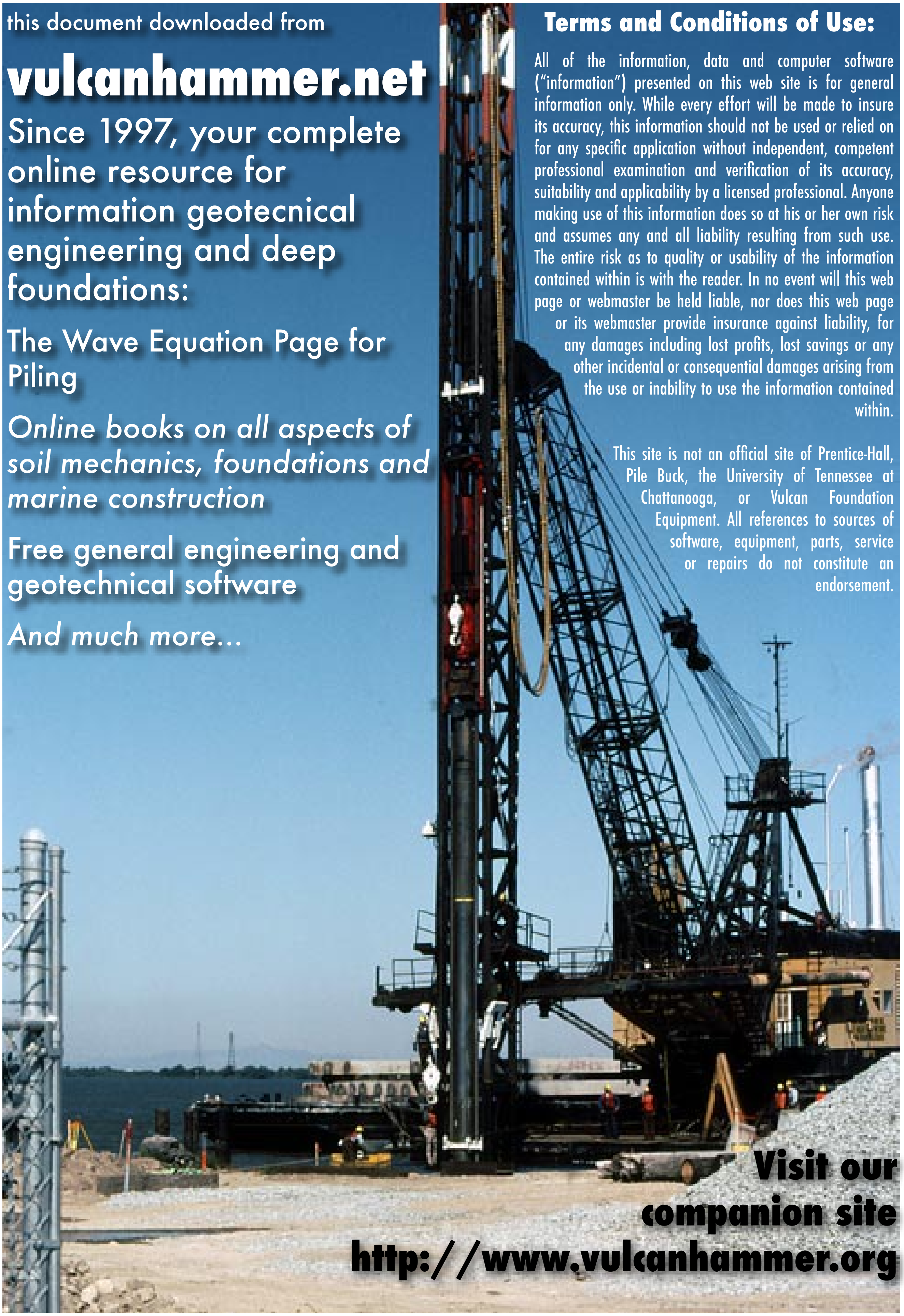
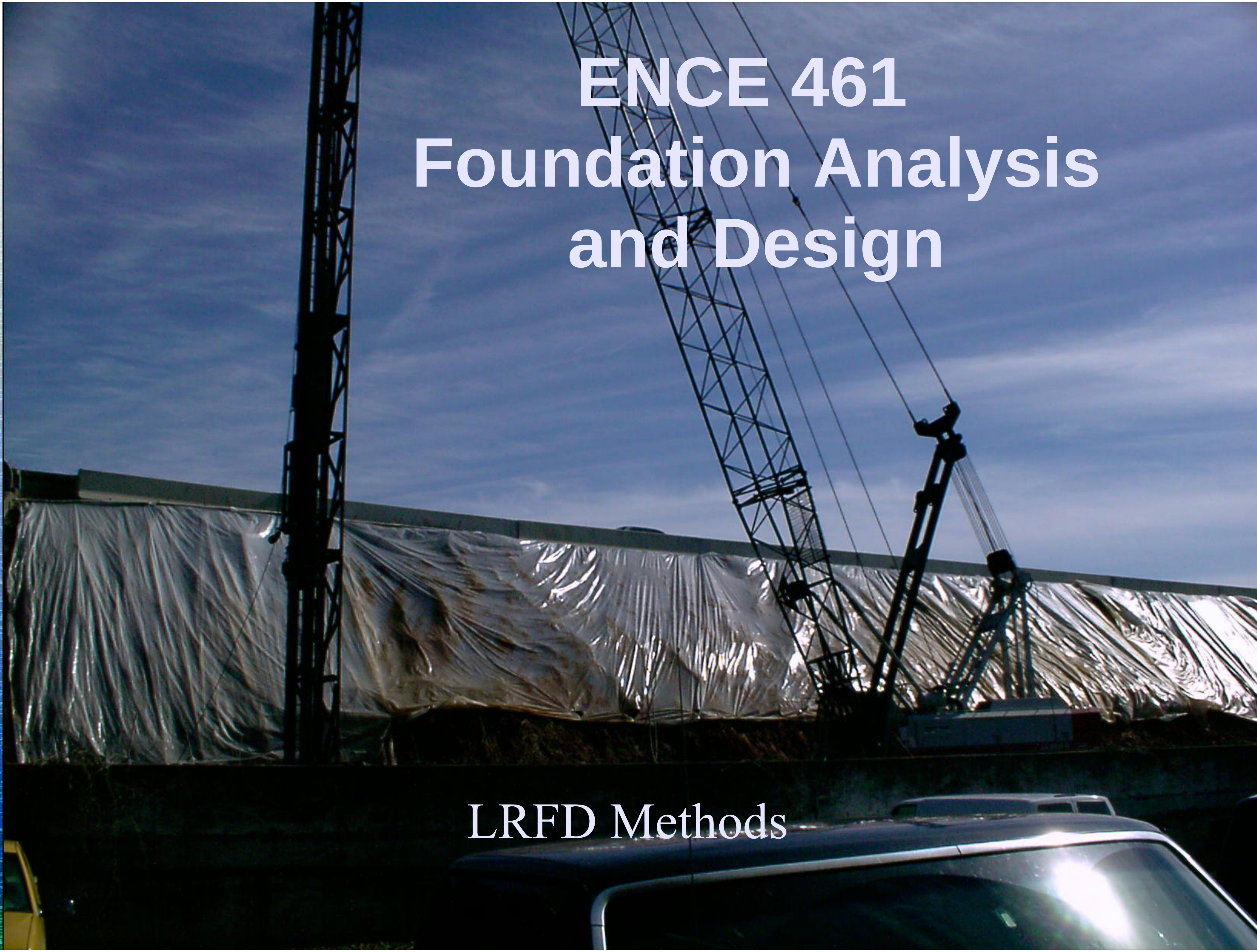




ENCE 461 Foundation Analysis and Design

LRFD Methods

Solving the “Factor of Ignorance” via Probability

- It should be remembered, however, that these are not true factors of safety, but include a "factor of ignorance." The author suggests that when the ultimate resistance of any pile has been determined, in fixing the factor of safety...the most unfavorable conditions possible in the supporting strata should be judged (the range of conditions possible being narrowed with better knowledge of the subsurface conditions and of the possibility of disturbance from extraneous sources) and a proportion of the factor of safety -- a "factor of ignorance" -- then allowed in respect to these possible conditions, the manner of determining the ultimate load, and the type of loading to be borne. The remaining proportion of the factor of safety -- or true margin of safety -- should be approximately constant for all classes of loading and foundation conditions involving the same value of loss in case of failure; and the overall factor of safety...will then be equal to the product of the true factor of safety with the "factor of ignorance." (David Victor Isaacs, 1931)
- LRFD is an attempt to define that “factor of ignorance” based on probabilistic considerations
- Main source for lecture: FHWA HI-98-032, “Load and Resistance Factor Design (LRFD) for Highway Bridge Substructures”

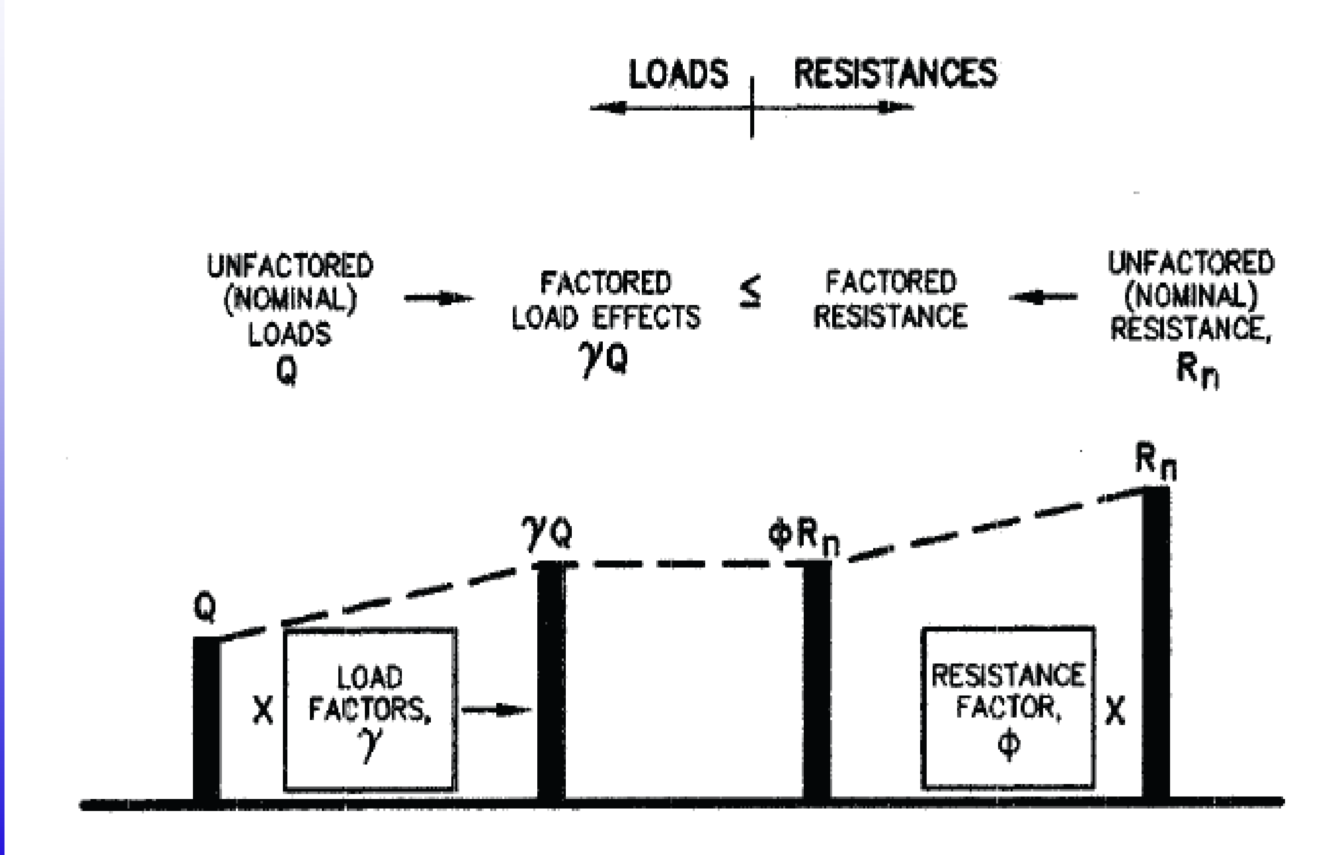
From ASD to LRFD

- History
  - Until early 1970's all civil engineering design was done using ASD
  - Transition for superstructures was complete by mid-1990's
  - Transition to LRFD for substructures began around this time and has continued to the present
- Limitations of ASD
  - Does not adequately account for variability of loads and resistances. The FS is applied only to resistance. Loads are considered to be without variation (i.e., deterministic).
  - Does not embody a reasonable measure of strength, which is a more fundamental measure of resistance than is allowable stress.
  - Selection of a FS is subjective, and does not provide a measure of reliability in terms of probability of failure.

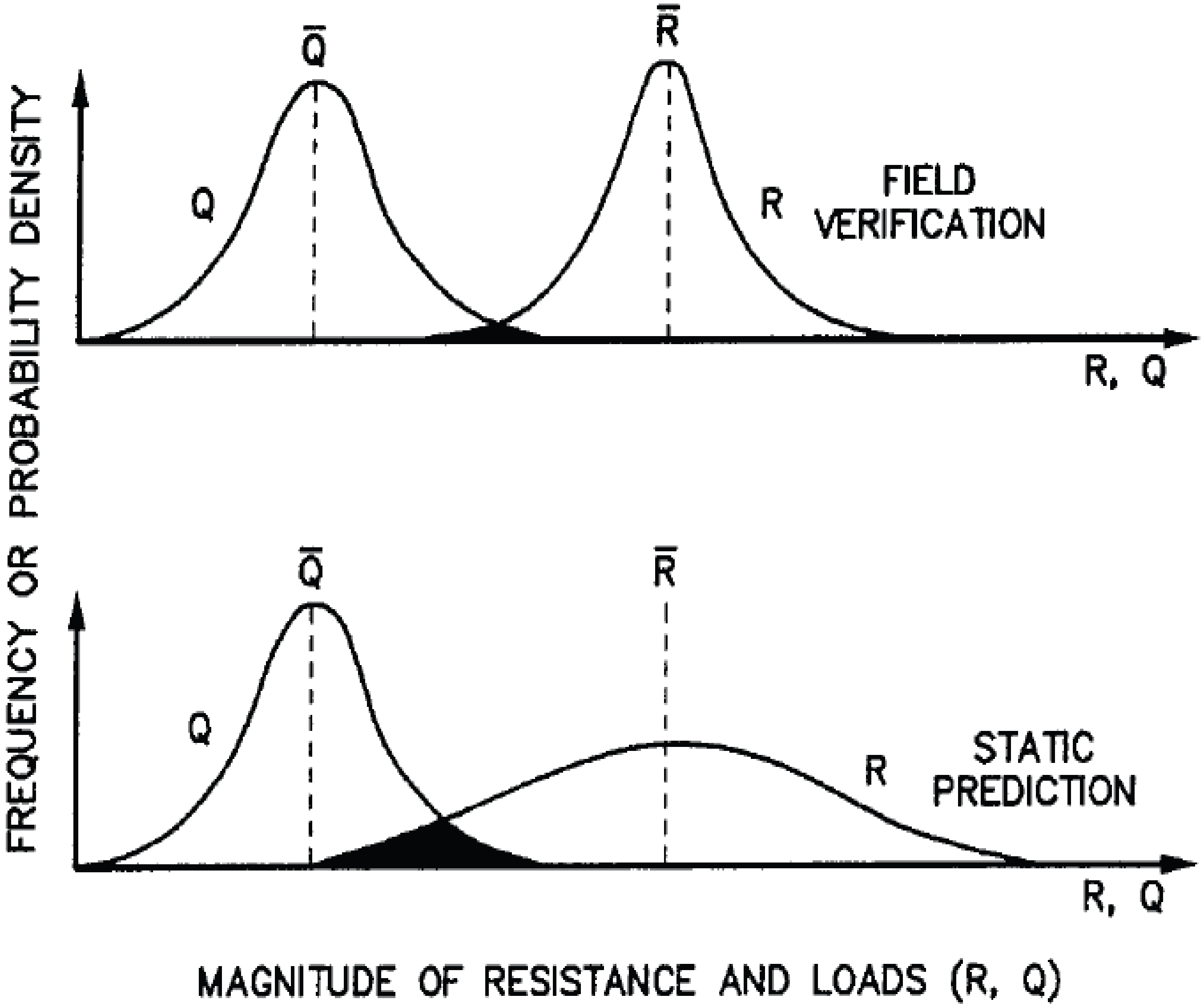
LRFD Design Approach

$$\sum_{i=1}^{m} \gamma_i Q_i \le \phi R_n$$

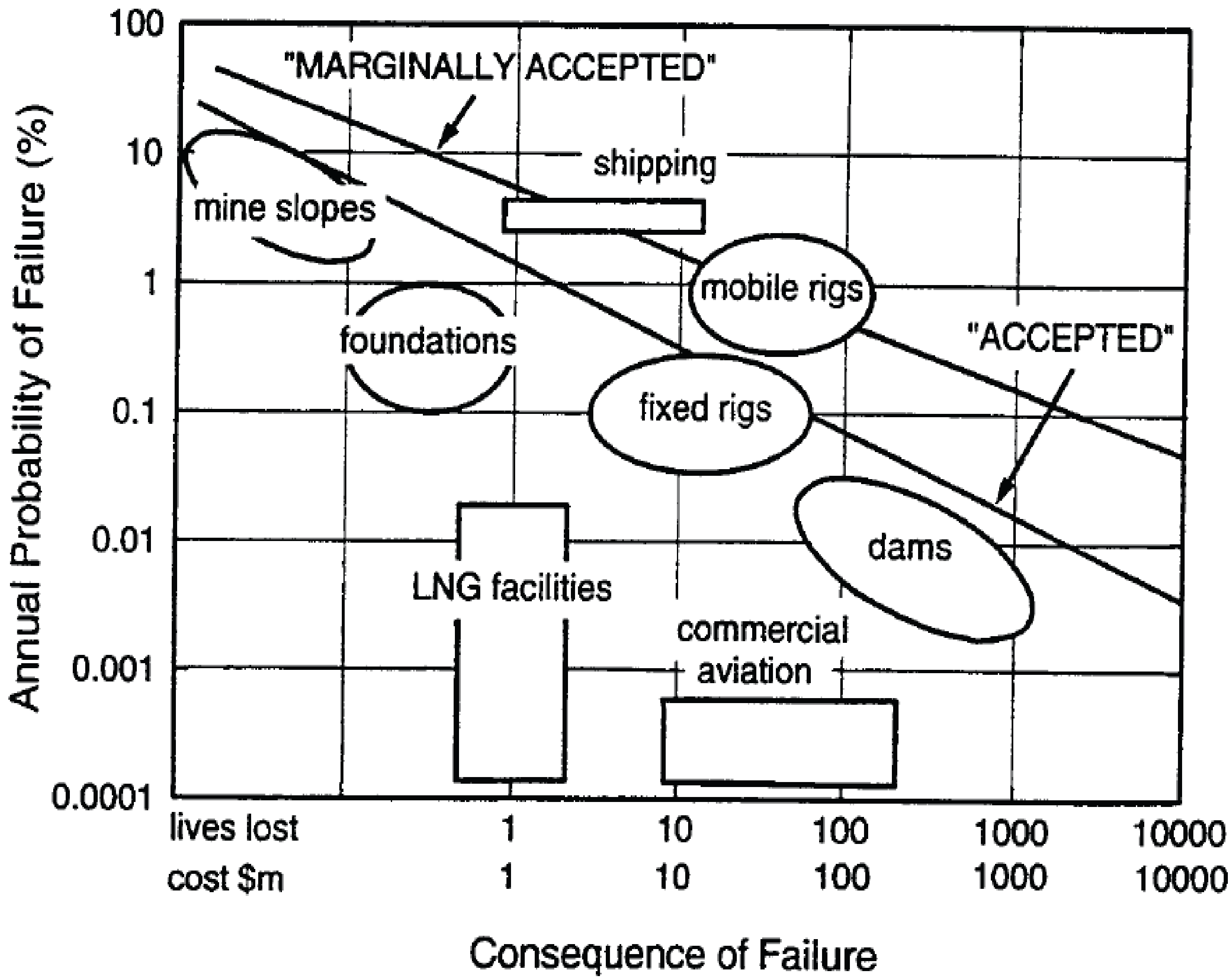
$$\gamma_i > 1,\ \phi < 1\ \text{(usually)}$$



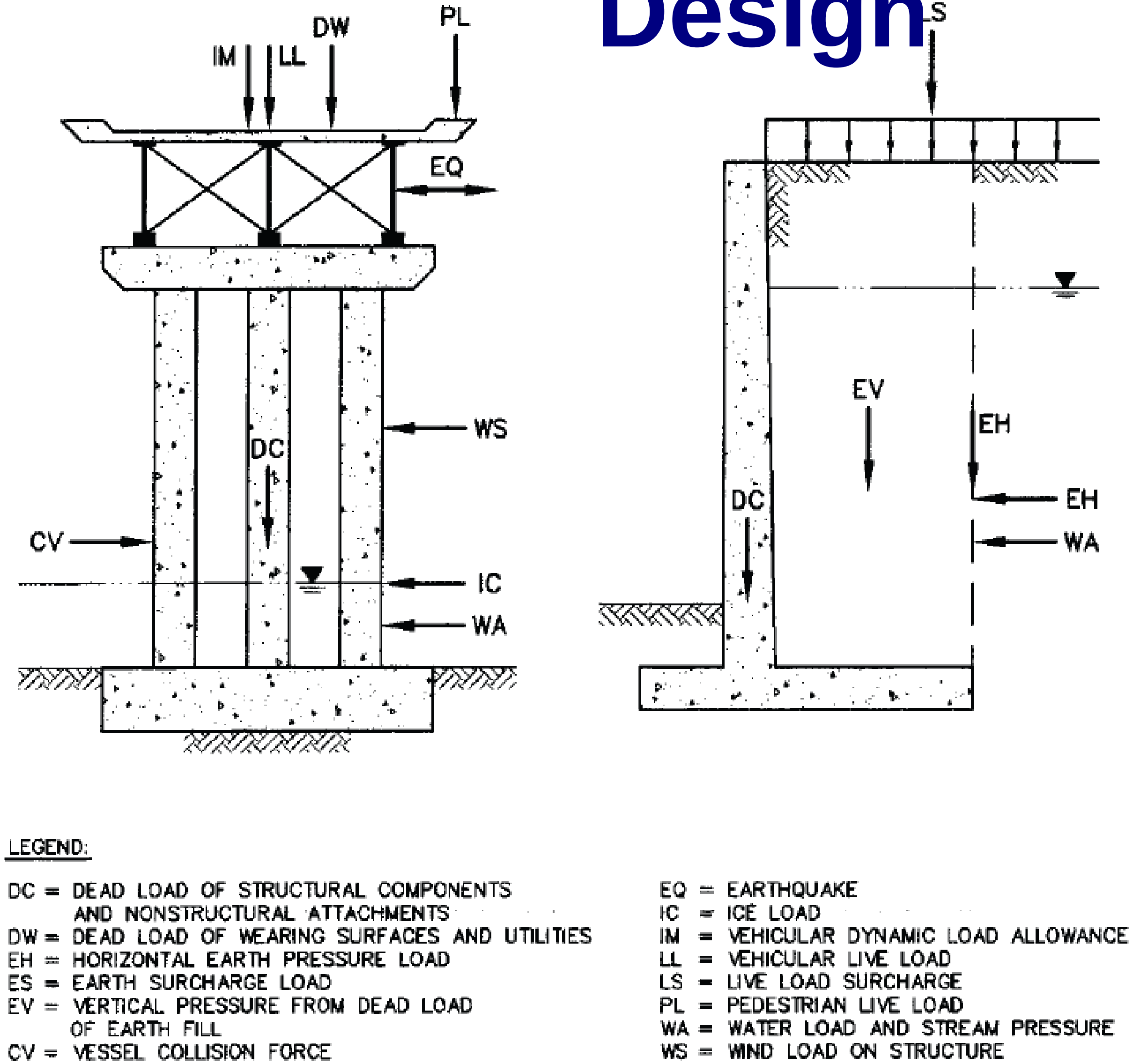
Distribution of Load and Resistance



Empirical Rates of Failure for Civil Works Facilities



Loading for Substructure Design



(a) Bridge Pier (b) Cantilever Retaining Wall

Determination of Resistance Factors

- Calibration of Resistance Factors
  - Engineering judgment
  - Fitting to ASD
  - Reliability theory
  - A combination of approaches
- Selection of Resistance Factors
  - Variability of the soil and rock properties
  - Reliability of the equations used for predicting resistance
  - Quality of the construction workmanship
  - Extent of soil exploration
  - Consequence(s) of a failure

Advantages of Challenges of LRFD

- Advantages
  - Accounts separately for variability in load and resistance prediction
  - Achieves more consistent levels of safety in structure and substructure design
  - Does not require knowledge of probability or reliability theory
- Challenges
  - Implementation requires a change for engineers accustomed to ASD
  - Resistance factors vary with design methods and are not constant
  - Rigorous calibration of load and resistance factors to meet individual situations requires availability of statistical data and probabilistic design algorithms

Notes on Load and Resistance Factors in Textbook

- Load Factors
  - Given in Chapter 2
  - Actual load factors subject to code and application
  - Codes are constantly changing, so these values can only be used for purposes of the course
- Resistance Factors
  - Given in Chapter 21
  - Resistance factors subject, to code, application, type of foundation or retaining wall, and design and/or verification
  - Same note on change with load factors

Example of LRFD For Shallow Foundations

- Given
  - Single column highway bridge bent to be supported on square spread footing
  - Factored vertical load (using AASHTO factors) = 4500 kN
  - Load includes weight of foundation
  - Bottom of footing will be 1.8 m below adjacent ground surface
- Given
  - Soil Conditions:
    - $c' = 0$
    - $\varphi = 31°$
    - $\gamma = 17.5\ kN/m^3$
    - Based on SPT Data
- Find
  - Foundation size using LRFD

(1997) Load Factors

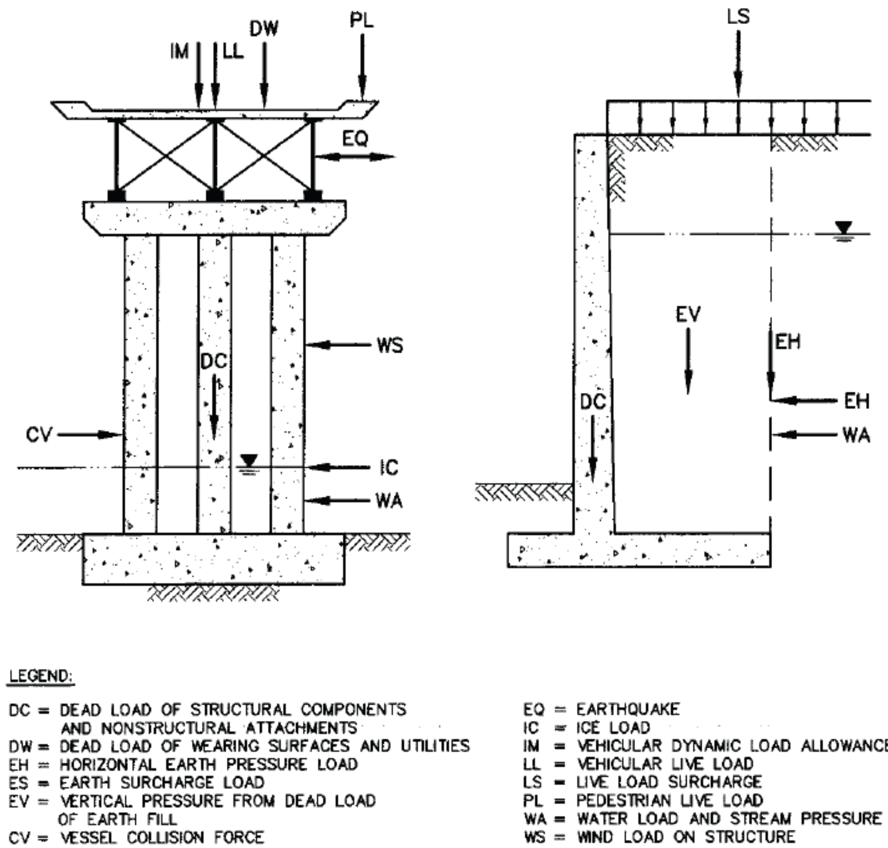
Load Combinations and Load Factors
(AASHTO, 1997a)

LOAD COMBINATION / LIMIT STATE	DC DD DW EH EV ES	LL IM CE BR PL LS	WA	WS	WL	FR	(1) TU CR SH EL	TG	SE	Use one of these at a time: EQ	IC	CT	CV
STRENGTH-I (unless noted)	γ_p	1.75	1.00	-	-	1.00	0.50/ 1.20	γ_{TG}	γ_{SE}	-	-	-	-
STRENGTH-II	γ_p	1.35	1.00	-	-	1.00	0.50/ 1.20	γ_{TG}	γ_{SE}	-	-	-	-
STRENGTH-III	γ_p	-	1.00	1.40	-	1.00	0.50/ 1.20	γ_{TG}	γ_{SE}	-	-	-	-
STRENGTH-IV EH, EV, ES, DW DC ONLY	γ_p 1.50	-	1.00	-	-	1.00	0.50/ 1.20	-	-	-	-	-	-
STRENGTH-V	γ_p	1.35	1.00	0.40	0.40	1.00	0.50/ 1.20	γ_{TG}	γ_{SE}	-	-	-	-
EXTREME EVENT-I	γ_p	γ_{EQ}	1.00	-	-	1.00	-	-	-	1.00	-	-	-
EXTREME EVENT-II	γ_p	0.50	1.00	-	-	1.00	-	-	-	-	1.00	1.00	1.00
SERVICE-I	1.00	1.00	1.00	0.30	0.30	1.00	1.00/ 1.20	γ_{TG}	γ_{SE}	-	-	-	-
SERVICE-II	1.00	1.30	1.00	-	-	1.00	1.00/ 1.20	-	-	-	-	-	-
SERVICE-III	1.00	0.80	1.00	-	-	1.00	1.00/ 1.20	γ_{TG}	γ_{SE}	-	-	-	-
FATIGUE-LL, IM & CE ONLY	-	0.75	-	-	-	-	-	-	-	-	-	-	-
CONSTRUCTION	1.25	1.50	1.00	1.25	1.25	1.25	1.00	1.00	1.00	-	-	-	-

[1] The reduced values of γ are used when calculating force effects other than displacements of joints and bearings (*A14.4.1*).

Load Factors for Permanent Loads, γ_P
(AASHTO, 1997a)

Type of Load	Load Factor: Maximum	Minimum
DC: Component and Attachments	1.25	0.90
DD: Downdrag	1.80	0.45
DW: Wearing Surfaces and Utilities	1.50	0.65
EH: Horizontal Earth Pressure		
• Active	1.50	0.90
• At-Rest	1.35	0.90
EV: Vertical Earth Pressure		
• Retaining Structure	1.35	1.00
• Rigid Buried Structure	1.30	0.90
• Rigid Frames	1.35	0.90
• Flexible Buried Structures	1.95	0.90
• Flexible Metal Box Culverts	1.50	0.90
ES: Earth Surcharge	1.50	0.75



(a) Bridge Pier (b) Cantilever Retaining Wall

Example Problem

- Bearing Capacity Factors (Terzaghi) for φ' = 31°
  - $N_c = 40.4$
  - $N_q = 25.3$
  - $N_\gamma = 23.7$

$$q_{ult} = 1.3cN_c + \sigma'_{zD}N_q + 0.4\gamma BN_\gamma$$

$$q_{ult} = 0 + (31.5)(25.3) + 0.4(17.5)(B)(23.7)$$

$$q_{ult} = 797 + 166B$$

- Effective Stress @ Base $\sigma_{vo} = (17.5)(1.8) = 31.5$ kPa

ce Factors for Shallow Foundations (AASHTO,

Method/Soil/Condition			Resistance Factor
Bearing Capacity		Sand	
		- *Semiempirical procedure using SPT data*	0.45
		- Semiempirical procedure using CPT data	0.55
		- Rational Method:	
		--using φ_f estimated from SPT data	0.35
		--using φ_f estimated from CPT data	0.45
		Clay	
		- Semiempirical procedure using CPT Data	0.50
		- Rational Method:	
		--using shear resistance measured in lab tests	0.60
		--using shear resistance measured in field vane tests	0.60
		--using shear resistance estimated from CPT data	0.50
		Rock	
		Semiempirical procedure, Carter and Kulhawy (1988)	0.60
		Plate Load Test	0.55
Sliding	φ_T	Precast concrete placed on sand	
		--using φ_f estimated from SPT data	0.90
		--using φ_f estimated from CPT data	0.90
		Concrete cast-in-place on sand	
		--using φ_f estimated from SPT data	0.80
		--using φ_f estimated from CPT data	0.80
		Clay (where shear resistance is less than 0.5 times normal pressure)	
		--using shear resistance measured in lab tests	0.85
		--using shear resistance measured in field tests	0.85
		--using shear resistance estimated form CPT data	0.80
		Clay (where the resistance is greater than 0.5 times normal pressure)	0.85
		Soil on soil	1.0
Passive Pressure	φ_{ep}	Passive earth pressure component of sliding resistance	0.50

Example Problem

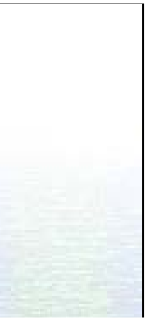
$$P_u \le \phi P_n = \phi q_{ult} A$$

$$P_u = 4500 \le (0.35)(797 + 166B)B^2$$

$$B \ge 3.2 \text{ meters}$$

Example 13.1 Using LRFD

- Given
  - Pile as shown
    - Ultimate Resistances
      - Layer 1 (Medium Clay) = 126 kN
      - Layer 2 (Silty Sand) = 1257 kN
      - Layer 3 (Glacial Till) = 1024 kN
      - Pile Toe (Glacial Till) = 504 kN
  - Assume 800 kN downward load is entirely dead load
  - Assume AASHTO Strength, I, Service I Load Combinations ("Normal" Structure)
- Given
  - Assumptions re Resistance Computations
    - Clay: α method
    - Sand: SPT method
    - Glacial Till: use same factors as clay
- Find
  - Whether 800 kN downward load is acceptable using LRFD



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STRENGTH-III	γ_p	-	1.00	1.40	-	1.00	0.50/ 1.20	γ_{TG}	γ_{SE}	-	-	-	-
STRENGTH-IV EH, EV, ES, DW DC ONLY	γ_p 1.50	-	1.00	-	-	1.00	0.50/ 1.20	-	-	-	-	-	-
STRENGTH-V	γ_p	1.35	1.00	0.40	0.40	1.00	0.50/ 1.20	γ_{TG}	γ_{SE}	-	-	-	-
EXTREME EVENT-I	γ_p	γ_{EQ}	1.00	-	-	1.00	-	-	-	1.00	-	-	-
EXTREME EVENT-II	γ_p	0.50	1.00	-	-	1.00	-	-	-	-	1.00	1.00	1.00
SERVICE-I	1.00	1.00	1.00	0.30	0.30	1.00	1.00/ 1.20	γ_{TG}	γ_{SE}	-	-	-	-
SERVICE-II	1.00	1.30	1.00	-	-	1.00	1.00/ 1.20	-	-	-	-	-	-
SERVICE-III	1.00	0.80	1.00	-	-	1.00	1.00/ 1.20	γ_{TG}	γ_{SE}	-	-	-	-
FATIGUE-LL, IM & CE ONLY	-	0.75	-	-	-	-	-	-	-	-	-	-	-
CONSTRUCTION	1.25	1.50	1.00	1.25	1.25	1.25	1.00	1.00	1.00	-	-	-	-

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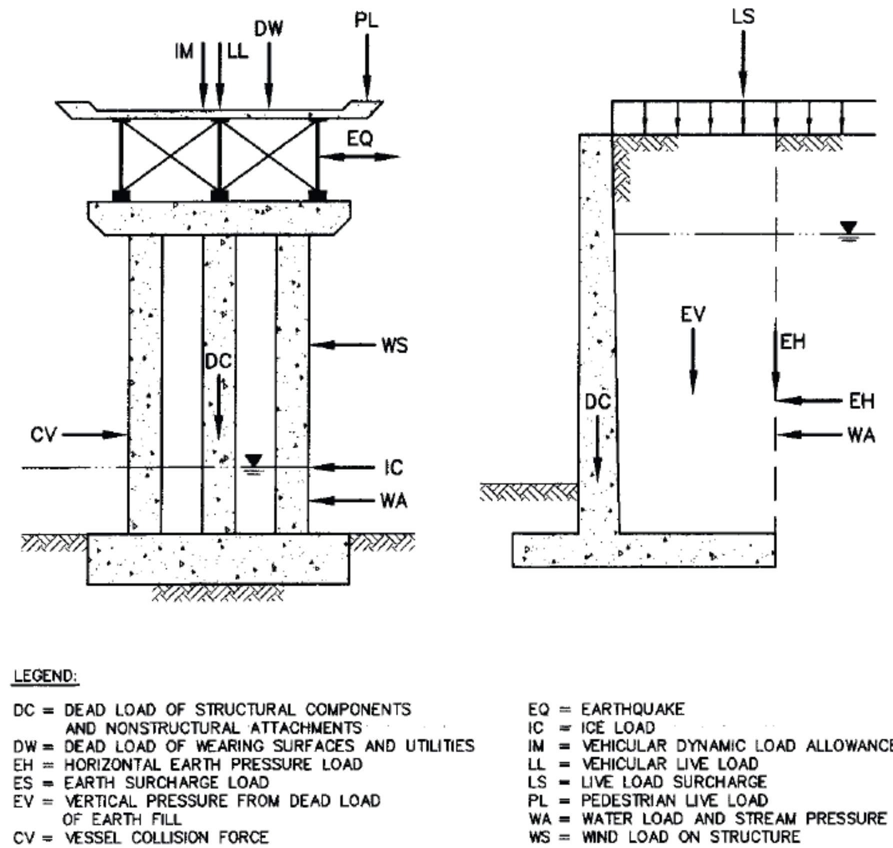

(a) Bridge Pier (b) Cantilever Retaining Wall

Resistance Factors for Piles

Clay Layer/Glacial Till

Glacial Till

Sand Layer

Resistance Factors for Geotechnical Strength Limit State for Axially Loaded Piles
(AASHTO, 1996)

METHOD/SOIL/CONDITION		RESISTANCE[1] FACTOR
Ultimate Bearing Resistance of Single Piles	Skin Friction: Clay	
	α-method	0.70
	β-method	0.50
	λ-method	0.55
	End Bearing: Clay and Rock	
	Clay	0.70
	Rock	0.50
	Skin Friction and End Bearing: Sand	
	SPT-method	0.45
	CPT-method	0.55
	Skin Friction and End Bearing: All Soils	
	Load Test	0.80
	Pile Driving Analyzer	0.70
Block Failure	Clay	0.65
Uplift Resistance of Single Piles	α-method	0.60
	β-method	0.40
	λ-method	0.45
	SPT-method	0.35
	CPT-method	0.45
	Load Test	0.80
Group Uplift Resistance	Sand	0.55
	Clay	0.55

Example 13.1

$$\sum_{i=1}^{m} \gamma_i Q_i = \phi R_n$$

- i = 1
- Q = 800 kN
- γ = 1.25 (by inspection, will use Service I value, since only one load factor and 1.25 > 1

- Resistance Factors φ by Layer
  - Layer 1 (Medium Clay) = 0.7
  - Layer 2 (Silty Sand) = 0.45
  - Layer 3 (Glacial Till) = 0.7
  - Pile Toe (Glacial Till) = 0.7

$$(1.25)(800) \leq (126)(0.7) + (1257)(0.45) + (1024)(0.7) + (504)(0.7)$$

$$1000 \leq 1723$$

So design is OK

Questions