

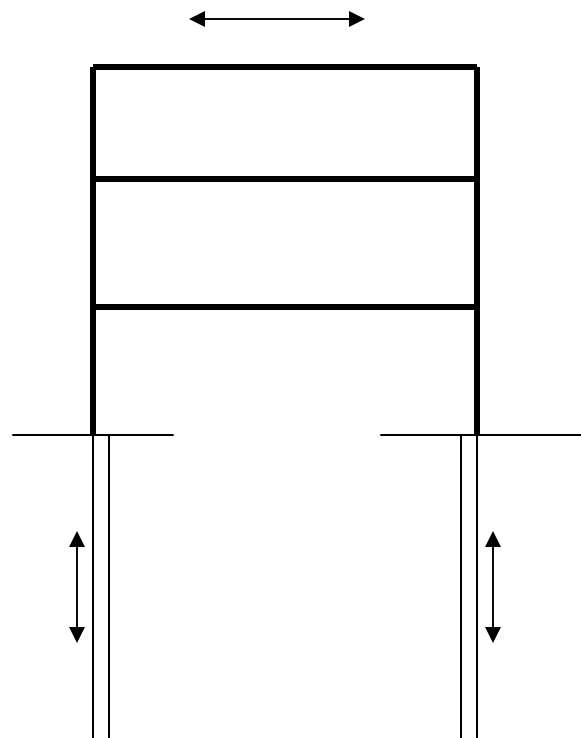


# A CYCLIC SOIL MODEL AND ITS APPLICATION IN SOIL-PIER INTERACTION UNDER AXIAL LOADING

Gang Wang and Nicholas Sitar  
Dept. of Civil and Environ. Eng.  
University of California at Berkeley

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# Dynamic Soil-Pile-Structure System

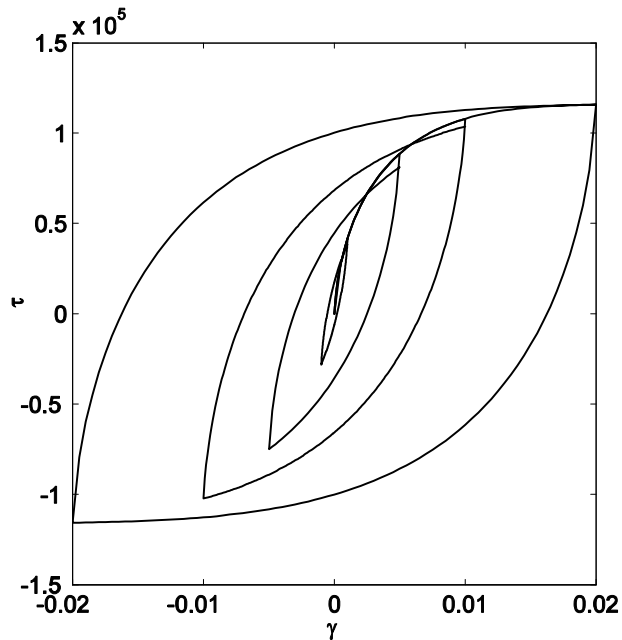


## System Response

- \* Structure Stiffness
- \* Foundation Stiffness
  - Loading Type
  - Soil Properties
  - Installation
- \* Energy Dissipation
  - Viscous Damping
  - Hysteretic Damping
  - Radiation Damping



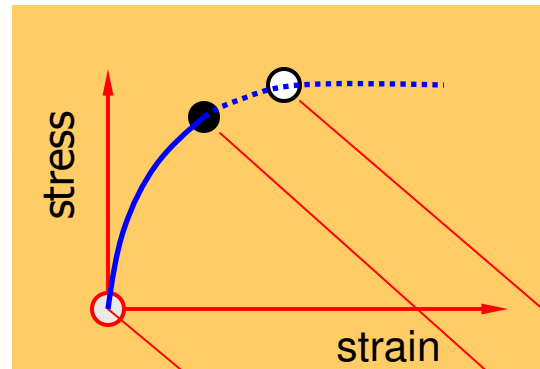
# Nonlinear Cyclic Soil Response



- Modulus Reduction
- Hysteretic Damping
- Strength

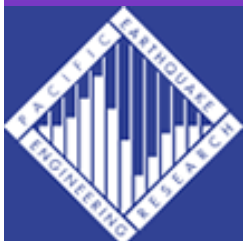
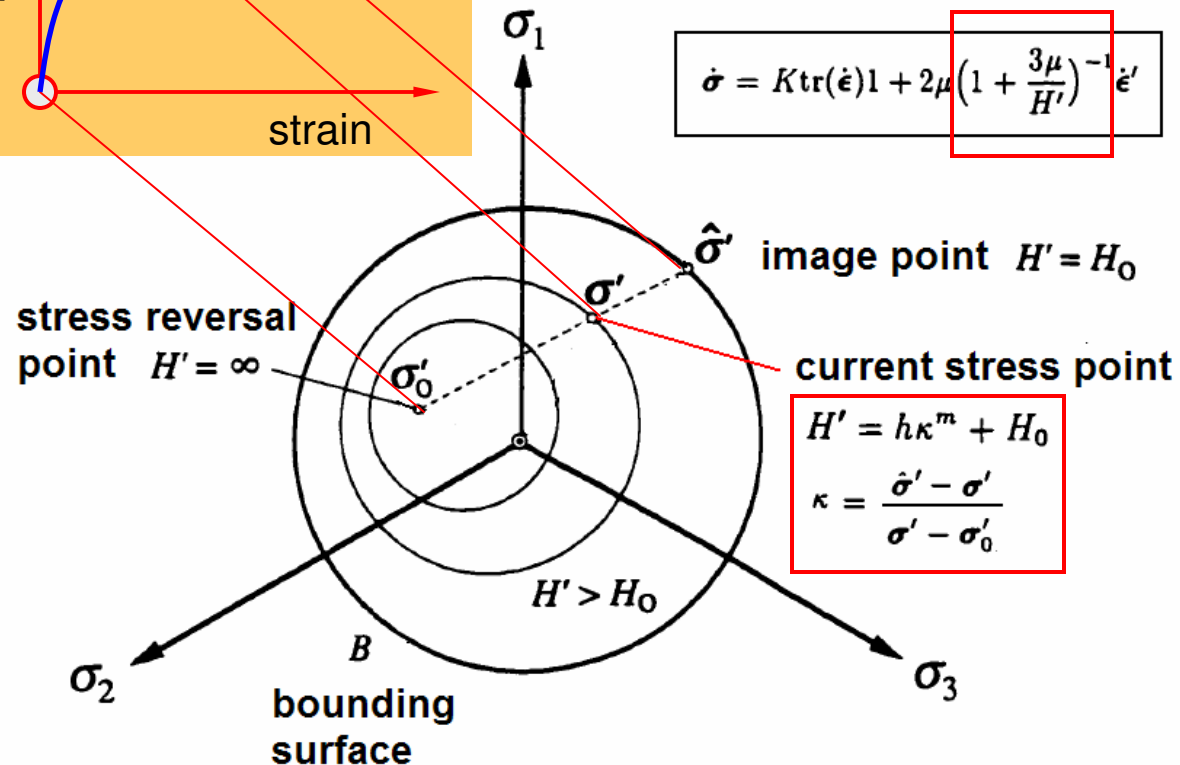


# Bounding Surface Cyclic Soil Model (R. Borja) --- Hardening Rule



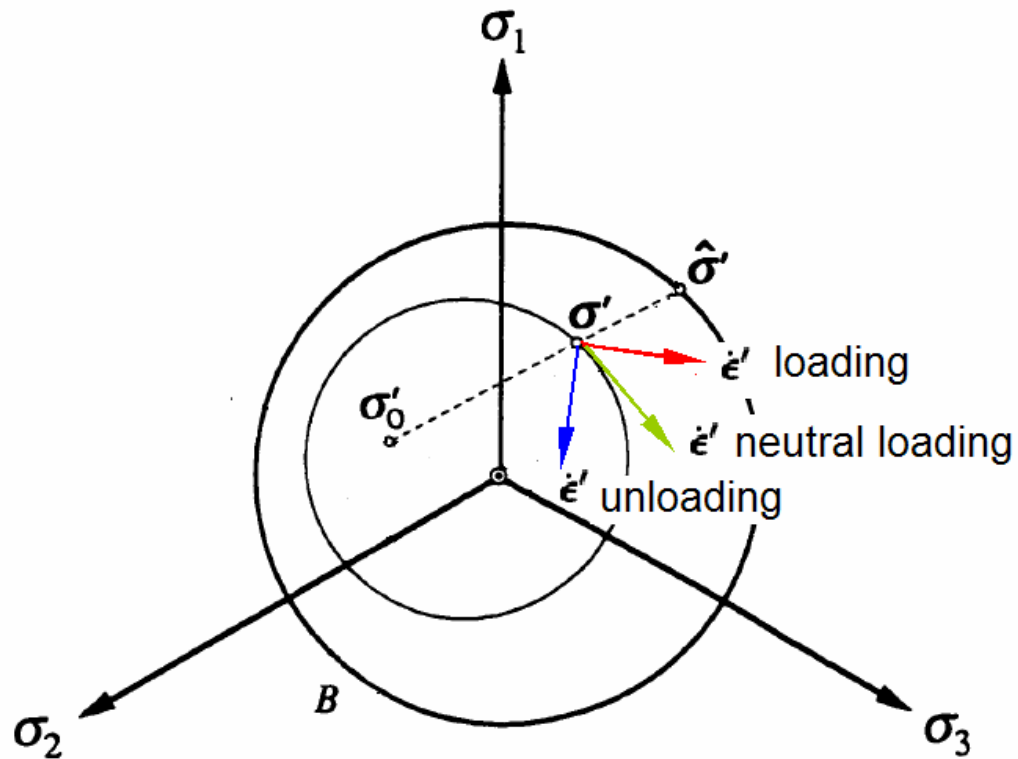
Constitutive Eqn.

$$\dot{\sigma} = K \text{tr}(\dot{\epsilon}) \mathbf{1} + 2\mu \left(1 + \frac{3\mu}{H'}\right)^{-1} \dot{\epsilon}'$$

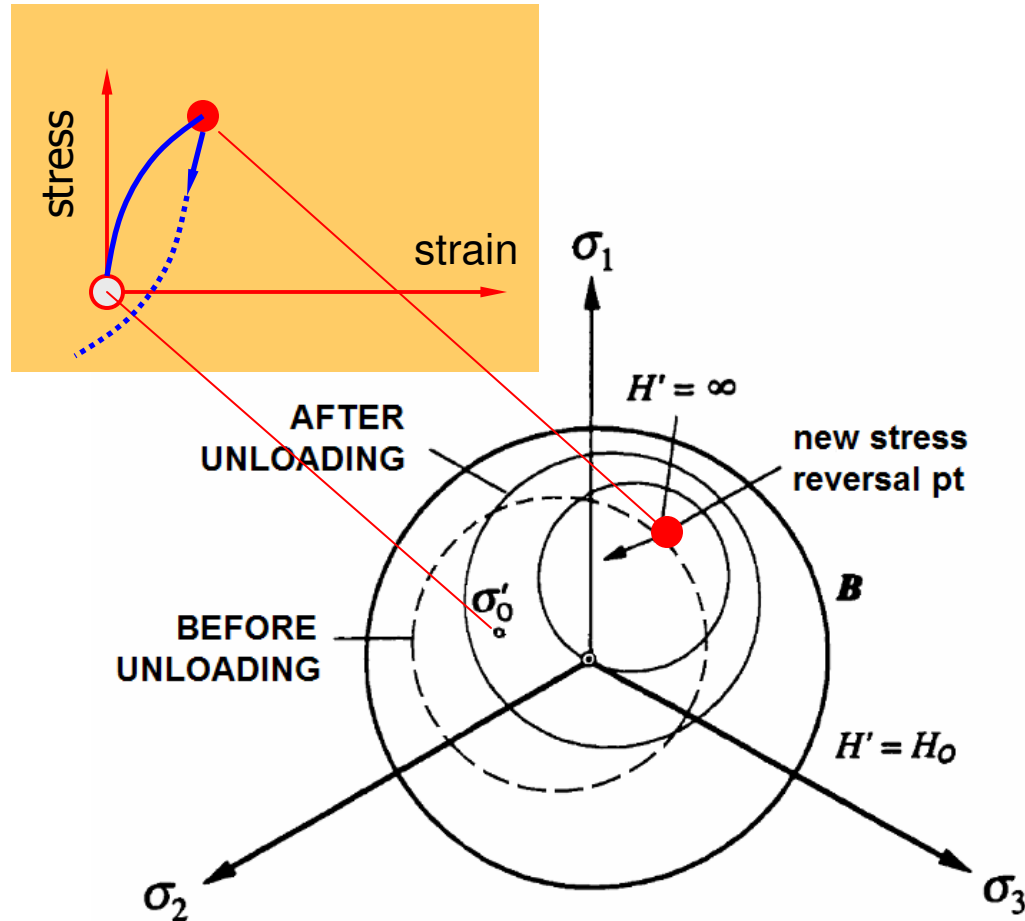


# Bounding Surface Cyclic Soil Model

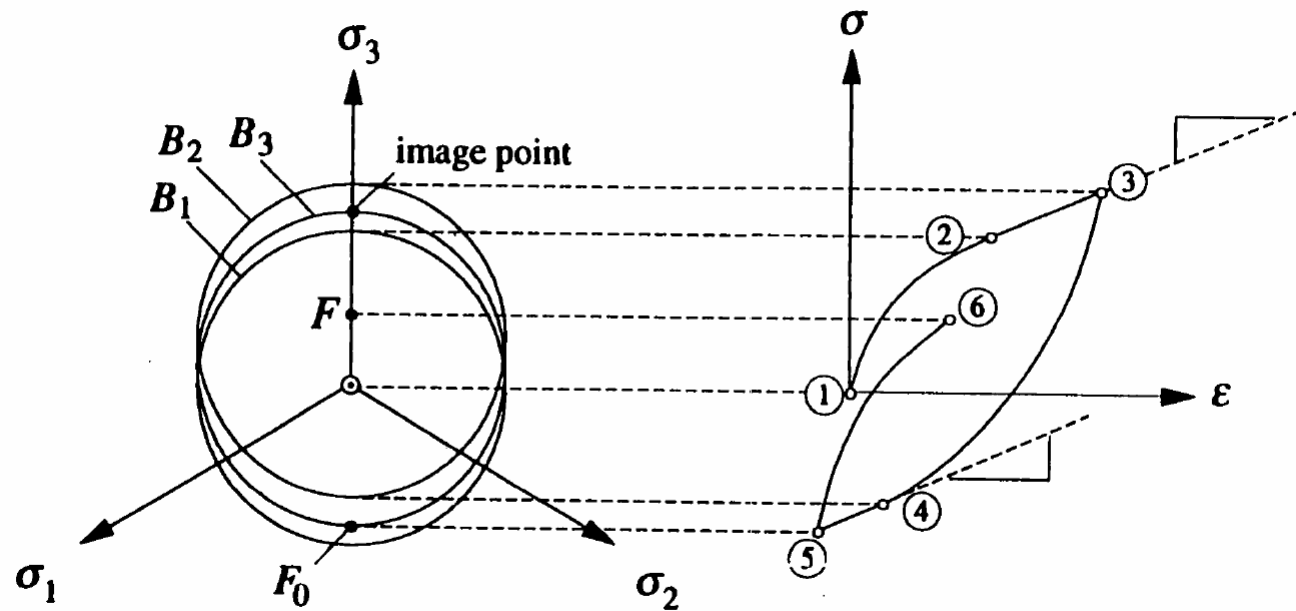
## --- Loading/Unloading Criterion



# Bounding Surface Cyclic Soil Model --- Unloading



# Bounding Surface Cyclic Soil Model --- Hardening of the Bounding Surface



## OpenSees Command

nDMaterial MultiaxialCyclicPlasticity

\$matTag \$rho \$v \$G<sub>max</sub> \$S<sub>u</sub> \$H<sub>o</sub> \$h \$m \$beta \$K<sub>o</sub>

- \$matTag: Material ID
- \$rho : Soil density
- \$v : Poisson's ratio
- \$G<sub>max</sub> : Small strain shear modulus
- \$S<sub>u</sub> : Undrained shear strength
- \$H<sub>o</sub> : Hardening modulus of bounding surface
- \$h : Exponential hardening parameter
- \$m : Exponential hardening parameter
- \$beta : Integration parameter (0.5)





# Parameter Determination

- Material Density

- Elastic Parameters

$$G_{max} = \rho V_s^2$$

$\nu$  Vs: shear wave velocity profile  
Poisson's ratio

- Undrained Shear Strength

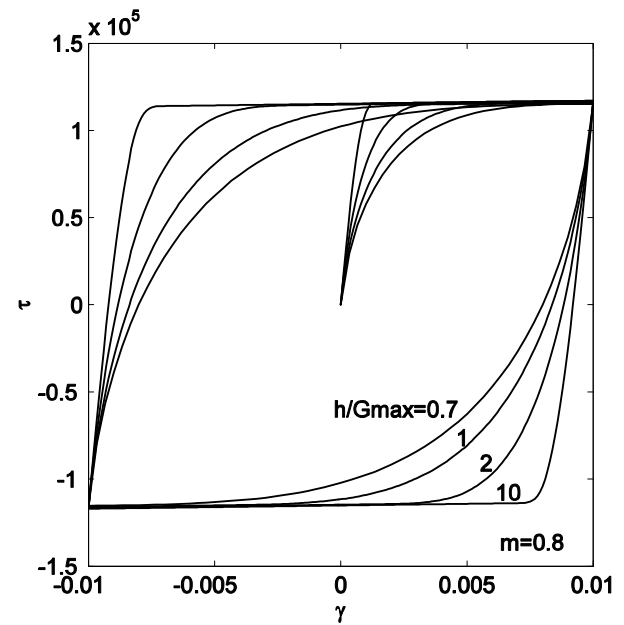
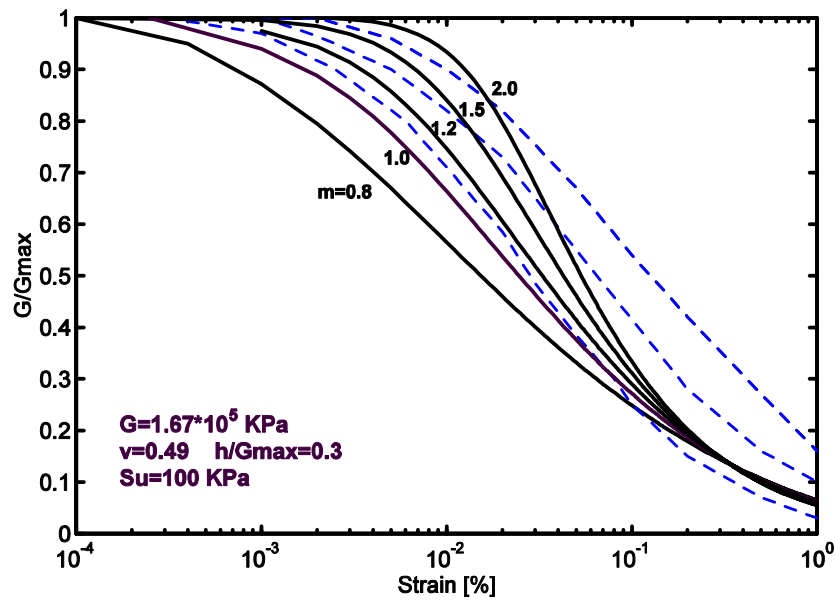
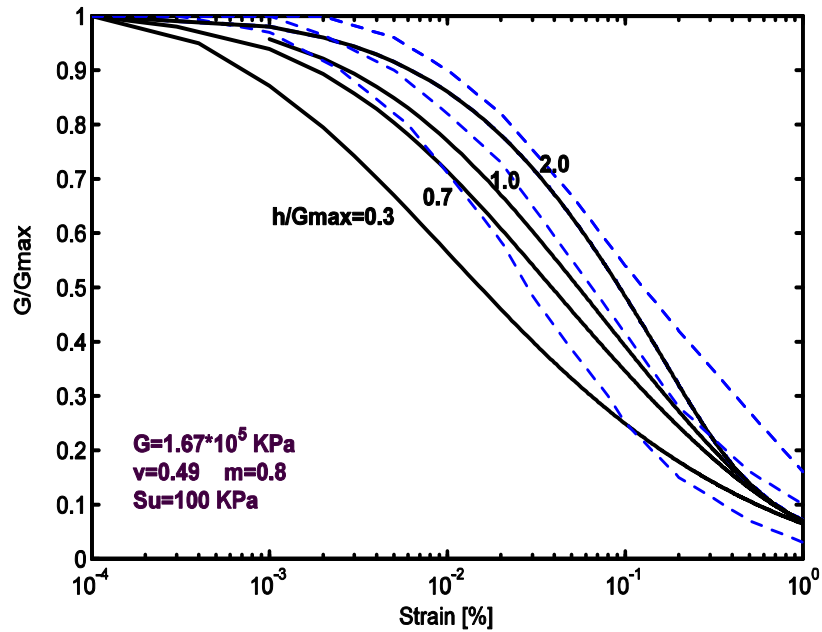
$S_u$  From Unconfined Compression Test  
or SPT correlation

- Hardening Parameters

$h, m$  Fit modulus reduction curves  
 $H_o$  Fit tangential shear modulus at large strain



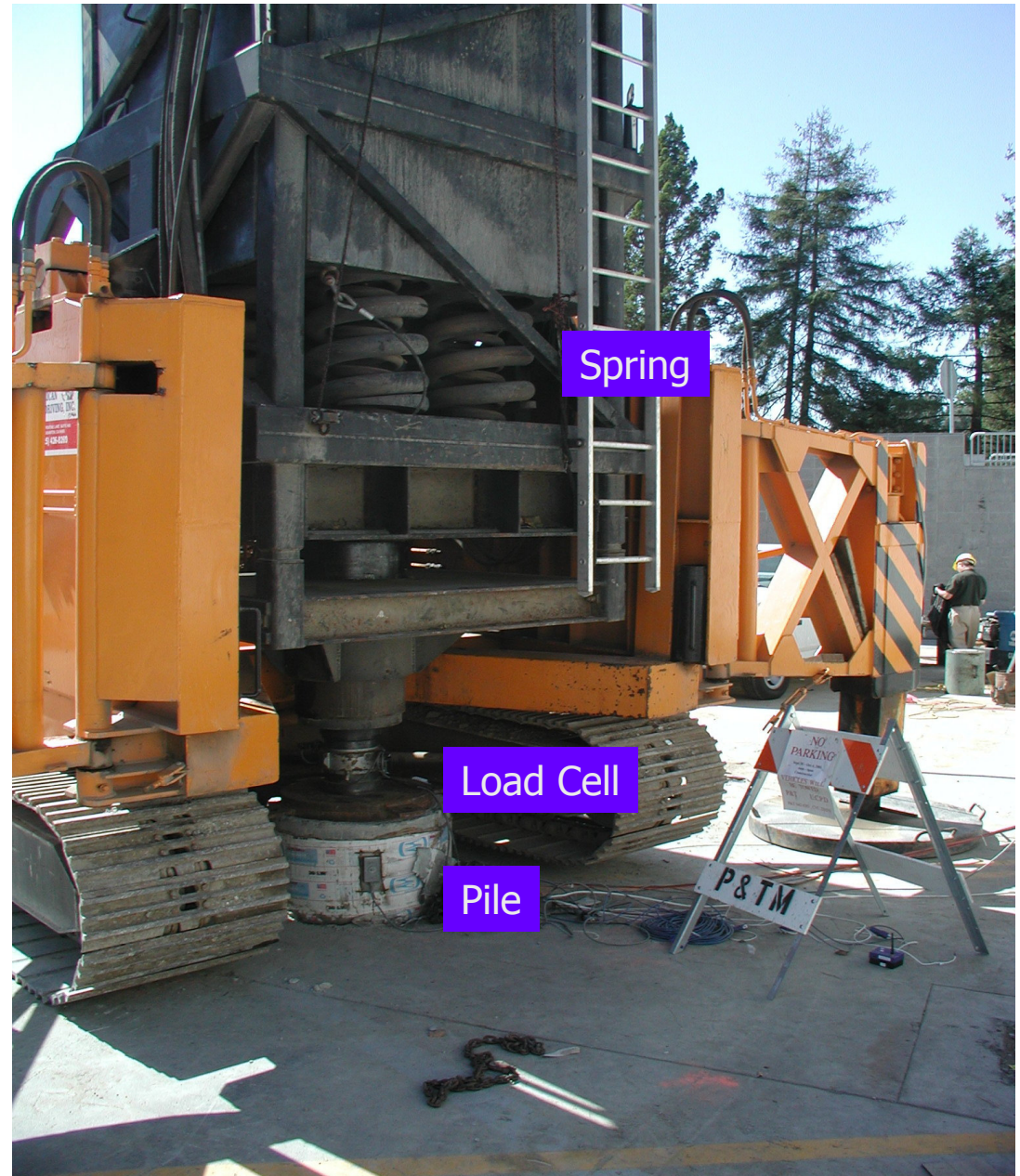
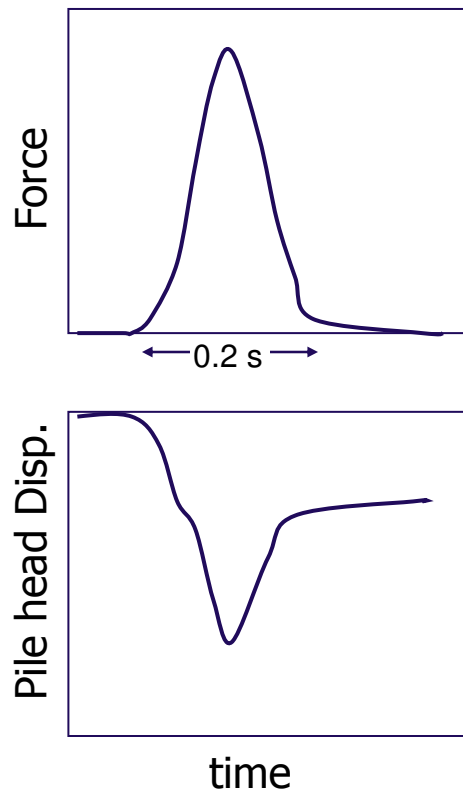
# Fit Modulus Reduction Curves



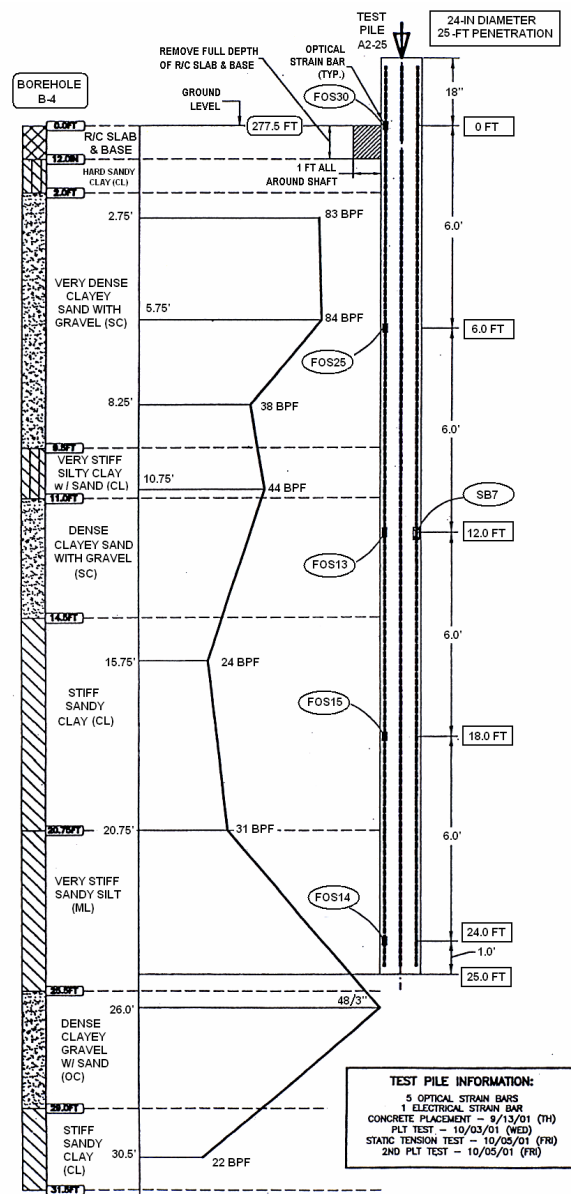
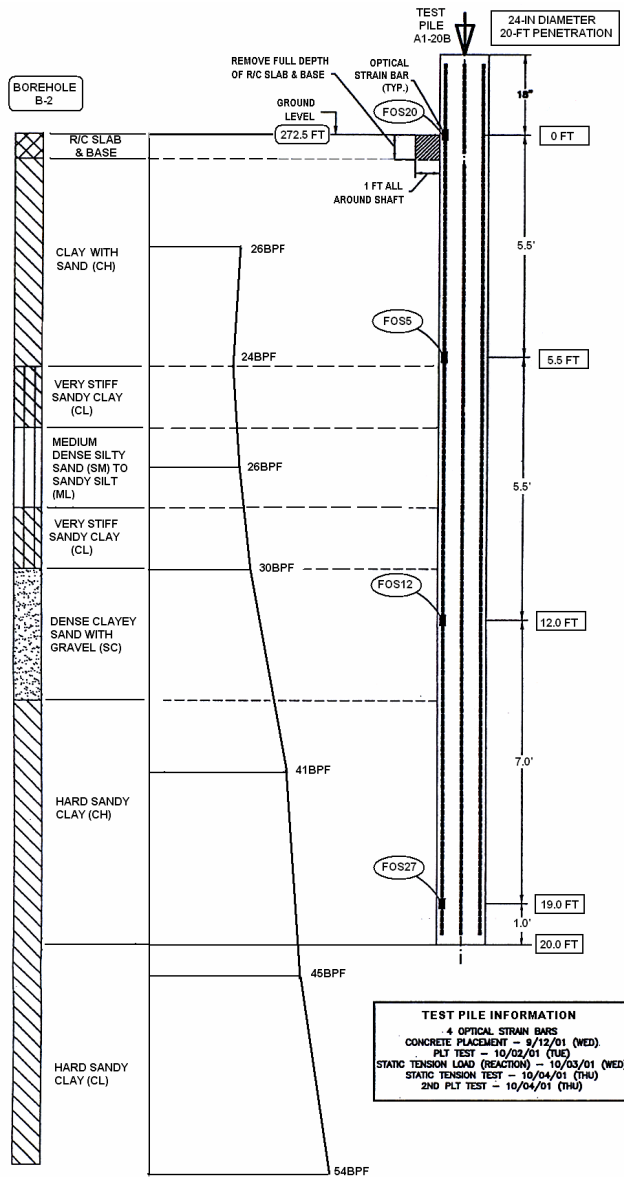
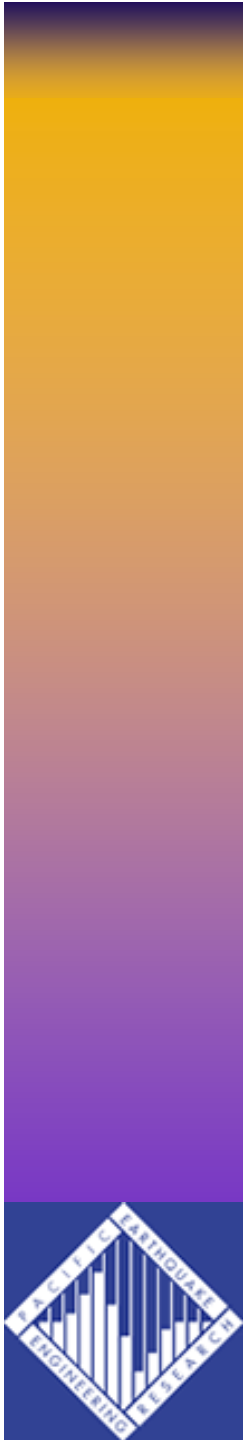
# Dynamic Pier Load Test (PLT)



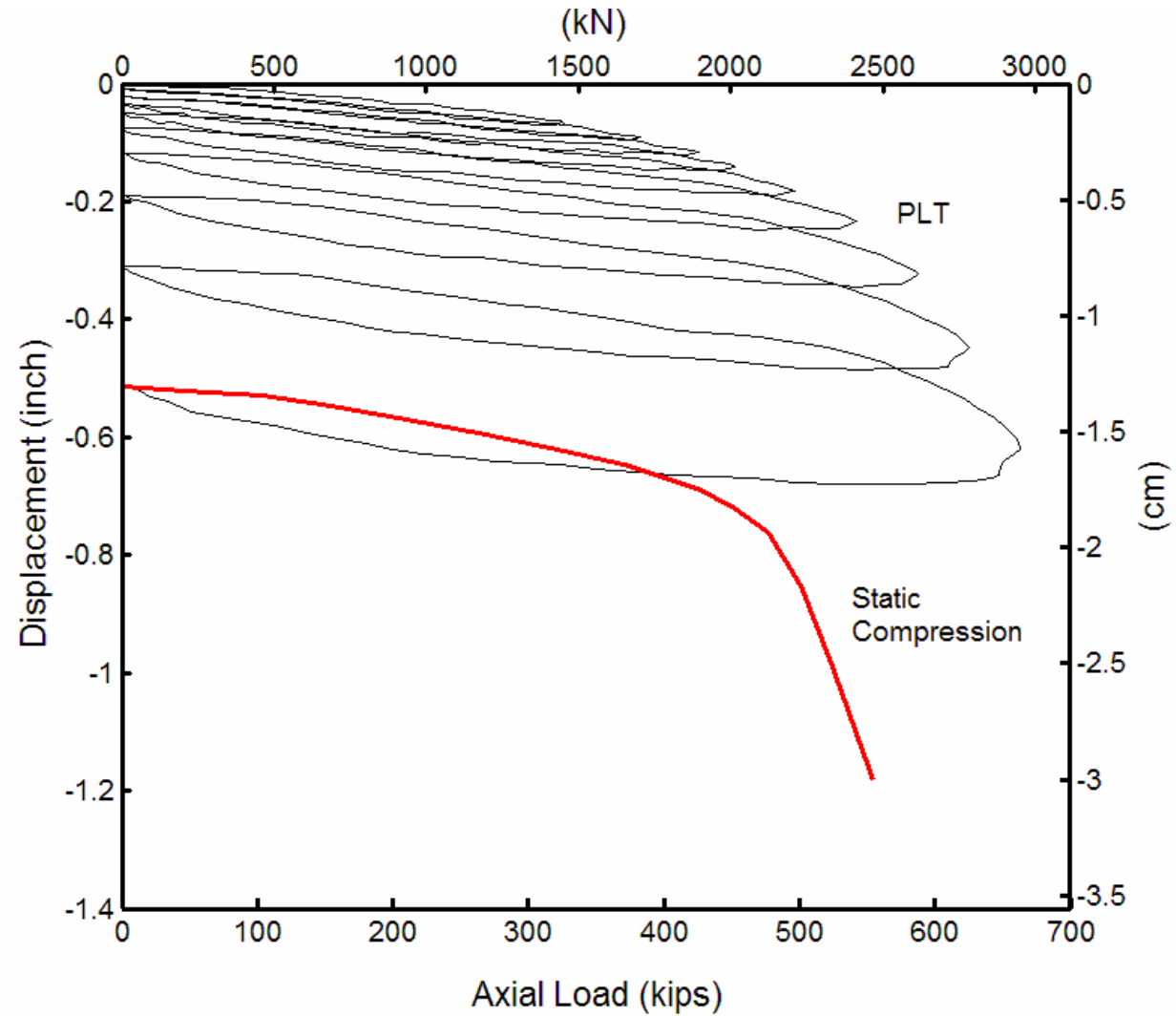
# PLT Test



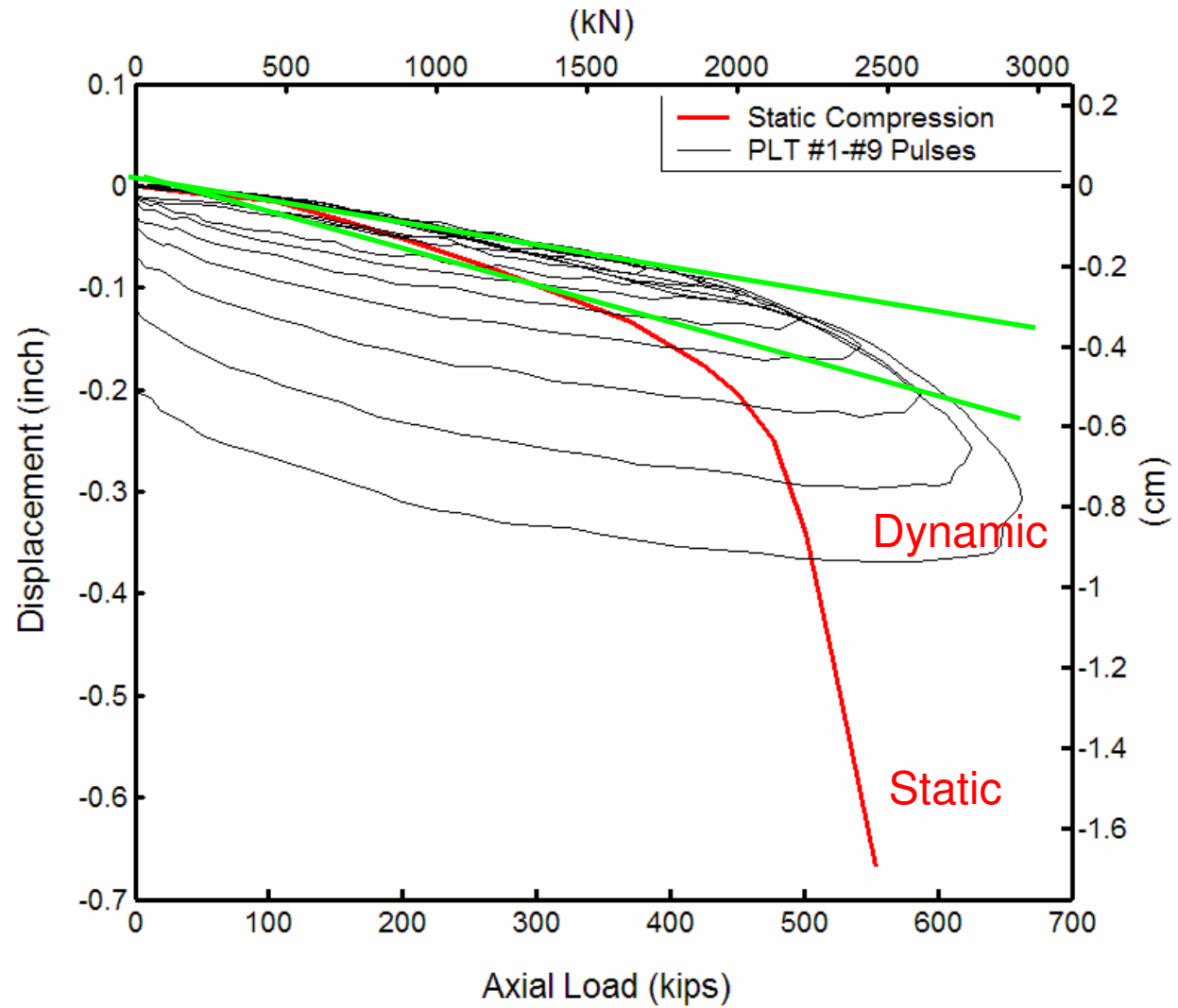




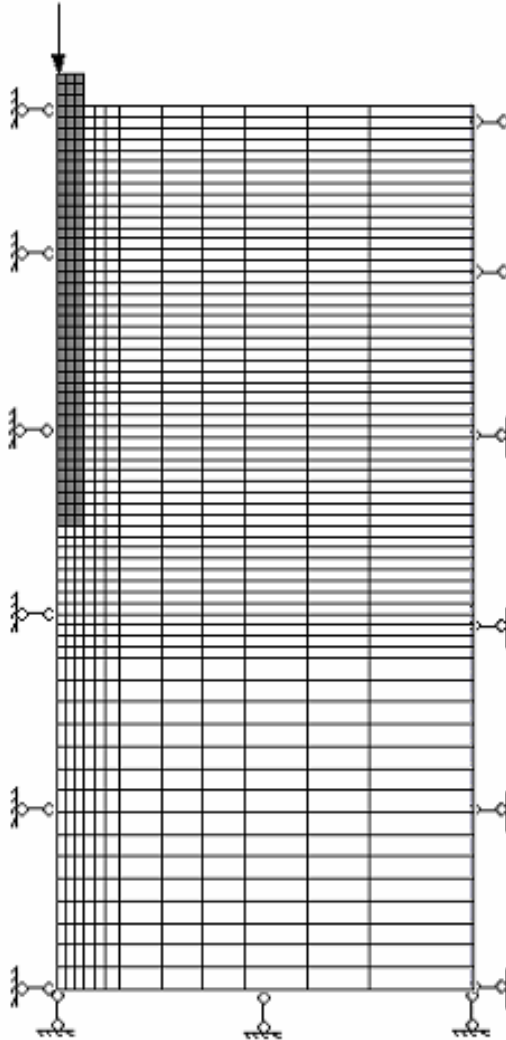
# PLT Test and Static Compression (Pier A1-19)



# Comparison of Dynamic and Static Stiffness

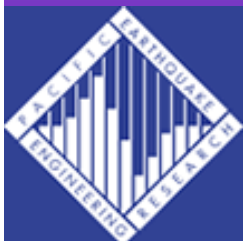
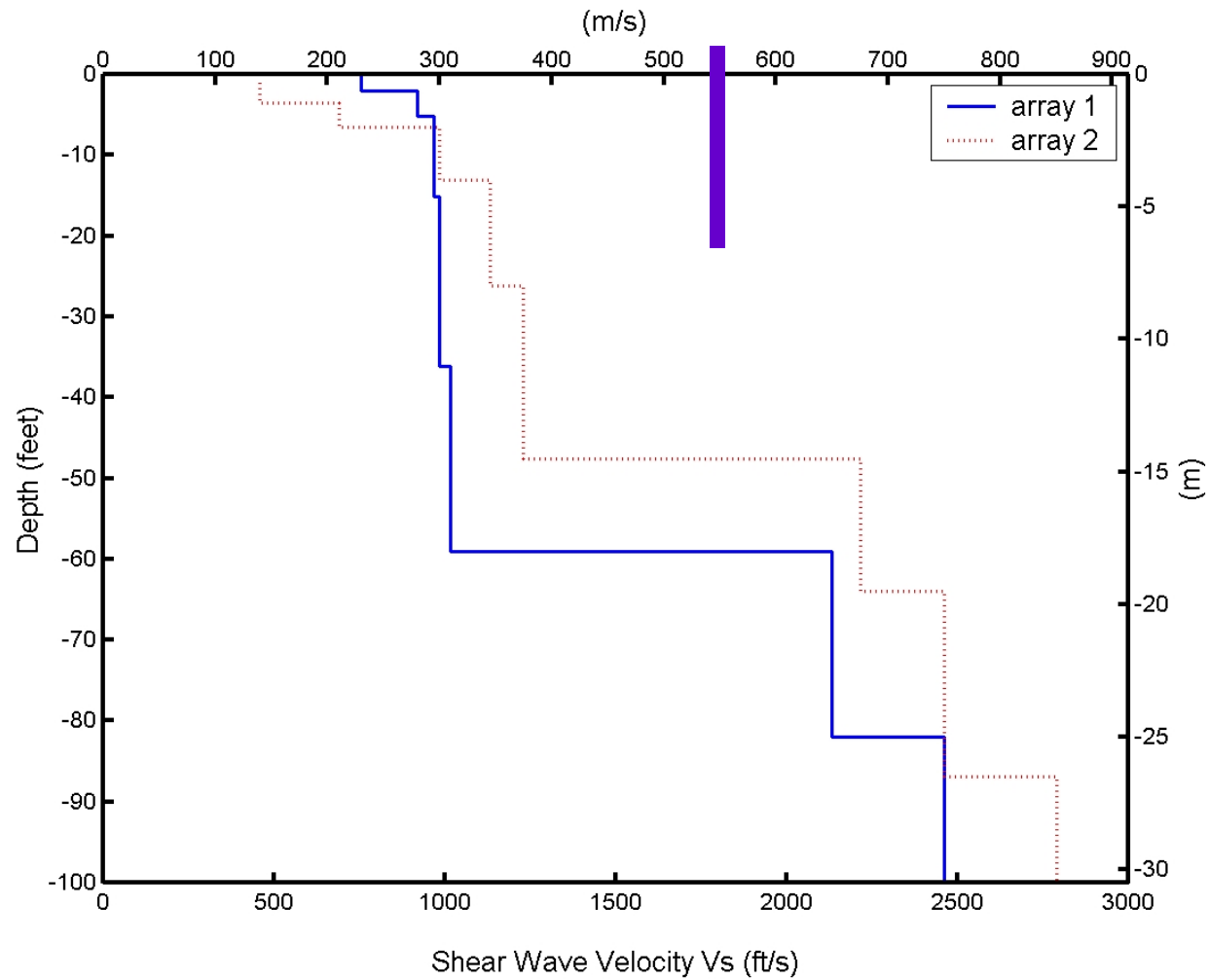


# Axially Loaded Pier in Nonlinear Soil

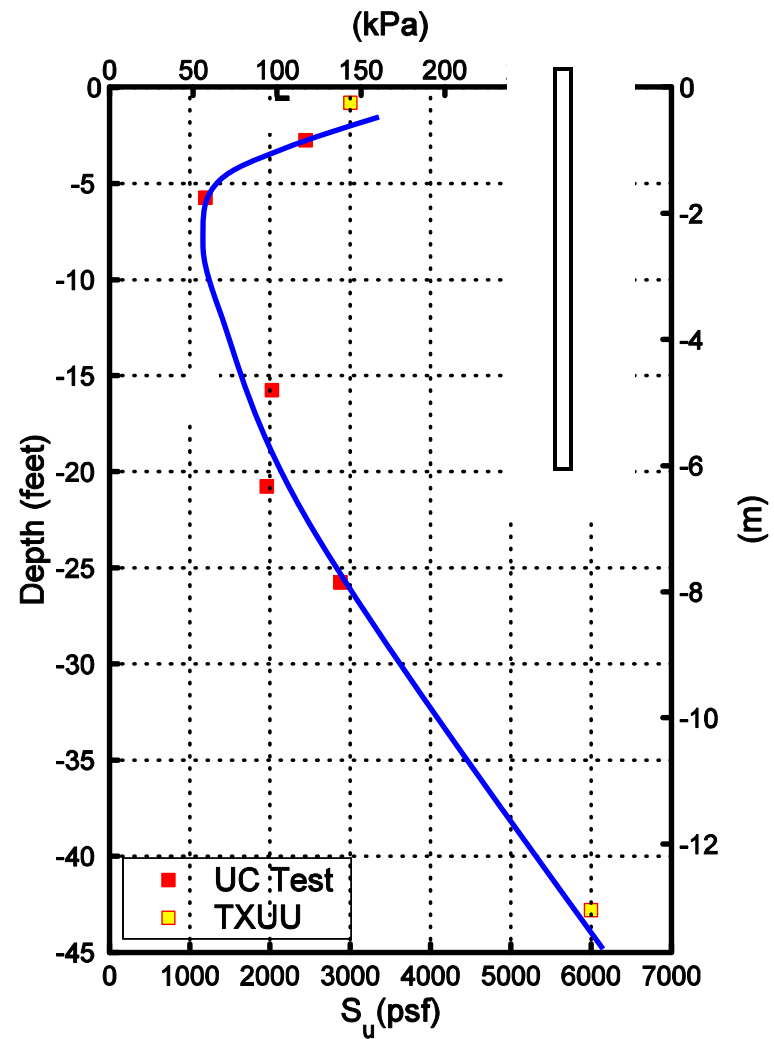




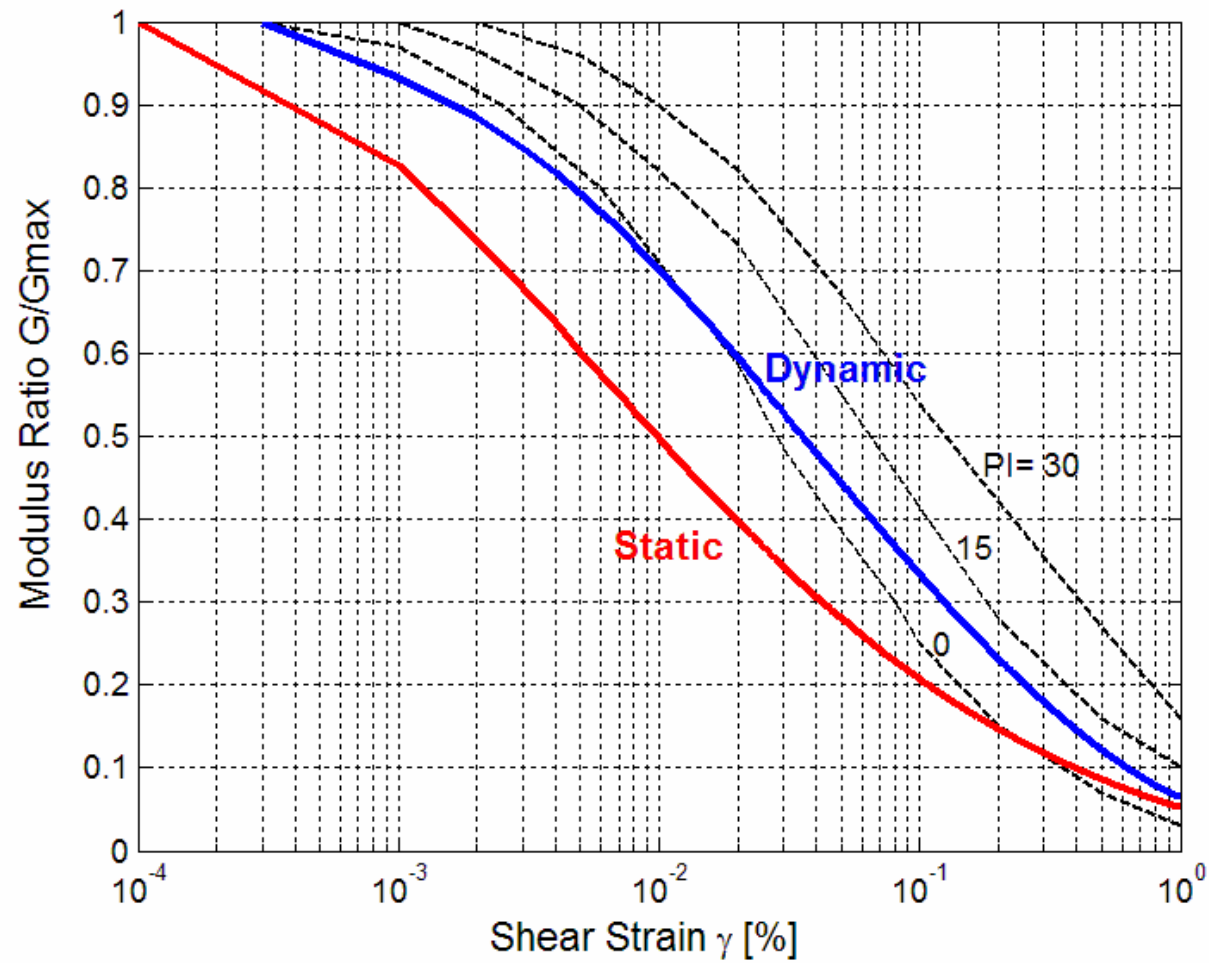
# Shear Wave Velocity Profiles



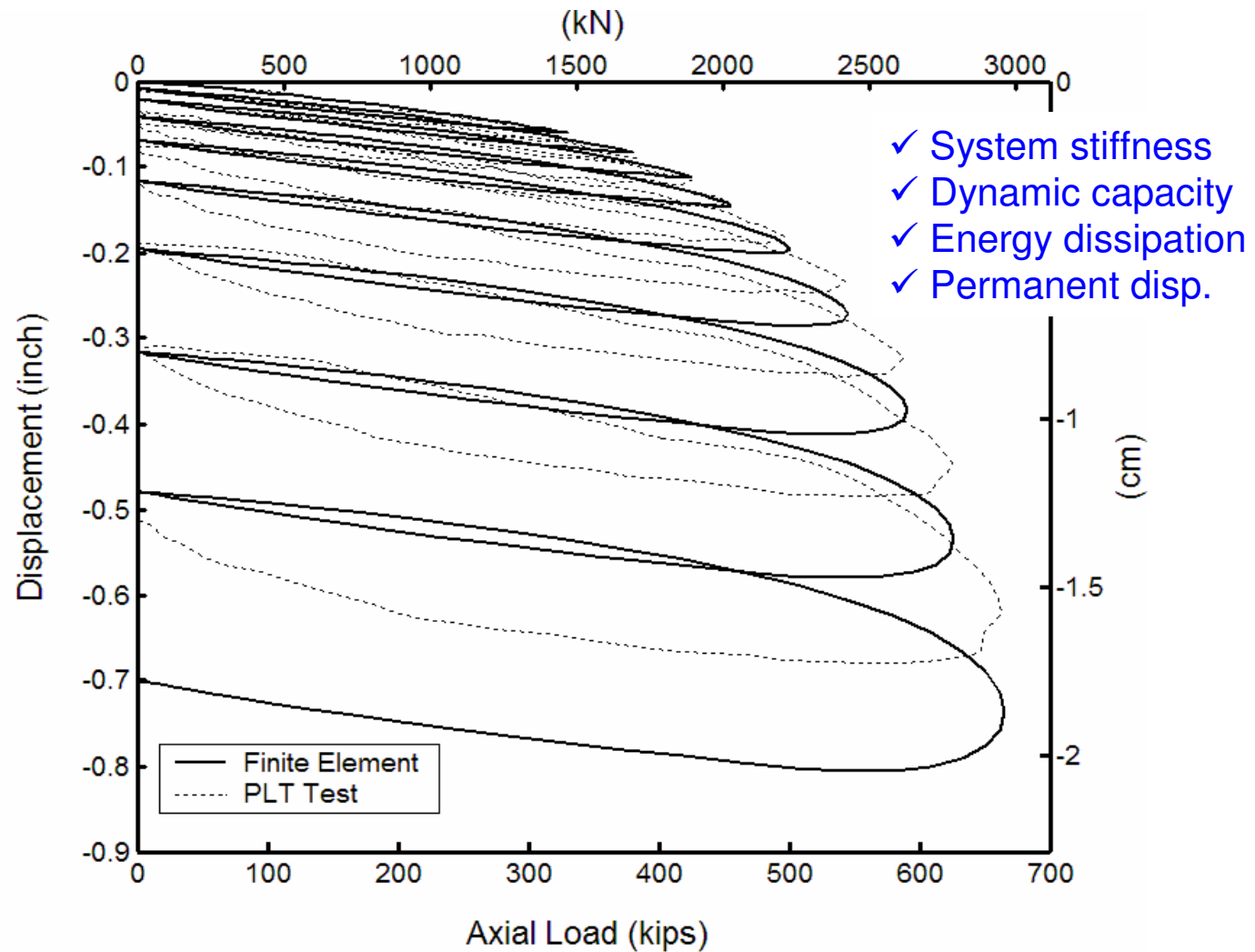
# Undrained Shear Strength Profile



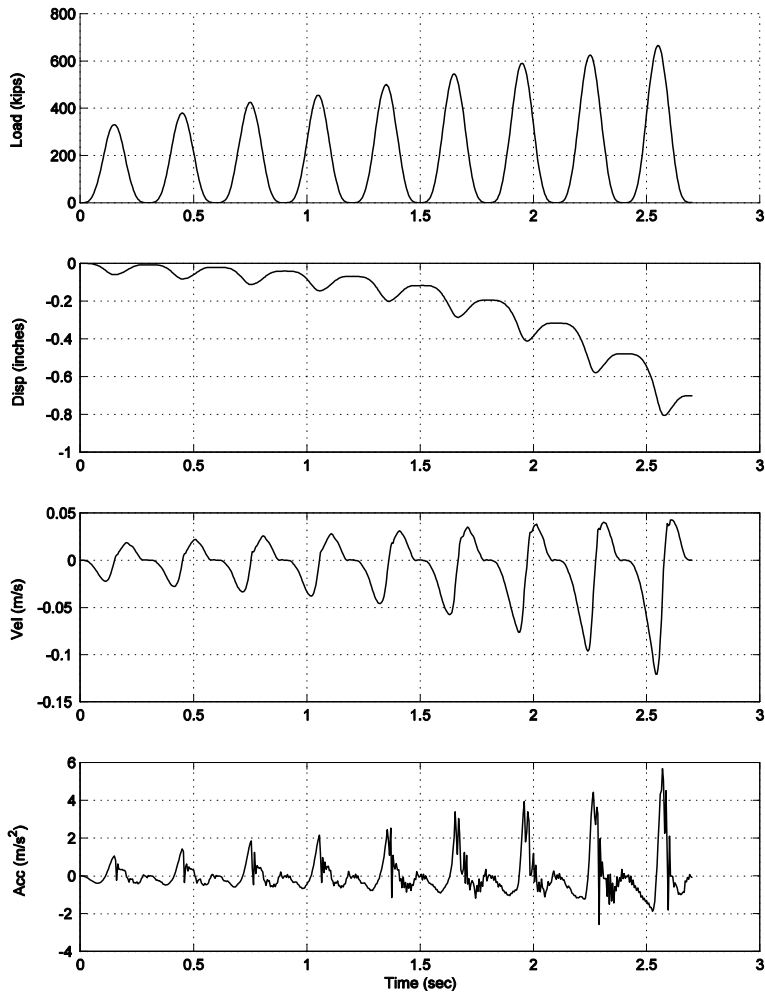
# Modulus Reduction Curves



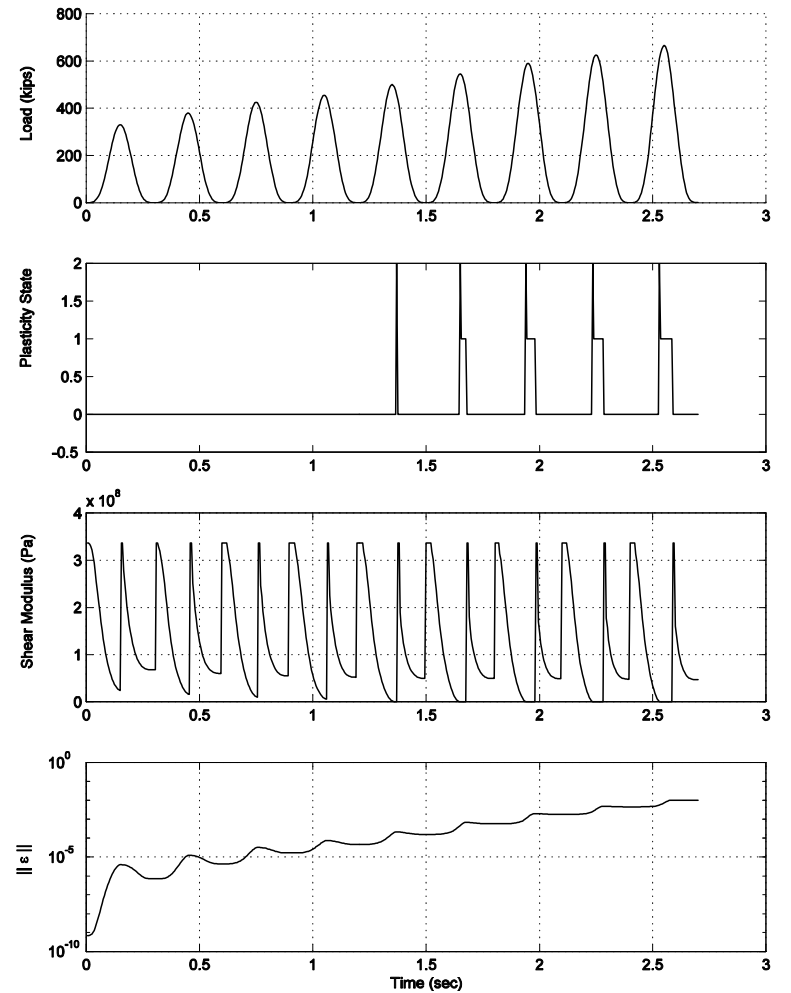
# Finite Element Simulation (Pier A1-19 PLT)



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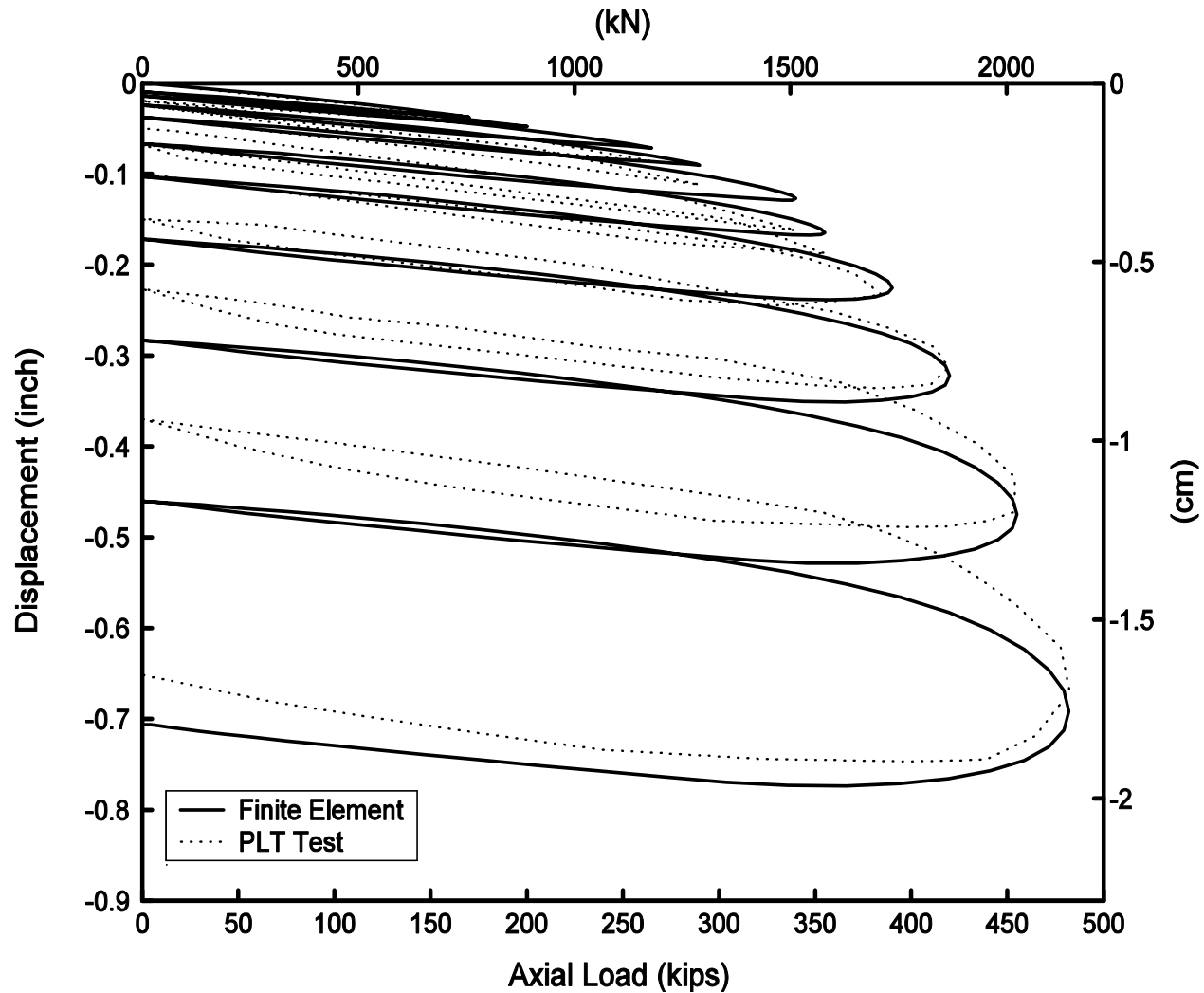
Top Node Reaction



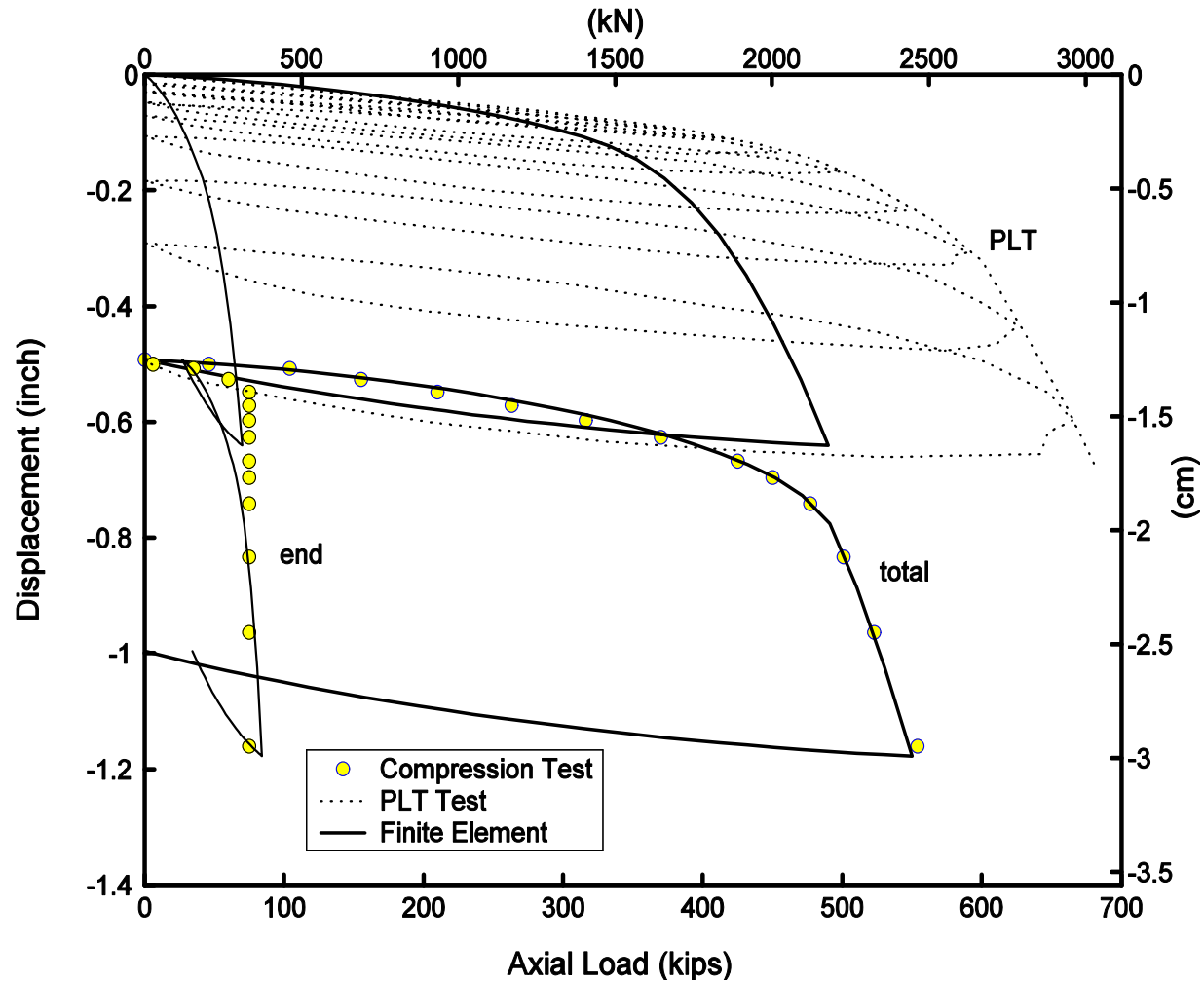
A Sample Element Reaction

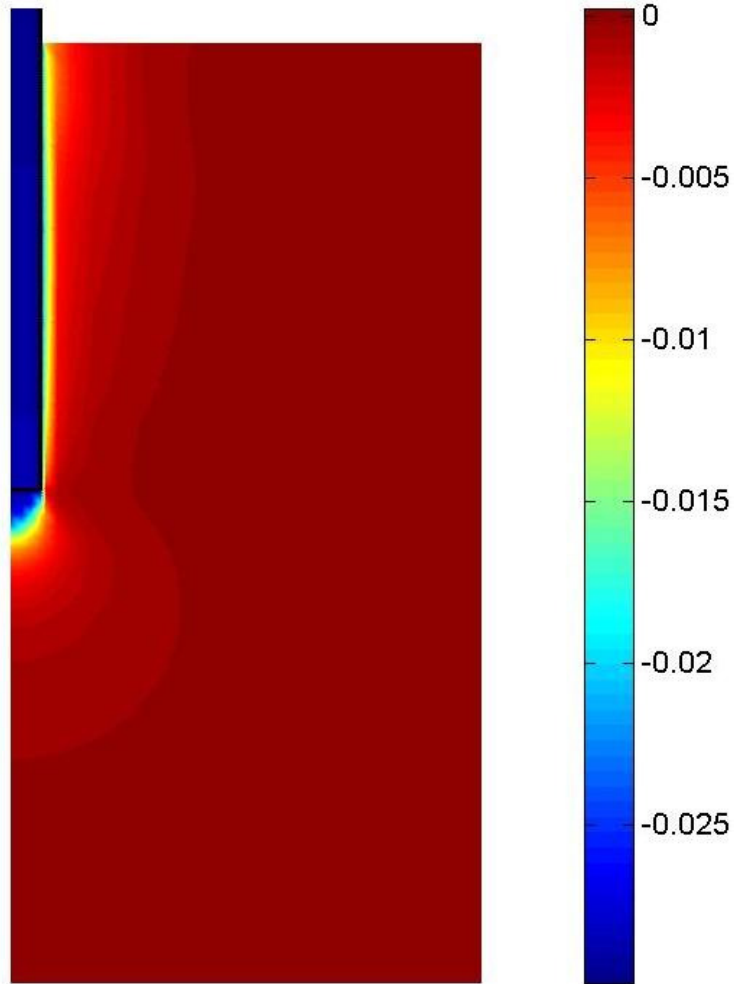
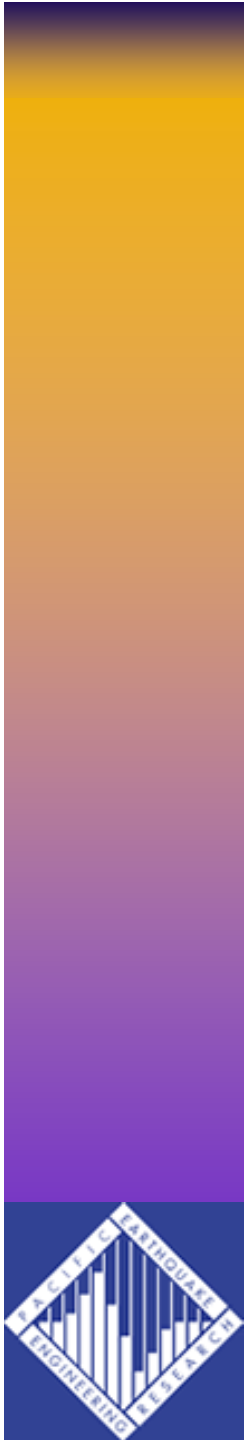


# Finite Element Simulation (Pier A1-20A PLT)

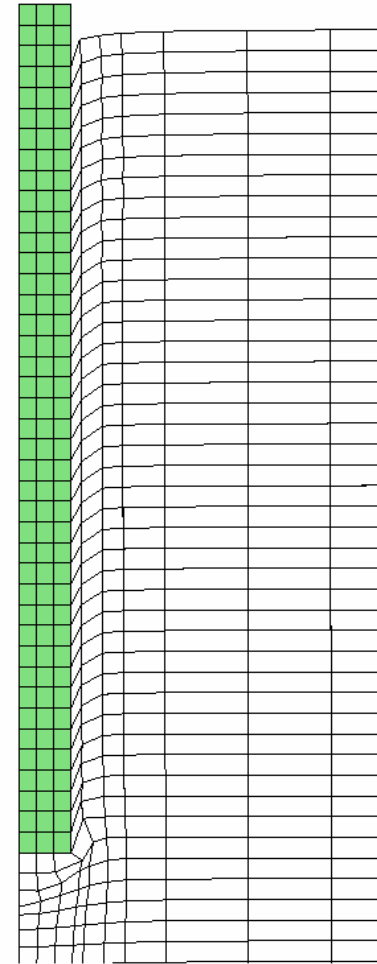


# Finite Element Simulation (Pier A1-19 Static Compression Test After PLT)



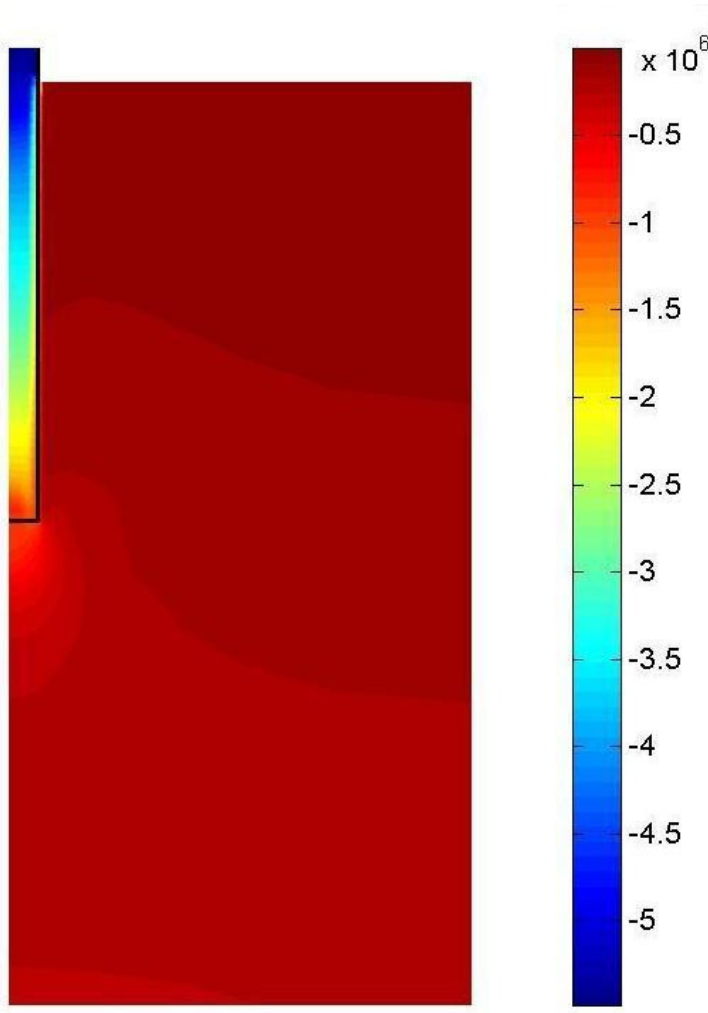
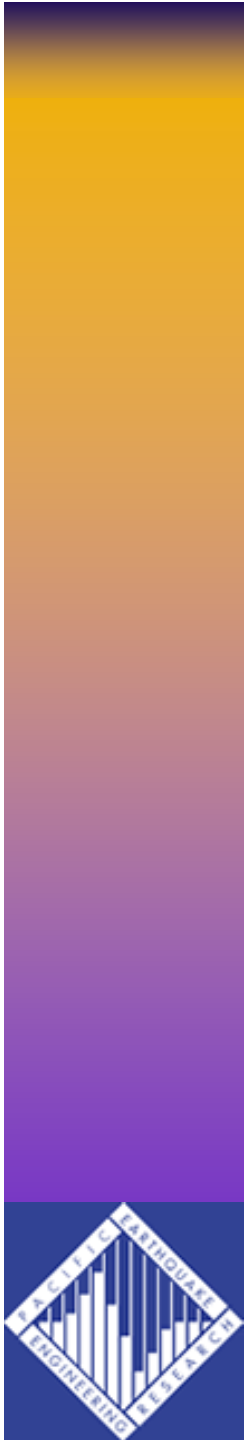


Vertical Displacement Field

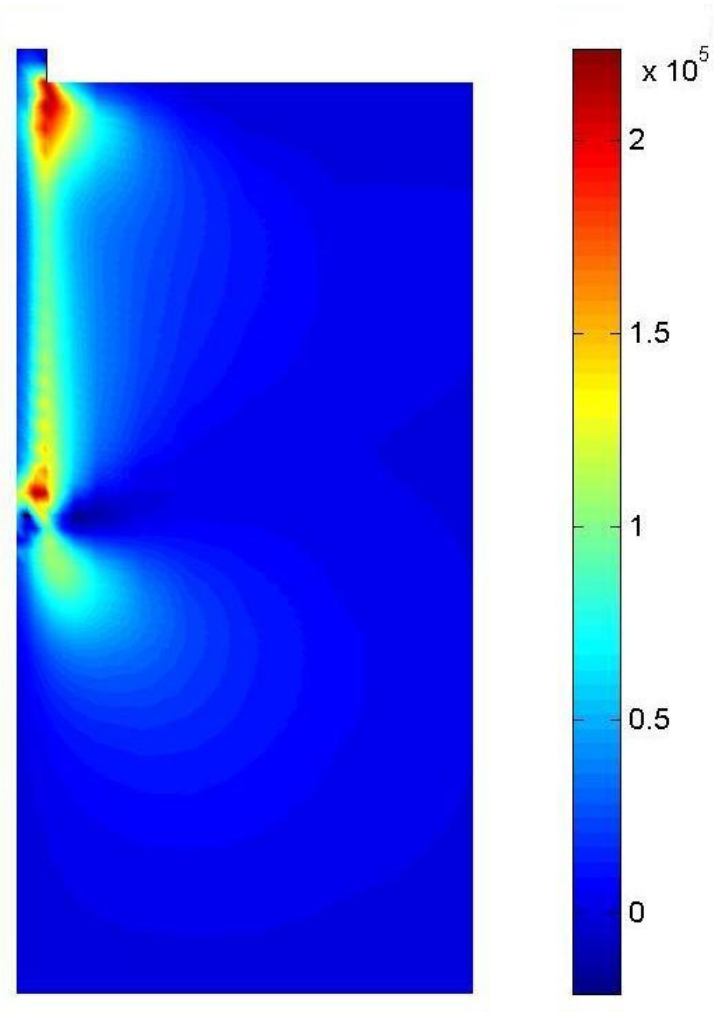


Deformed Mesh ( $\times 10$ )





Vertical Stress Field



Shear Stress Field

## SUMMARY

- The nonlinear finite element and cyclic soil model we developed has successfully captured the pier-soil system stiffness, capacity and energy dissipation for the dynamic and static loadings.
- The nonlinear cyclic soil model has been implemented in OpenSees, and it is ready to be used in a three dimensional fully coupled nonlinear soil-structure analysis.

`OpenSees/.../nDMaterial/cyclicSoil/`



# ACKNOWLEDGEMENTS



**PACIFIC EARTHQUAKE  
ENGINEERING RESEARCH  
CENTER (PEER) NSF  
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