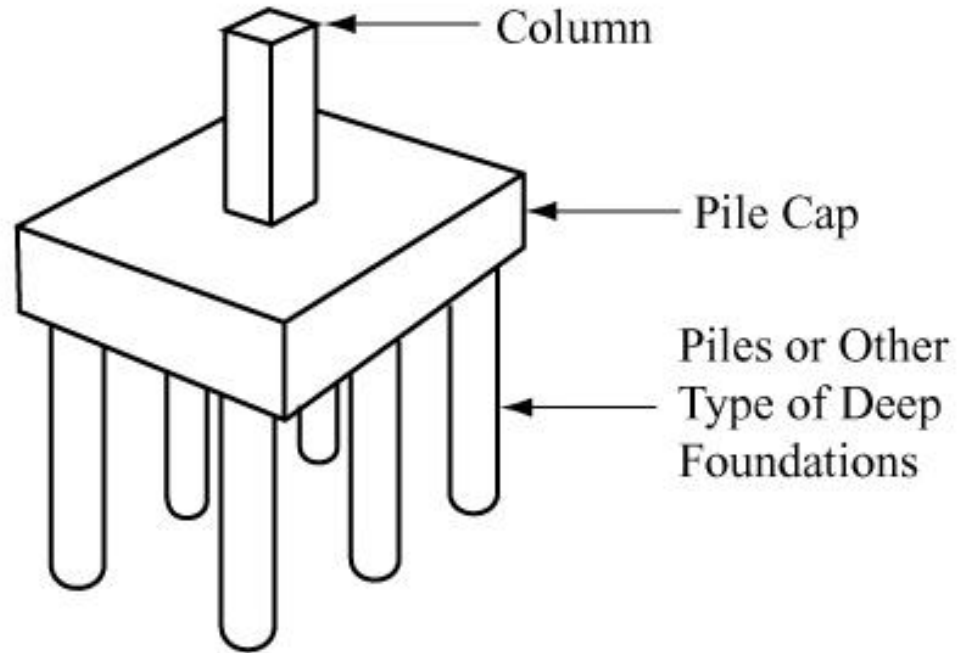
Soft to Firm Clay

Dense Sand

Strong Rock



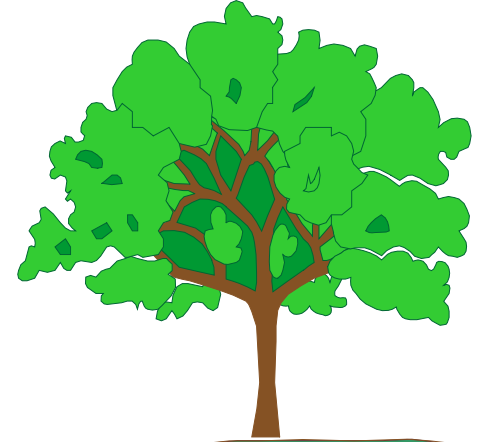
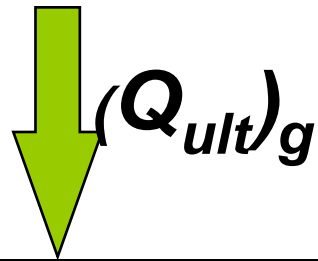
Pile Cap



A pile cap is a structural member that connects the piles in a group.

Design of pile groups

- Group capacity
- Effect of pile cap
- Group settlement



Pile Cap

- ***Overlapping stress fields***
- ***Progressive densification***
- ***Progressive loosening***
- ***Case-by-case basis***

$$(Q_{ult})_g \neq n \cdot Q_{ult}$$

$$\eta_e = (Q_{ult})_g / n \cdot Q_{ult}$$

Group efficiency-depends on

- Number, length, diameter, arrangement and spacing of piles
 - (Typical centre to centre pile spacing = $2.5D$ to $3D$)
- Installation procedures and sequence
- Side friction vs. end-bearing
- Elapsed time since installation
- Effect of pile cap
- Direction of applied load

Pile Group Failure Modes

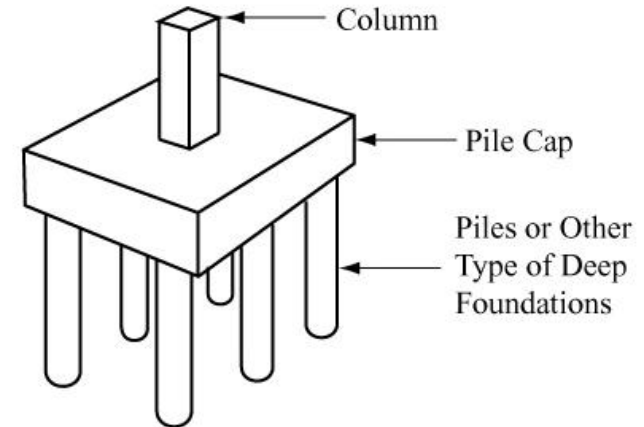
– BLOCK FAILURE

Pile layout matrix = $m \times n$

$$\text{Area} = [(m-1)s + D] [(n-1)s + D]$$

$$\text{Perimeter} = 2[(m-1)s + D] + 2[(n-1)s + D]$$

Where, s = centre to centre pile spacing

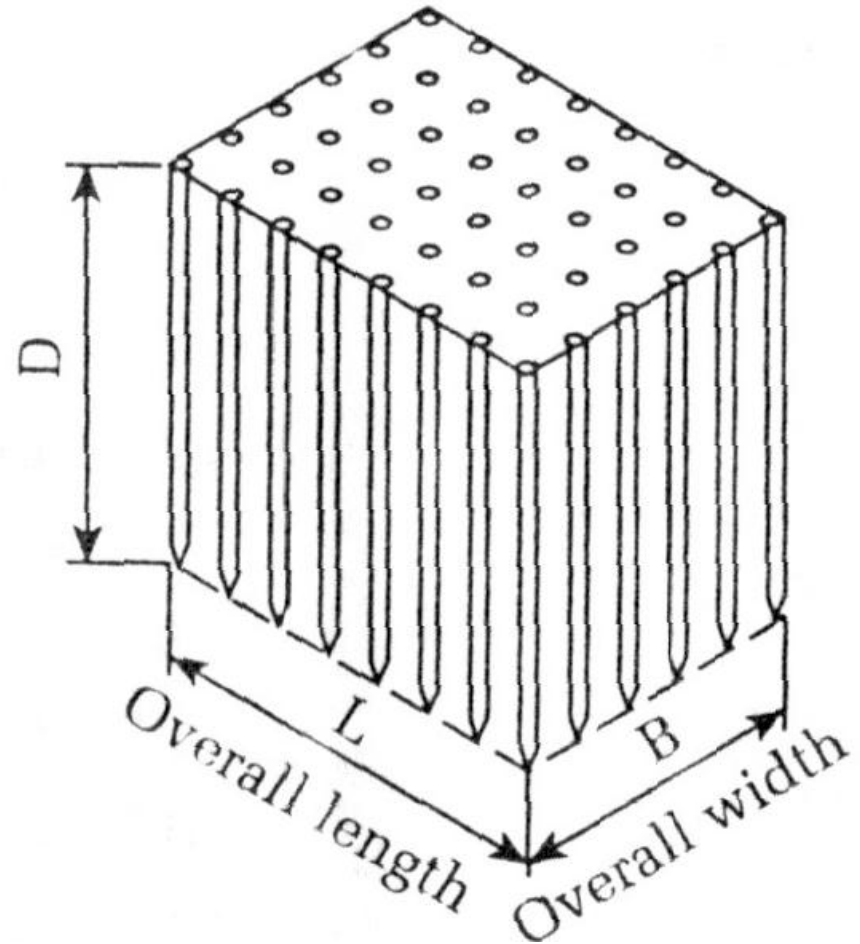
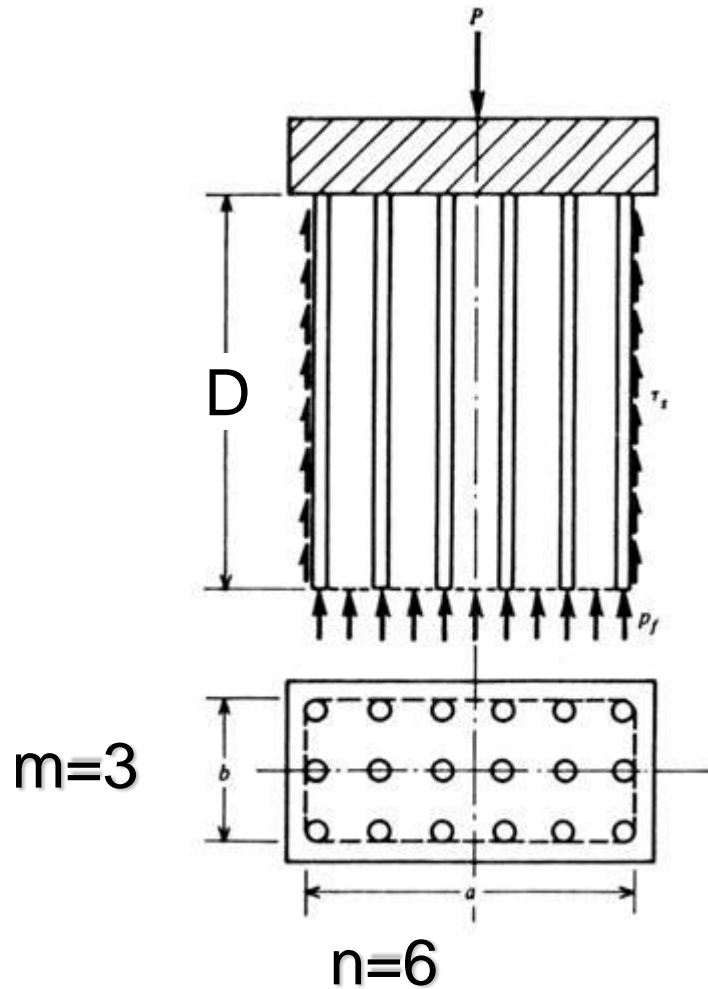


– AS A MULTIPLE OF SINGLE PILE FAILURE

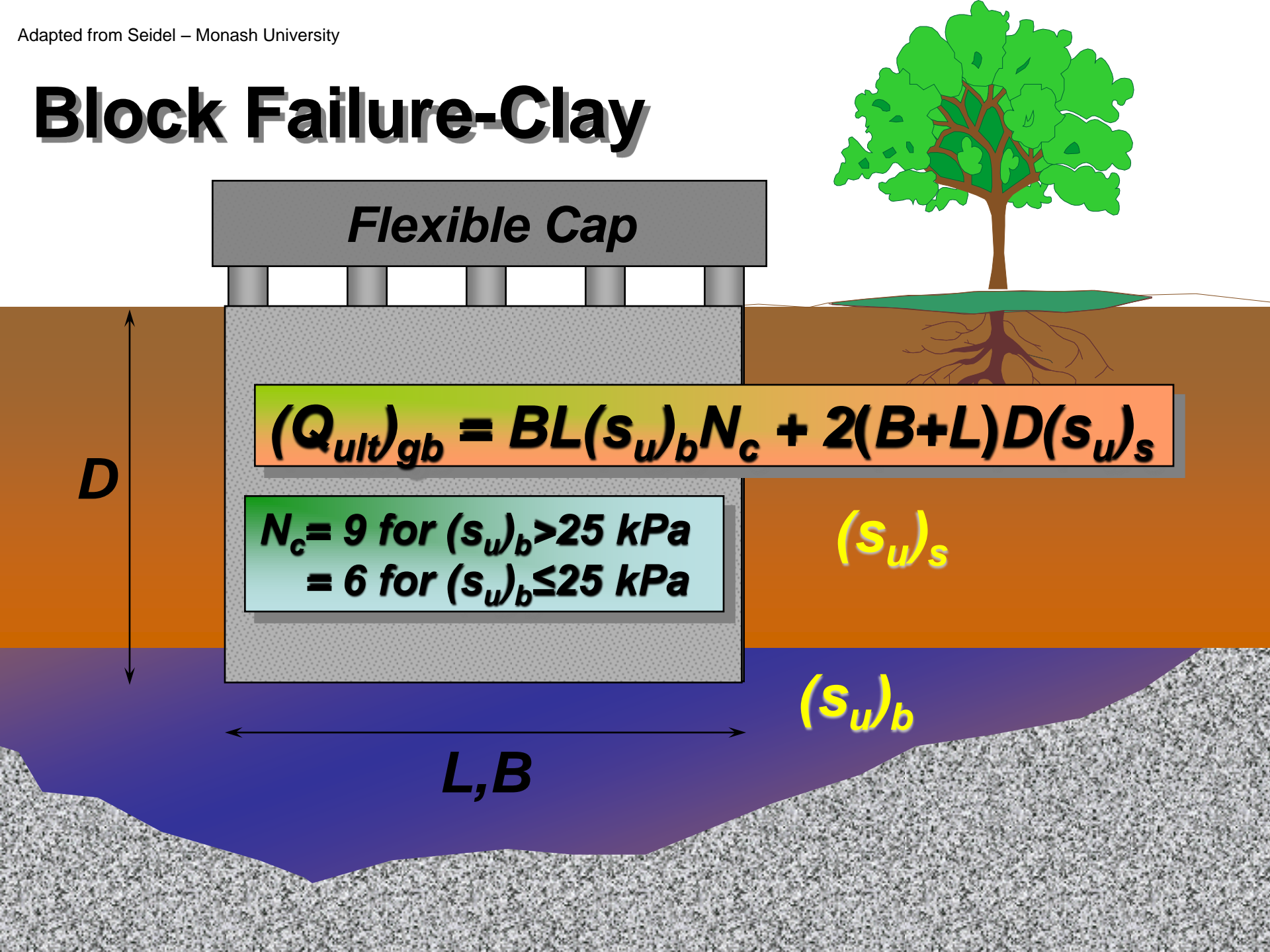
$$\text{Ultimate load} = mn (Q_{\text{ult}})_{\text{single pile}}$$

The expressions for the bearing capacities for ESA and TSA are the same as those for single piles except the perimeter and area are different.

Bearing Capacity of Pile Group – Block Failure in Clay



Block Failure-Clay



Empirical Modification-Clay

$$(Q_{ult})_{gb} = BL(s_u)_b N_c + 2(B+L)D(s_u)_s$$

gb denotes group-block failure

$$(Q_{ult})_g = \text{lower of } n(Q_{ult})_{pile} \text{ and } (Q_{ult})_{gb}$$

n

Settlement of piles and pile groups

Settlement of single piles

- Most deep foundations up to 600 mm diameter, designed using methods presented so far, will have settlements of no more than about 15 mm.
- **Therefore, typically, no settlement calculations are carried out.**
- Cases do occur when estimates of pile settlement are required.

Cases requiring estimates of pile settlement

- Large diameter end-bearing piles
- Sensitive structures
- Highly compressible strata below toe
- If downdrag loads may occur during life of structure
- Cases where structural engineer wants estimate of equivalent spring at pile location

Plant Layout Plan and Aerial View (Looking south)

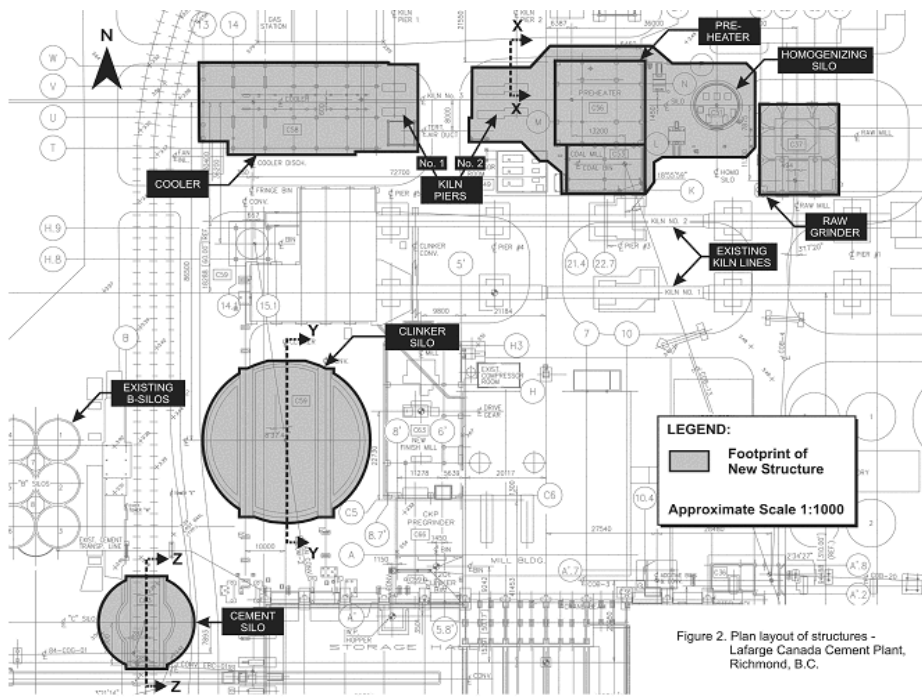
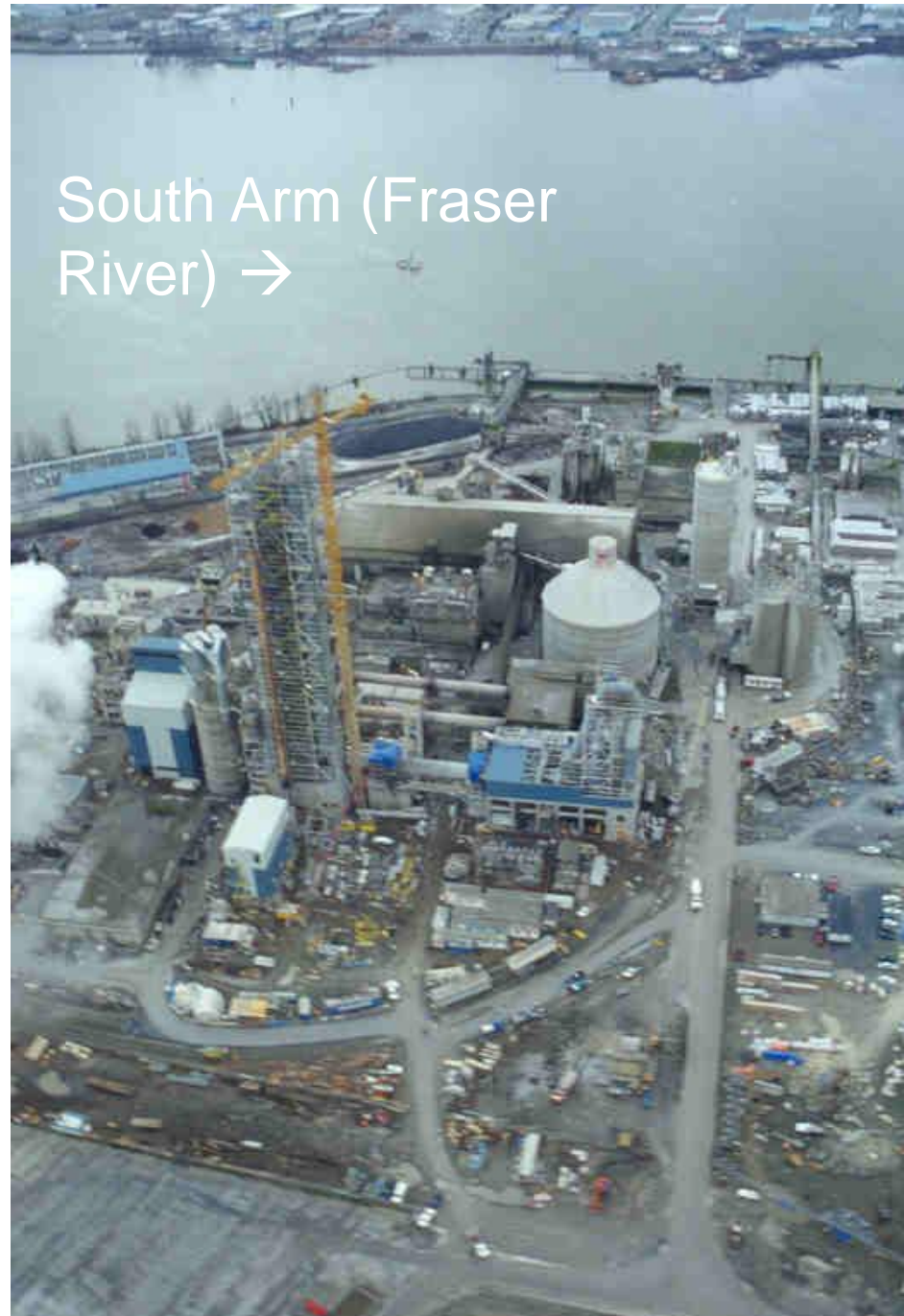
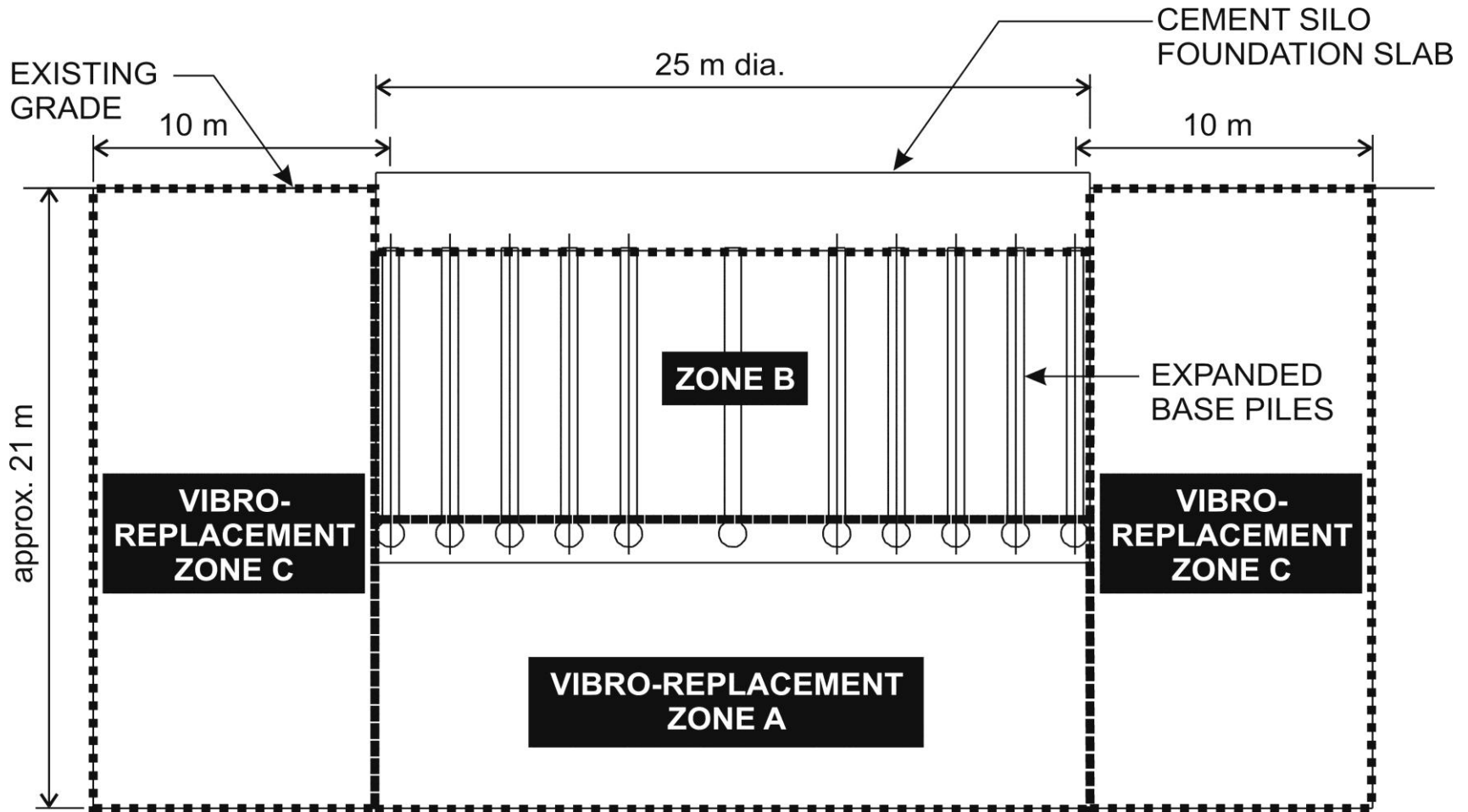


Figure 2. Plan layout of structures - Lafarge Canada Cement Plant, Richmond, B.C.

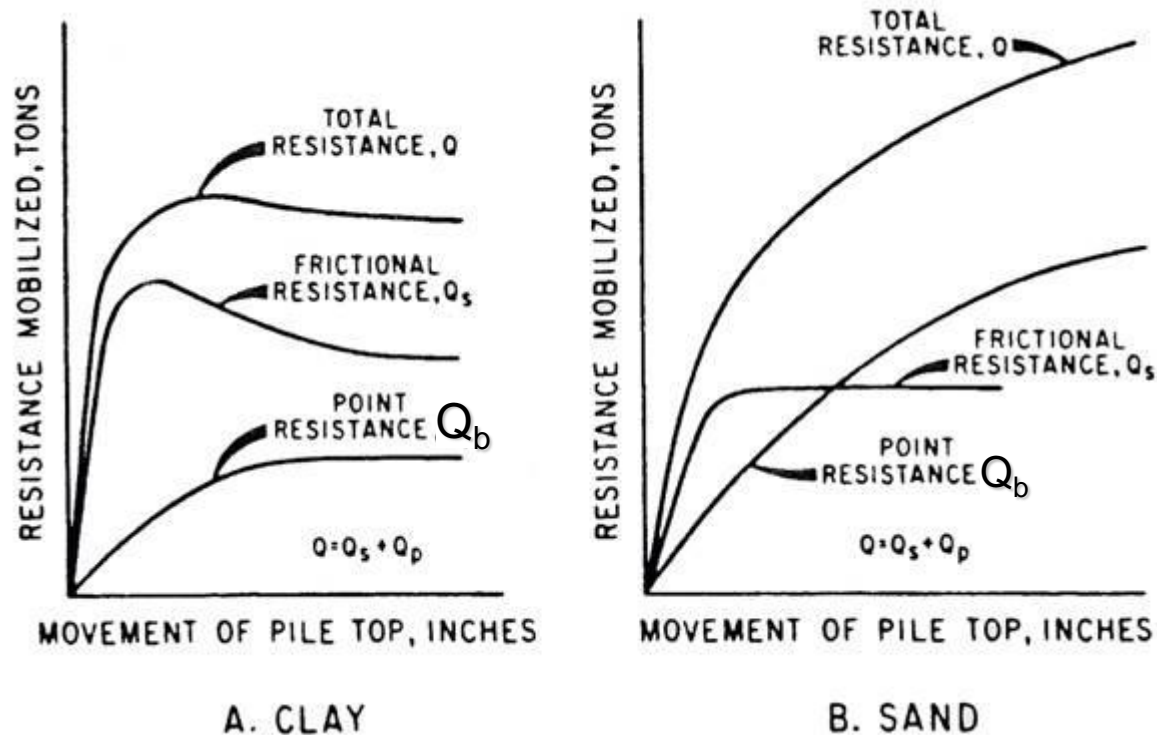


Cement Silo Foundation System



SECTION Z-Z (see Figure 2 for section location)

Typical Load – Movement Characteristics of an Axially Loaded Pile



Relative Movements Required to Fully Mobilize

- Shaft Resistance = 0.5 to 2 % x Diameter
- Toe Resistance = 3 to 10 % x Diameter

Implications of load transfer

- At working load,
 - most of the load is being supported in side friction – side friction may even have exceeded its peak value
 - No or very little base resistance has been mobilized

Conclusion on load transfer

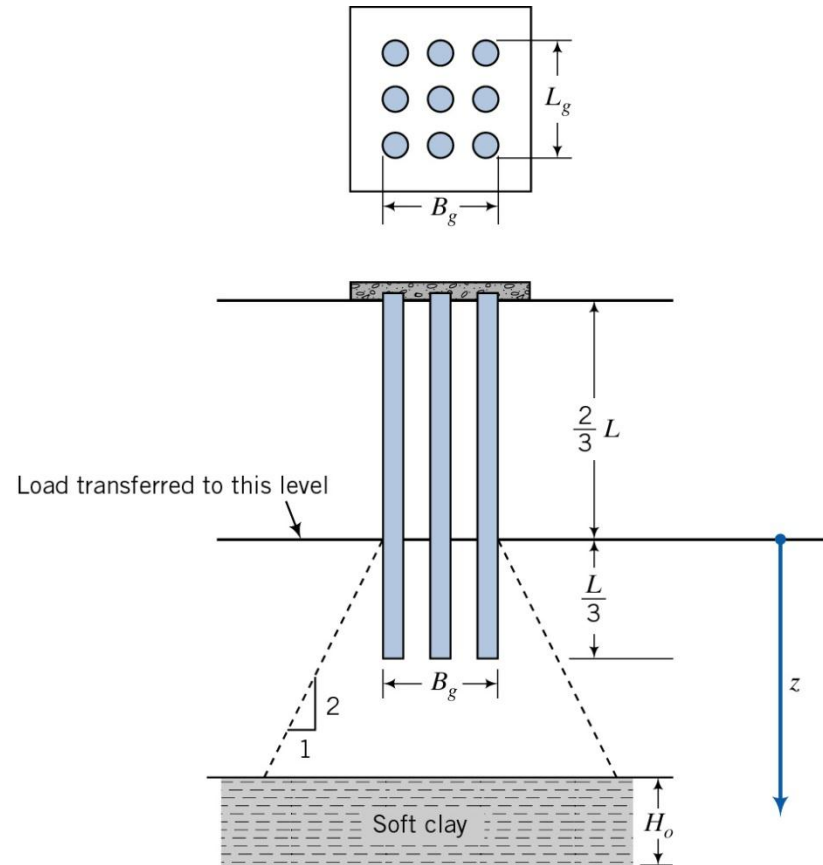
- Maximum theoretical side friction cannot be mobilized unless pile is rigid
- Limiting pile side friction is mobilized at much smaller deformations than pile tip resistance
- Residual stresses can result in available tip resistance being overestimated

Settlement of pile groups

- Elastic methods
 - interaction factors
- Equivalent raft approach

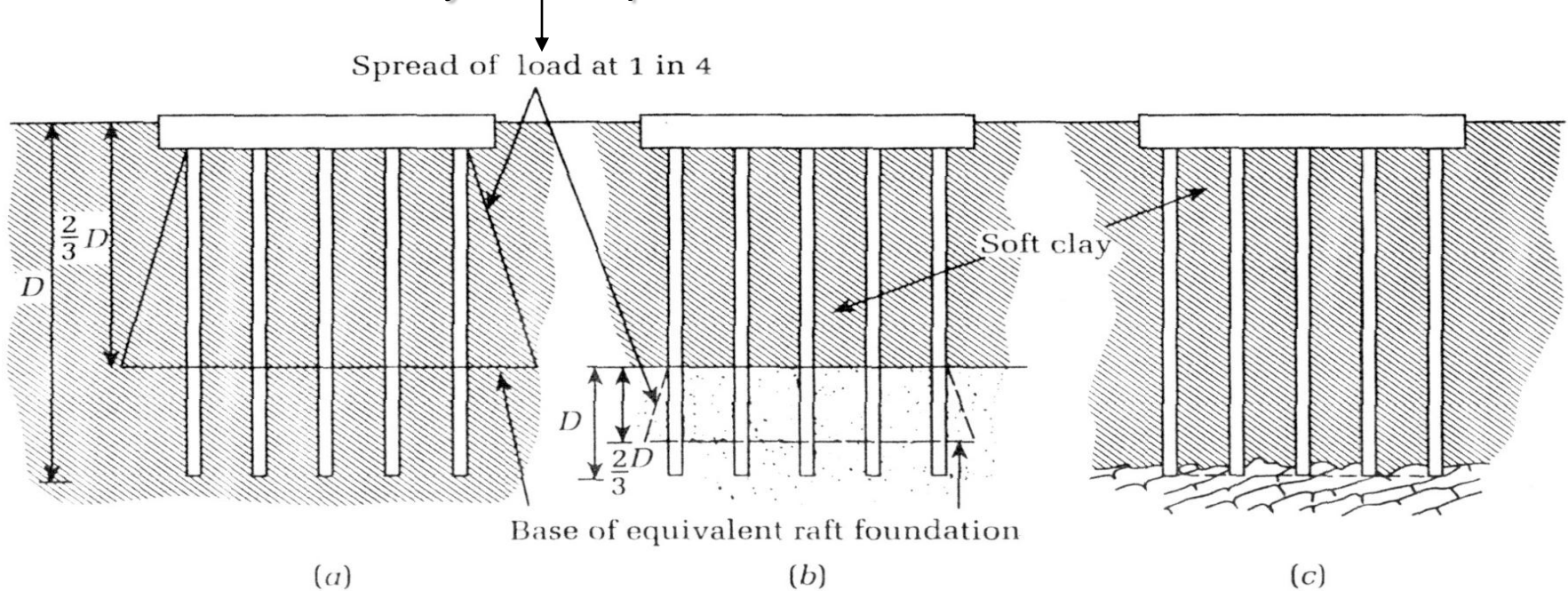
Consolidation Settlement

$$\Delta\sigma_z = \frac{Q_a}{(B_g + z)(L_g + z)}$$



Equivalent raft approach - Tomlinson

Mobilization of resistance by skin
friction is allowed for by 4V:1H spread



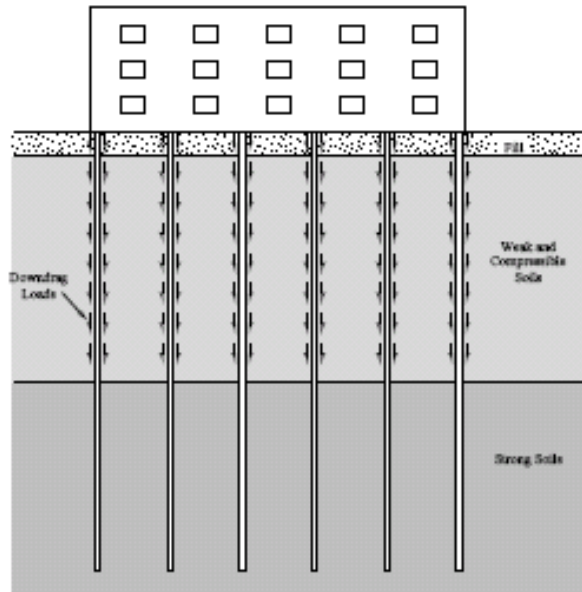
Carry out settlement analysis using methods for
shallow foundations

Downdrag

- Often called negative skin friction
- See Budhu, Section 8.10
- Effects:
 - May cause excessive settlements of foundations
 - May result in structural overstress

Negative skin friction

- Downdrag is a settlement problem, rarely a capacity problem



- if the pile moves, the downdrag disappears and then begins to build up again.
- Do not include live load and drag load in calculations, e.g. load cases:

- DL+negative skin friction or
- DL+LL

DESIGN FOR LATERAL LOADS ON PILES

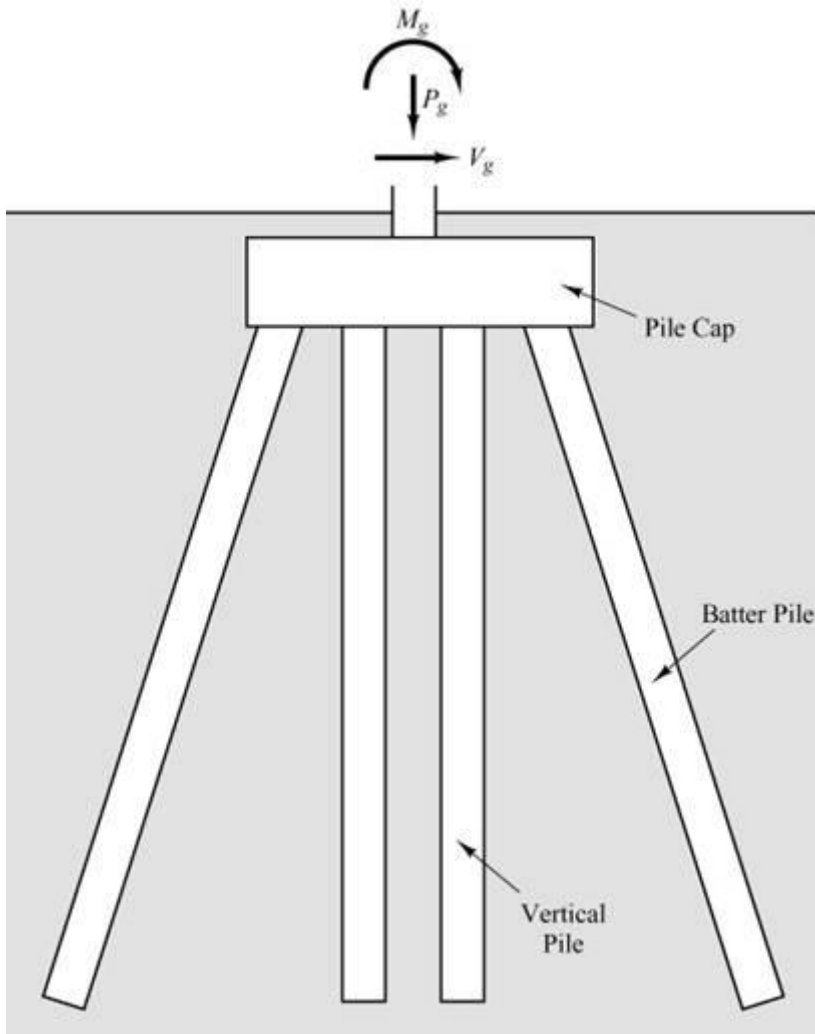
Sources of lateral loads

- Earth pressures on pile supported retaining walls
- Seismic loads
- Pile supported dolphins and docks
- Wave forces on offshore structures
- Wind loads on structures
- Etc.

Pile arrangements to take lateral loads

- Batter or raker piles
- Vertical piles

Batter Piles

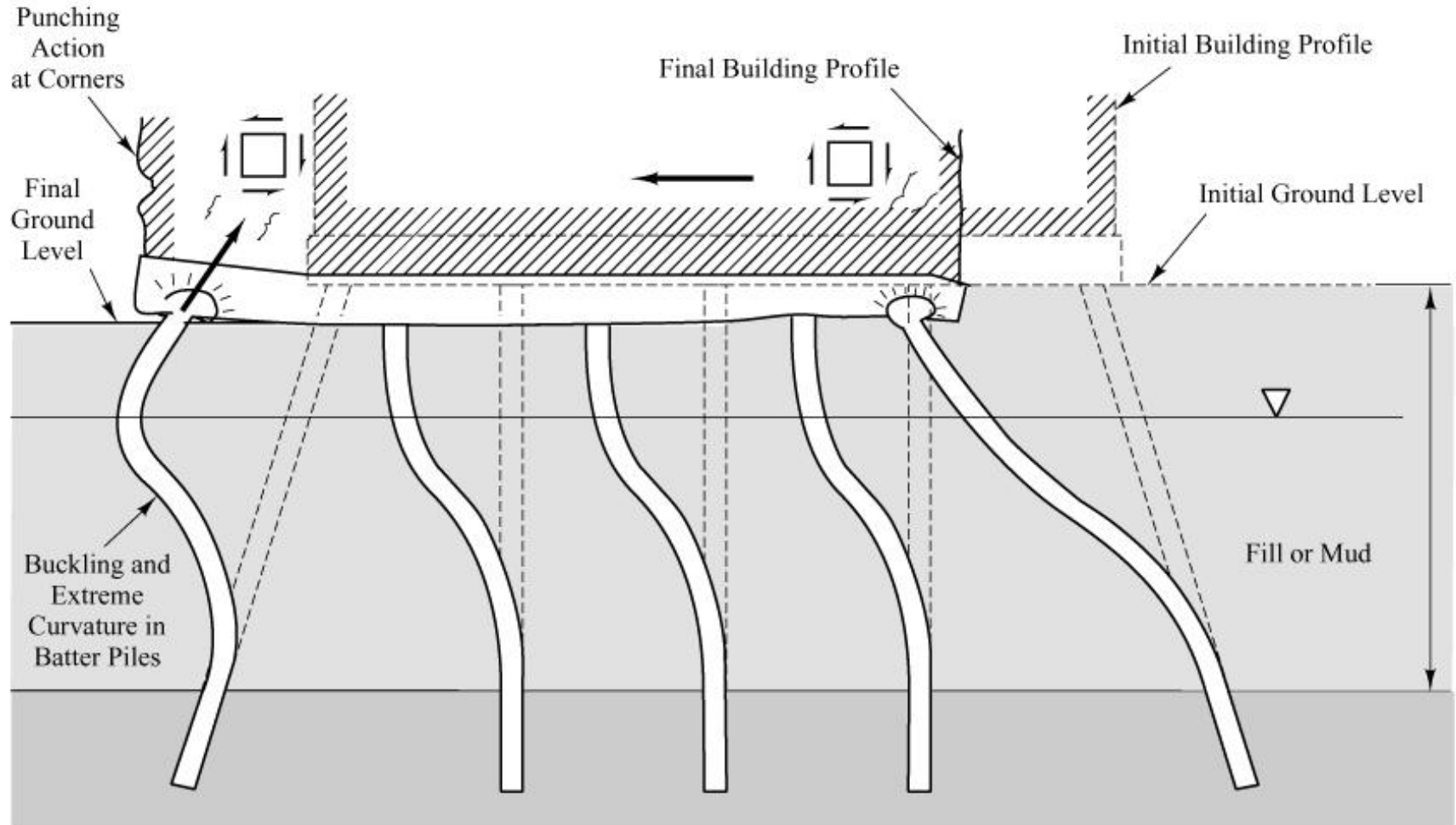


Piles driven at an angle in an attempt to have them be loaded axially when pile group is subjected to lateral load.

Problems:

- Very stiff system – not good in seismic loading
- Piles really take shear and moment loads
- Soil settlement may cause problems

Seismic Behaviour of Batter Piles



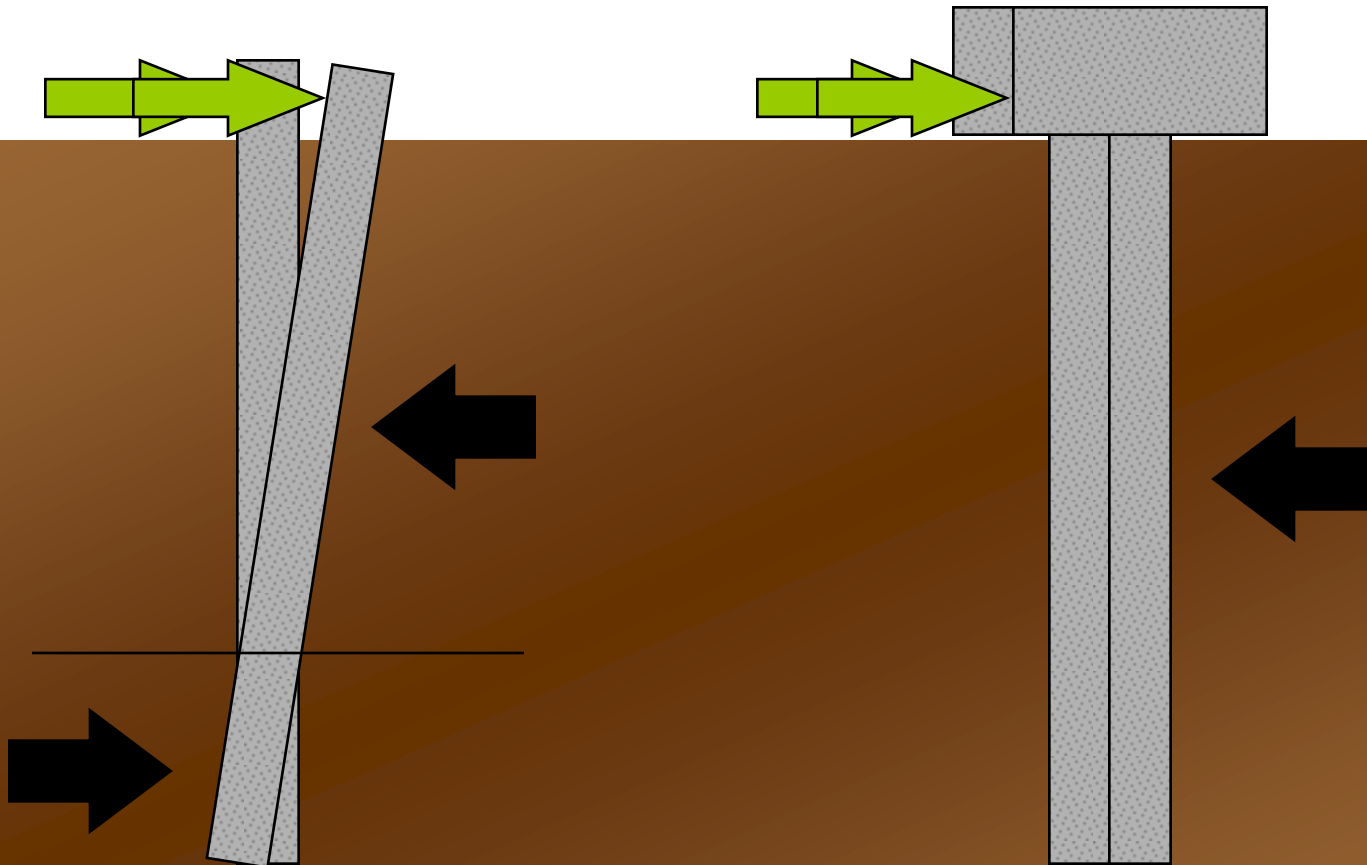
Methods of estimating lateral capacity

- Full-scale lateral load tests
- Model lateral load tests
- Lateral Static tests
- Analytical methods
 - Rigid analyses
 - Depth to fixity analysis
 - Soil-structure interaction analyses
 - P-y curves
 - Finite elements

Pile Head Constraint

Free

Fixed



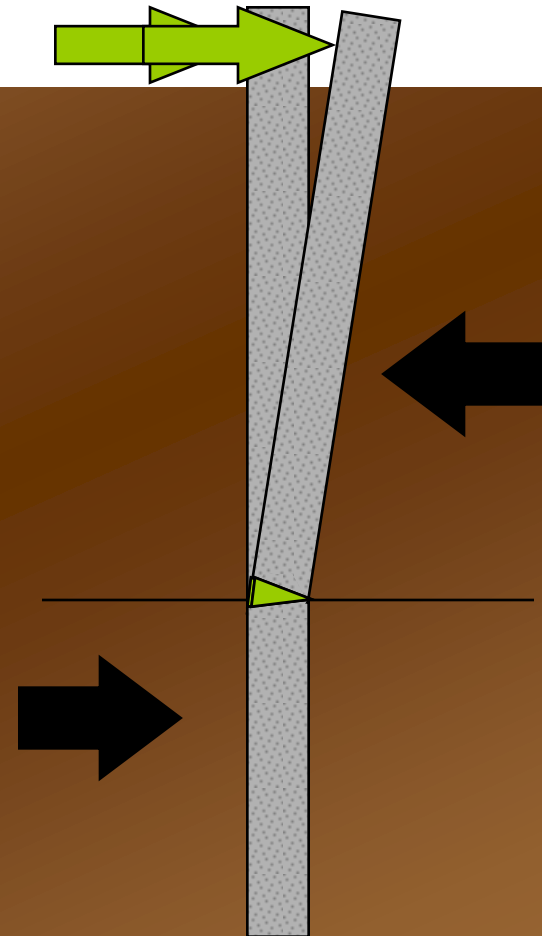
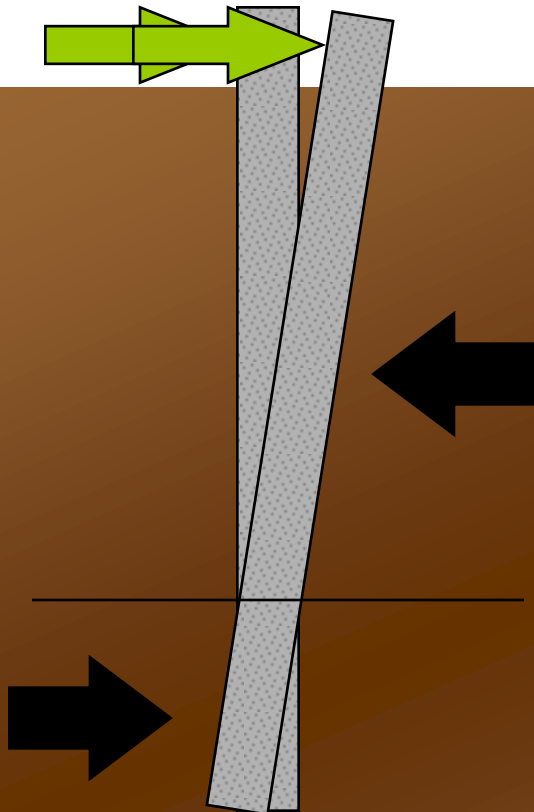
Pile Length

Short ($L/D < 10$)

Long ($L/D > 10$)

Soil fails first

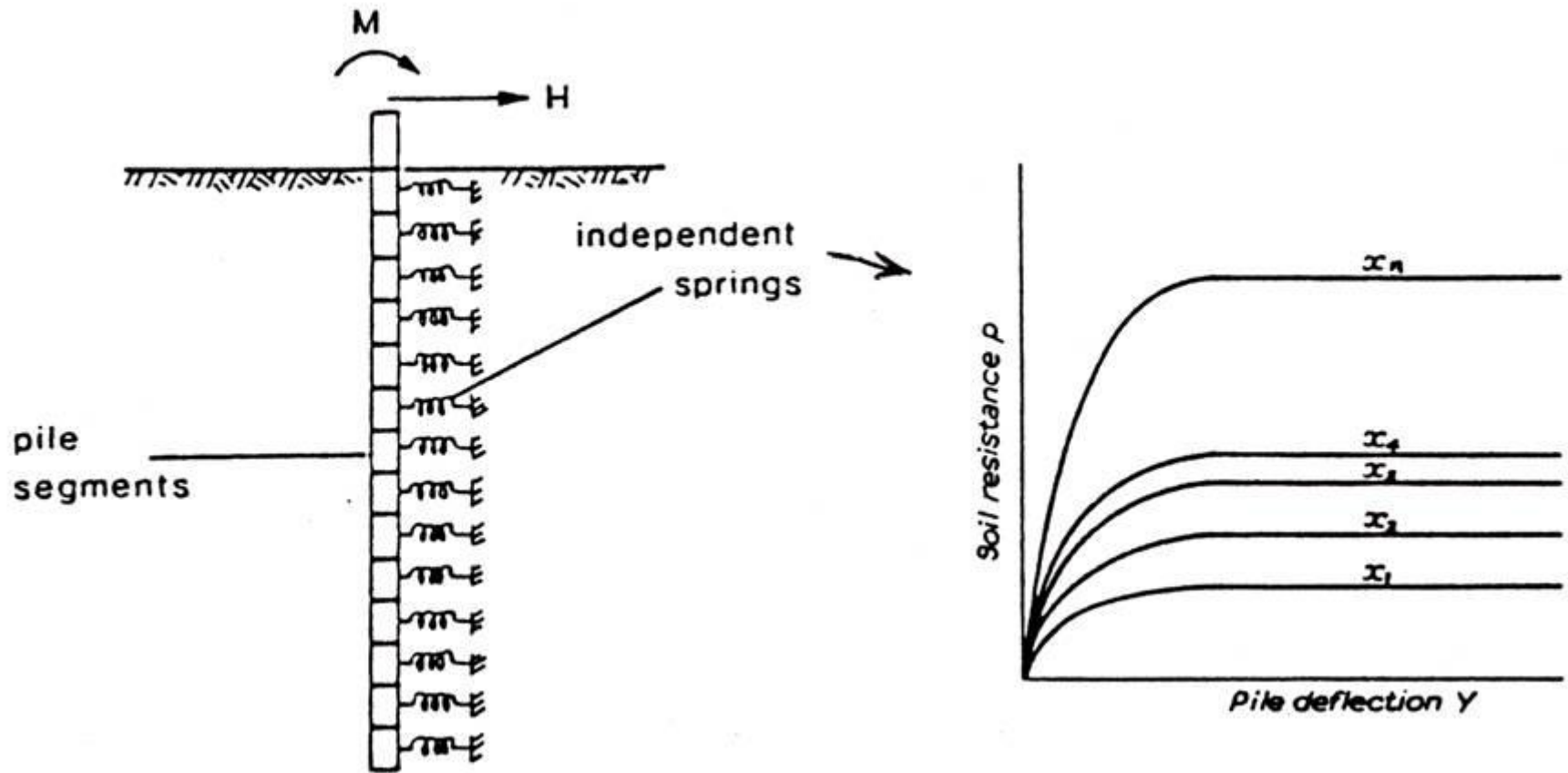
Pile fails first



Deflections under lateral load

- Single Piles
 - Elastic beam on elastic foundation method
 - P-Y curves
 - Finite elements (continuum analysis)
- Pile Groups
 - Lead row takes more load than subsequent rows – “shadow” effect

P-y curves



Conclusion on Piles

- Piles used to transmit loads to bearing strata at depth
- Axial loading
 - Carry load in side and base resistance
 - Pile installation alters the properties of the ground
 - design approaches must recognize installation effects and nature of load transfer
 - Settlement usually small for piles with adequate safety factor
 - Calculate settlements for large diameter piles and downdrag
- Lateral loading
 - Short pile vs long pile
 - P-y curves used to calculate load-deformation

Conclusion on Pile Groups

- Piles operate independently if at wide spacing $>6D$
- Piles interact at closer spacing
- Group capacity depends on effects of installation
 - Efficiency <1.0 in clays
 - Efficiency ≥ 1.0 in sands – use 1.0
- Check block failure
- Calculate settlements assuming equivalent raft concept