LATERALLY LOADED PILE ANALYSIS FOR THE LRFD DESIGN OF BRIDGE FOUNDATIONS

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Presented at:

Session 4D: LRFD Seismic Design Considerations
Western Bridge Engineers Seminar
Sacramento, California
September 21, 2009

"He was living like an engineer in a mechanical world. No wonder he had become dry as a stone."

- *Simone de Beauvoir*
The Mandarins

"...as for earthquakes, though they were still formidable, they were so interesting that men of science could hardly regret them."

- *Bertrand Russell*
on the rise of science, History of Western Philosophy

"No village or man shall be forced to build bridges at river banks, except those who ought to do so by custom and law."
- Chapter 23 of Magna Carta

- TOPICS -

1.0 OVERVIEW OF LRFD REQUIREMENTS

1.1 Basic LRFD Structure Design Requirements

- LRFD = (LIMIT STATE + RELIABILITY) BASED DESIGN
- A Limit State is a defined Safety or Serviceability performance requirement (with due regard to constructibility, economy and aesthetic)
  - FOR ALL LIMIT STATES, each component and connection shall have:

∑(Resistance x Resistance Factor) ≥ ∑(Load Effects x Load Factor)

i.e., $\sum(R_n \times \varphi) \geq \sum(Q \times \gamma)$ **or** $(\sum Q \times \gamma) \leq (R_n \times \varphi)$

Q = Load Nominal Load
R_n = Resistance (Capacity)
γ & φ = Inter-dependant multipliers or load and resistance factors, respectively, corresponding to a given reliability

Note: Resistance can be Ultimate (R_n) or Mobilized at a Given (Tolerable or Permissible) Movement =$(R_n)_{\delta perm}$

1.2 LRFD Limit States

- Three Limit States

1. Service Limit States
   - Stress/Deformation/Cracks etc. under regular operating conditions
2. Strength Limit States:
   - Strength and Stability under regular operating conditions during the design life.
3. Extreme Event Limit States
   - Strength and Stability during extreme events (e.g. earthquake) with a return period greater than the design life.\

1.3 Reliability

- Minimum Required Probability of Meeting the Specified Limit State Requirements = (1- Acceptable Probability of Not Meeting the Limit State Requirements)

2.0 LRFD REQUIREMENTS FOR LATERAL LOAD (P)

2.1 Service Limit State Design

- Limit State: Tolerable (Permissible) Lateral Deflection (at pile top) = δ_{perm}
- (Factored) Service Lateral Load ≤ (Factored) Lateral Resistance at $\delta = \delta_{perm}$

i.e., $[(P_n)_{service} \times \gamma_{service})] \leq [(H_n)_{service} \times \varphi_{service}]$

Denoting, $(P_n)_{service} \times \gamma_{service} = (P_{nf})_{service}$ and $(H_n)_{service} \times \varphi_{service} = (H_{nf})_{service}$

$$(P_{nf})_{service} \leq (H_{nf})_{service}$$

- $\varphi_{service} = 1.0$

2.0 LRFD Requirements for Lateral Load (H)

2.2 Strength Limit State Design

❑ Limit States:

- Stabilty/Failure (Bearing/Sliding/Flexure/Shear)

- **Failure NOT to be associated with any amount of movement** (unless a movement is specified and the corresponding reliability load and resistance factors are established)

- Factored Resistance ≥ Factored Load

  i.e., $\sum[(H_n)_{strength} \times \varphi_{Strength}] \geq \sum[(P_n)_{strength} \times \gamma_{strength}]$

  or $(H_{nf})_{strength} \geq (P_{nf})_{strength}$

Here,

$(P_n)_{Strength}$ = Pile Nominal Lateral (Horizontal?) Resistance or Capacity

2.0 LRFD Requirements for Lateral Load (H)

2.2(b) Strength Limit State Design

- Failure/Stability Modes for **PILES Foundations**
  - Pile Structural Failure
    - Shear or Flexure (with Axial Load)
    - $\varphi_{Strength}$ = From AASHTO BDS Section 5.0 (Concrete) or 6.0 (Steel)
    - Failure not purely structural (?) It depends on soil-pile interaction or soil resistance. No resistance factor is applied to soil resistance in the AASHTO Spec (Unsafe).
  - Pile Soil/Geotechnical Failure
    - Passive Soil Wedge Failure if L< Critical Length (L_c)
    - Soil/Geotechnical Failure will not occur if L≥ Lc
    - $\varphi_{Strength}$ = 1.0 (Current AASHTO BDS)
      - UNSAFE FOR PASSIVE SOIL FAILURE
      - Should be ≥ 0.45 for Bridges (FS = 3.0), and ≥0.9 ((FS=1.5) for Earth Retaining Structures

2.0 LRFD Requirements for Lateral Load (H)

2.3 Extreme Event Limit State Design

- Seismic (Extreme Event I Load Combination)
- Limit States: Collapse/Failure/Stability (To Provide Life Safety)
- Factored Resistance (at Failure/Stability) ≥ Factored Load (at Extreme Event)

i.e., $\Sigma[(H_n)_{seismic} \times \varphi_{Seismic}] \geq \Sigma[(P)_{seismic} \times \gamma_{seismic}]$

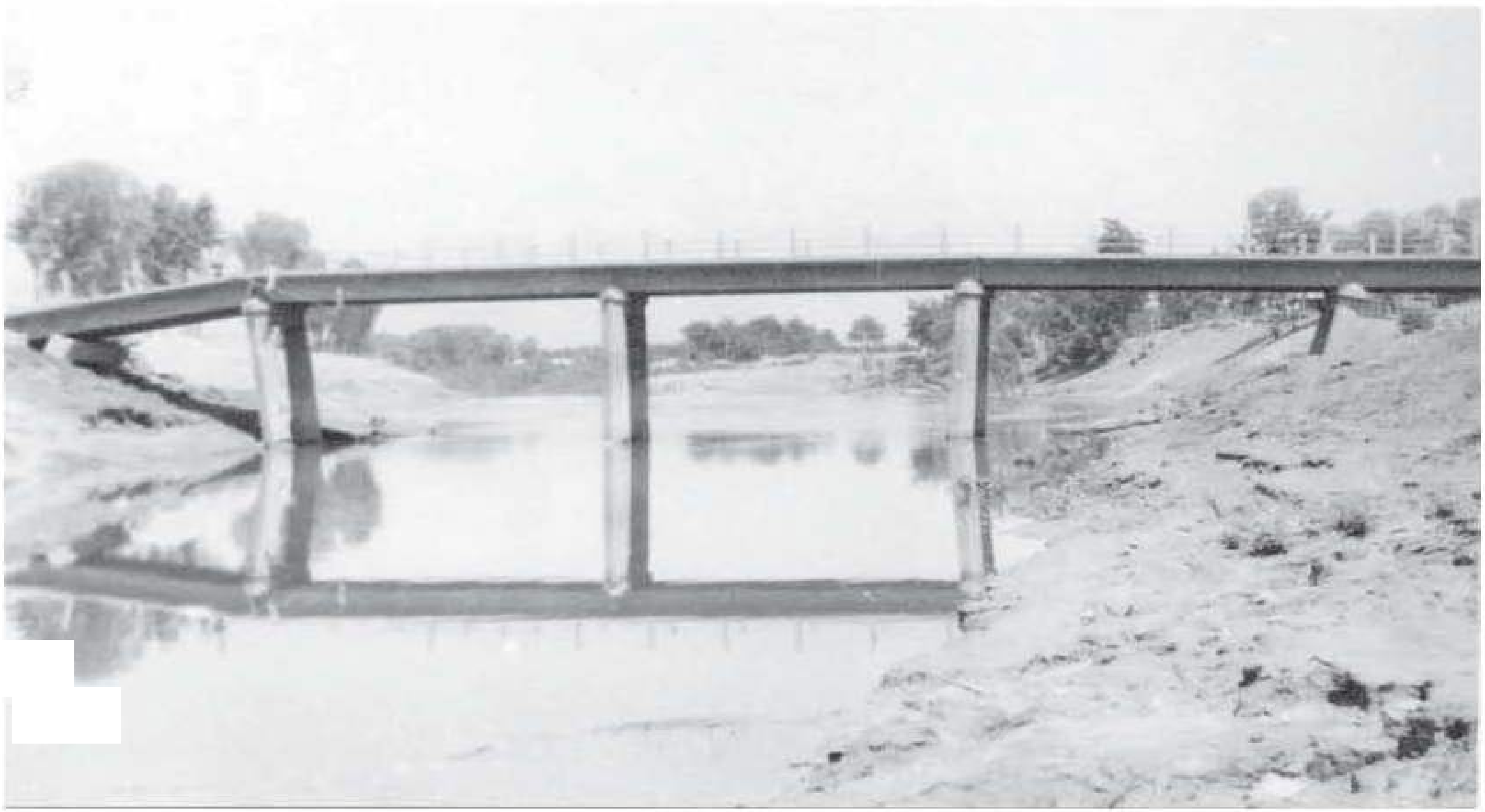
or $(H_{nf})seismic \geq (P_{nf})_{seismic}$

Here, $(H_n)_{seismic}$ = Pile Seismic Nominal Lateral Resistance or Capacity

- Failure Modes:
  - **PILES (Deep Foundations)**
    - Structural : Shear, Flexure
    - Geotechnical/Soil: Passive Soil Wesdge Failure if $L < (L_c)_{seismic}$
    - Geotechnical/Soil Failure will not occur if $L \geq (L_c)_{seismic}$
    - $\varphi_{seismic} = 1.0$ (Irrespective of failure mode/mechanism)
    - Thus, $(P_{nf})_{seismic} = (P_n)_{seismic}$

3.0 LATERAL LOADS ON PILES

3.1 Some Examples of Lateral Loads on Piles

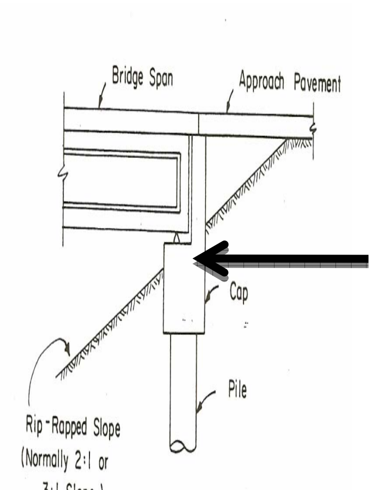


The Yuehe Bridge in the city of Tangshan had poured piles and simple beams. The bank slopes slipped toward the center of the river and the bridge piers tilted. (Photo: Xu Fengyun)

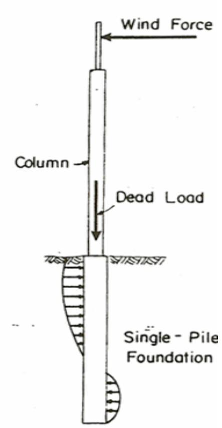
1976 M7.8 Tangshan Earthquake

3.0 LATERAL LOADS ON PILES

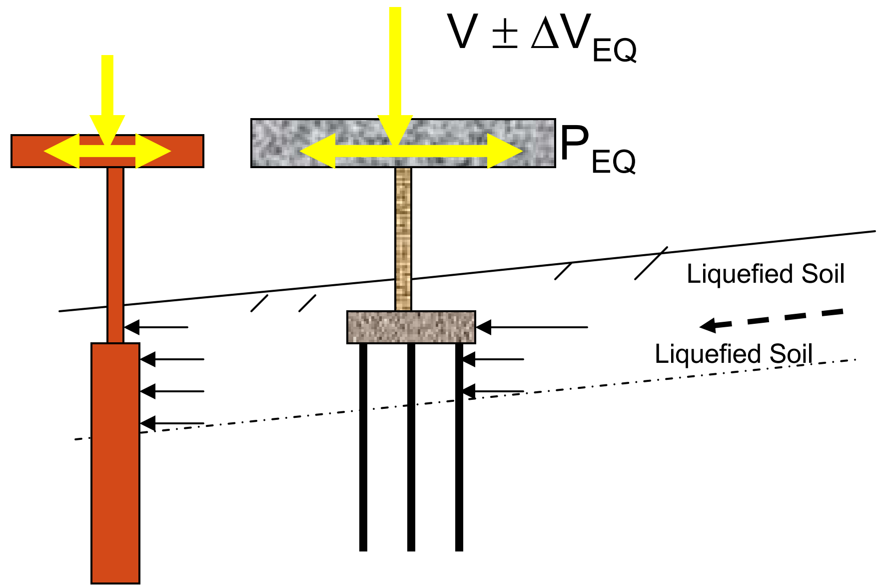
3.2 Additional Examples of Lateral Loads on Piles



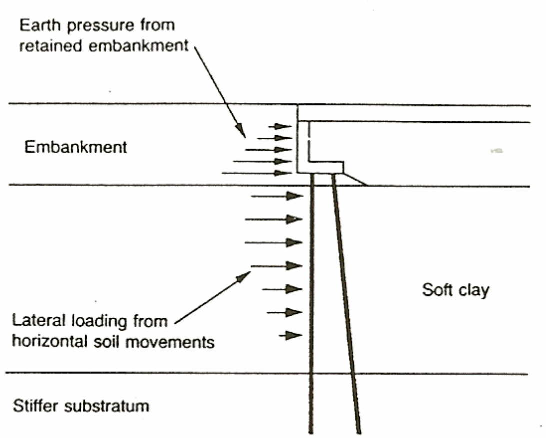
(1a) Abutment



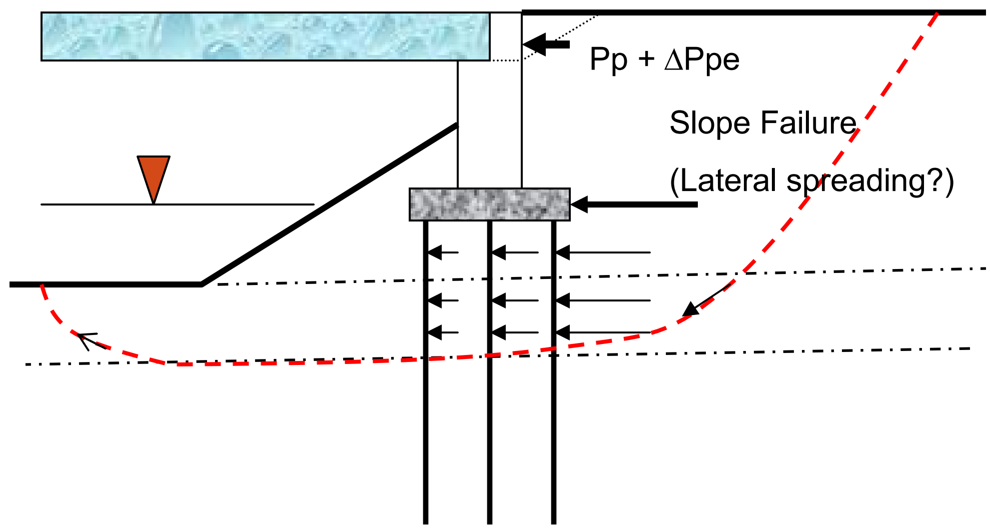
(1b) Sign Structure



(1c) Lateral Spreading (Seismic)



(1d) Lateral Spreading (Static)



(1e) Abutments Slope Movement/Lateral Spreading

3.0 LATERAL LOADS ON PILES

3.3 Lateral Loads on Transportation Structures/Foundations

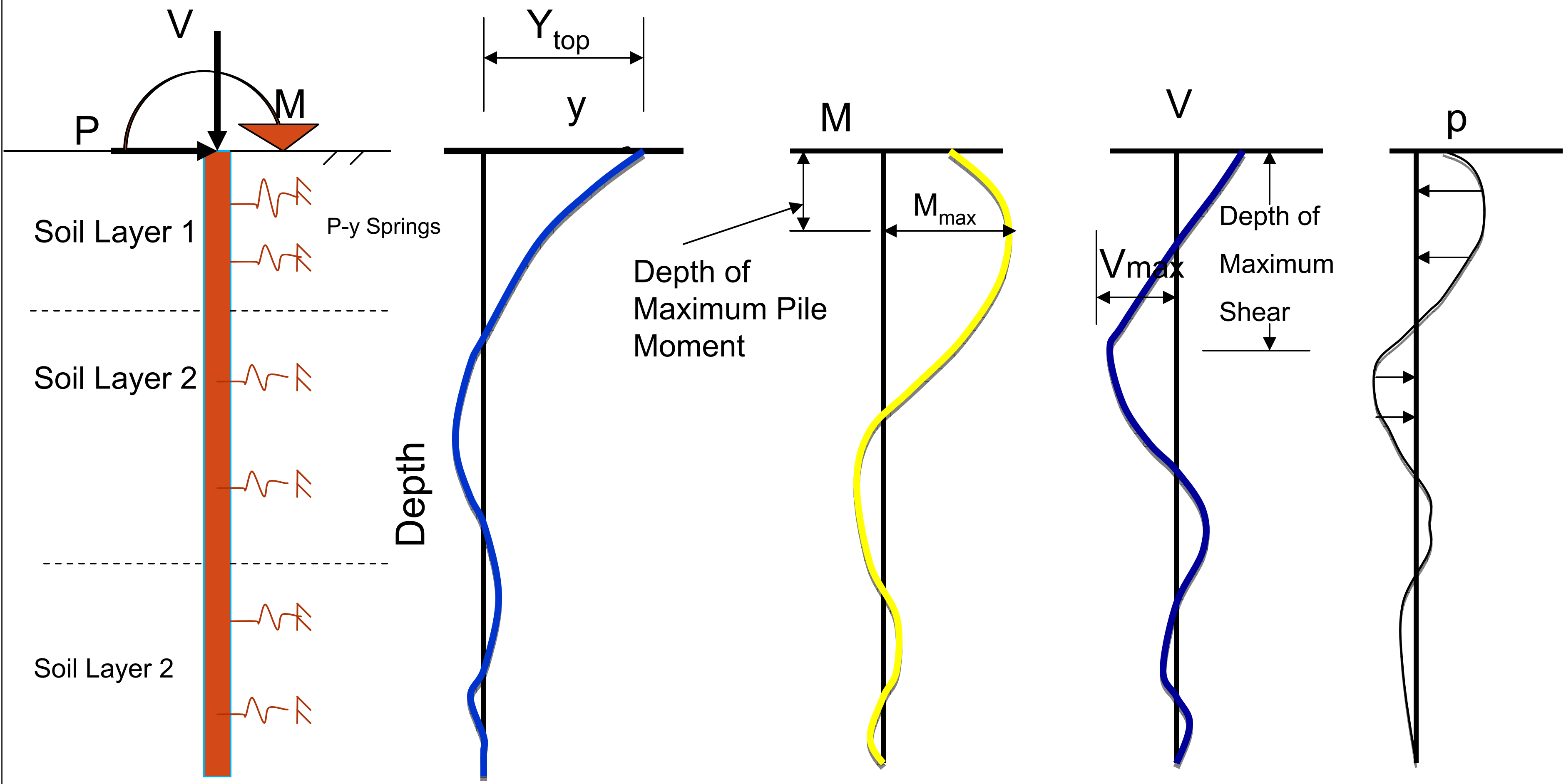
- Lateral Earth Pressures /Surcharge
- Ground/Slope/Landslide Movements
- Temperature/expansion/compression
- Wind/Storms
- Water Current and Waves Force/Flood/Storm Surge/Tsunamis
- Centrifugal/Braking Forces from Vehicles
- Anchoring/Suspension

- Storms/Hurricanes/Tornadoes
- Flood/Storm Surge/Tsunamis Vehicle/Vessel/Ship Collusion
- Blasts
- Earthquakes
  - Inertial (Structures, Retaining Soils/Porewater)
  - Kinematical (Ground Deformation/Slope Movement/Lateral Spreading)
  - Hydrodynamics (Free Water/Highly Pervious Groundwater)

Note: Remember to Consider Loss of Lateral Support

4.0 OVERVIEW OF LATERALLY LOADED PILE ANALYSIS

2.1 Typical Results from a p-y Type Laterally Loaded Pile Analysis (Schematic)



Pile (2a)

Deflection (2b)

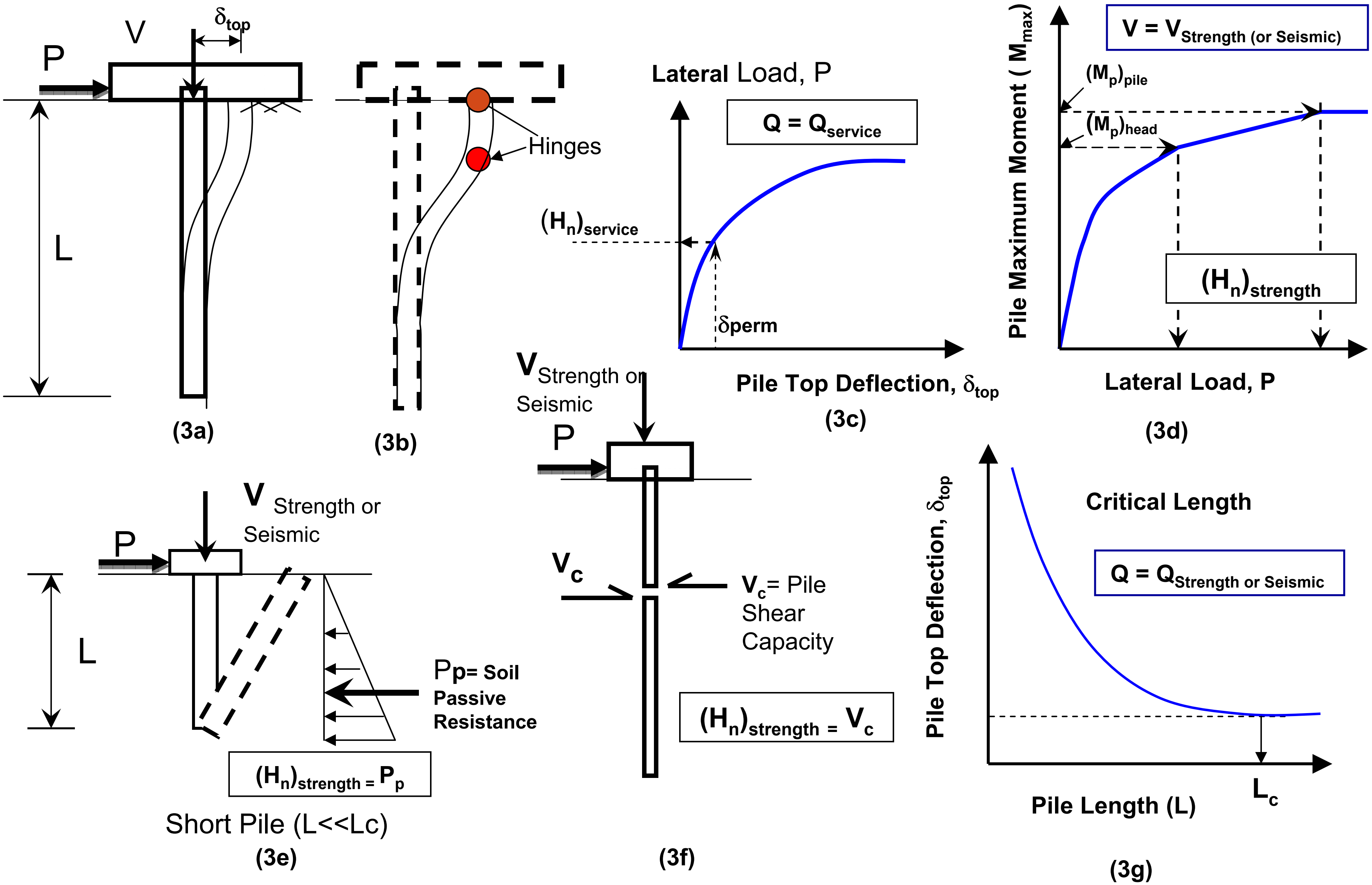
Moment (2c)

Shear (2d)

Soil Reaction (2e)

4.0 OVERVIEW OF LATERALLY LOADED PILE ANALYSIS

4.2 Interpretation of Results from a Laterally Loaded Pile Analysis for LRFD Design

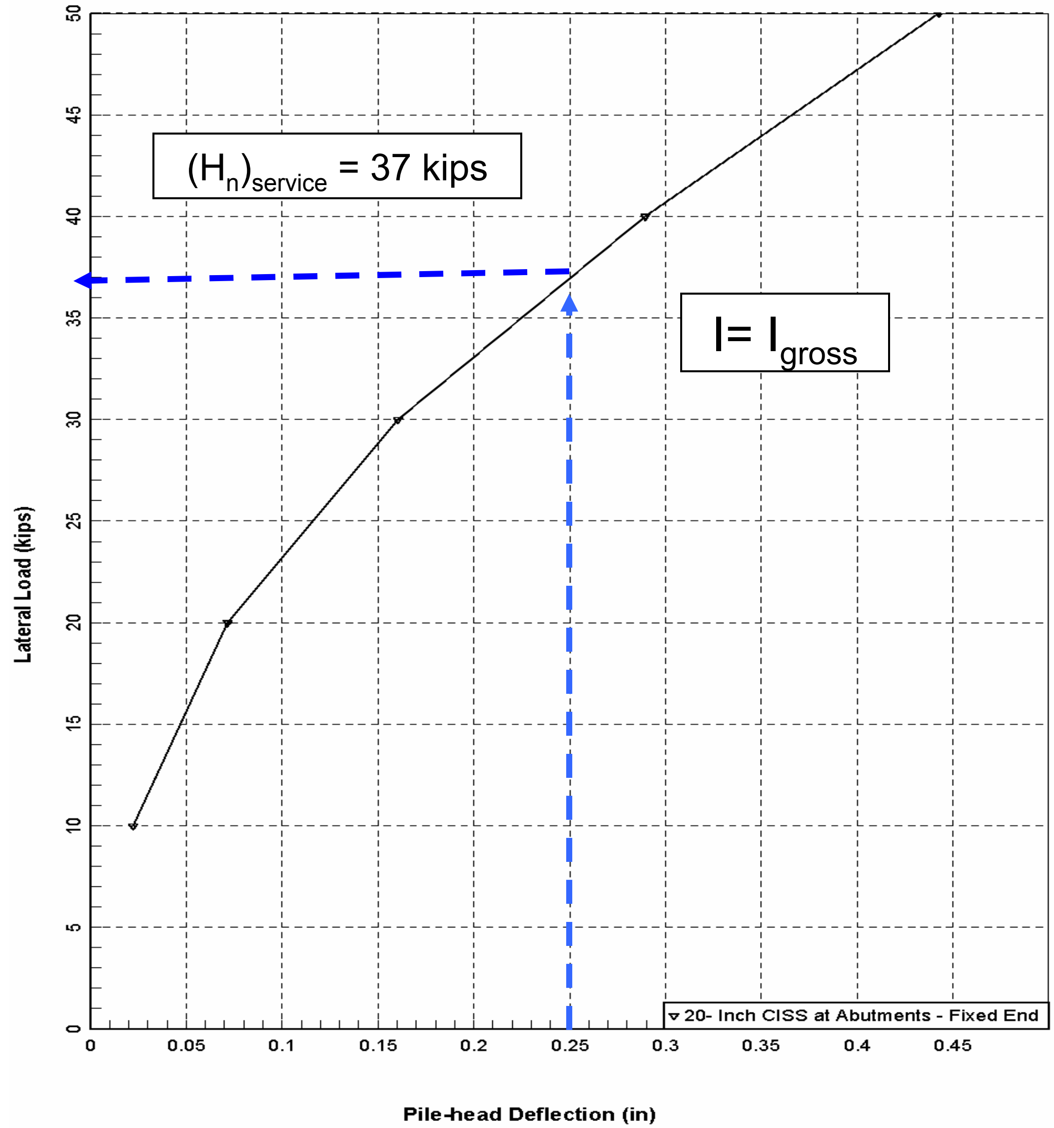


5.0 Laterally Loaded Pile Analysis for LRFD: Example

5.1 Service Limit State

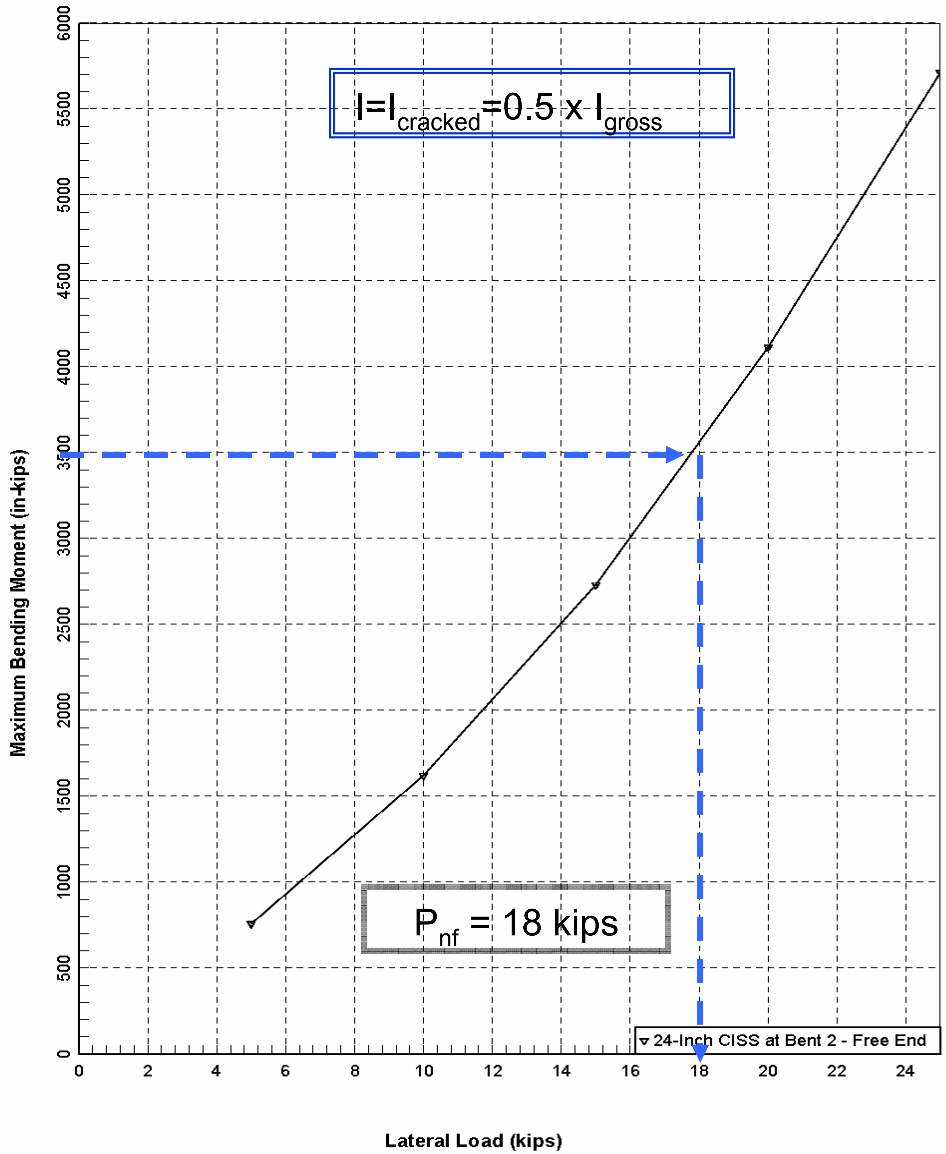
Hints

- Start analysis with the pile length required based on the axial demand but no shorter than 15 to 20 D.
- The upper 5 to 7 D most critical
- Should have small effects, if any, from depths> 10 to 12 D



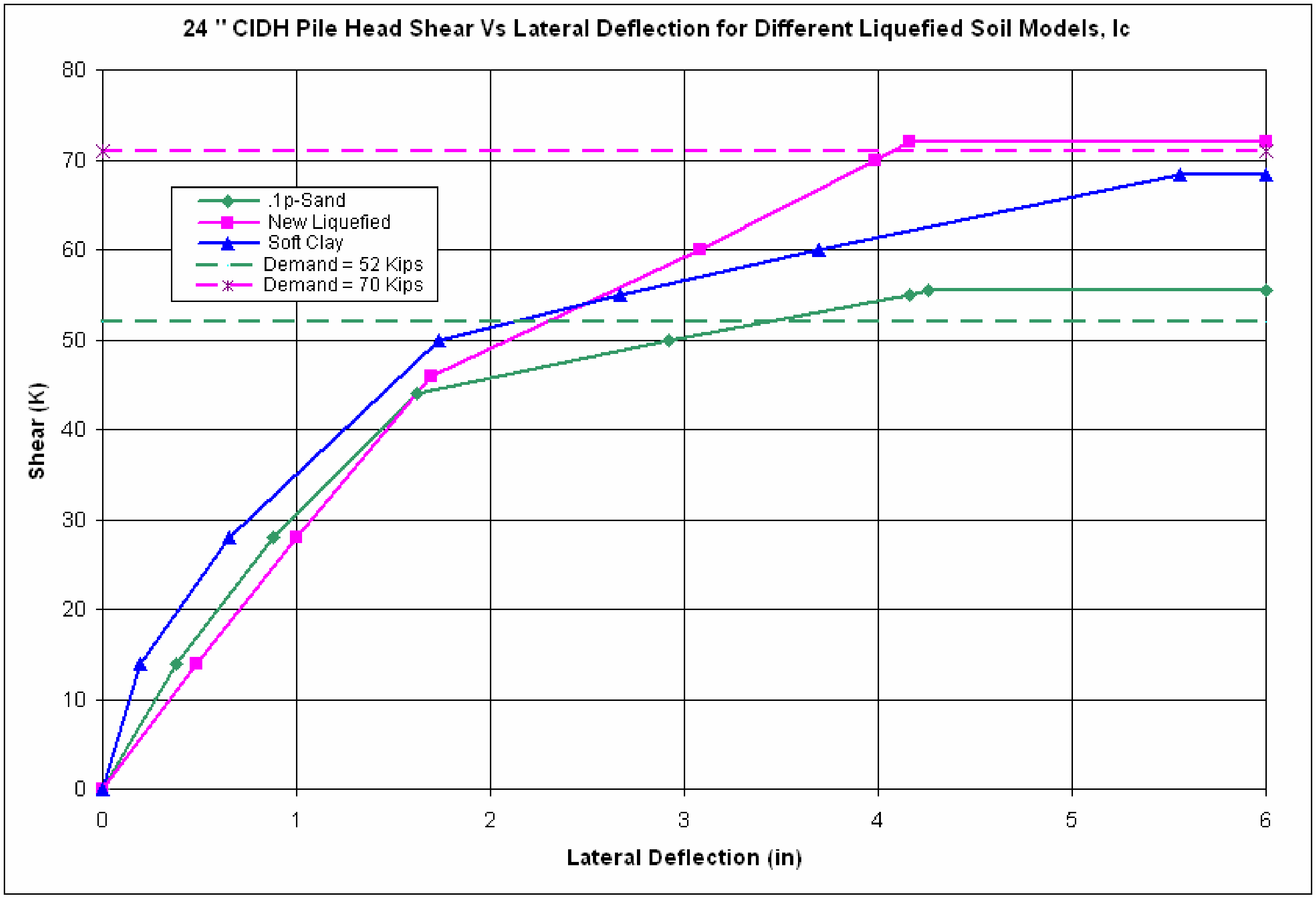
5.0 Laterally Loaded Pile Analysis for LRFD: Example

5.2(a) Flexural Resistance



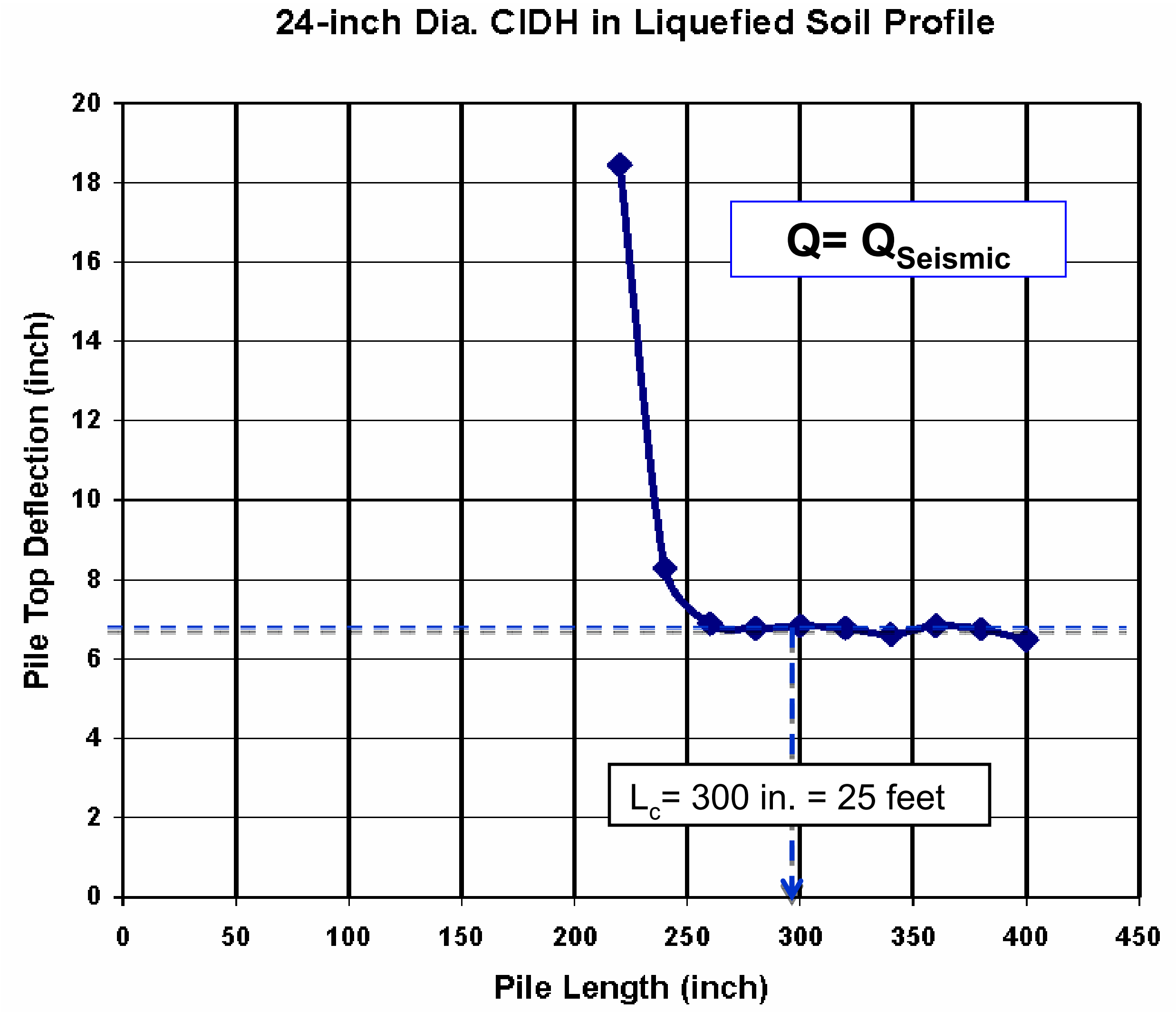
5.0 Laterally Loaded Pile Analysis for LRFD: ExampleS

5.2(b) Flexural Resistance



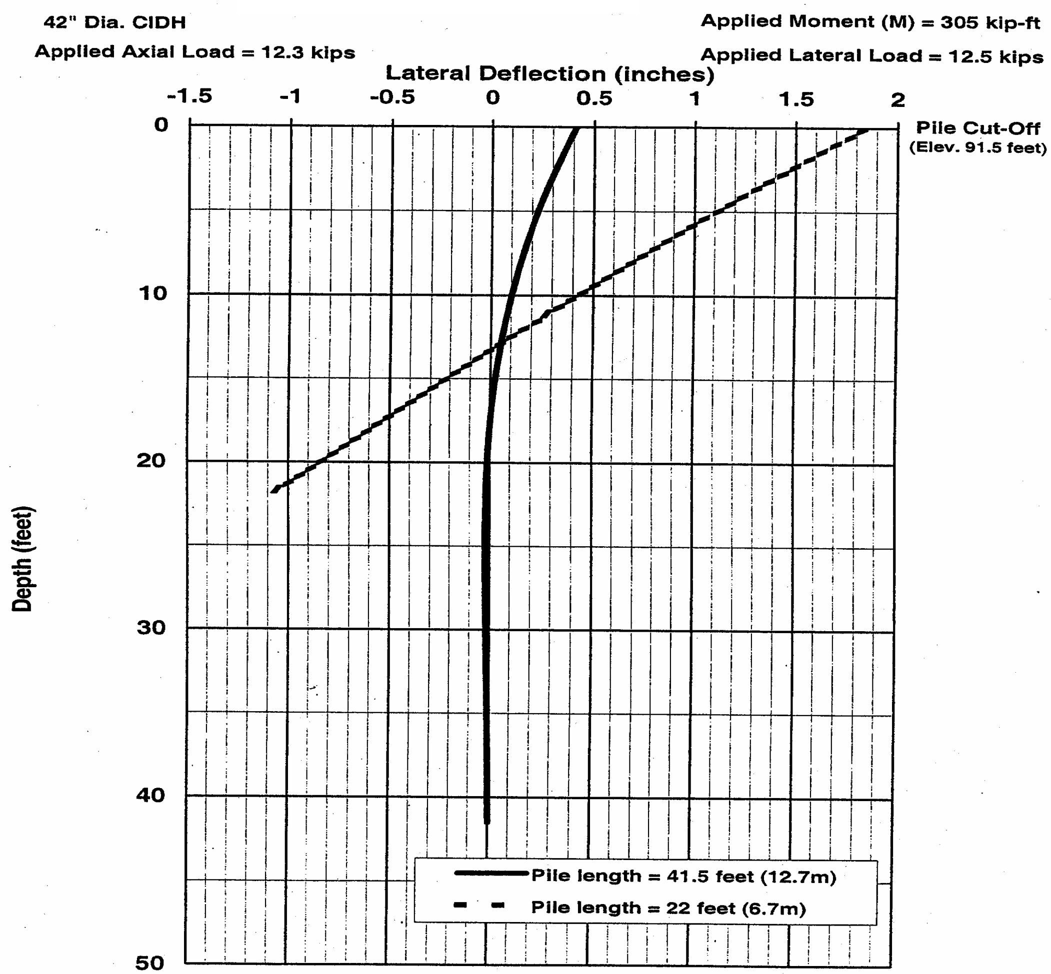
5.0 Laterally Loaded Pile Analysis for LRFD: Example

5.3(b) Pile Critical Length (L_c)



5.0 Laterally Loaded Pile Analysis for LRFD: Examples

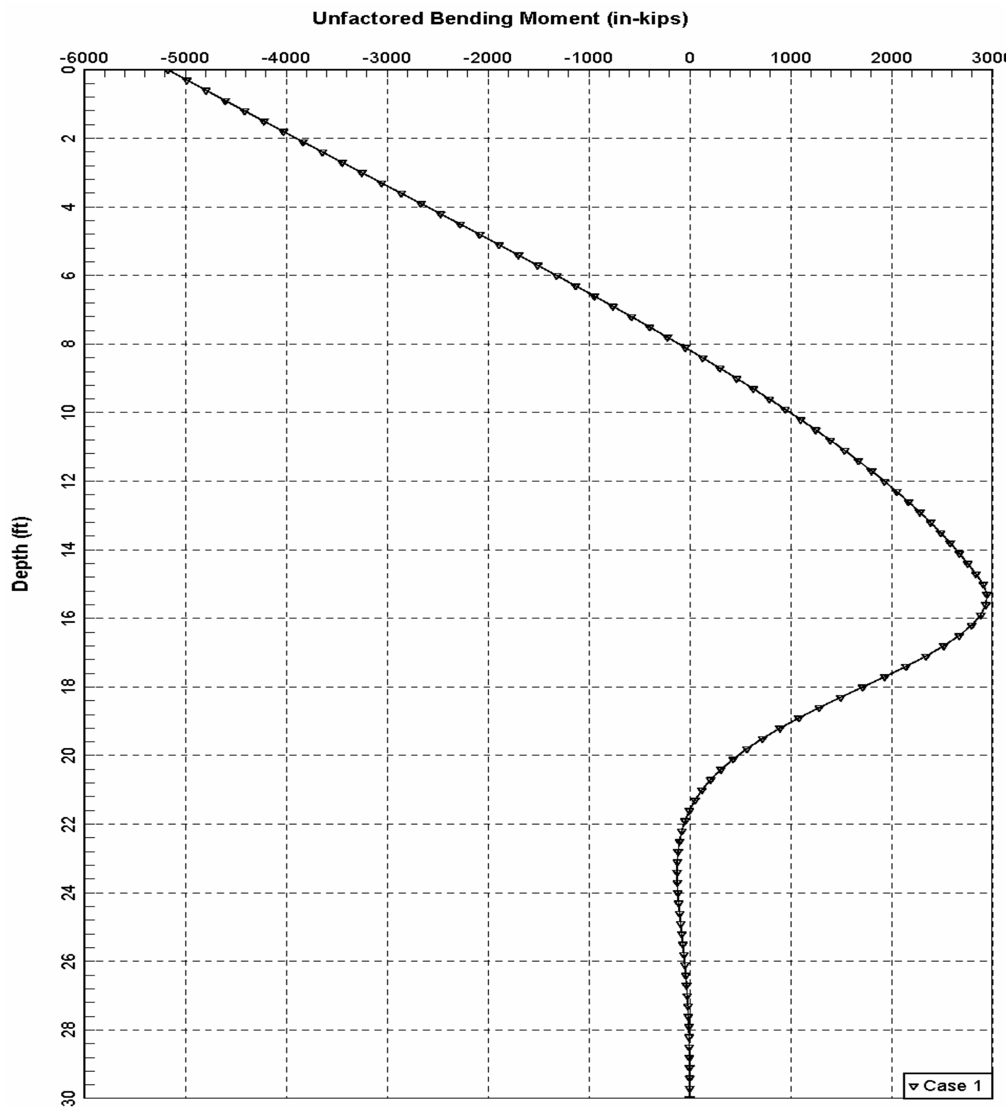
5.4 SHORT PILE VS. LONG PILE



Plot of Pile Lateral Deflection vs. Depth

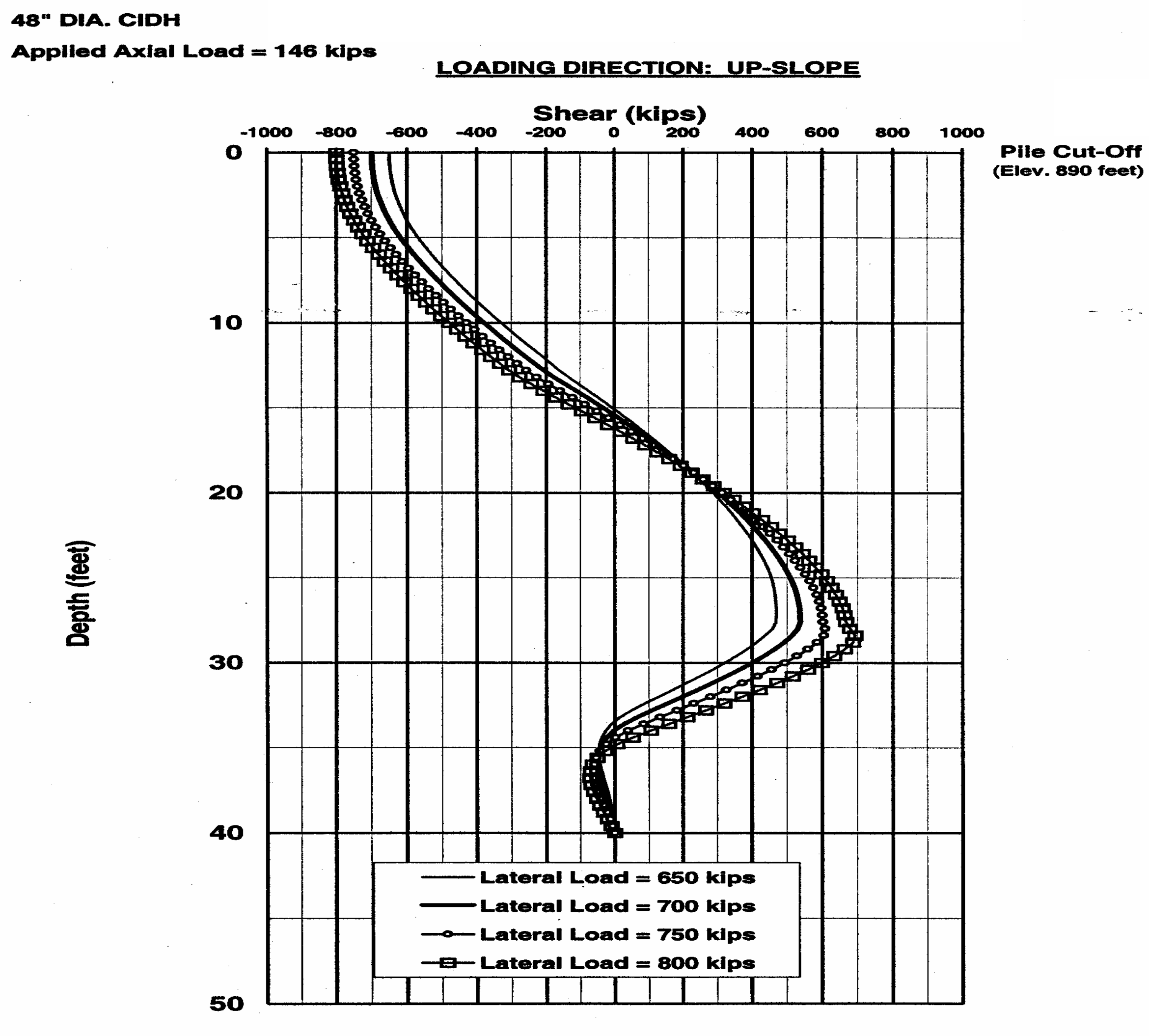
5.0 Laterally Loaded Pile Analysis for LRFD: Examples

5.5 Depth of Maximum Moment



5.0 Laterally Loaded Pile Analysis for LRFD: Example

5.6 Pile Maximum Shear



Plot of Shear vs. Depth for Piles 1 and 4

6.0 SUMMARY LRFD DESIGN REQUIREMENTS

❑ Design for Three Limit States

- **Service Limit State:**

(1) $(P_{nf})_{service} \leq (H_n)_{service}$

- **Strength Limit State Design**

(2) $(H_{nf})_{strength}\,[= \varphi_{strength} \times (H_n)_{strength}] \geq (P_{nf})_{strength}$

(3) To ensure $(H_n)_{strength}$ is structural provide:, provide $(L_{min})_{strength} \geq (L_c)_{Strength}$

(4) Check and Design for Depths of Maximum Moment and Maximum Shear

- **Extreme Event (Seismic) Limit State Design**

(5) $(H_n)_{seismic}\,[= \varphi_{strength} \times (H_n)_{strength}] \geq (P_{nf})_{seismic}$

(6) To ensure $(H_n)_{seismic}$ is structural provide, provide $(L_{min})_{seismic} \geq (L_c)_{seismic}$

(7) Check and Design for the Depths of Maximum Moment and Maximum Shear

QUESTIONS?

“Therefore O students study mathematics and do not build (bridge) without foundations”

- Leonardo Da Vinci
The Notebooks of Leonardo Da Vinci

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“Question everything. Learn something. Answer nothing.”

-- Engineer's Motto

THANK YOU