New Nonlinear Analyses Methodology: Displacement Capacity of Piles

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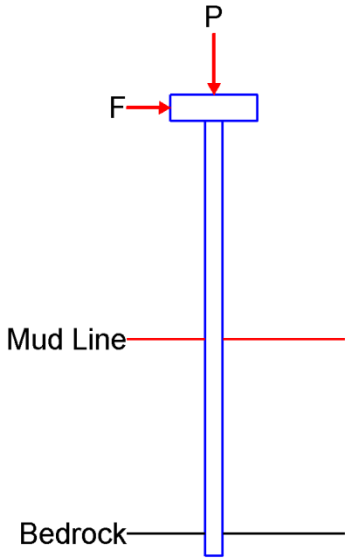
Rakesh K. Goel, PhD, PE, F.ASCE
California Polytechnic State University
San Luis Obispo, CA
rgoel@calpoly.edu

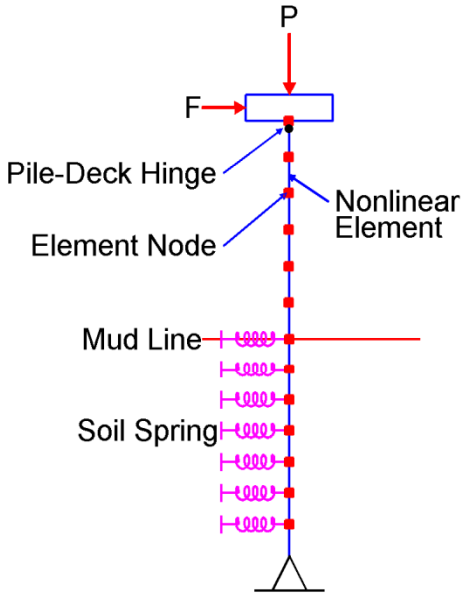
Objectives

- Develop a simple model to estimate displacement capacity of piles in Marine Oil and LNG Terminals
  - Satisfy strain MOTEMS material strain limits
  - Eliminate need for pile nonlinear pushover analysis
- Evaluate “accuracy” of simple model

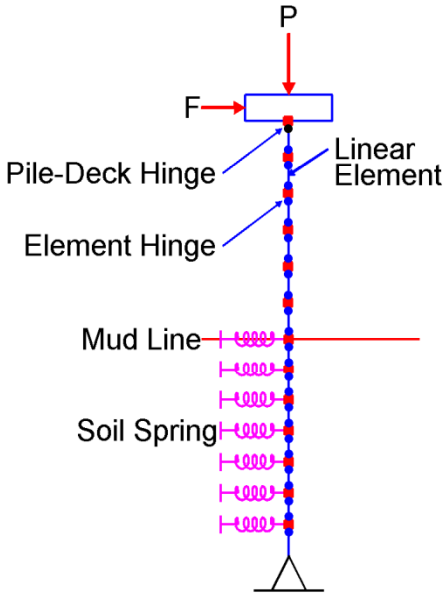
Pile Model for Seismic Analysis



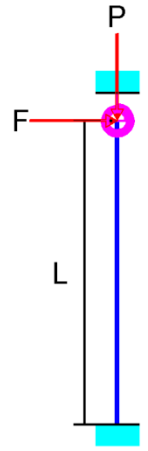
Pile-Deck System



Model with Nonlinear Elements

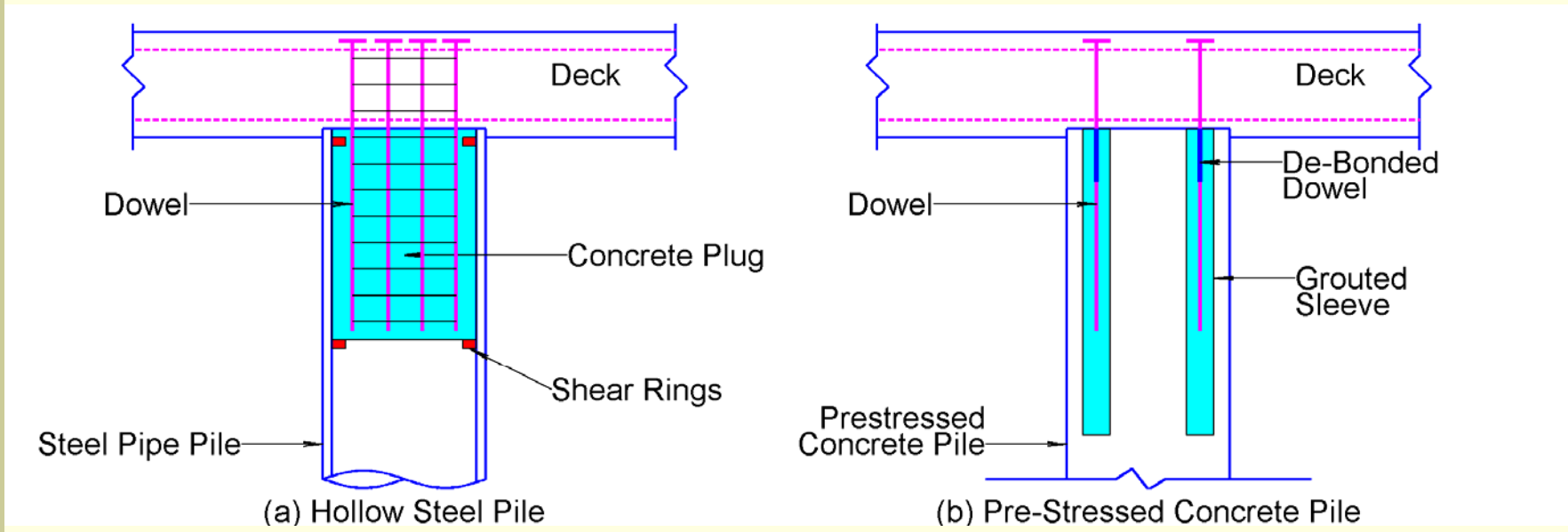


Model with Linear Elements and Hinges



Simple Model

Piles-Deck Connection



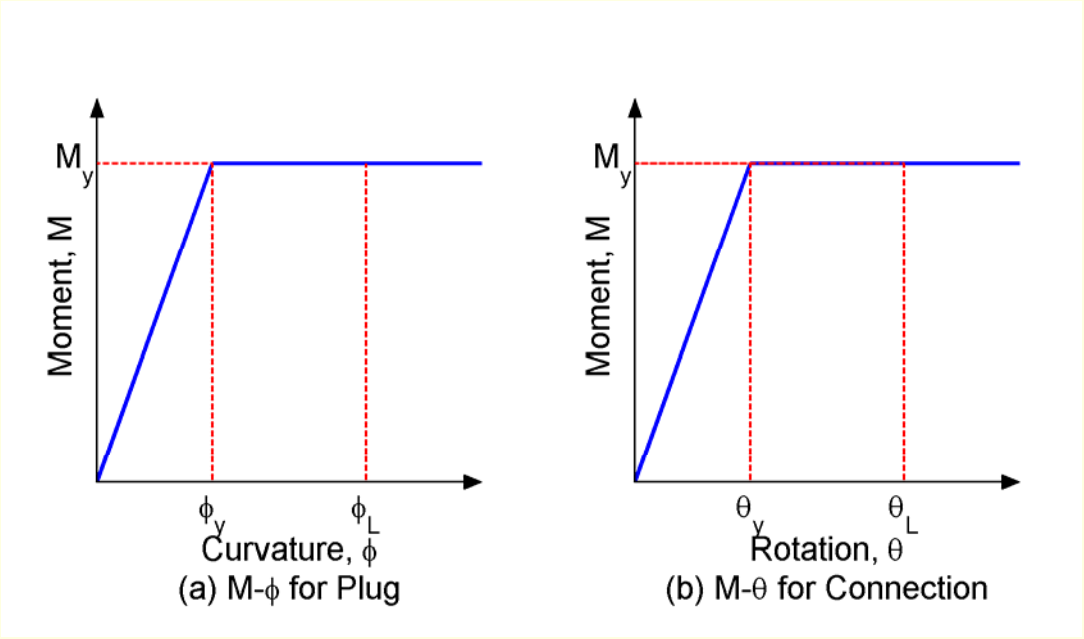
Pile-Deck M-θ Relationship

$$\theta_y = L_{sp}\phi_y$$

$$L_{sp} = 0.12 f_{ye} d_{bl}$$

$$\theta_L = \theta_y + \theta_P$$

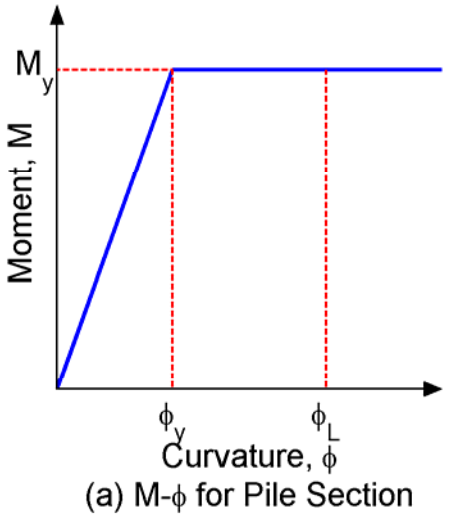
$$\theta_P = L_P\left(\phi_L - \phi_y\right)$$



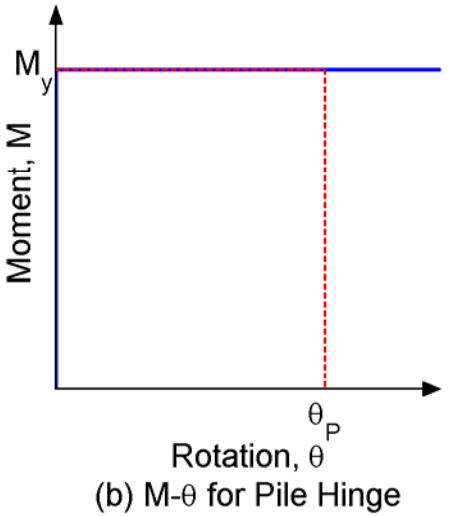
$$L_P = \begin{cases} 0.08L_e + 0.12 f_{ye} d_{bl} \geq 0.2 f_{ye} d_{bl} & \text{for PS Concrete} \\ 0.3 f_{ye} d_{bl} + d_{gap} & \text{for Hollow-Steel} \end{cases}$$

In-Ground Pile Hinge M-θ Relationship

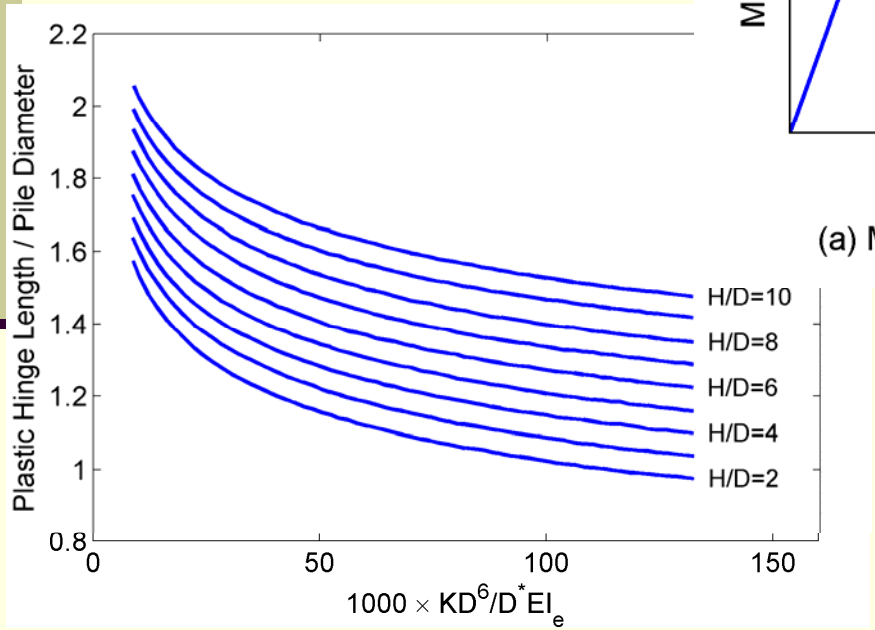
$$\theta_P = L_P\left(\phi_L - \phi_y\right)$$



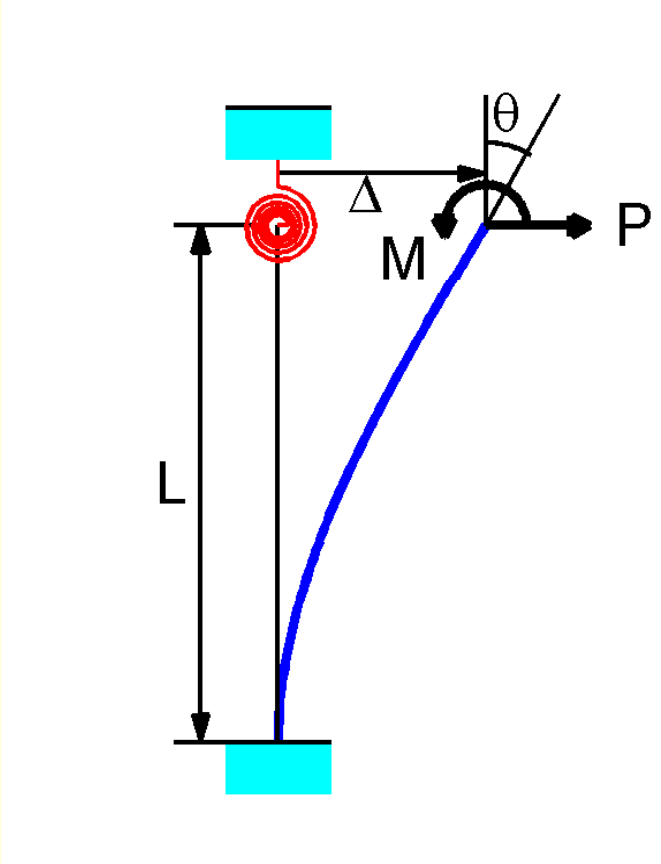
(a) M-ϕ for Pile Section



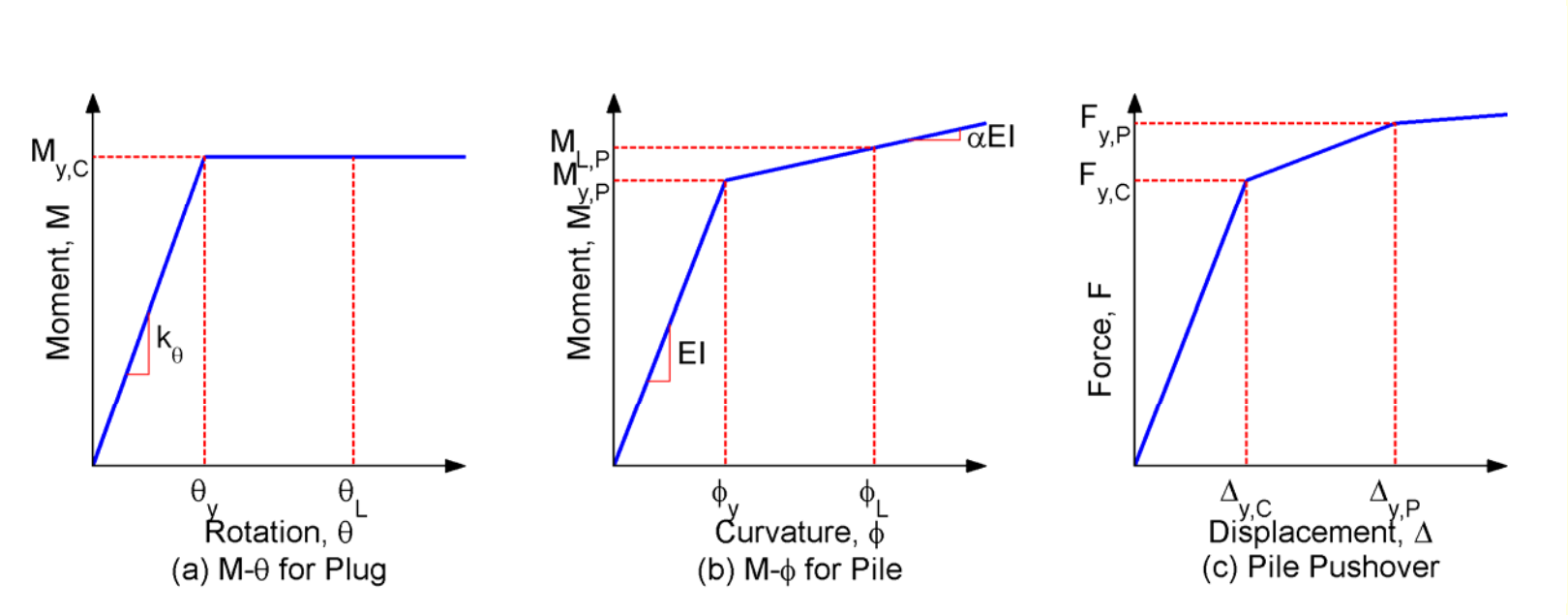
(b) M-θ for Pile Hinge



Simplified Model



Simplified Model



Idealized behavior assumed in development of formulas for ductility capacity of piles with plug-connection to the deck

Ductility Capacity: Connection Hinging

$$\mu_{\Delta,C} = \begin{cases} \dfrac{1+4\beta\mu_\theta}{1+4\beta} & \text{for } \mu_\theta \le \dfrac{\eta-1}{2\beta} \\ \dfrac{2-\eta+6\beta\mu_\theta}{1+4\beta} & \text{for } \mu_\theta > \dfrac{\eta-1}{2\beta} \end{cases} \qquad \eta = \frac{M_{y,P}}{M_{y,C}} \qquad \beta = \frac{EI}{k_\theta L}$$

μ_θ = Rotation ductility of plug at selected design

k_θ = Moment-Rotation stiffness of plug

EI = Effective EI of pile

L = Pile length of equivalent displacement-fixity

Ductility Capacity: Pile Hinging

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

$$\eta = \frac{M_{y,P}}{M_{y,C}}$$

$$\beta = \frac{EI}{k_\theta L}$$

μ_ϕ = Curvature ductility of pile at selected design

k_θ = Moment-Rotation stiffness of plug

EI = Effective EI of pile

L = Pile length of equivalent displacement-fixity

ρ = Plastic hinge length as a fraction of pile length

Displacement Capacity

$$\Delta_{y,C} = \frac{\theta_{y,C} L (1 + 4\beta)}{6\beta}$$

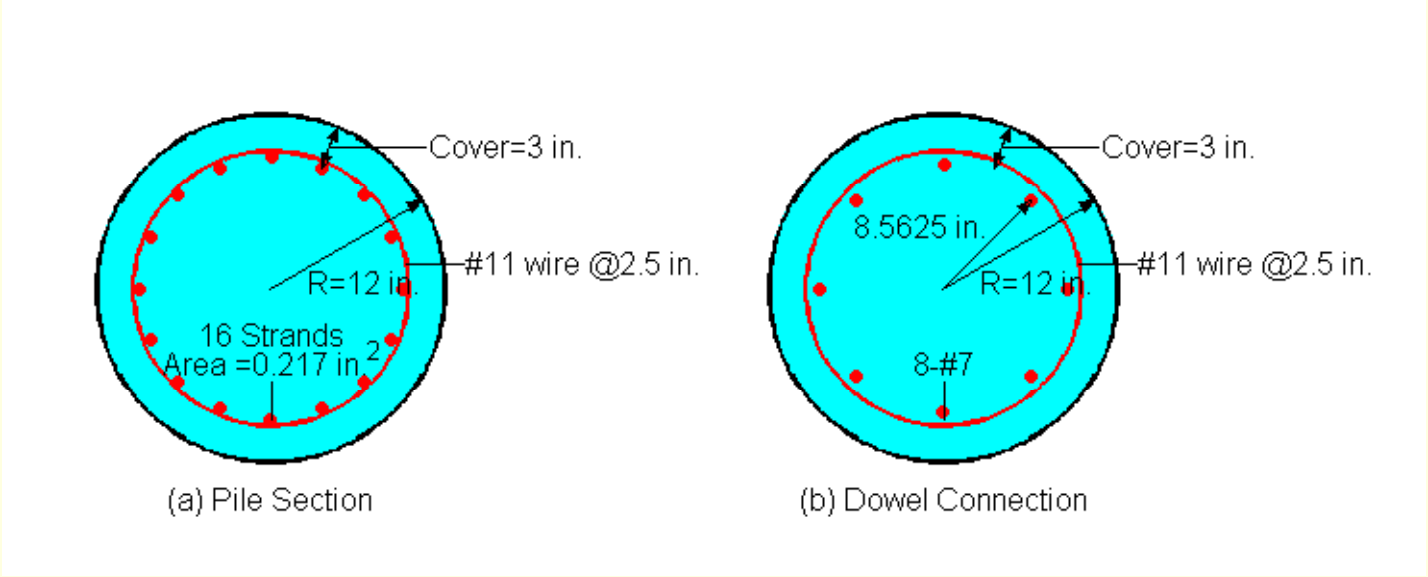
$$\eta = \frac{M_{y,P}}{M_{y,C}}$$

$$\beta = \frac{EI}{k_\theta L}$$

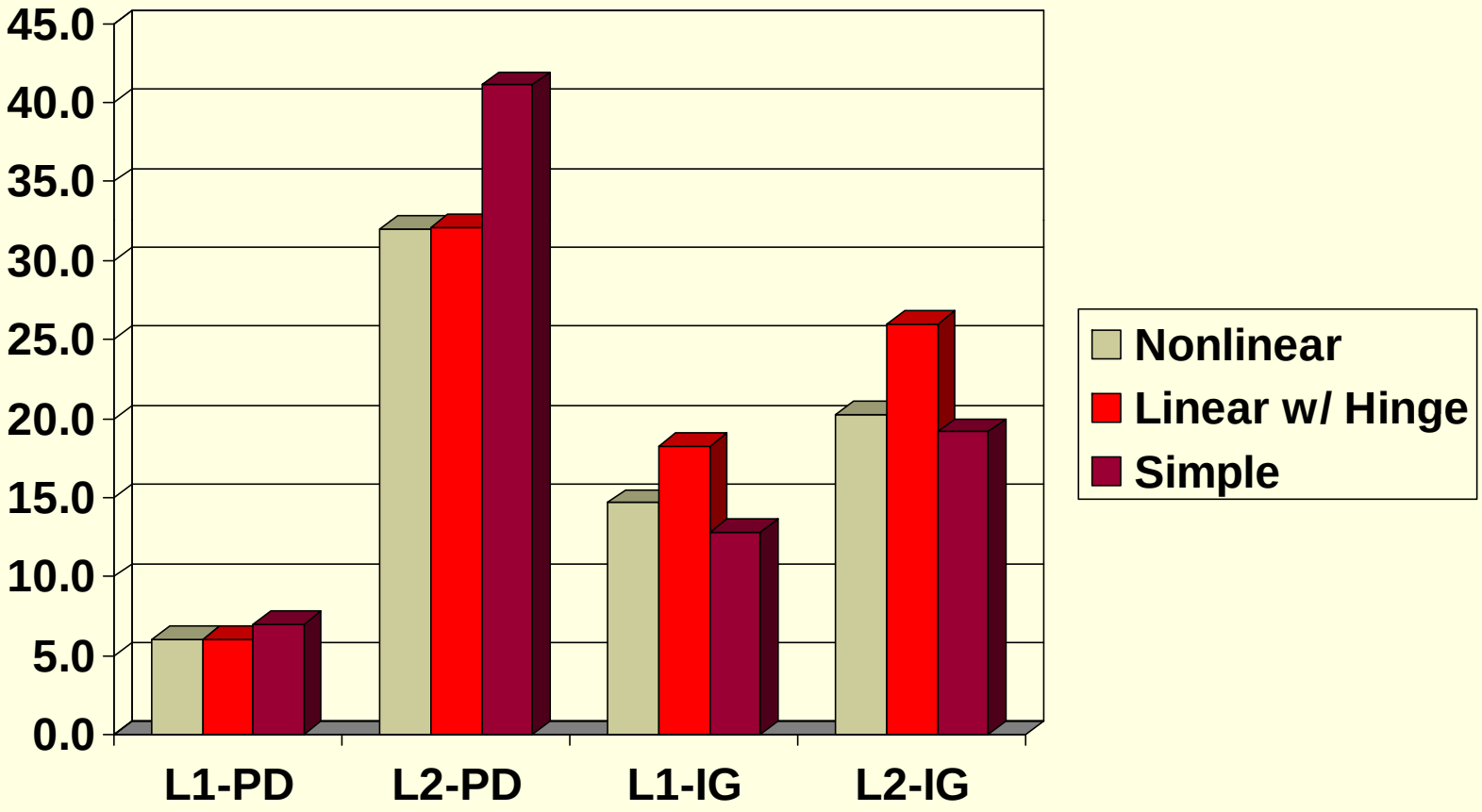
$\theta_{y,c}$ = Yield rotation of plug/dowel connection

$$\Delta = \Delta_{y,C} \times \{\mu_{\Delta,C}, \text{ or } \mu_{\Delta,P}\}$$

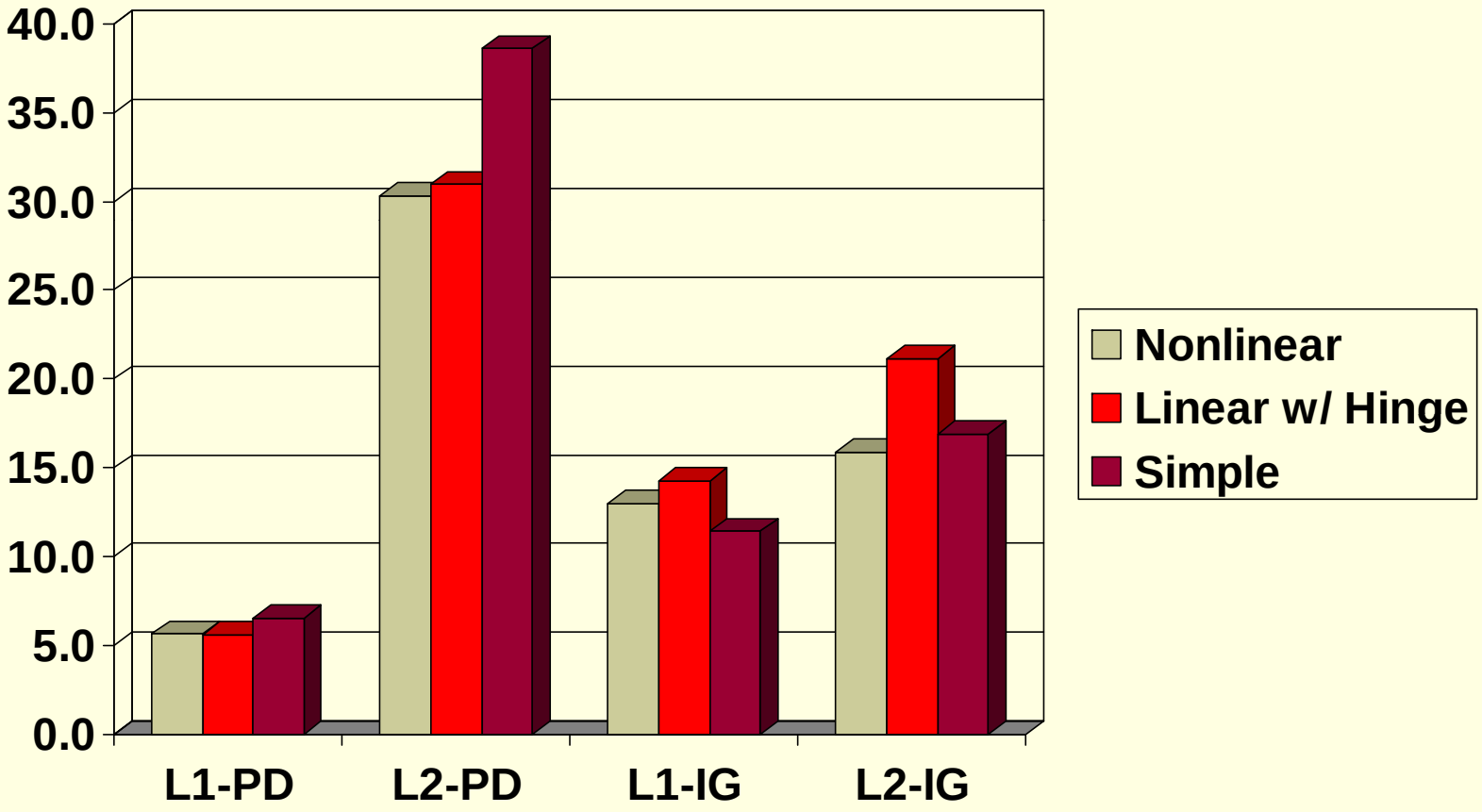
Pre-Stressed Concrete Pile



Displacement Capacity: K = 0.2 kip/in^3 (Medium Clay)



Displacement Capacity: K = 0.5 kip/in^3 (Stiff Clay)



Conclusions

- Simple model provides results “accurate” enough for practical purposes
  - Use for preliminary design
  - Check on results from detailed nonlinear pushover analysis

Conclusions

- Model with linear beam and plastic hinges provides reasonable results
  - Requires assumption on plastic hinge length
  - Limited data for current in-ground plastic hinge length recommendations in MOTEMS
  - Displacement capacity appears to very sensitive to plastic hinge length assumption

Recommendations

- Develop in-ground plastic hinge length charts for piles typically used in Marine and LNG Terminals considering appropriate soil conditions
  - Current recommendations are based on Cast-In-Drilled-Hole (CIDH) piles for bridges
- Develop moment-rotation model for pile-deck connections
  - Traditional models based on plastic hinge length may not be applicable