A Simplified Procedure for Nonlinear Analysis of Marine Structures

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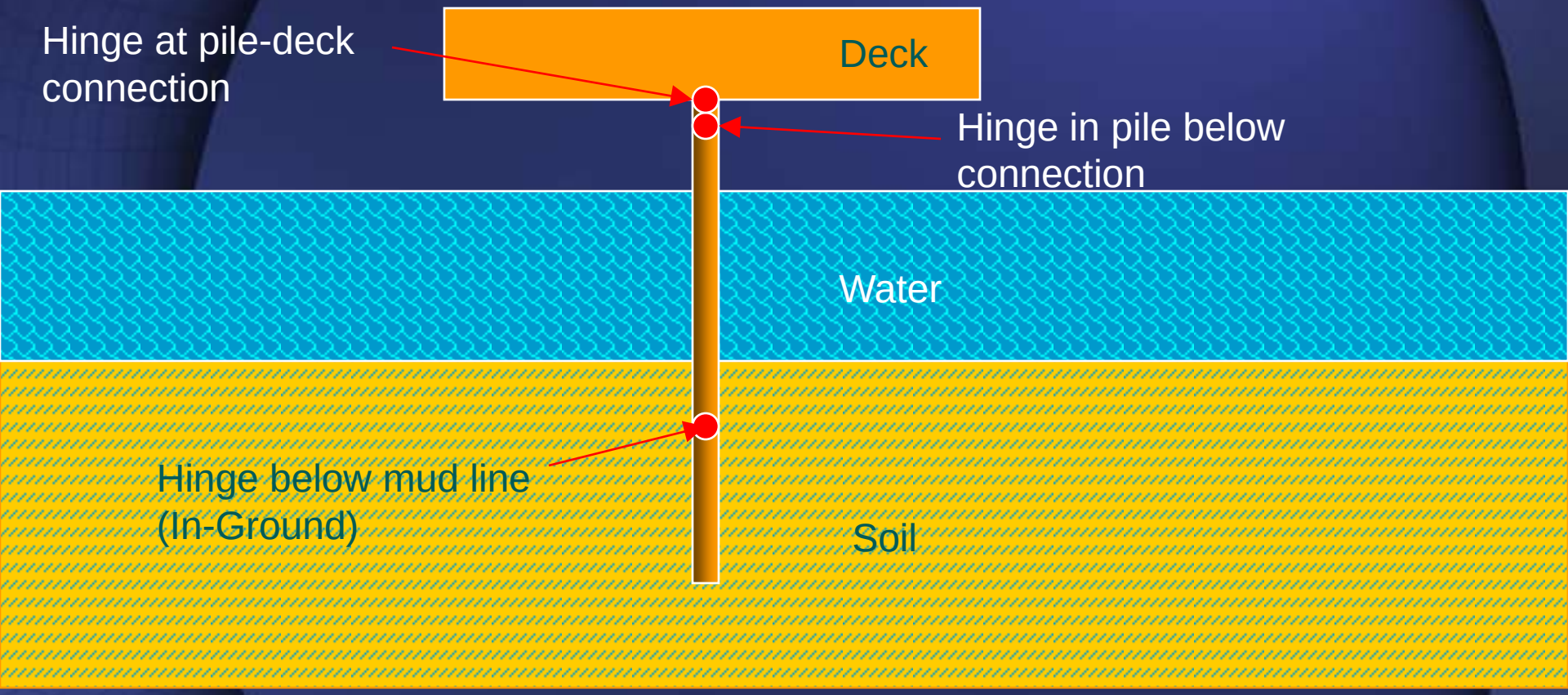
Objectives

- Develop a simplified procedure to estimate seismic displacement capacity of piles in Marine Oil and LNG Terminal structures
  - Avoid direct monitoring of material strains
  - Use concept of seismic displacement ductility capacity
  - Propose simple values or closed-form equations for seismic displacement ductility capacity
- Simplified procedure to be used either for preliminary design or quick check on results from detailed nonlinear analysis

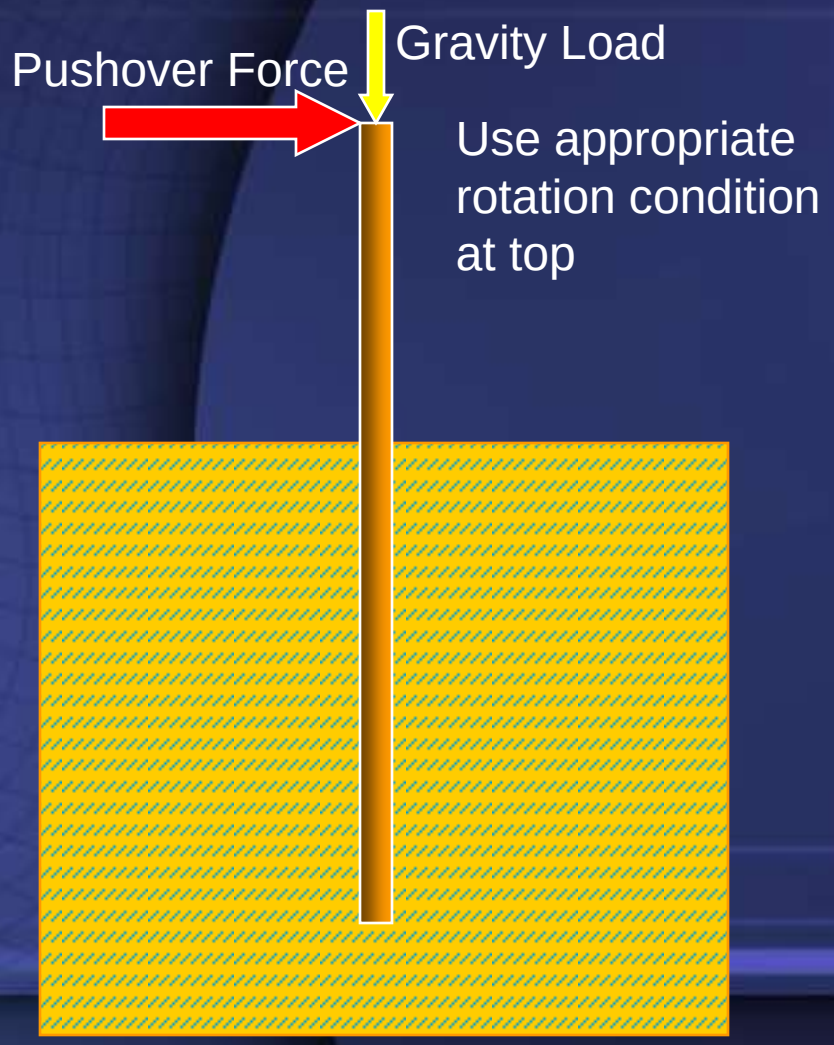
Nonlinearity in Pile



Material Strain Limits in MOTEMS

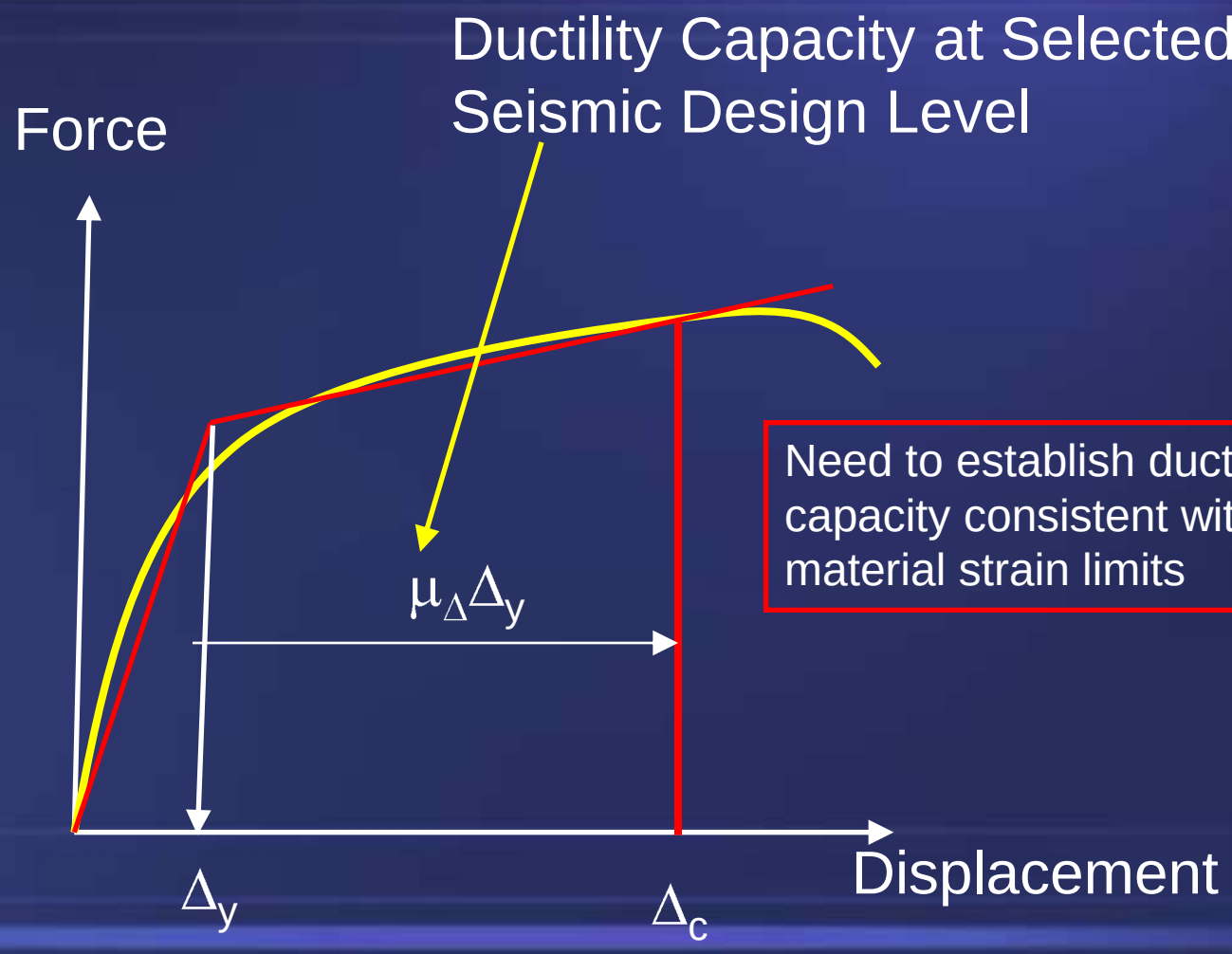
Pile Type	Material	Hinge Location	Level 1	Level 2
RC	Concrete	Pile/Deck	$\varepsilon_c \leq 0.005$	$\varepsilon_c \leq 0.025$
		In-Ground	$\varepsilon_c \leq 0.005$	$\varepsilon_c \leq 0.008$
	Steel Rebar	Pile/Deck	$\varepsilon_s \leq 0.01$	$\varepsilon_s \leq 0.05$
		In-Ground	$\varepsilon_s \leq 0.01$	$\varepsilon_s \leq 0.01$
PS Concrete	Strand	Pile-Deck	$\varepsilon_p \leq 0.005$ (Incremental)	$\varepsilon_s \leq 0.04$ (Total)
		In-Ground	$\varepsilon_s \leq 0.01$	$\varepsilon_s \leq 0.05$
Hollow Steel	Steel		$\varepsilon_s \leq 0.008$	$\varepsilon_s \leq 0.025$
Concrete Filled Steel Pipe	Steel		$\varepsilon_s \leq 0.008$	$\varepsilon_s \leq 0.03$

Pile Displacement Capacity



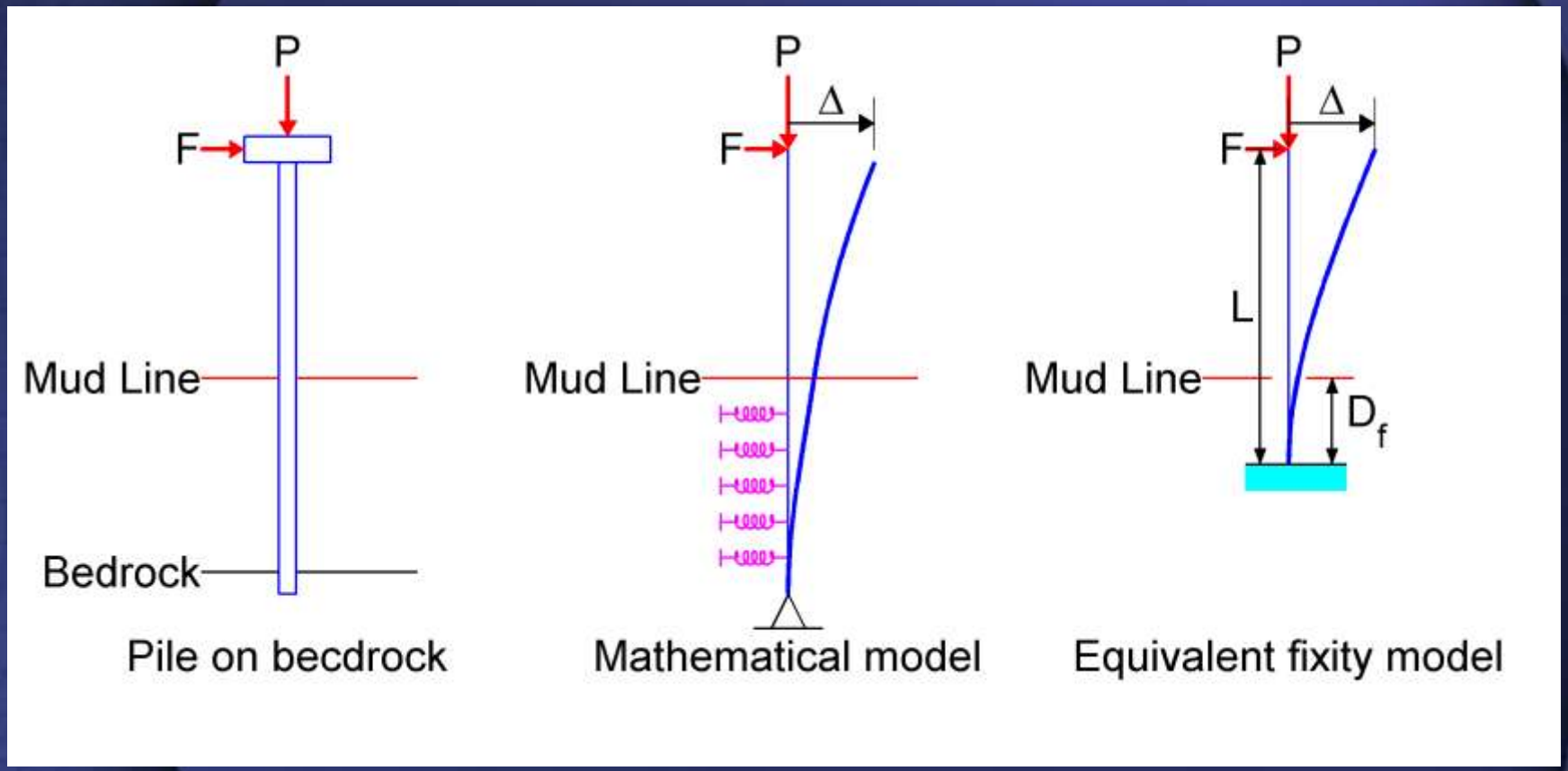
- Established from nonlinear static pushover analysis
  - Displacement capacity = maximum displacement at the pile tip without exceeding specified material strains
  - Need to monitor strains during pushover analysis
- Pile modeling
  - Spread plasticity with fiber section
    - Direct material strain monitoring
  - Concentrated plasticity with moment-rotation hinge
    - Monitoring hinge rotation corresponding to curvature at strain limit
    - Needs expression for plastic hinge length

Pile Seismic Displacement Capacity



Need to establish ductility capacity consistent with material strain limits

Simplified Pile Model

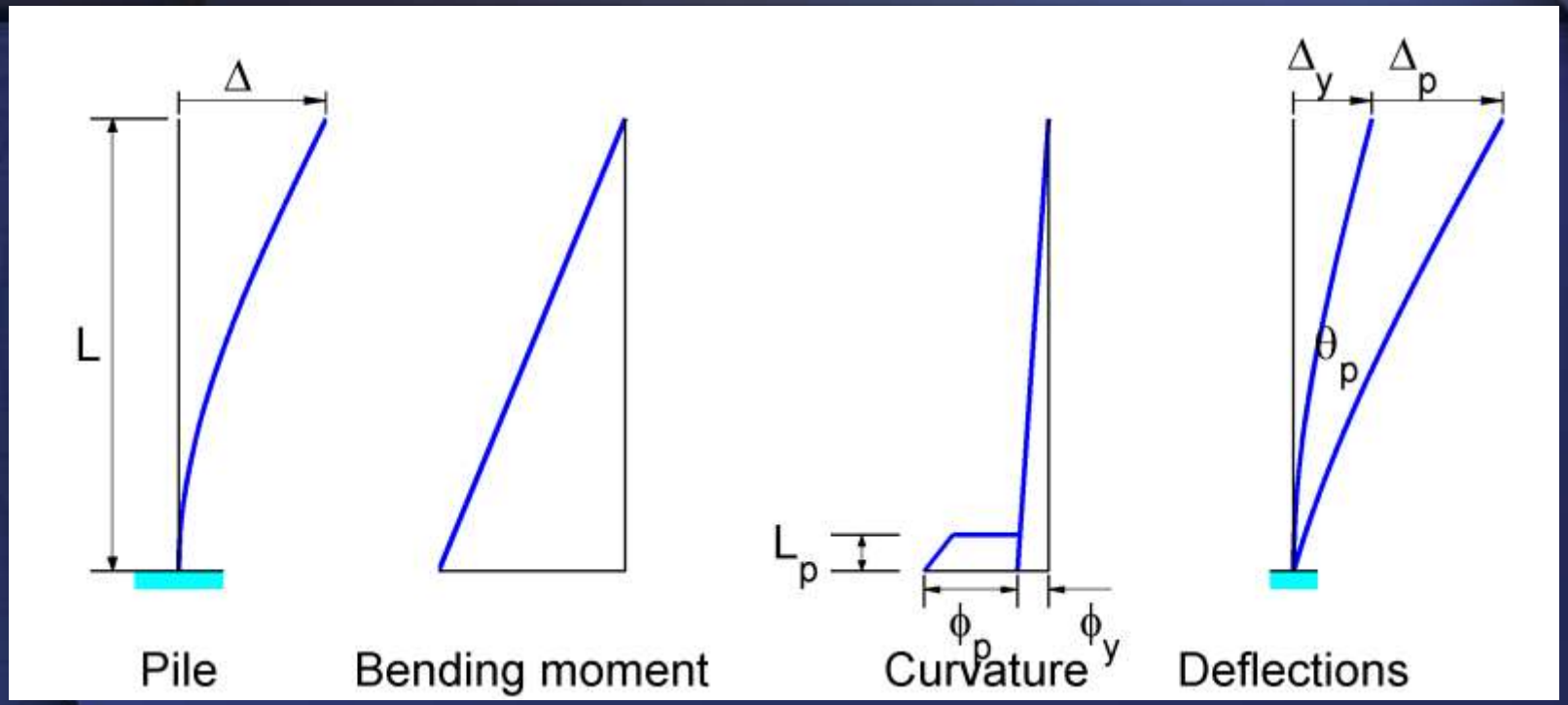


Displacement Ductility Capacity

- Simplified expressions have been developed for displacement ductility capacity of two categories of piles
  - Piles with either pin or full-moment connection to the deck
    - Pile-deck connection is stronger than the pile is a pin connenction
    - Hinge forms either in the pile below the deck or below ground
  - Piles with partial-moment connection
    - Pile-deck connection is weaker than the pile
    - Hinge forms either in the pile-deck connection or in pile below ground

Piles with Pin or Full-Moment Connection

Displacement Ductility Capacity



$$\mu_\Delta \approx 1 + 3\,\mu_\phi - 1\left(\frac{L_p}{L}\right)\left(1 - 0.5\frac{L_p}{L}\right)$$

Displacement ductility – curvature ductility equation

Plastic Hinge Length

$$L_p = \boxed{0.08L} + \boxed{0.15 f_{ye} d_{bl}} \geq 0.3 f_{ye} d_{bl}$$

Neglect for long free-standing piles in Marine Oil Terminal structures

Is it appropriate for both seismic design levels?

Comparison of results from ductility equation and nonlinear finite-element analysis indicate

Material	Level 1	Level 2
Concrete	$L_p \cong 0.06L$	$L_p \cong 0.08L$
Steel	$L_p \cong 0.03L$	$L_p \cong 0.075L$

Observations from Parametric Study: Finite Element Analysis

- Pile seismic displacement ductility capacity is a very robust parameter
  - For a selected pile type (reinforced-concrete, steel) and desired seismic design level (level 1 or level 2), it is essentially independent of cross-sectional properties and pile length
- Displacement ductility – curvature ductility equation may not be needed
  - A numerical value may be assigned based on hinge location, seismic design level, and type of pile (reinforced-concrete or steel)

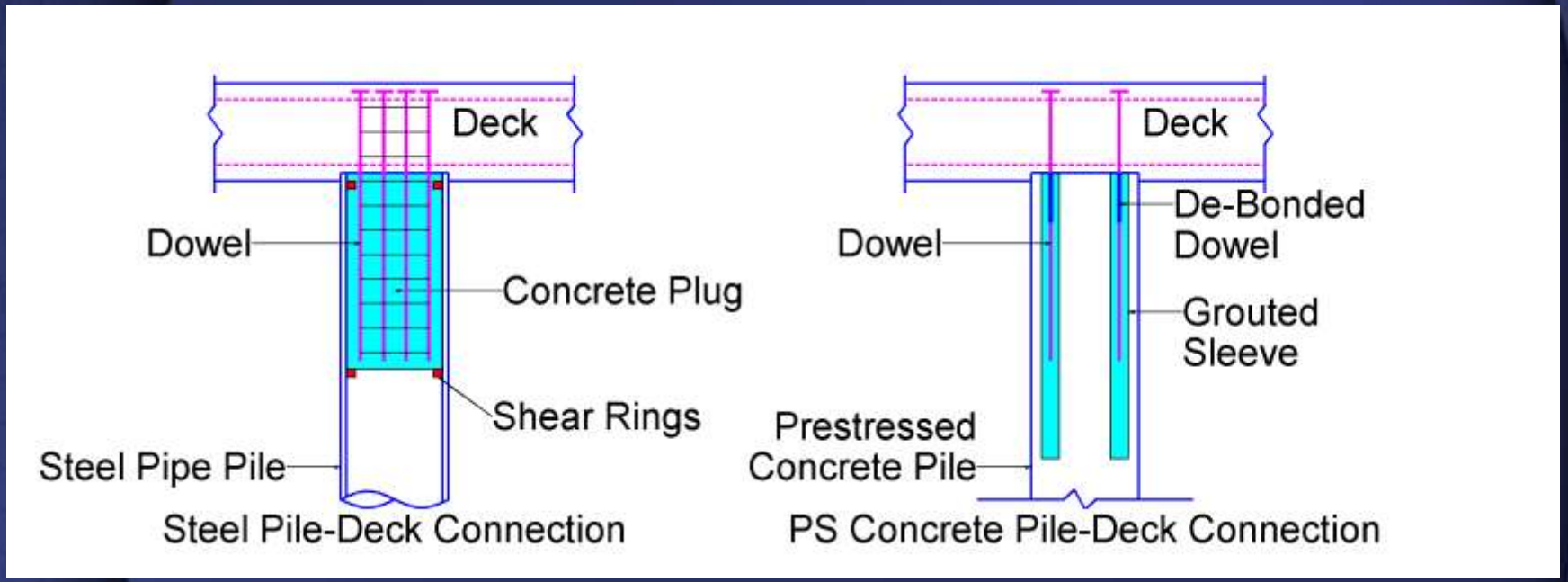
Displacement Ductility Capacity

Recommended Values for Piles with Pin- or Full-Moment Connection

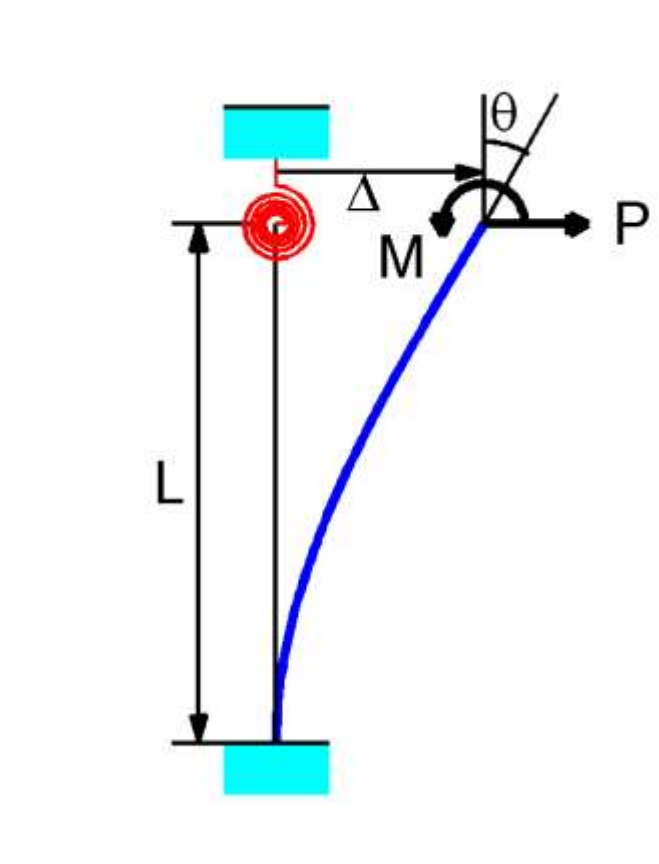
Seismic Level	Concrete		Steel	
	Pile-Deck Hinge	In-Ground Hinge	Pile-Deck Hinge	In-Ground Hinge
Level 1	1.5	1.5	1.2	1.2
Level 2	5	1.5	2.75	2.75

Piles with Partial-Moment Connection

Typical Pile-Deck Connections

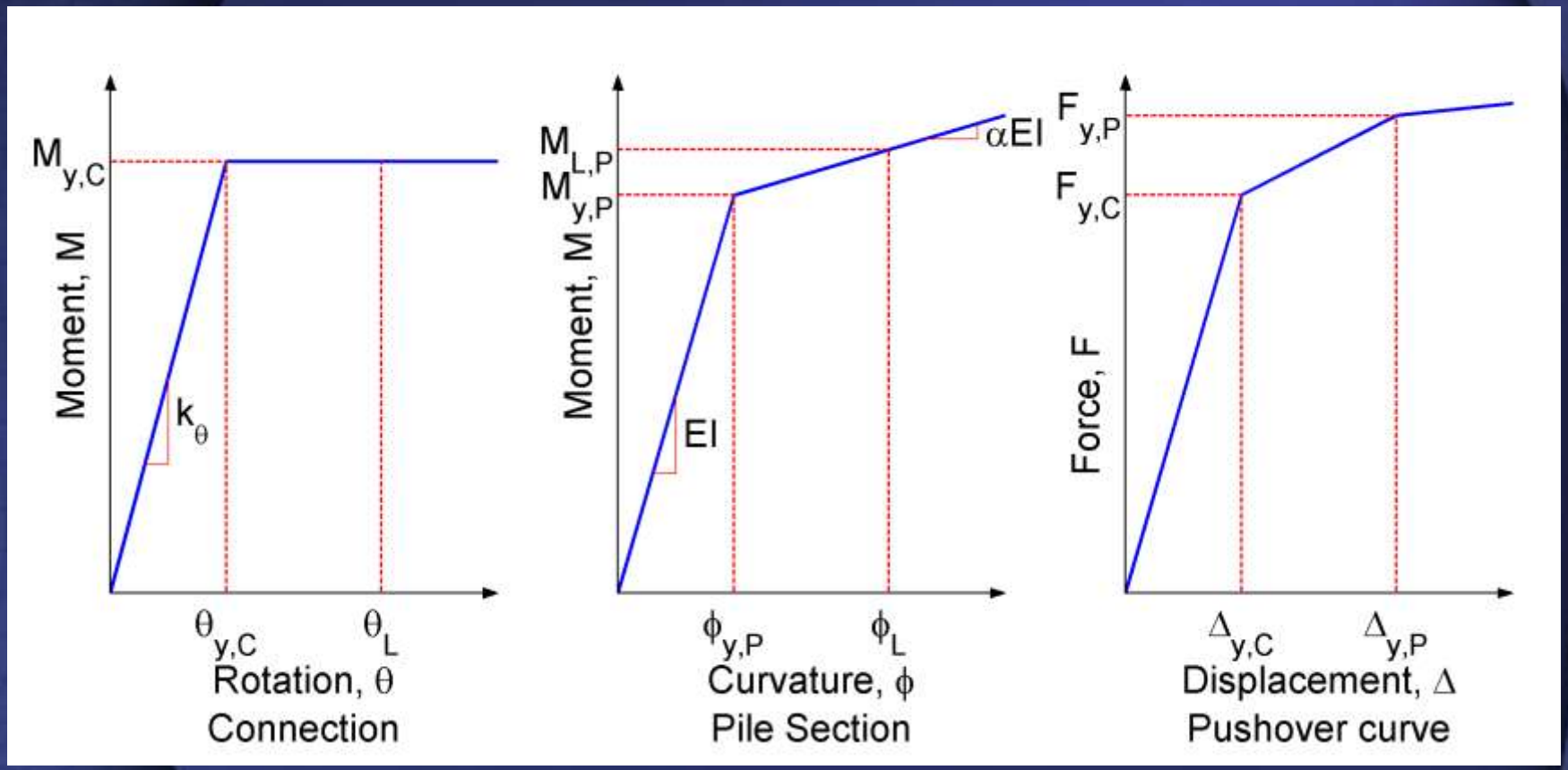


Mathematical Model



Pile with partial-moment connection

Idealized Behavior



Seismic Displacement Capacity: Closed-Form Solution

- Displacement capacity: $\Delta=\mu_\Delta\Delta_{y,C}$
  - $\Delta_{y,C}= \theta_{y,C}L(1+4\beta)/6\beta$
- Parameters
  - Ratio of rotational stiffness of pile and connection: $\beta=EI/k_\theta L$
  - Ratio of yield moment of pile and connection: $\eta = M_{y,P}/M_{y,C}$
  - Length of plastic hinge as a fraction of pile effective length: $\rho=L_p/L$
  - Rotation ductility of connection: $\mu_\theta = \theta_L/\theta_{y,c}$
  - Curvature ductility of pile section: $\mu_\phi = \phi_L/\phi_{y,P}$

Displacement Ductility Capacity: Closed-Form Solution

Select lower value from the following two equations

$$\mu_{\Delta,C} = \begin{cases} \dfrac{1+4\beta\mu_\theta}{1+4\beta}; & \mu_\theta \le \dfrac{\eta-1}{2\beta} \\ \dfrac{2-\eta+6\beta\mu_\theta}{1+4\beta}; & \mu_\theta > \dfrac{\eta-1}{2\beta} \end{cases}$$

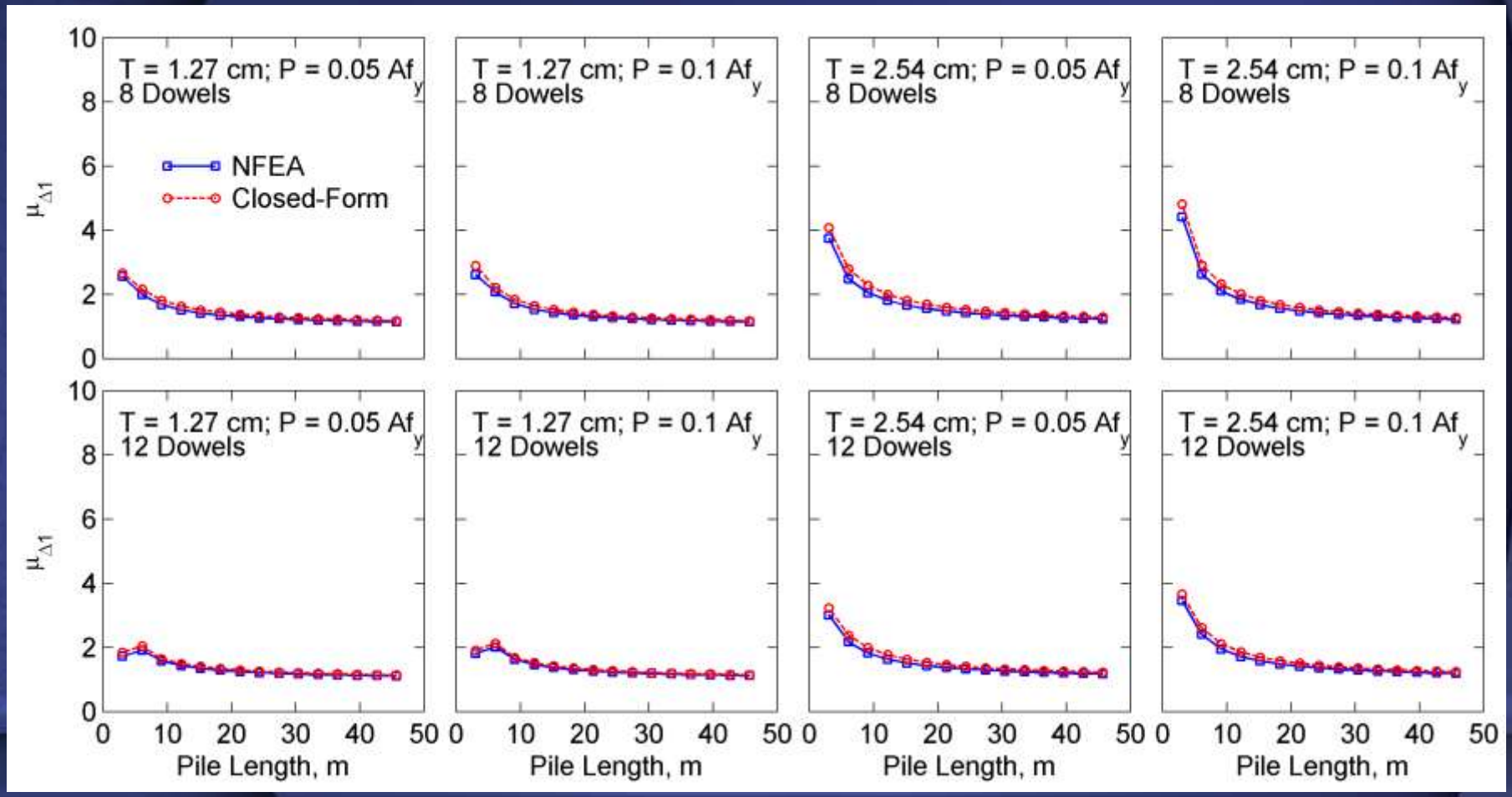
$$\mu_{\Delta,P} = \frac{2\eta-1}{1+4\beta} + \left(\frac{6\eta}{1+4\beta}\right)\left(\frac{\rho\eta}{1+\eta}\right)\left(1-\frac{\rho\eta}{2\ 1+\eta}\right)\ \mu_\phi - 1$$

Recommendation for ρ

- Hollow-steel pile
  - ρ = 0.03 for Level 1
  - ρ = 0.075 for Level 2
- Prestressed concrete pile
  - ρ = 0.05 for Level 1 and Level 2
- Recommended values of ρ are based on judgment and calibration against results from nonlinear finite-element analysis
  - Should be further verified against experimental data

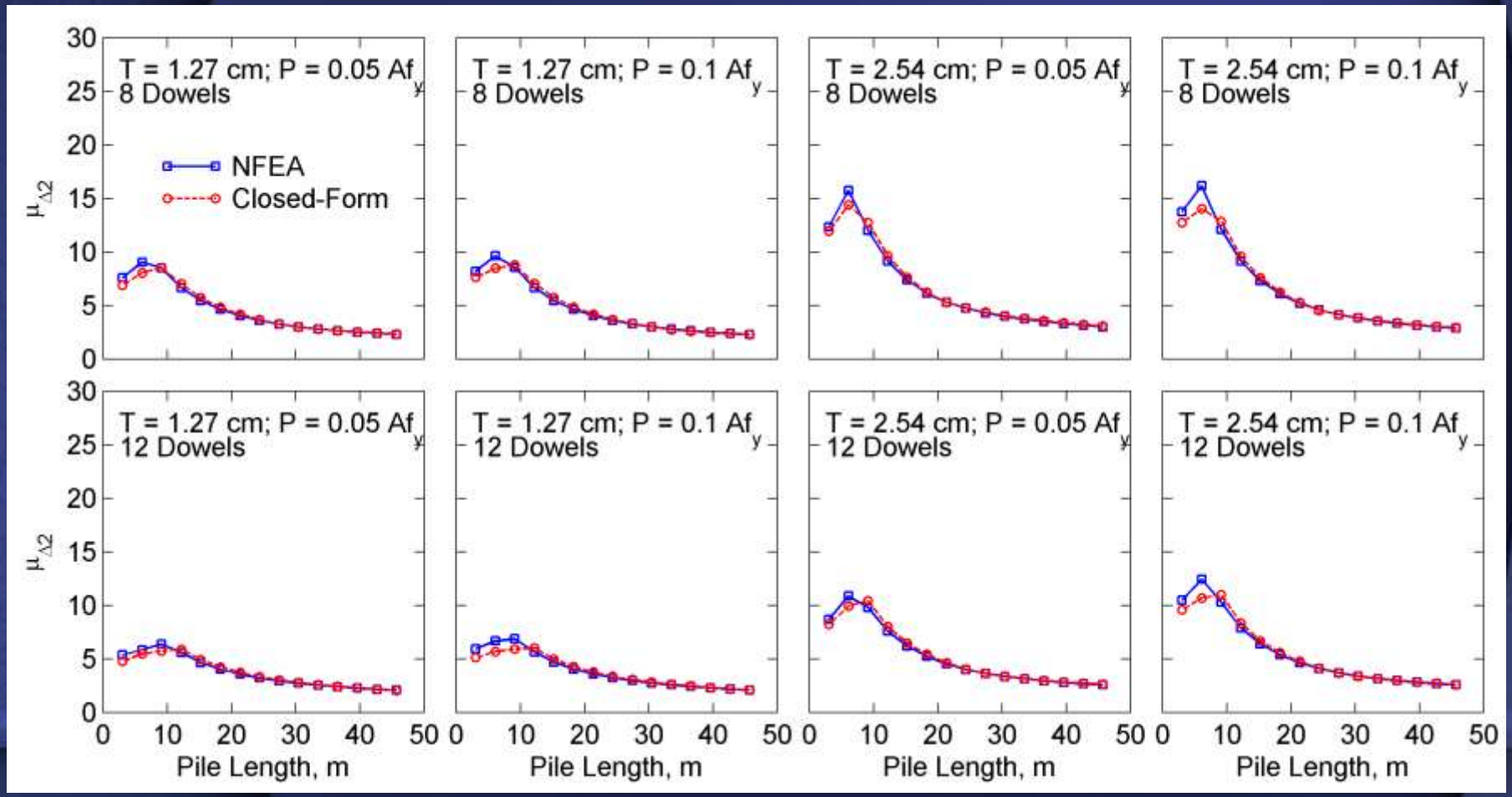
Validation of Closed-Form Equations

Hollow-Steel Piles: Level 1



Validation of Closed-Form Equations

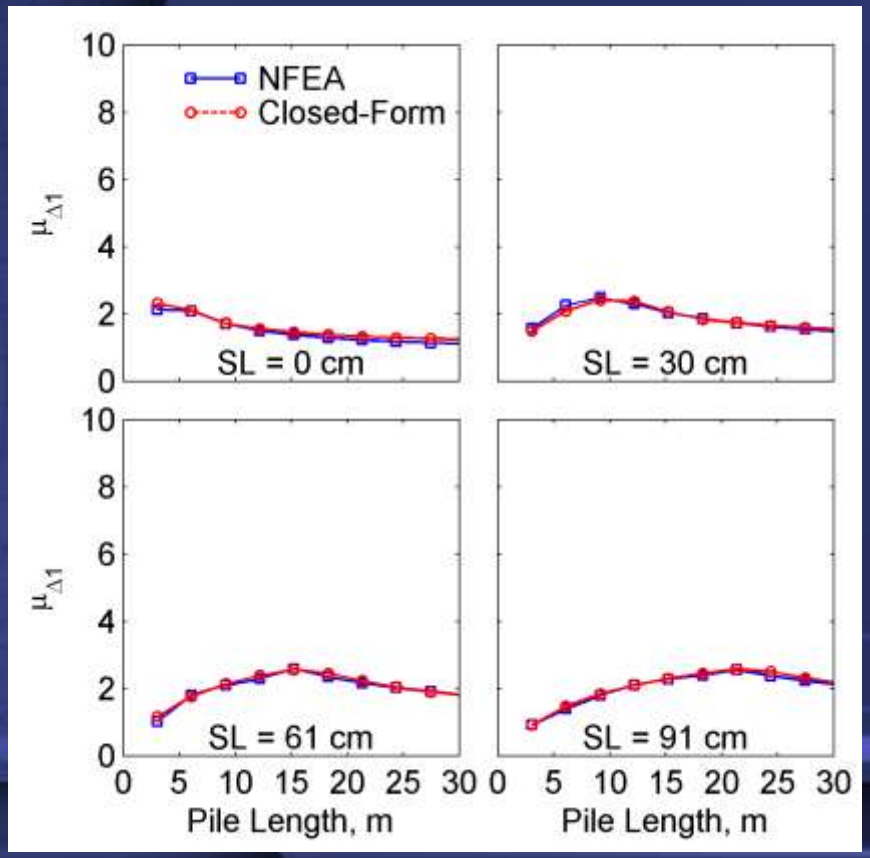
Hollow-Steel Piles: Level 2



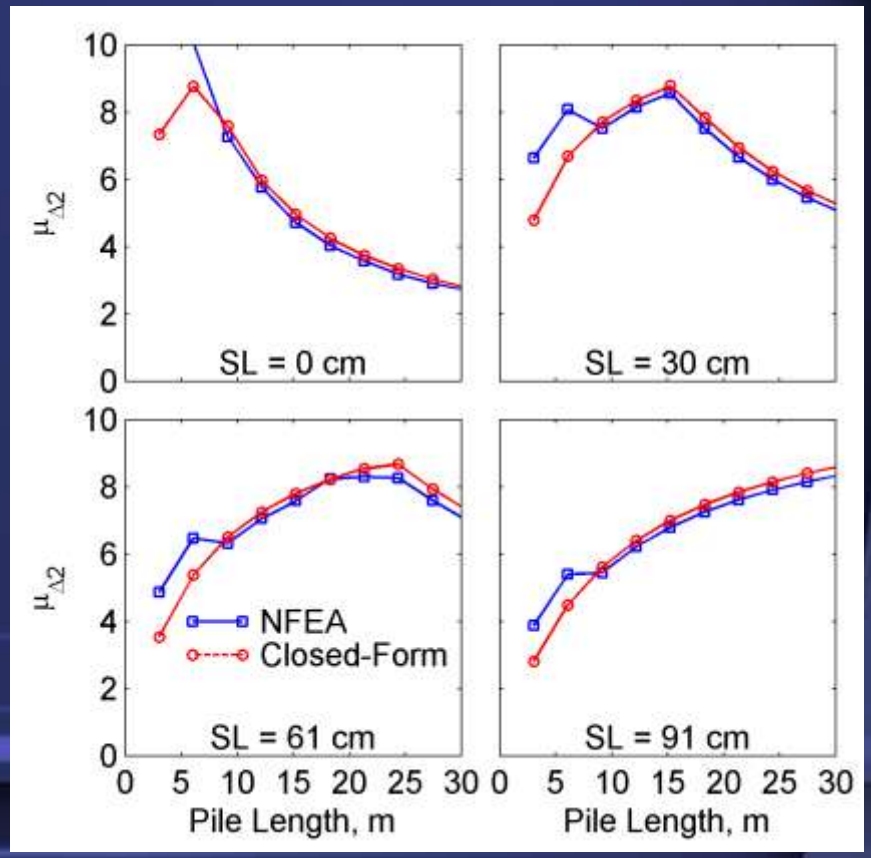
Validation of Closed-Form Equations

Prestressed Concrete Piles

Level 1



Level 2



Conclusions and Recommendations

- A simple procedure to estimate displacement capacity of piles has been presented
  - Used fundamental concept of displacement ductility
  - Avoids direct monitoring of material strains during pushover analysis
  - Procedure is demonstrated to be “accurate” against results from nonlinear finite-element analysis
- Plastic hinge length depends on pile-type (steel, concrete, prestressed concrete) and seismic design level
  - Careful when using concentrated plasticity model in pushover analysis
- Results should be verified against experimental data