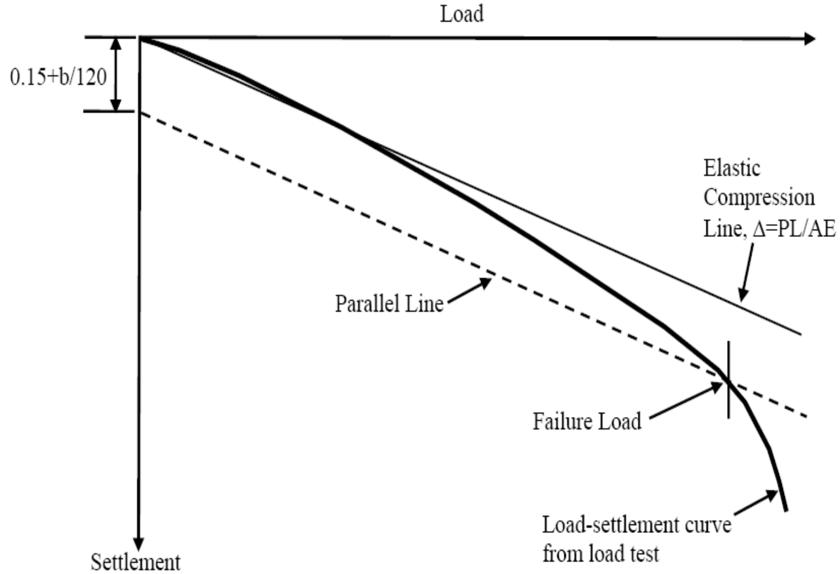
ENCE 4610 Foundation Analysis and Design



Performance Requirements for Foundations

Definition of Failure

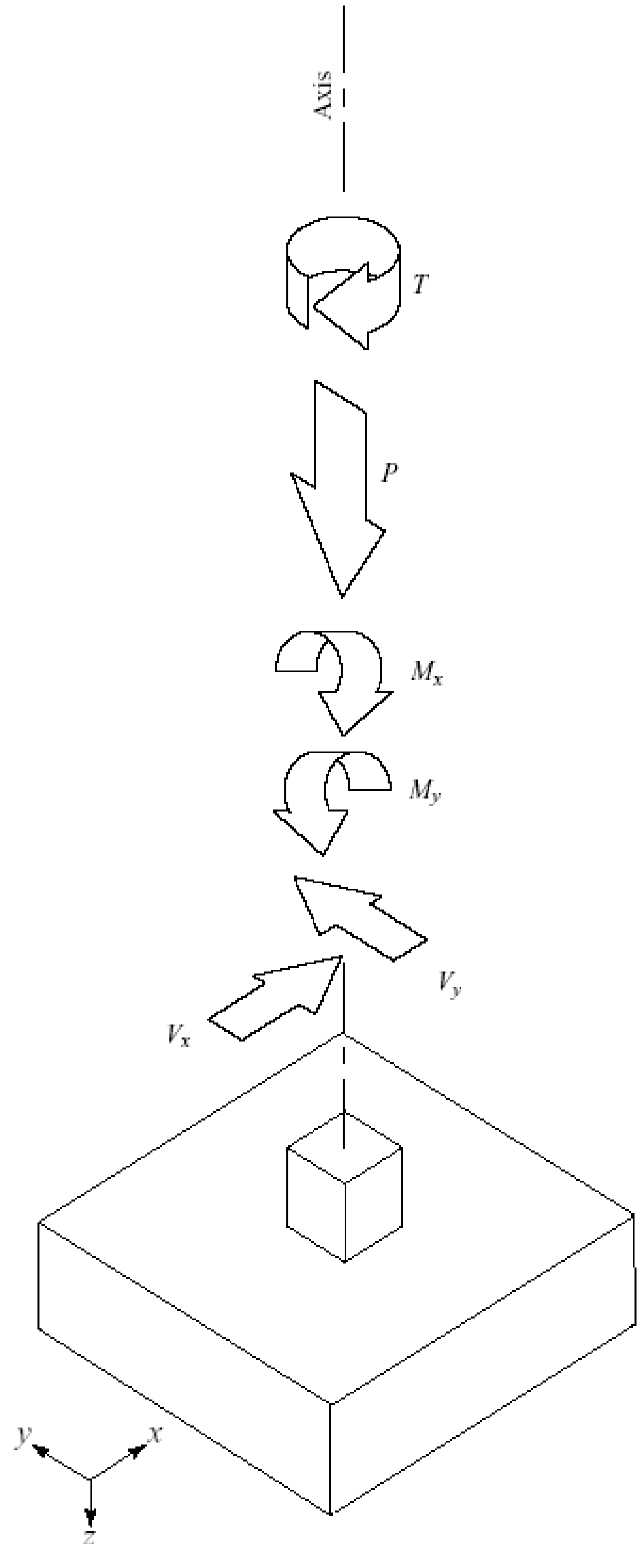
- “...an unacceptable difference between expected and observed performance.” (G.A. Leonards)
- Foundations are not typically perfectly rigid or unyielding
- They can fail either catastrophically (bearing or shear failure) or by excessive settlement (consolidation, differential settlement, etc.)
- Failure is also dependent on other factors not directly related to the foundation and soil interaction (type of structure, etc.)

Requirements for Foundation Design

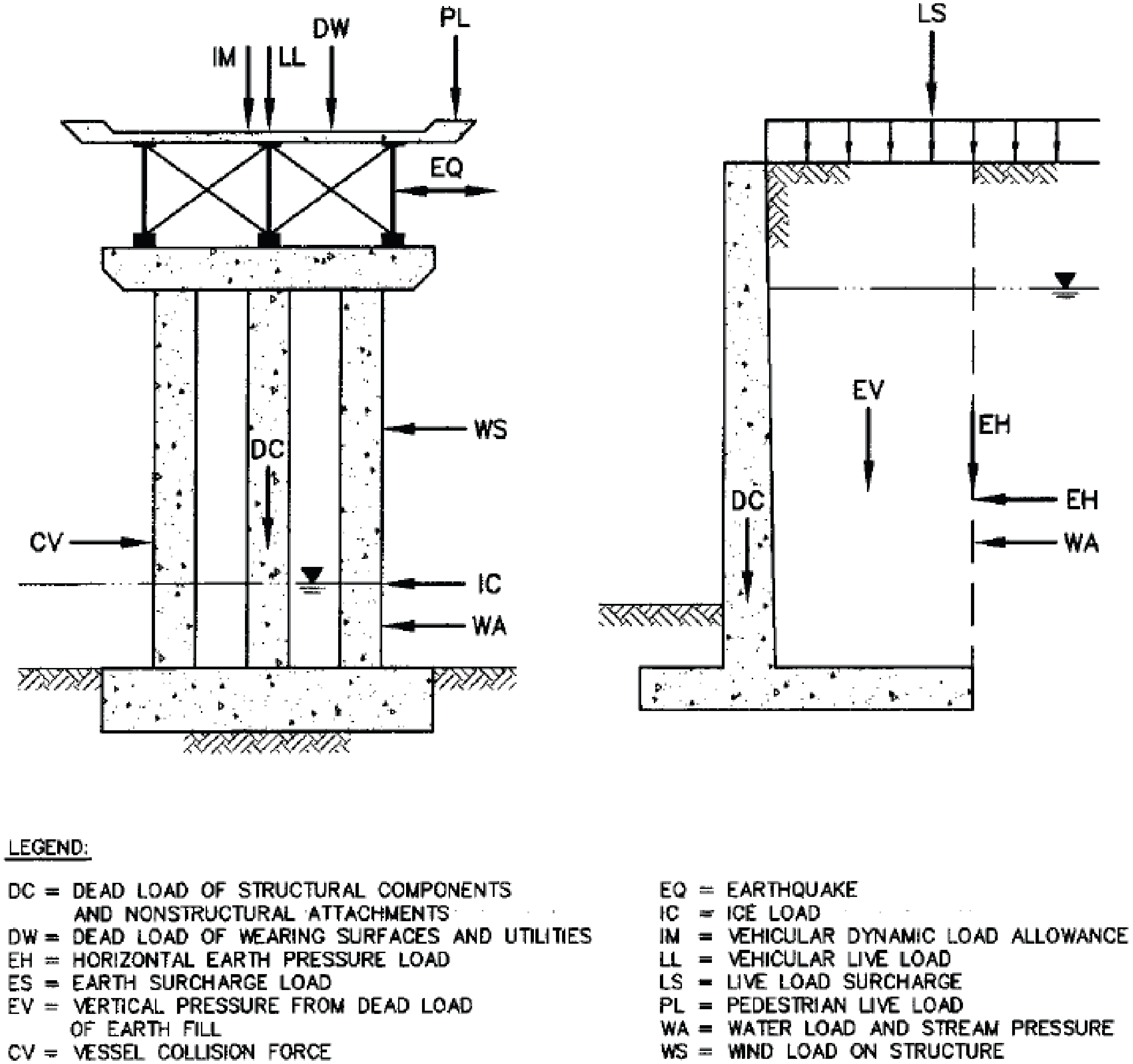
- Basic Requirements
  - Strength Requirements
  - Serviceability Requirements
  - Constructibility Requirements
  - Economic Requirements
- Foundation Loading
  - Types of Loads
  - Sources of Loads
- Questions to consider
  - How to we deal with uncertainty in loading?
  - How do we deal with combined loads?
  - What is the code environment?
  - How do different foundations respond to different loading?

Types of Design Loads

- Axial Loads (P)
- Torsional Loads (T)
- Moments (M_x, M_y)
- Shear and Lateral Loads (V_x, V_y)



Loading Sources for Substructure Design



(a) Bridge Pier (b) Cantilever Retaining Wall

Sources of Loading

- Dead loads (D)
- Live Loads (L)
- Snow (S) and Rain (R) Loads
- Earth Pressure Loads (H)
- Fluid Loads (F)
- Earthquake Loads (E)
- Wind Loads (W)
- Self-straining loads (S)
- Impact Loads (I)
- Stream Flow (SF) and Ice (ICE) Loads
- Vehicle Motion: Centrifugal (CF) and Braking (BF) Loads

…but how to properly account for them together? And how to deal with uncertainty?

Method of Expression of Design Load

- **Allowable Stress Design (ASD)**
  - Deals with uncertainty by applying a global "factor of safety" to reduce the design resistance of the foundation
  - Design load is the most critical combination of the various load sources, as defined by the applicable code
  - The traditional method of geotechnical design
  - Load combinations computed with ASD are referred to as *unfactored loads*

- **Load and Resistance Factor Design (LRFD)**
  - Applies separate load and resistance factors
    - Load factor usually > 1
    - Resistance Factor usually < 1
  - For loads, the result is referred to as a *factored load*
  - Factored load is then compared to a resistance factored by its own resistance factor
  - Becoming more important in foundation design

Notes on Design Codes

- Codes chosen in this course are primarily for example purposes
- The applicability of any given code will vary from project to project, so make sure you are referring to the correct code when designing
- Adherence to a building or design code is NOT a guarantee that your design is correct, safe, or constructible.
- Adherence to a code is not a substitute for proper engineering judgment

Allowable Stress Design ANSI/ASCE Load Combinations

- ANSI/ASCE (*Minimum Design Loads for Buildings and Other Structures*) criteria for most critical combination of the various load sources: greatest of the following:

$$D$$

$$D + L + F + H + T + (L_r \vee S \vee R)$$

$$D + L + (L_r \vee S \vee R) + (W \vee E)$$

$$D + (W \vee E)$$

- Alternative Method of Evaluation Wind and Seismic Loads (IBC, UBC, BOCA)

$$0.75\,[D + L + (L_r \vee S \vee R) + (W \vee E)]$$

$$0.75\,[D + (W \vee E)]$$

- Substitute for last two equations to the left
- Enables foundation to be sized only once rather than for wind and seismic loads separately

Example of ASD Design

- Given
  - Column carries following vertical compressive loads:
    - P_D (D) = 2100 kN Downward (Dead Load)
    - P_L (L) = 1400 kN Downward (Live Load)
    - P_W (W) = 600 kN Upward (Wind Load)
- Find
  - Compute normal design load for use in foundation design using ASD load combinations
  - Include evaluation using alternative method for wind/seismic loads (default in this course)

Example of ASD Design

- Governing Equations (ANSI/ASCE)

$$D$$

$$D + L + F + H + T + (L_r \vee S \vee R)$$

$$0.75\,[D + L + (L_r \vee S \vee R) + (W \vee E)]$$

$$0.75\,[D + (W \vee E)]$$

- D = 2100 kN
- L = 1400 kN
- W = - 600 kN (note sign convention)

- Substituting Variables

$$2100\ kN$$

$$2100 + 1400 + 0 + 0 + 0 + 0 = 3500\ kN$$

$$\frac{3}{4}[2100 + 1400 + 0 - 600] = 2175\ kN$$

$$\frac{3}{4}[2100 - 600] = 1125\ kN$$

- 3500 kN is the governing load

"Typical" Factors of Safety

Factor of safety, F

$$F = \frac{\Sigma \text{ Forces preventing failure}}{\Sigma \text{ Forces initiating failure}}$$

$$F = \frac{\Sigma \text{ Moments preventing failure}}{\Sigma \text{ Moments initiating failure}}$$

Type	F
Dams, fills	1.2 - 1.6
Retaining walls	1.5 - 2.0
Sheet pile walls and coffer dams	1.2 - 1.6
Braced excavations	1.2 - 1.5
Footings	2 - 3
Mats, rafts	1.7 - 2.5
Uplift, heave	1.5 - 2.5
Piping	3 - 5

Example of Application of Factors of Safety

- Given
  - Previous problem, 3500 kN design load
- Find
  - Ultimate Downward Capacity, FS = 2
- Solution
  - P_u = (P)(FS) = (3500 kN)(2) = 7000 kN
- Interpretation of the Solution
  - 3500 kN is defined as the *allowable resistance* of the foundation
  - 7000 kN is defined as the *ultimate resistance* of the foundation
  - Result of geotechnical capacity should normally be compared to the *ultimate resistance*

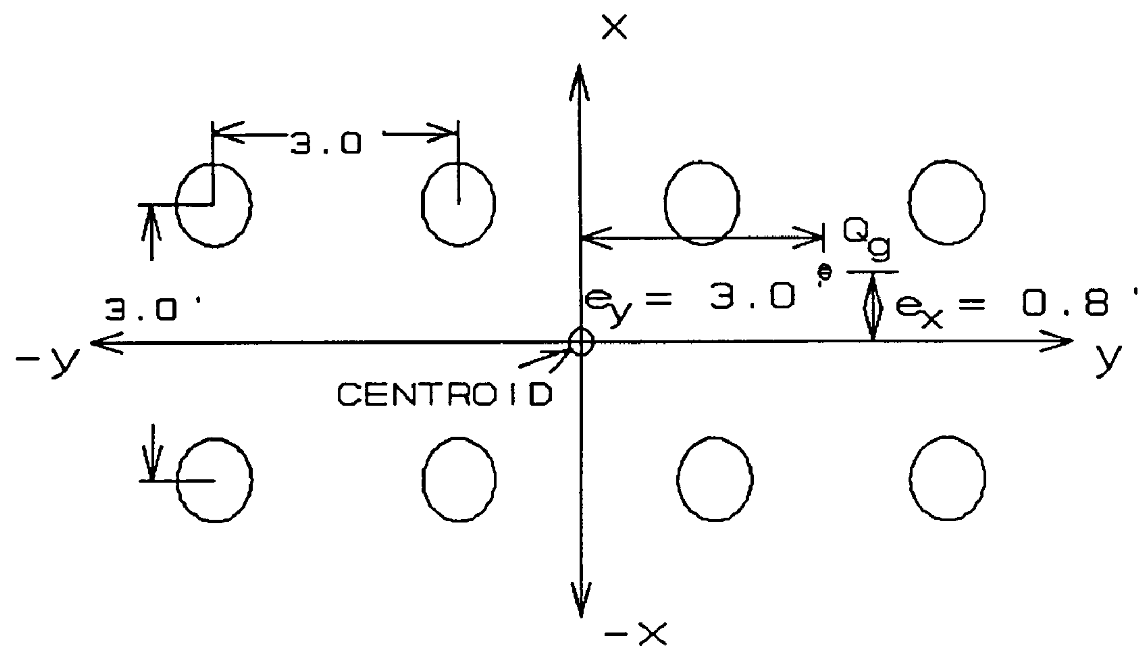
Example Applied to Material Sizing

- Given
  - Foundation with design load of 3500 kN
  - To be supported by four (4) H-piles, made of ASTM A 36 steel
    - Yield Strength = 36 ksi
    - Allowable Strength = 10 ksi = 69 MPa = 69,000 kPa
  - Eccentricity and bending not taken into consideration; purely axial load
- Find
  - Required cross-sectional area of steel

Definitions:
H-Piles and Load Eccentricity

- H-Piles

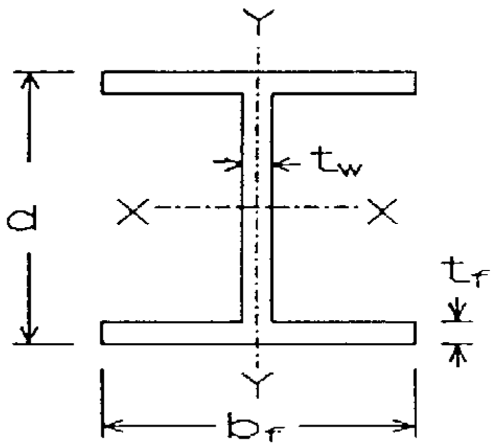
- Load Eccentricity



Computation of Cross-Sectional Area

- Load Divided among the four H-beams
  - P/pile = 3500 kN/4 = 875 kN
- Computation of cross-sectional area per pile based on allowable stresses
  - A = Load/Allowable Stress = 875 kN/69,000 kPa = 0.01268 m^2 = 12,681 mm^2 = 19.66 in^2
- Select H-Beam Size Based on H-Beam Tables

H-Beam Tables



I = MOMENT OF INERTIA, IN.^{4}, mm^4

S = SECTION MODULUS, IN.^{3}, mm^3

r = RADIUS OF GYRATION, IN., mm

Area = 12,681 mm^2 = 19.66 in^2

a. English Units

Designation	Area A, in.^{2}	Depth d, in.	Flange Width b_f, in.	Flange Thickness t_f, in.	Web Thickness t_w, in.	Axis X–X I, in.^{4}	Axis X–X S, in.^{3}	Axis X–X r, in.	Axis Y–Y I, in.^{4}	Axis Y–Y S, in.^{3}	Axis Y–Y r, in.
HP14 x 117	34.4	14.21	14.885	0.805	0.805	1220	172.0	5.96	443.0	59.5	3.59
x 102	30.0	14.01	14.785	0.705	0.705	1050	150.0	5.92	380.0	51.4	3.56
x 89	26.1	13.83	14.695	0.615	0.615	904	131.0	5.88	326.0	44.3	3.53
x 73	21.4	13.61	14.585	0.505	0.505	729	107.0	5.84	261.0	35.8	3.49
HP13 x 100	29.4	13.15	13.205	0.765	0.765	886	135.0	5.49	294.0	44.5	3.16
x 87	25.5	12.95	13.105	0.665	0.665	775	117.0	5.45	250.0	38.1	3.13
x 73	21.6	12.75	13.005	0.565	0.565	630	98.8	5.40	207.0	31.9	3.10
x 60	17.5	12.54	12.900	0.460	0.460	503	80.3	5.36	165.0	25.5	3.07
HP12 x 84	24.6	12.28	12.295	0.685	0.685	650	106.0	5.14	213.0	34.6	2.94
x 74	21.8	12.13	12.215	0.610	0.610	569	93.8	5.11	186.0	30.4	2.92
x 63	18.4	11.94	12.125	0.515	0.515	472	79.1	5.06	153.0	25.3	2.88
x 53	15.5	11.78	12.045	0.435	0.435	393	66.8	5.03	127.0	21.1	2.86
HP10 x 57	16.8	9.99	10.225	0.565	0.565	294	58.8	4.18	101.0	19.7	2.45
x 42	12.4	9.70	10.075	0.420	0.420	210	43.4	4.13	71.7	14.2	2.41
HP8 x 36	10.6	8.02	8.155	0.445	0.445	119	29.8	3.36	40.3	9.88	1.95

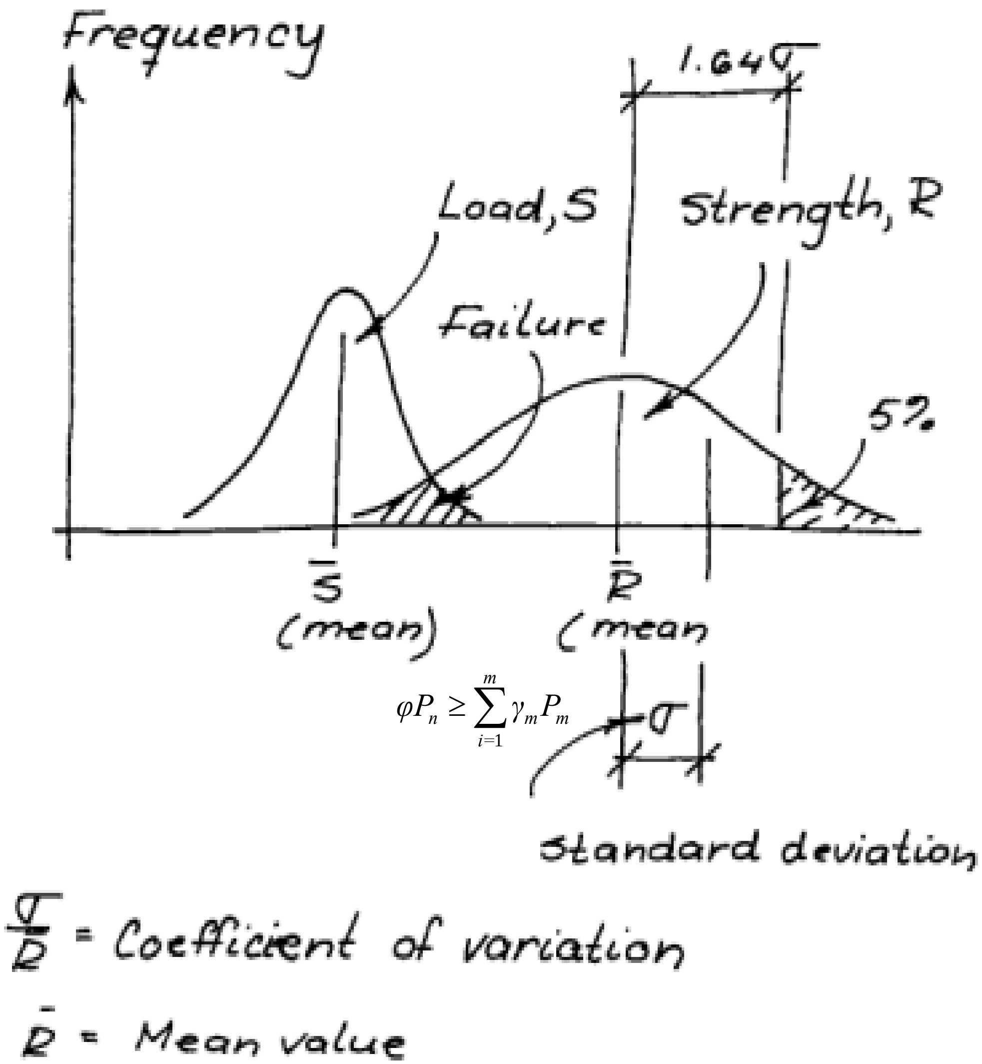
H-Beam Tables

Area = 12,681 mm^2 = 19.66 in^2

b. Metric Units

Designation	Area A, mm^2	Depth d, mm	Flange Width b_f, mm	Flange Thickness t_f, mm	Web Thickness t_w, mm	Section Properties: Axis X-X I, 10^6 mm^4	Axis X-X S, 10^3 mm^3	Axis X-X r, mm	Axis Y-Y I, 10^6 mm^4	Axis Y-Y S, 10^3 mm^3	Axis Y-Y r, mm
HP360 x 174	22200	361	378	20.4	20.4	504	2810	151	184	974	91.0
x 152	19400	356	376	17.9	17.9	439	2470	150	159	846	90.5
x 132	16900	351	373	15.6	15.6	375	2140	149	135	724	89.4
x 108	13800	346	370	12.8	12.8	303	1750	148	108	584	88.5
HP330 x 149	19000	334	335	19.4	19.4	368	2200	139	122	728	80.1
x 129	16400	329	333	16.9	16.9	315	1910	139	104	625	79.6
x 109	13900	324	330	14.4	14.4	263	1620	138	86.3	523	78.8
x 89	11300	319	328	11.7	11.7	211	1320	137	68.9	420	78.1
HP310 x 125	15900	312	312	17.4	17.4	270	1730	130	88.2	565	74.5
x 110	14100	308	310	15.5	15.4	237	1540	130	77.1	497	73.9
x 93	11900	303	308	13.1	13.1	196	1290	128	63.9	415	73.3
x 79	10000	299	306	11.0	11.0	163	1090	128	52.6	344	72.5
HP250 x 85	10800	254	260	14.4	14.4	123	969	107	42.3	325	62.6
x 62	7970	246	256	10.7	10.5	87.5	711	105	30.0	234	61.4
HP200 x 53	6820	204	207	11.3	11.3	49.8	488	85.5	16.7	161	49.5

Load and Resistance Factor Design (LRFD)



$$\varphi P_n \ge \sum_{i=1}^{m} \gamma_m P_m$$

φ = resistance factor

P_n = nominal normal load capacity

γ_m = load factor for load "type" m

P_m = load for load "type" m

m = load "type": dead (D), live (L), etc.

Dead loads
Live loads
Wind loads
Earth quake loads

Load factors

Implementations of LRFD

- Load Factor Implementations
  - American Concrete Institute (ACI) Code
  - ANSI/ASCE and AISC Codes
  - AASHTO Code
- Resistance Factor Implementations
  - PDCA Proposal (Driven Piles)
  - AASHTO Resistance Factors
  - FHWA (for drilled shafts)
  - Electric Power Research Institute (EPRI)

Factored Loads

- ACI Code

$$U = 1.4D + 1.7L$$
$$U = 0.75(1.4D + 1.4T + 1.7L)$$
$$U = 0.9D + 1.4F$$
$$U = 1.4D + 1.7L + 1.4F$$
$$U = 1.4D + 1.7L + 1.7H$$
$$U = 0.9D + 1.3W$$
$$U = 0.9D + 1.43E$$
$$U = 0.75(1.4D + 1.7L + 1.7W)$$
$$U = 0.75(1.4D + 1.7L + 1.87E)$$
$$U = 0.9D + 1.7H$$
$$U = 1.4(D + T)$$

- ANSI/ASCE Code

$$U = 1.4D$$
$$U = 1.2(D + F + T) + 1.6(L + H) + 0.5(L_r \vee S \vee R)$$
$$U = 1.2D + 1.6(L_r \vee S \vee R) + (0.5L \vee 0.8W)$$
$$U = 1.2D + 1.3W + 0.5L + 0.5(L_r \vee S \vee R)$$
$$U = 1.2D + E + 0.5L + 0.2S$$
$$U = 0.9D + (1.3W \vee 1.0E)$$

Example of LRFD Design

- Given
  - Column carries following vertical compressive loads:
    - P_D (D) = 2100 kN Downward (Dead Load)
    - P_L (L) = 1400 kN Downward (Live Load)
    - P_W (W) = 600 kN Upward (Wind Load)
- Find
  - Compute normal design load for use in foundation design using ANSI/ASCE load factors and PDCA structural resistance factors
  - Compute Cross-Sectional Area for A-36 H-piles

Computation of Factored Load

$$U = (1.4)(2100) = 2940\ kN$$

$$U = 1.2(2100) + 1.6(1400) = 4760\ kN$$

$$U = 1.2(2100)$$
$$+ (0.5(1400) \vee 0.8(-600)) = 2380\ kN$$

$$U = 1.2(2100)$$
$$+ 1.3(-600) + 0.5(1400) = 2440\ kN$$

$$U = 1.2(2100) + 0.5(1400) = 2380\ kN$$

$$U = 0.9(2100)$$
$$+ (1.3(-600) \vee 1.0(0)) = 1890\ kN$$

Factored Load and Resistance Per Pile

- Factored Load Per Pile = 4760 kN/4 = 1190 kN

$$\varphi P_n \geq 1190\ kN$$

$$P_n = \frac{1190\ kN}{\varphi}$$

- Need to determine φ using PDCA recommendations (always know applicable code!)

PDCA Structural Resistance Factors

Pile Material	Using ACI Load Factors	Using ANSI Load Factors
Timber	0.6	0.55
Steel	0.95	0.85
Prestressed Concrete with Spiral Reinforcement that Satisfies the ACI code	0.75	0.7
Prestressed Concrete with other types of transverse reinforcement	0.7	0.65

Solution for Normal Load and Cross-Sectional Area

- Normal Load

$$\varphi P_n \geq 1190 \;\; kN$$

$$P_n = \frac{1190 \;\; kN}{0.85} = 1400 \;\; kN$$

- Area = (1400 kN)/(248,000 kPa) = 0.00564 m^2 = 5,645 mm^2 (note use of full yield strength of material)
- Solution with ASD method = 12,681 mm^2

Selection of H-Beam

Any H-beam meets the criteria. Red arrows: ASD suitable H-beams

b. Metric Units

Designation	Area	Depth	Flange		Web	Section Properties					
						Axis X-X			Axis Y-Y		
	Area A, mm^2	Depth d, mm	Width b_f, mm	Thickness t_f, mm	Thickness t_w, mm	I, $10^6 mm^4$	S, $10^3 mm^3$	r, mm	I, $10^6 mm^4$	S, $10^3 mm^3$	r, mm
HP360 x 174	22200	361	378	20.4	20.4	504	2810	151	184	974	91.0
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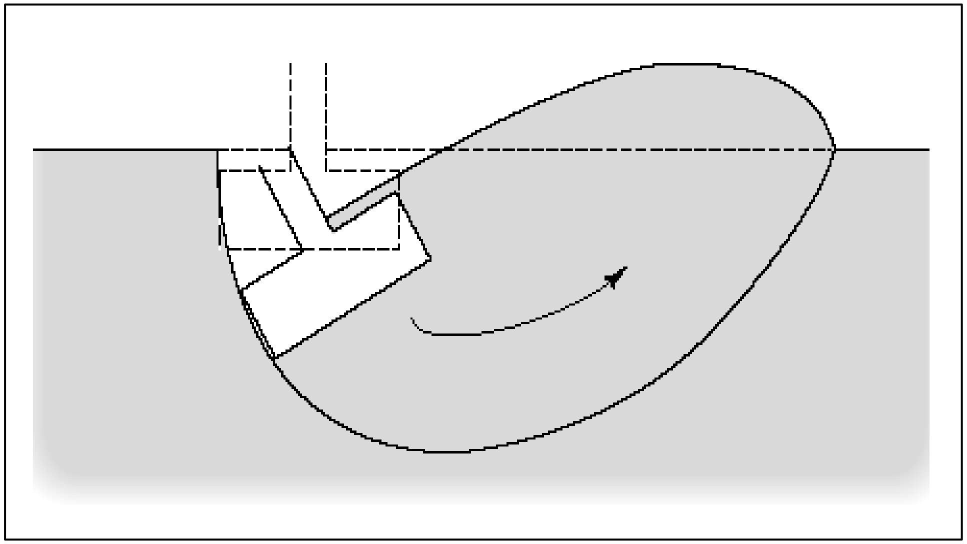
HP200 x 53	6820	204	207	11.3	11.3	49.8	488	85.5	16.7	161	49.5

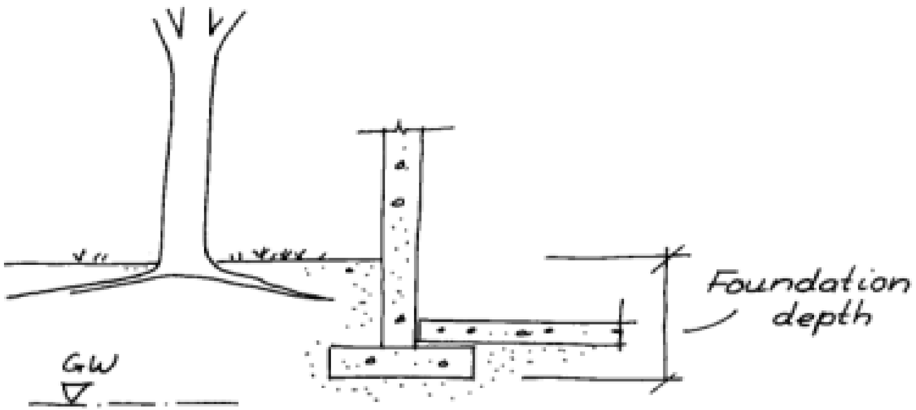
Strength Requirements

- Geotechnical Strength Requirements
  - Design to prevent failure by soil shear failure
  - Geotechnical strength for shear failure is referred to as the *bearing capacity* of the soil
  - Analysis usually performed by ASD analysis; LRFD becoming more common
- Structural Strength Requirements
  - Design to avoid structural failure of foundation components
  - Similar to other structural analyses

- Most common strength requirement: avoid bearing capacity failure



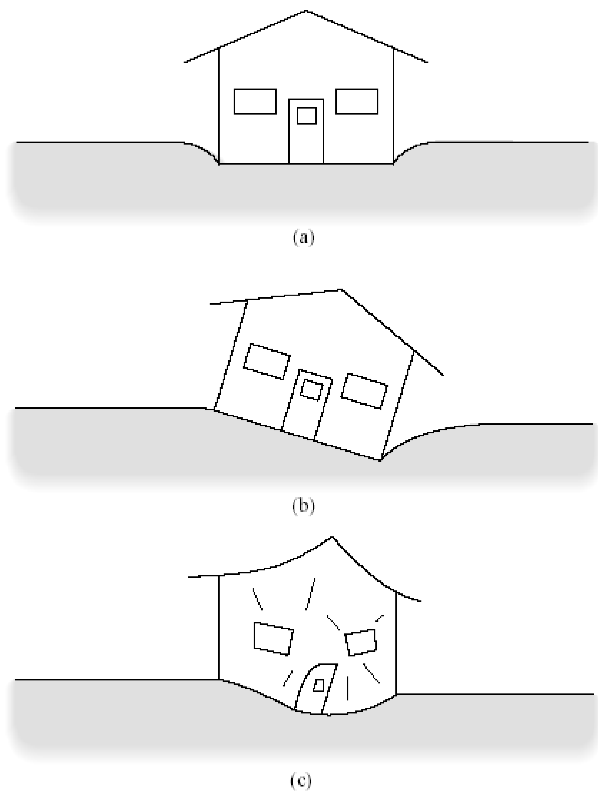
Serviceability Considerations



Design considerations.

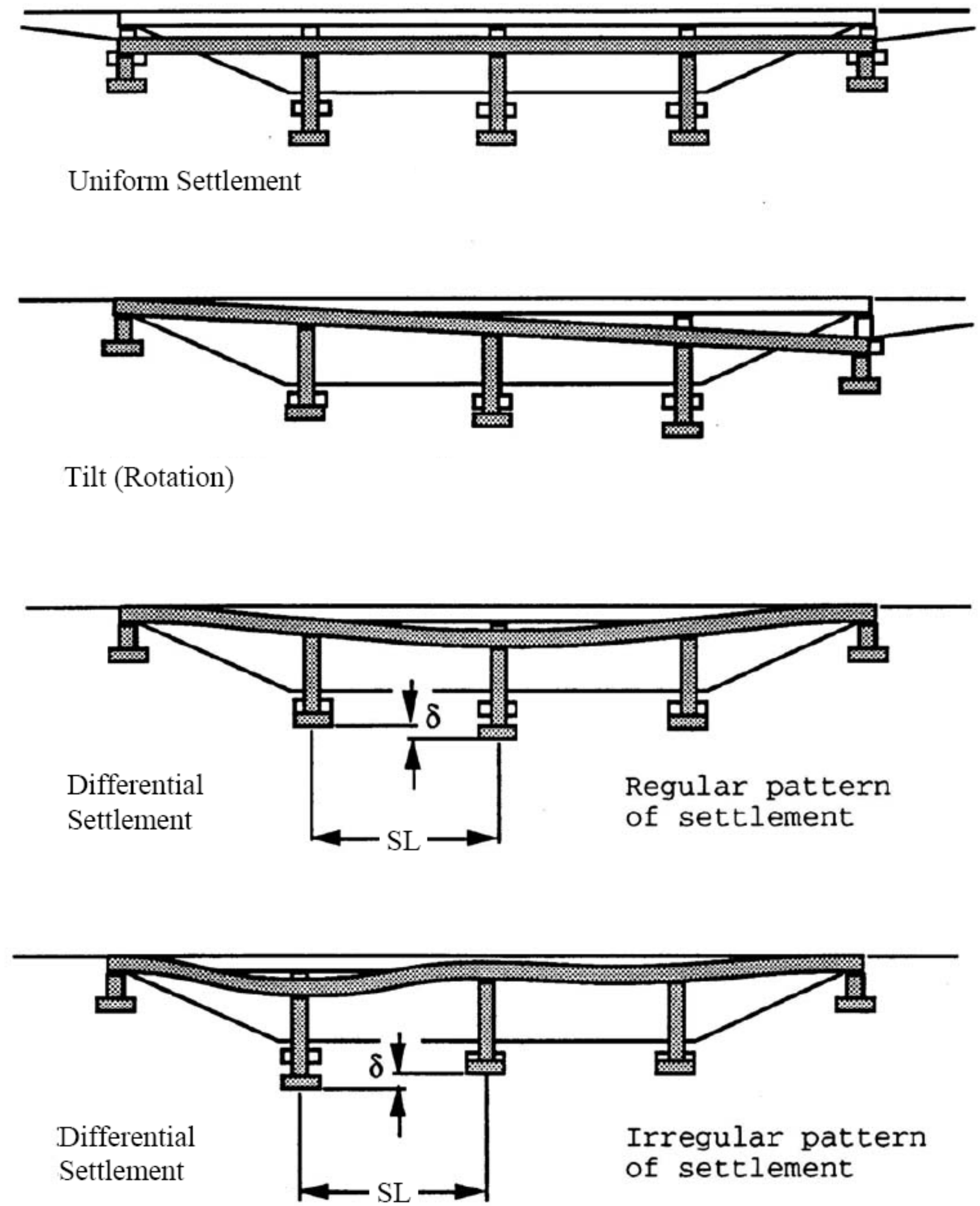
1. Seasonal changes (wet and dry periods)
2. Frost heave
3. Change of ground water level
4. Internal erosion (piping)
5. Adjecent excavations and buildings
6. Soil creep
7. Sinkholes (karst)
8. Vibrations
9. Deterioration of concrete (sulphate)

- Most common issue in serviceability: settlement



Types of Settlement

- Definitions of Settlement
  - Absolute Settlement, usually associated with uniform/total settlement (units of length, Table 2.1)
  - Angular distortion settlement, usually associated with differential settlement (ratio of settlement to distance between foundations and structures, Table 2.2)



A = Angular Distortion

$$A = \frac{\text{Difference in Settlement Between Foundations}}{\text{Distance Between Foundations}} = \frac{\delta}{SL}$$

Factors to Determine Acceptable Settlement

- Connections with existing structures
- Utility Lines
  - Total settlement of permanent facilities can harm or sever connections to outside utilities such as water, natural gas, and sewer lines.
  - Water and sewer lines may leak contributing to localised wetting of the soil profile and aggravating differential displacement.
  - Leaking gas from breaks caused by settlement can lead to explosions.
- Surface Drainage
- Access
- Aesthetics
- Material of structure (steel, concrete)
- Usage Requirements
  - Settlement of bridges/overpasses vs. settlement of embankments, the "bump in the bridge"

"Typical" Values of Acceptable Settlement

Maximum Allowable Average Settlement of Some Structures
(Data from Item 53)

Type of Structure	Settlement, inches
Plain brick walls	
Length/Height ≥ 2.5	3
Length/Height ≤ 1.5	4
Framed structure	4
Reinforced brick walls and brick walls with reinforced concrete	6
Solid reinforced concrete foundations supporting smokestacks, silos, towers, etc	12

Some Limiting Deflection Ratios
(After Items 17, 53, 65)

Structure	Deflection Ratio, Δ/L: Sand and Hard Clay	Deflection Ratio, Δ/L: Plastic Clay
Buildings with plain brick walls		
Length/Height ≥ 3	1/3333	1/2500
Length/Height ≥ 5	1/2000	1/1500
One story mills; between columns for brick clad column frames	1/1000	1/1000
Steel and concrete frame	1/500	1/500

Tolerable movement criteria for bridges (FHWA, 1985; AASHTO 2002, 2004)

Limiting Angular Distortion, δ/SL	Type of Bridge
0.004	Multiple-span (continuous span) bridges
0.005	Single-span bridges

Note: δ is differential settlement, SL is the span length. The quantity, δ/SL, is dimensionless and is applicable when the same units are used for δ and SL, i.e., if δ is expressed in inches then SL should also be expressed in inches.

Limiting Angular Distortions to Avoid
Potential Damages (Data from Items 53, 65, TM 5-818-1)

Situation	Length/Height	Allowable Angular Distortion, β = δ/ℓ
Hogging of unreinforced load-bearing walls		1/2000
Load bearing brick, tile, or concrete block walls	≥ 5	1/1250
	≤ 3	1/2500
Sagging of unreinforced load-bearing walls		1/1000
Machinery sensitive to settlement		1/750
Frames with diagonals		1/600
No cracking in buildings; tilt of bridge abutments; tall slender structures such as stacks, silos, and water tanks on a rigid mat		1/500
Steel or reinforced concrete frame with brick, block, plaster or stucco finish	≥ 5	1/500
	≤ 3	1/1000
Circular steel tanks on flexible base with floating top; steel or reinforced concrete frames with insensitive finish such as dry wall, glass, panels		1/300 - 1/500
Cracking in panel walls; problems with overhead cranes		1/300
Tilting of high rigid buildings		1/250
Structural damage in buildings; flexible brick walls with length/height ratio > 4		1/150
Circular steel tanks on flexible base with fixed top; steel framing with flexible siding		1/125

Example of Settlement Calculations

- Given
  - Steel framed office building, 20' column spacing
  - Supported on spread footings founded on clayey soil
- Find
  - Allowable total settlement
  - Allowable differential settlement
- Solution
  - Typical total settlement specification = 1" (Table 2.1)
  - Use δ = 1/500 (Table 2.2); δ_{du} = (1/500)(20') = 0.04' = 0.5"

Settlement vs. Bearing Capacity (Shear Failure)

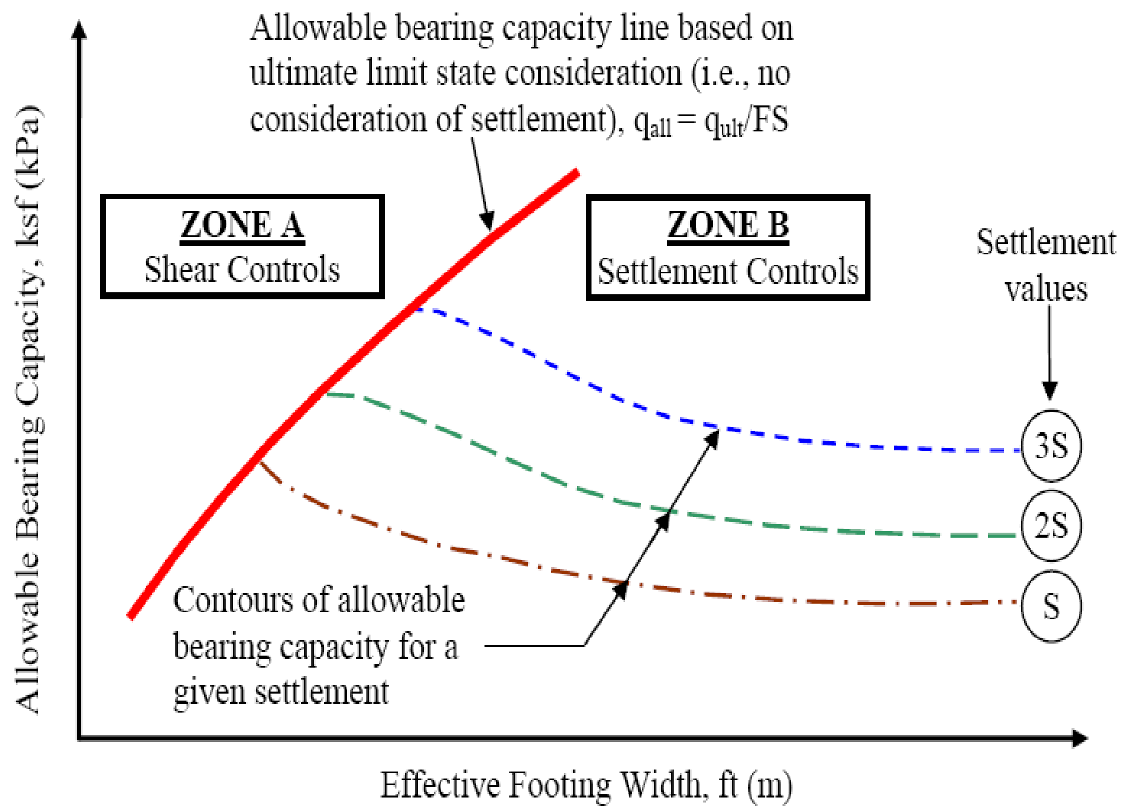
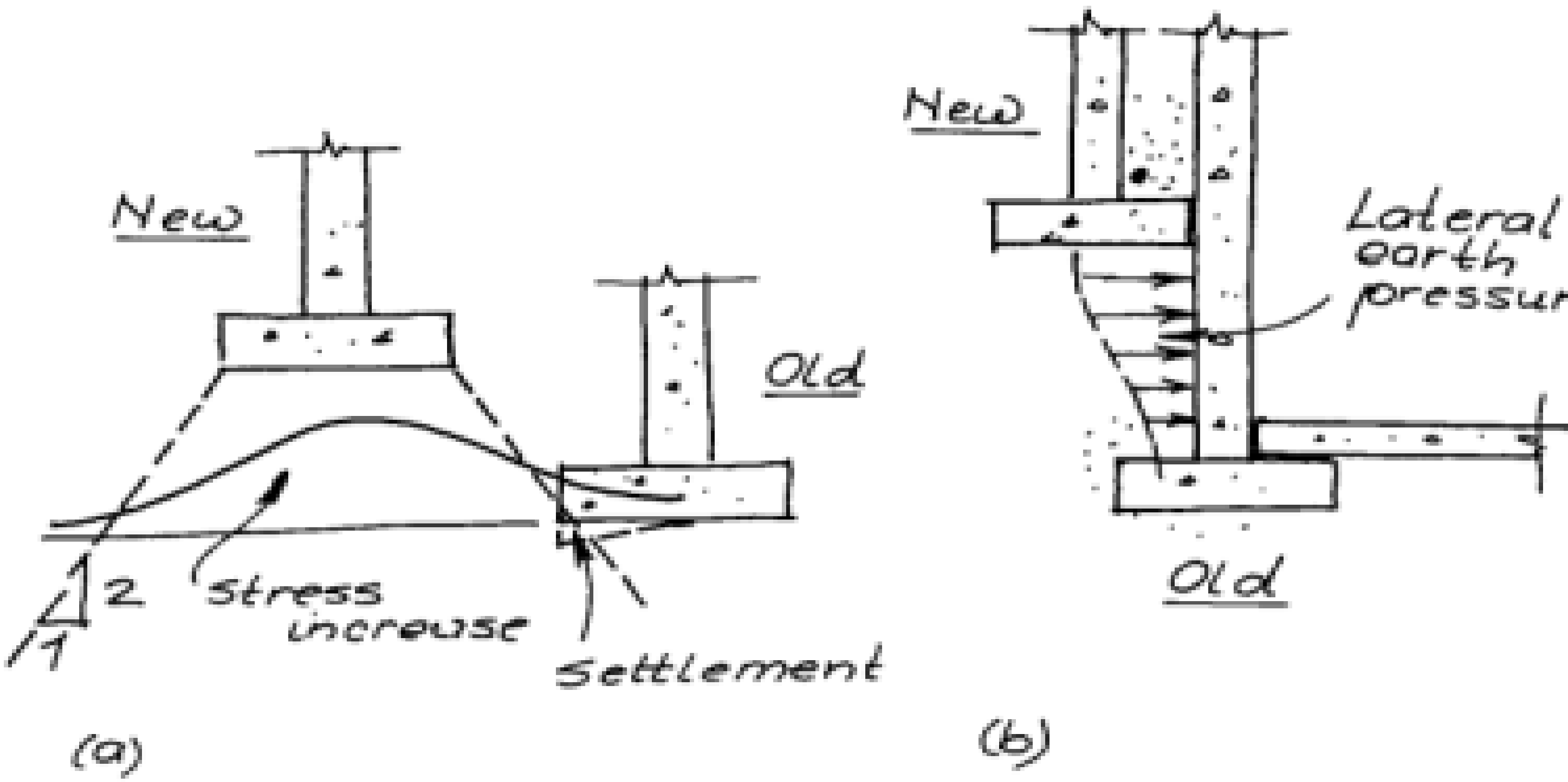
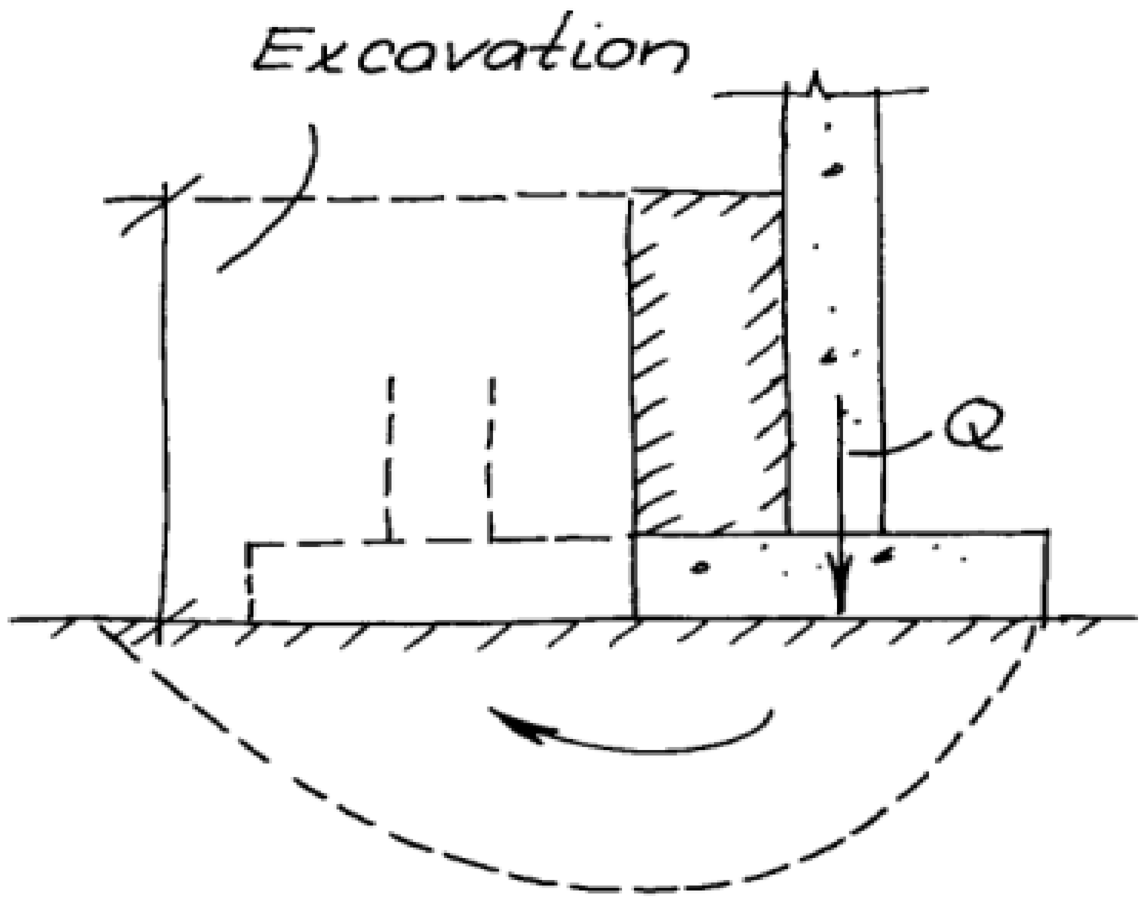


Figure 8-10. Shear failure versus settlement considerations in evaluation of allowable bearing capacity.

Interaction of Neighbouring Structures

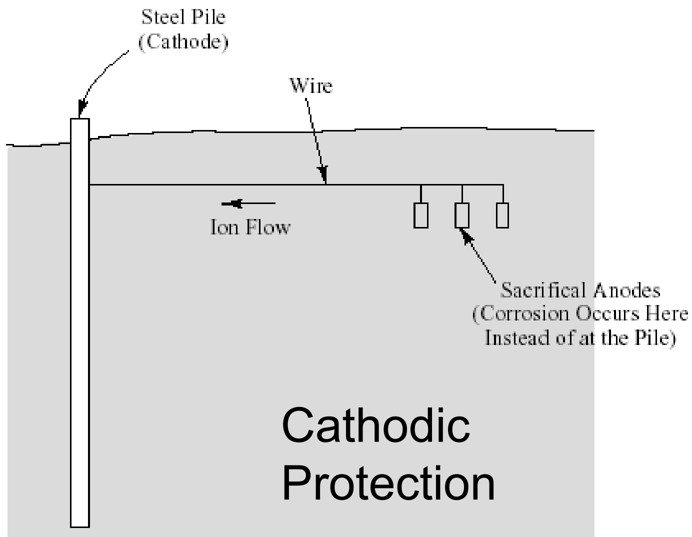


Changes in Excavation Conditions

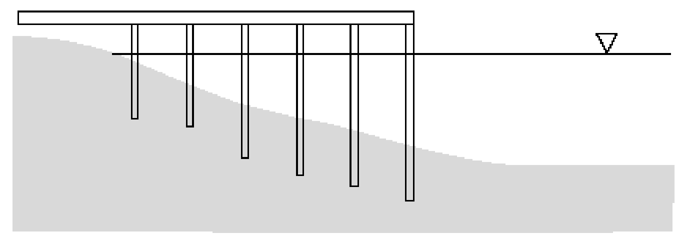


Deterioration of Structures

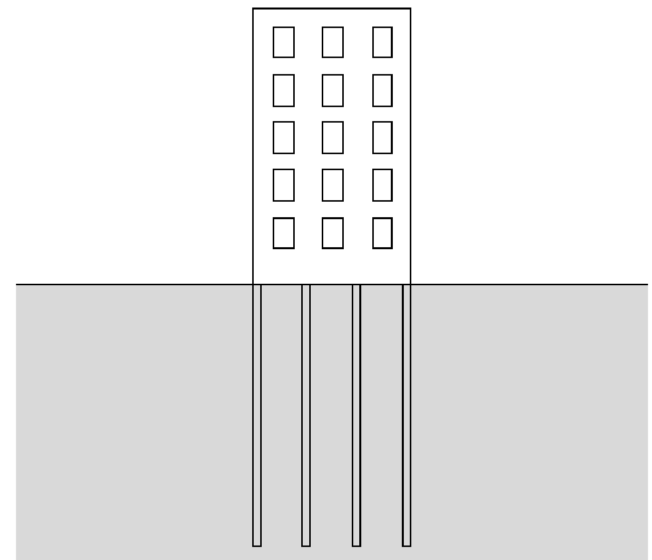
- Environmental attack is an important consideration in design of foundations
  - Corrosion
  - Sulphate attack on concrete
  - Marine borers on timber structures
  - Fire on timber structures
- Although environmental attack is more common with marine structures, but is also present on non-marine structures as well



Marine Environments



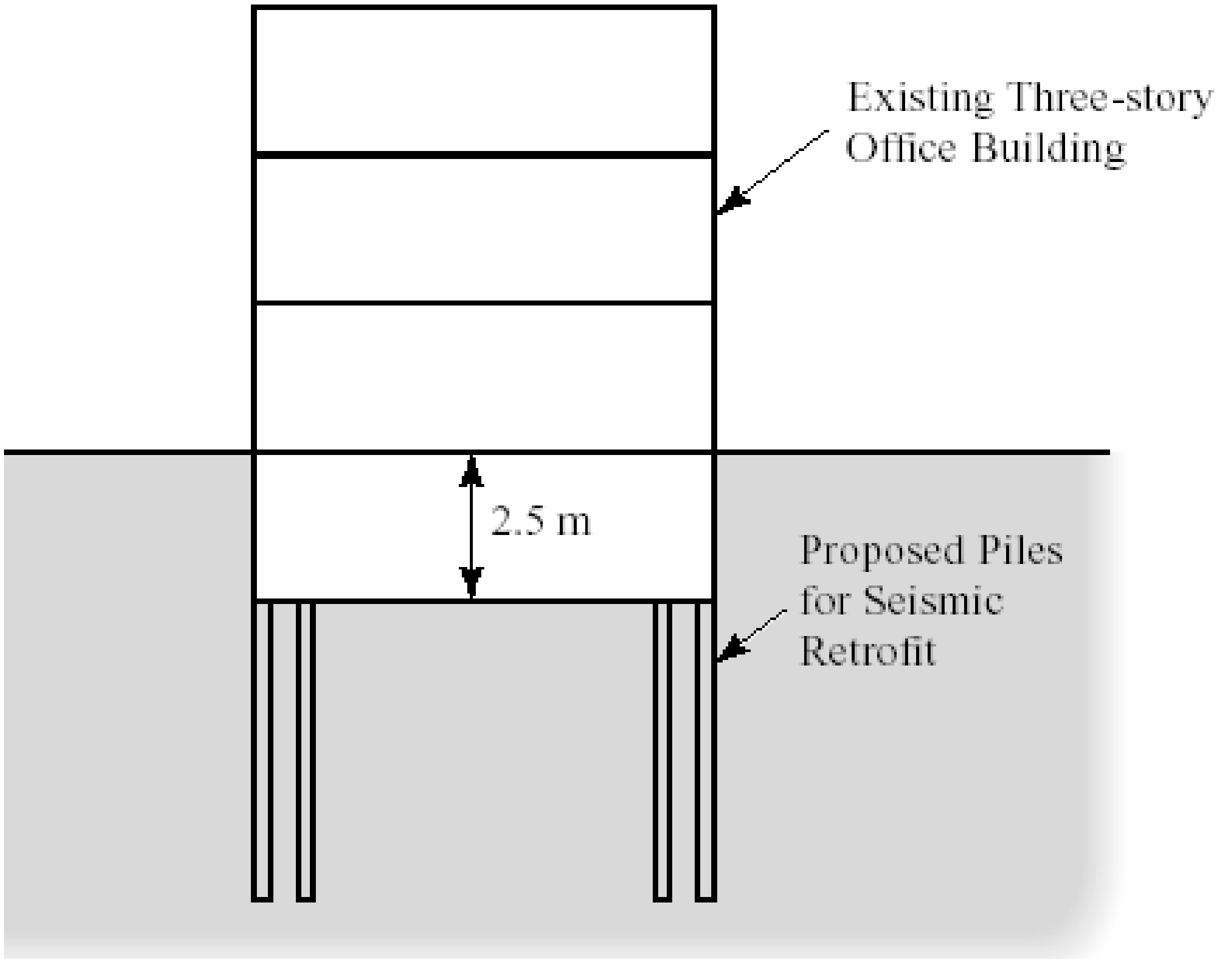
(a)



(b)

Land Environments

Constructibility Requirements



Economic Requirements

- Foundation design tends to be more conservative than structural design because the unknowns are not as well quantified
- Consequences of catastrophic foundation failure are much greater, as the entire structure fails with the foundation
- Reduction in weight may not be beneficial in foundation design, depending upon the circumstance

Questions?