Analytical Evaluation of Plastic-Hinge Length and Depth for Piles in Marine Oil Terminals

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Organization

- Background
- Current Practice
- Limitations of Current Practice
- Analytical Approach
- Verification of Analytical Approach
- Evaluation for Pre-Stressed Concrete Piles
- Conclusions

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BACKGROUND

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Seismic Design of Piles in Marine Oil Terminals

- Seismic design governed by Marine Oil Terminal Engineering and Maintenance Standard (MOTEMS)
- Performance criteria specified for two levels of earthquake motions
  - Level 1: No or minor damage without interruption in service or with minor temporary interruption in service
  - Level 2: controlled inelastic behavior with repairable damage resulting in temporary closure of service, restorable within months and the prevention of a major oil spill

MOTEMS Acceptability Criteria

Seismic acceptability criteria is based on material strain limits

Component Strain	Level 1	Level 2
Maximum Concrete Compression Strain: Pile-Deck Hinge	$\varepsilon_c \leq 0.004$	$\varepsilon_c \leq 0.025$
Maximum Concrete Compression Strain: In-ground Hinge	$\varepsilon_c \leq 0.004$	$\varepsilon_c \leq 0.008$
Maximum Reinforcing Steel Tension Strain: Pile-Deck Hinge	$\varepsilon_s \leq 0.01$	$\varepsilon_s \leq 0.05$
Maximum Reinforcing Steel Tension Strain: In-Ground Hinge	$\varepsilon_s \leq 0.01$	$\varepsilon_s \leq 0.025$
Maximum Prestressing Steel Tension Strain: In-ground Hinge	$\varepsilon_p \leq 0.005$ (Incremental)	$\varepsilon_p \leq 0.025$ (Total)

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CURRENT PRACTICE

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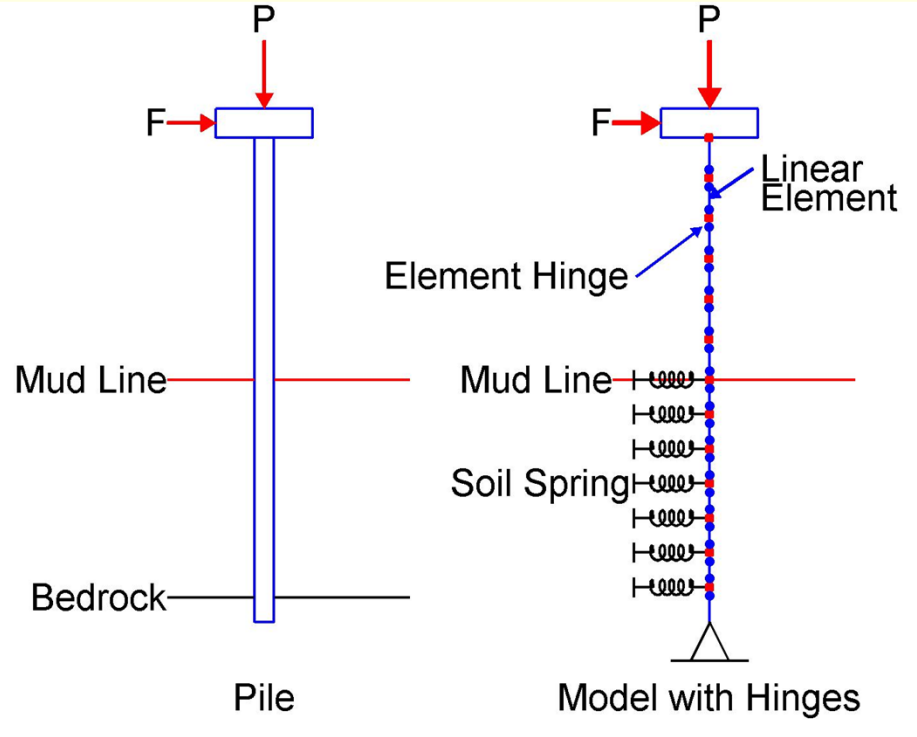
Typical Analysis Procedure

- Pile modeled with linear-elastic beam-column element connected by nonlinear hinges
  - Hinges are rigid-perfectly-plastic
  - Plastic rotations in hinges are monitored
  - Allowable plastic rotation computed from allowable curvature and plastic hinge length



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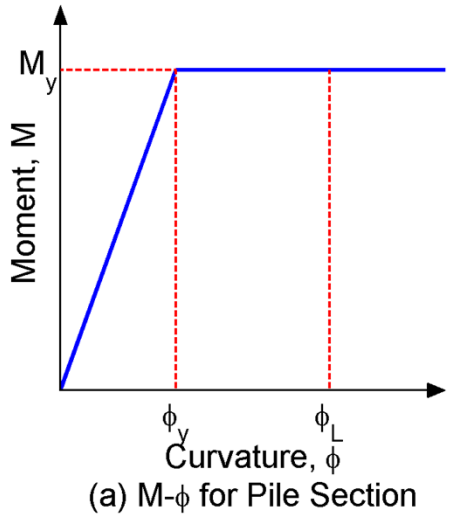
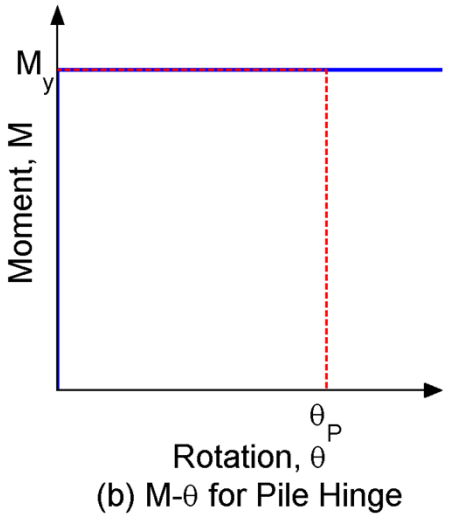
Allowable Plastic Hinge Rotation

$$\theta_P = L_P\left(\phi_L - \phi_y\right)$$

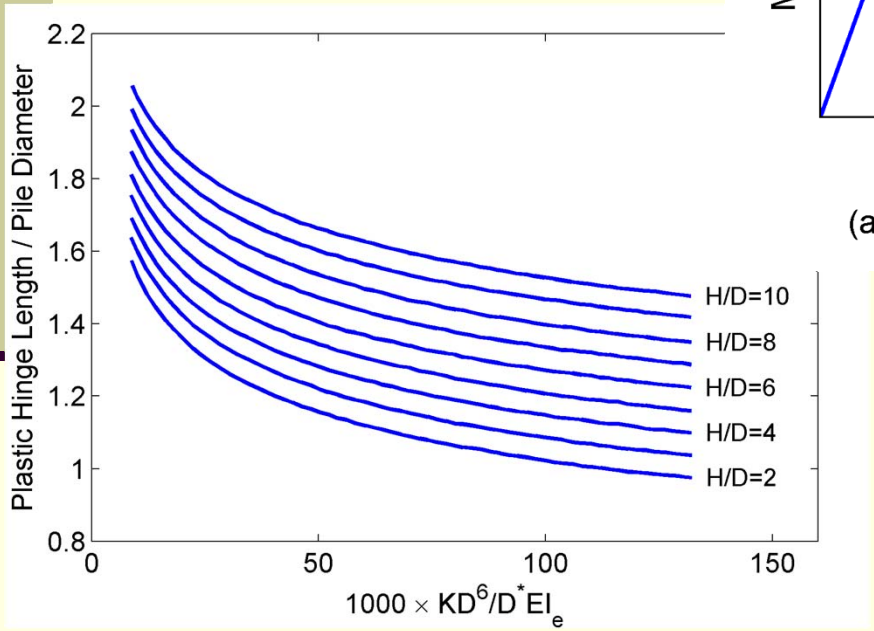
Allowable curvature based on material strains



(a) M-ϕ for Pile Section



(b) M-θ for Pile Hinge



Recommendations for In-Ground Plastic Hinge Length

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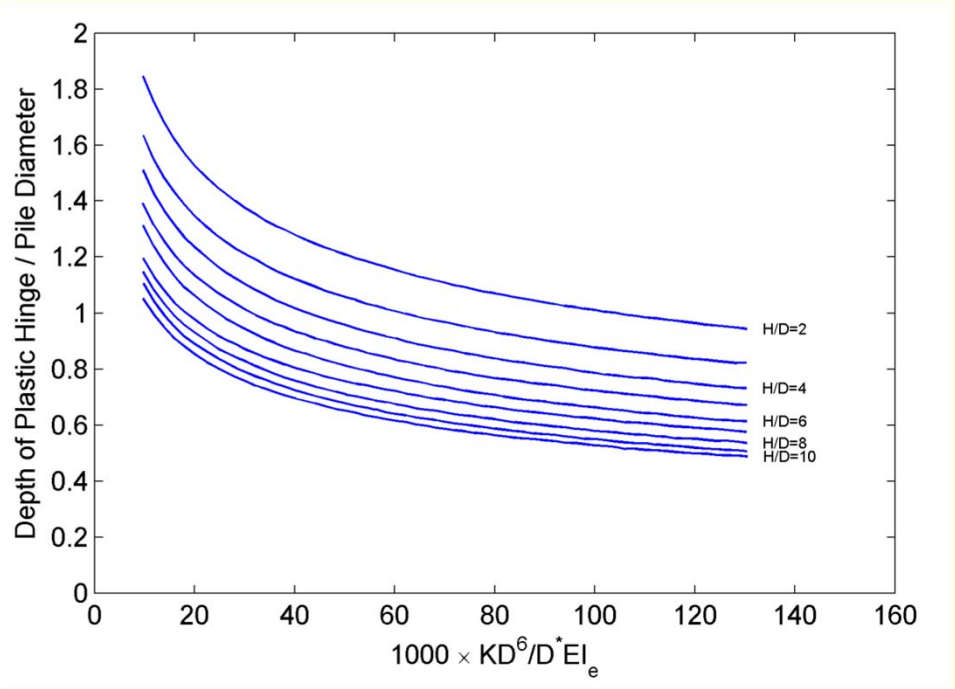
Depth of Plastic Hinge

- No depth recommendation in MOTEMS
- Depth needed to ensure sufficient confinement of pile in the plastic hinge region
- Recommendation developed by Priestley, Seible, and Calvi (1996)



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LIMITATIONS OF CURRENT PRACTICE

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Limitations of Current Recommendations

- May not be appropriate for piles typically used in Marine Oil Terminals
  - Developed for 6-foot diameter Cast-In-Drilled-Hole (CIDH) reinforced concrete piles
    - Smaller pile size used in Marine Oil Terminals
  - Plastic hinge length recommendation based only on ultimate failure strain in confined concrete
    - MOTEMS strain limits are specified for both concrete and steel
    - Strain limits are specified for Level 1 and Level 2
  - Only linear elastic soil behavior considered

ANALYTICAL APPROACH

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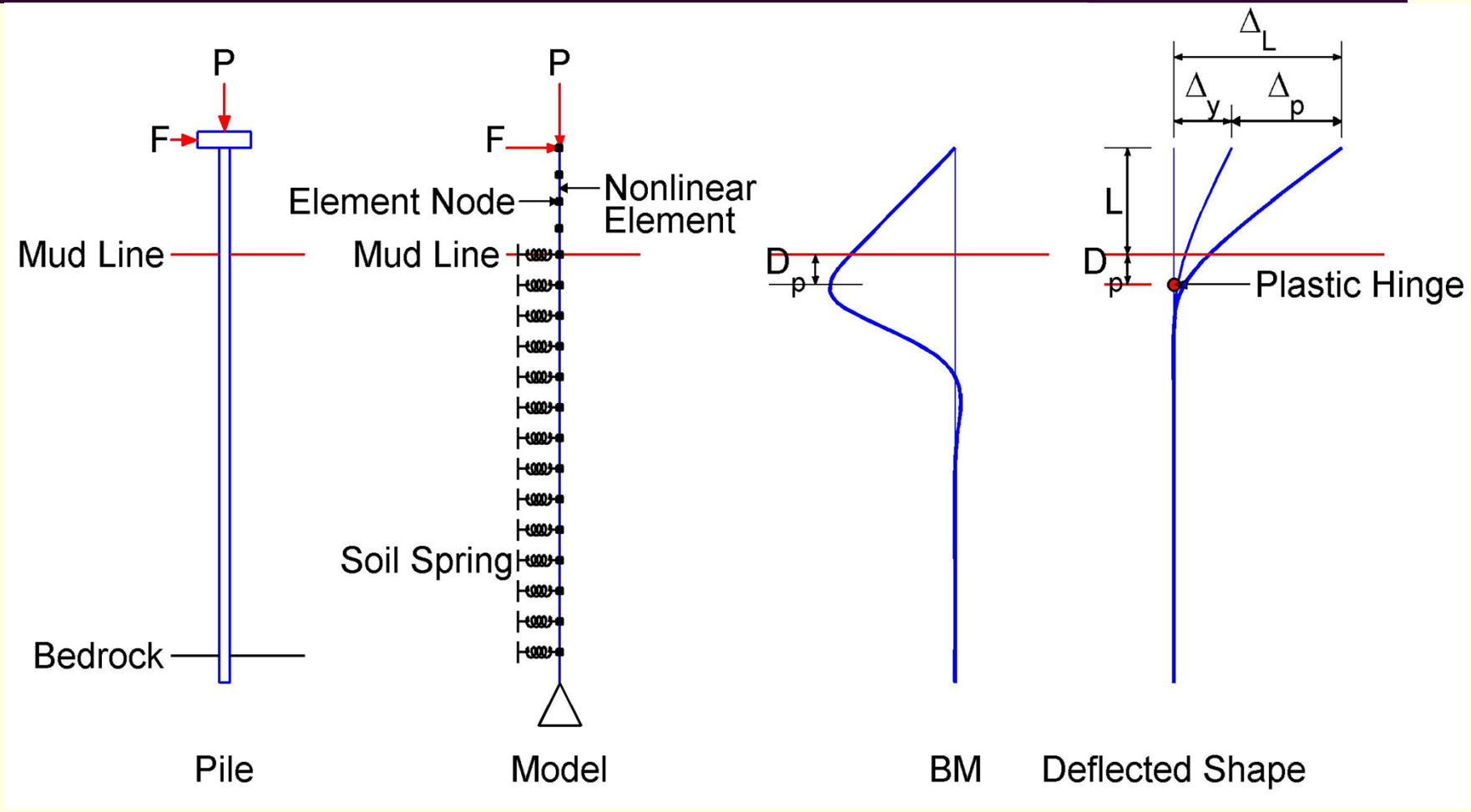
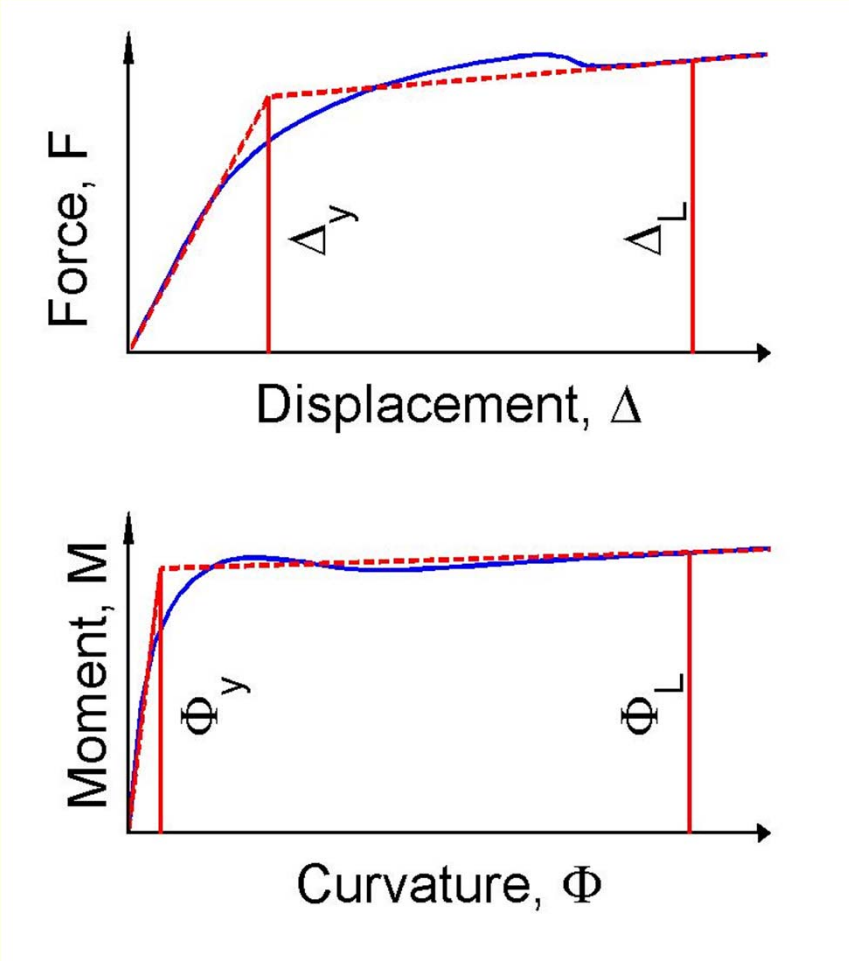
Analytical Approach



Analytical Procedure

- Pile pushover analysis to estimate Δ_L and Δ_y
- Pile section M-ϕ analysis to estimate ϕ_L and ϕ_y
- Δ_L and ϕ_L at material strain limits for selected level



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Analytical Procedure

- Depth of plastic hinge, D_p, at location of maximum bending moment
- Length of plastic hinge computed from

$$L_P = \frac{\theta_P}{\Phi_L - \Phi_y} \qquad \text{where} \qquad \theta_P = \frac{\left(\Delta_L - \Delta_y\right)}{\left(L + D_p\right)}$$

- Nonlinear soil behavior considered by specifying p-y curves

Soil Types Considered

MOTEM Site Class	Shear Wave Velocity	Stand Penetration Resistance	Undrained Shear Strength	Soil Type	Subgrade Modulus, K
Sand (API sand)					
D. Dense soil	600-1200 ft/s 183-366 m/s	15 to 50		Dense Sand	275 pcf 43200 kN/m^3
				Medium Sand	90 pcf 14138 kN/m^3
E. Loose soil	< 600 ft/s < 183 m/s	< 15		Loose Sand	25 pcf 3927 kN/m^3
Clay (Matlock)					
D. Dense soil	600-1200 ft/s 183-366 m/s		1000-2000 psf 48-96 kN/m^2	Stiff Clay	500 pcf 78544 kN/m^3
E. Loose soil	< 600 ft/s < 183 m/s		< 1000 psf <48 kN/m^2	Medium Clay	100 pcf 15709 kN/m^3
				Soft Clay	20 pcf 3142 kN/m^3

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VERIFICATION

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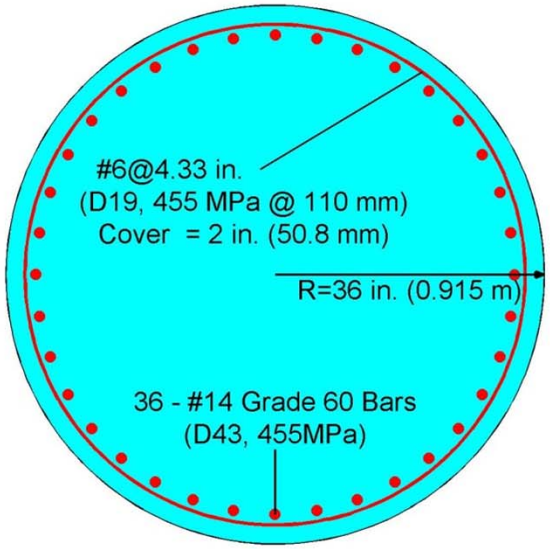
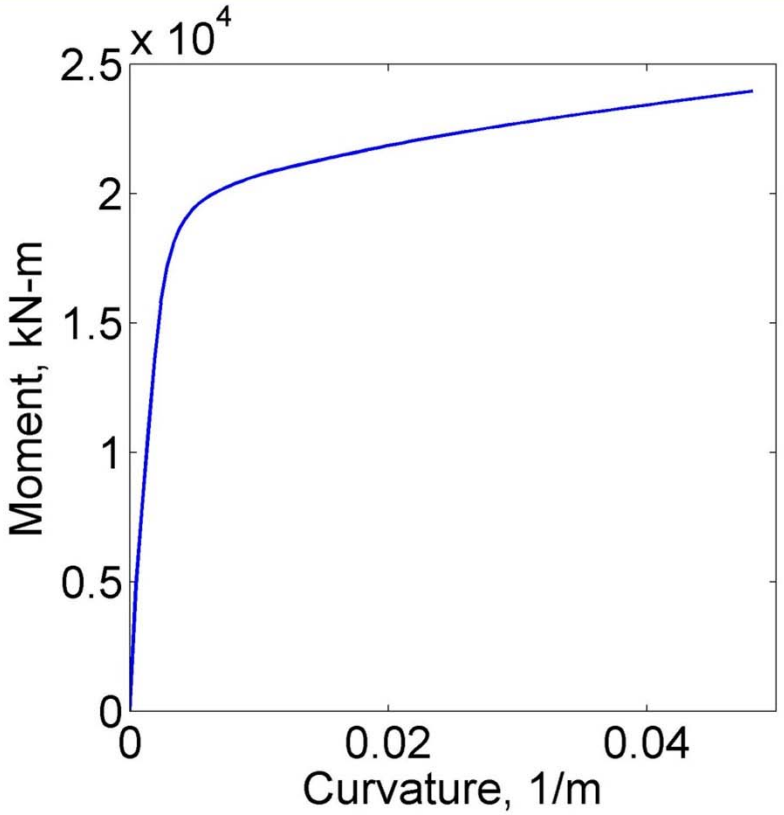
CIDH Pile Properties



CIDH Pile Section



Moment-Curvature Relationship

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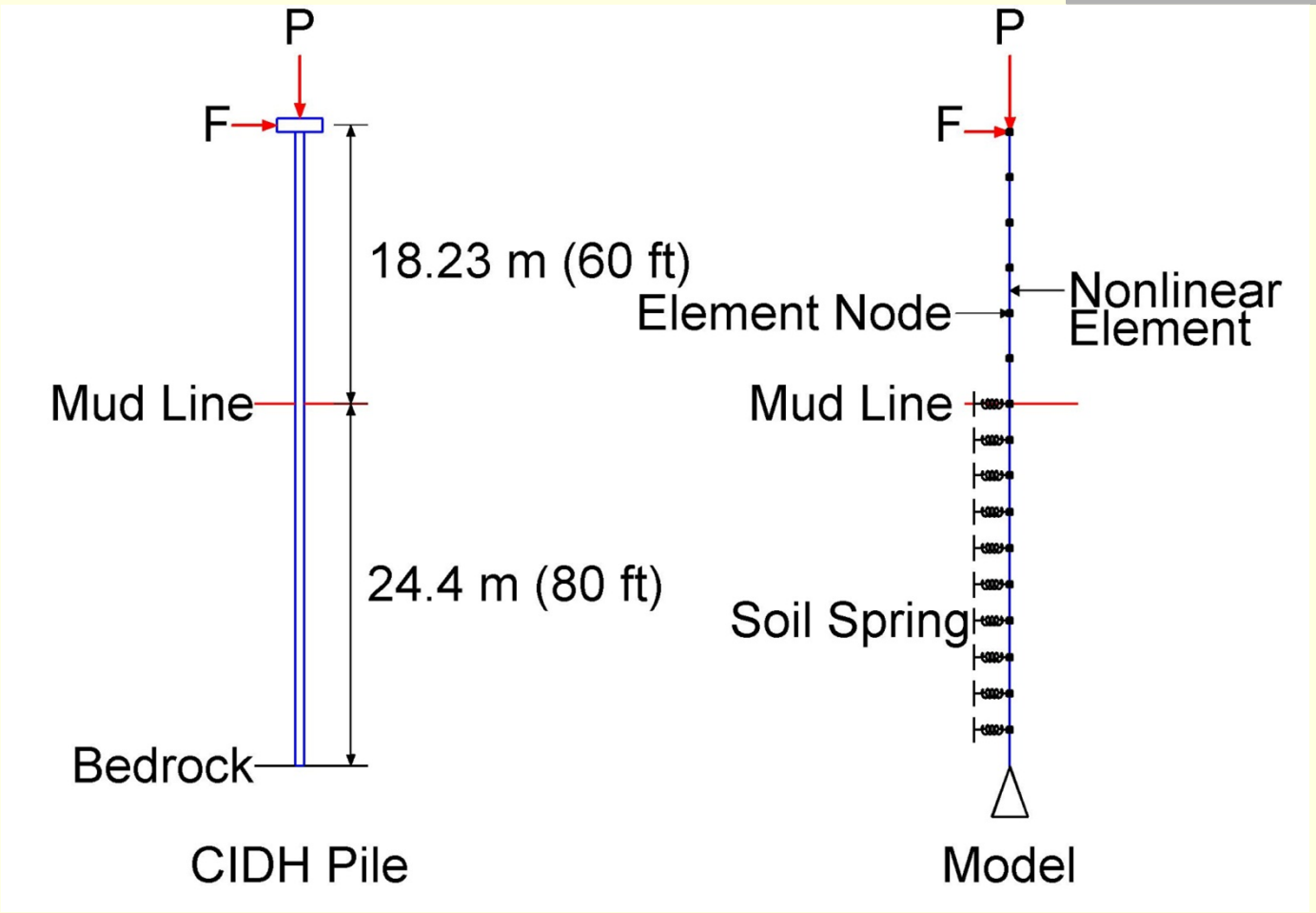
CIDH Pile Model



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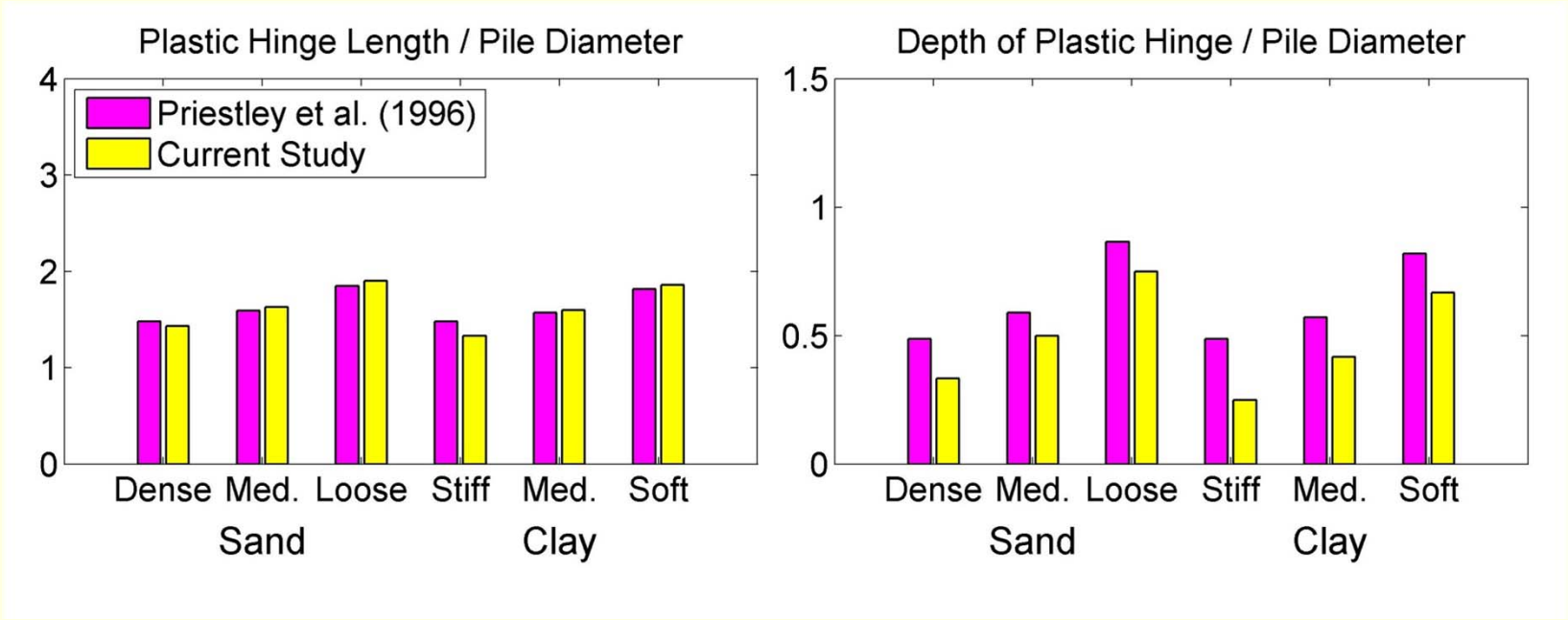
Results for CIDH Pile



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EVALUATION FOR PRE-STRESSED CONCRETE PILES

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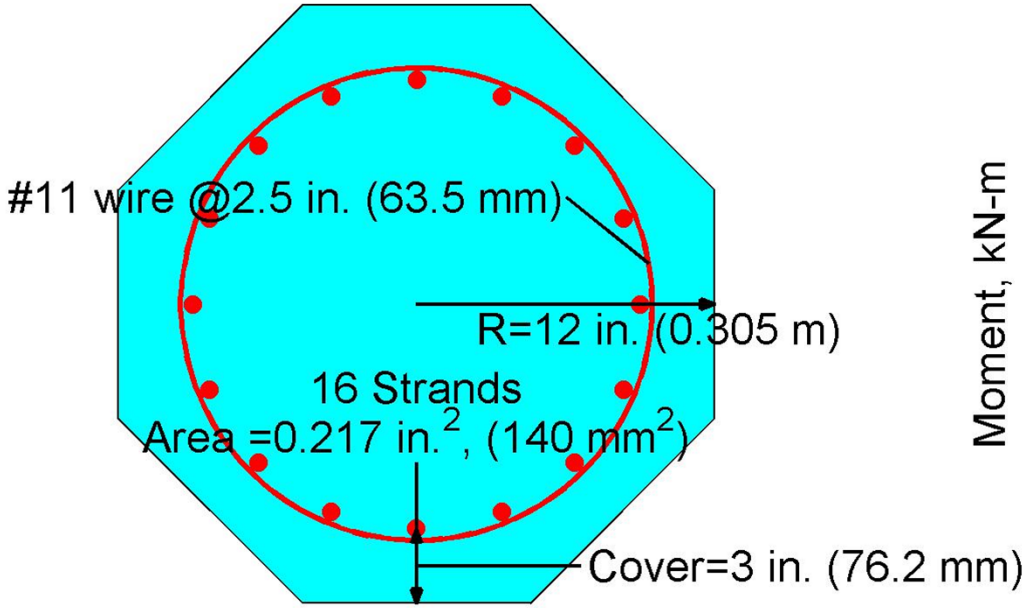
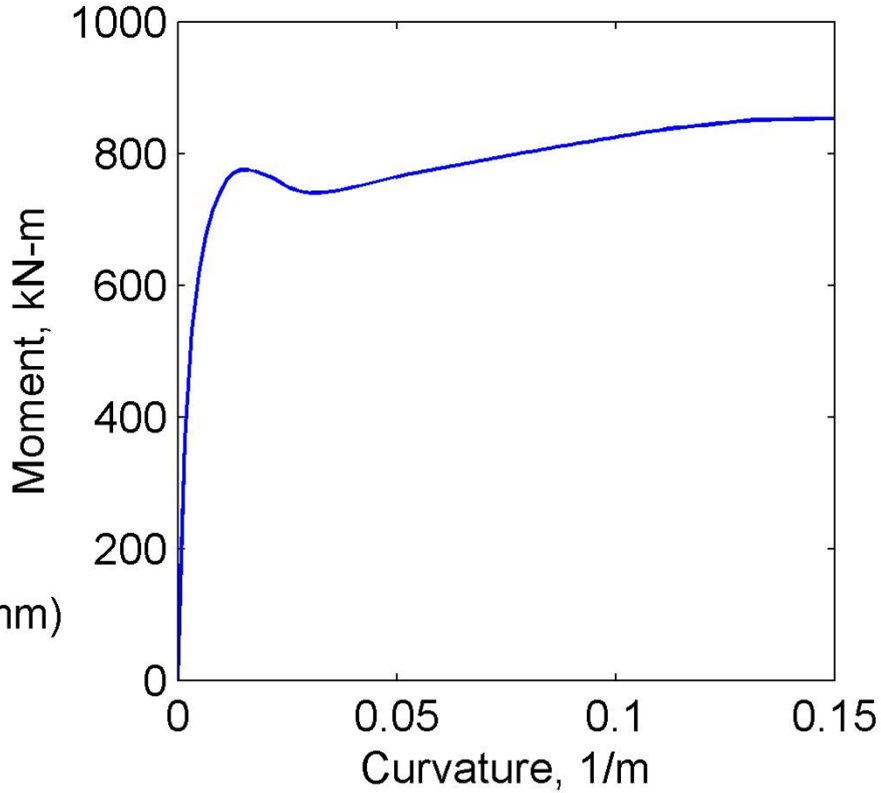
Piles Considered



Pile Section



Pile Section M-Φ Relationship

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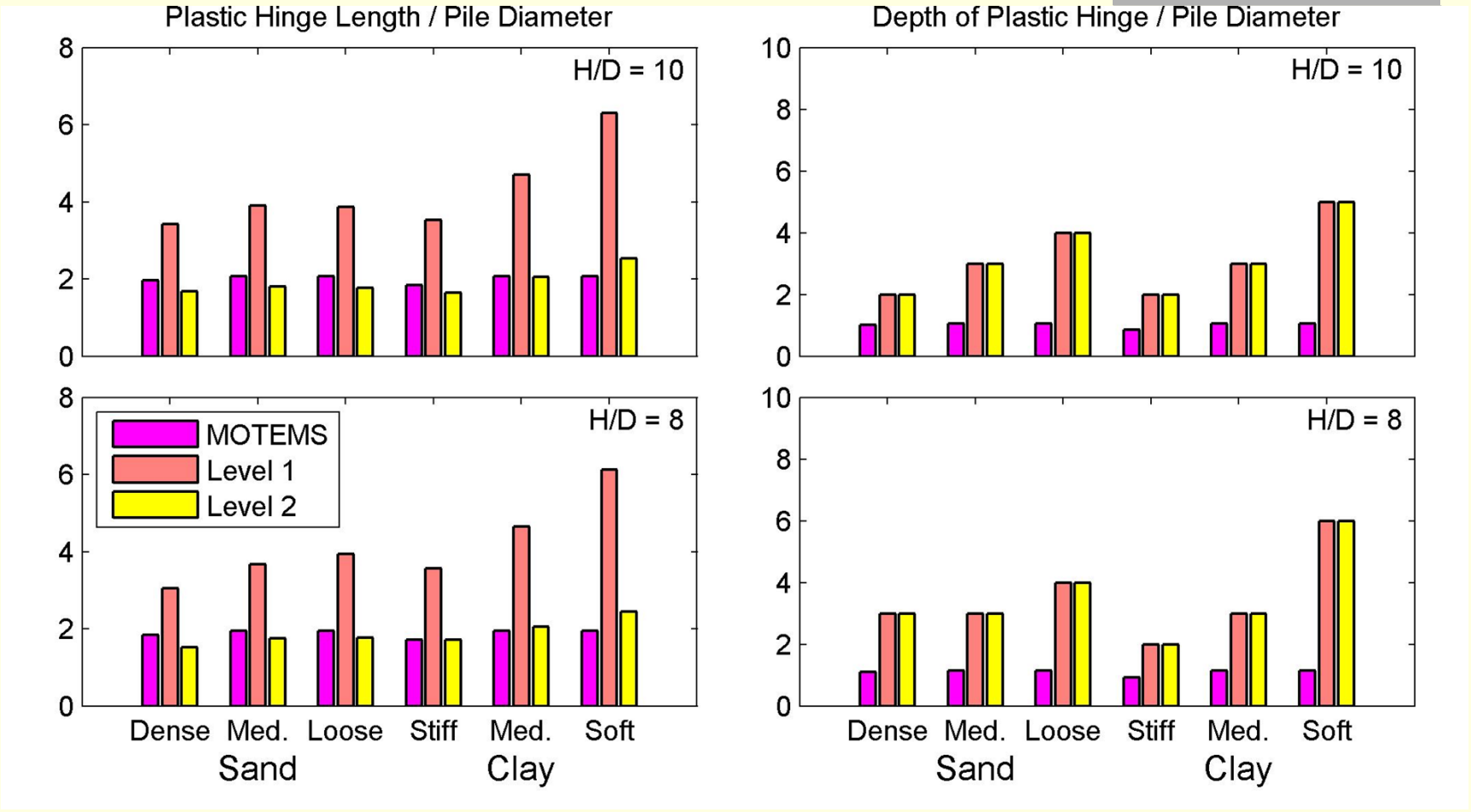
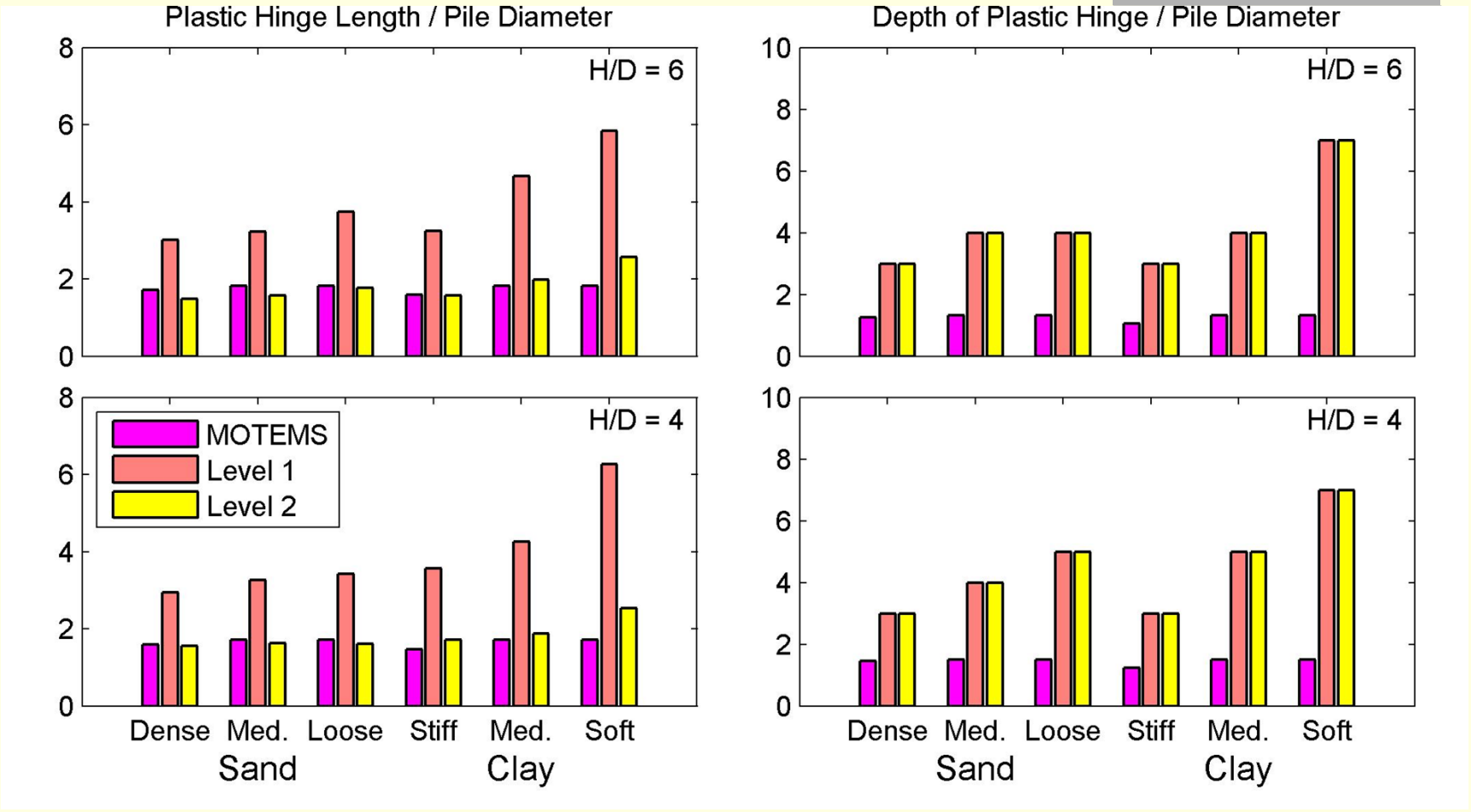
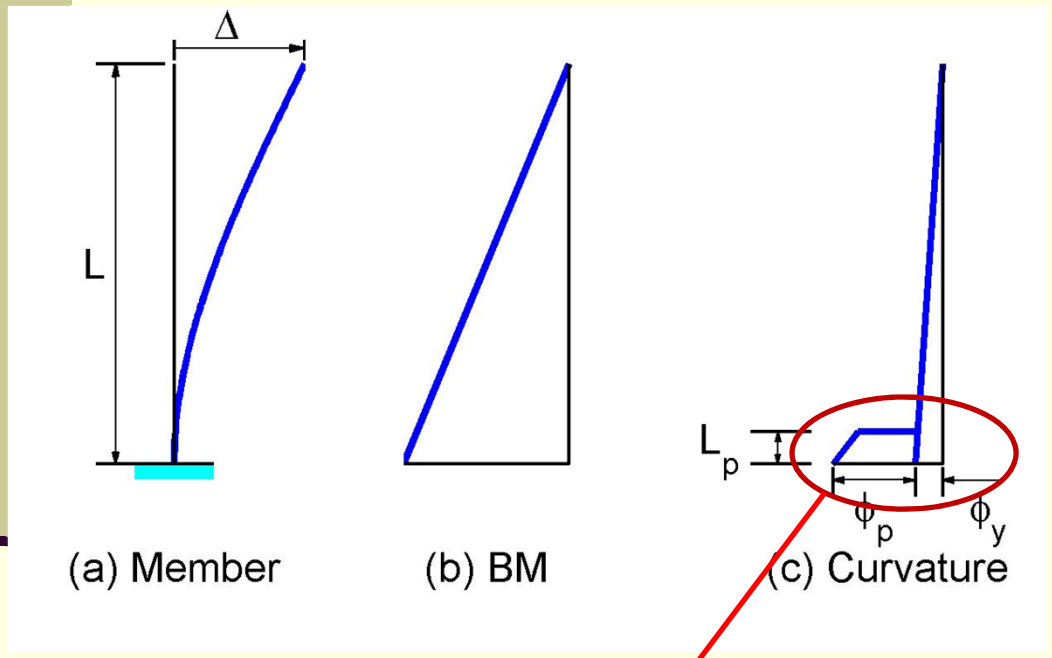
Results from Analytical Simulation



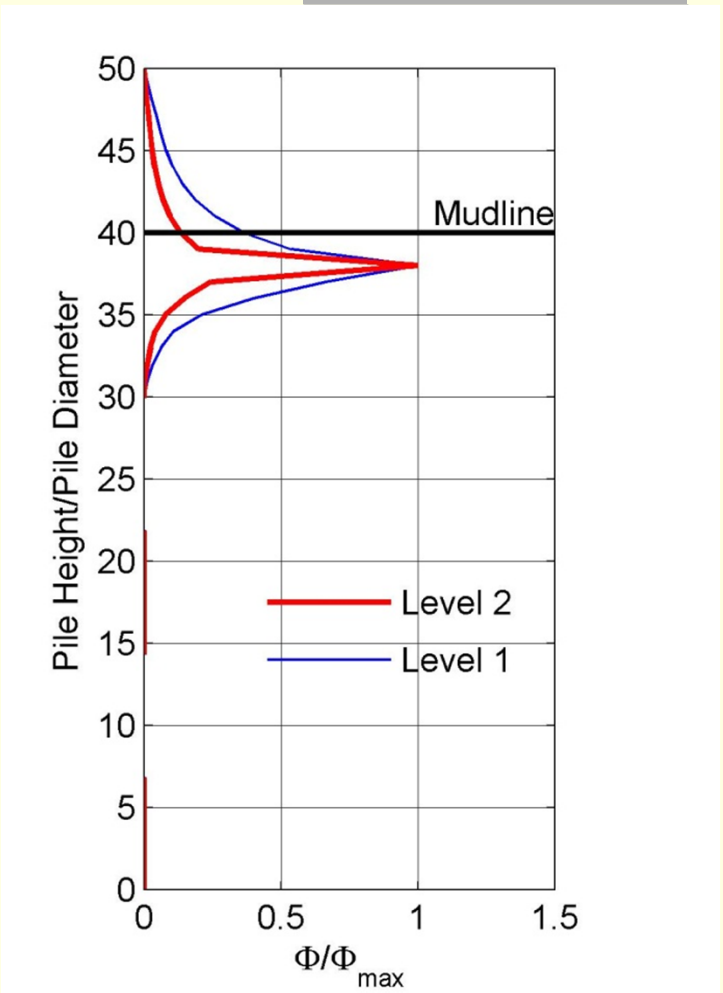
Results from Analytical Simulation



Why Longer Plastic-Hinge Length for Level 1



Sharper curvature distribution will lead to shorter plastic hinge length



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Conclusions

- Plastic hinge length differs for two Levels
  - Longer length for Level 1 compared to Level 2
- Current plastic hinge length recommendation is reasonable for Level 2
- Current recommendation leads to shorter plastic hinge length for Level 1
  - Leads to conservative displacement capacity calculation
- As expected, plastic hinge length depends on soil type

Conclusions

- Same plastic hinge depth for two levels
- Current recommendation lead to much shallower depth of plastic hinge
- Plastic hinge depth depends on soil type
  - Deeper location for softer soils