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

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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

Shear Wave
Nonlinear Cyclic Soil Response

- Modulus Reduction
- Hysteretic Damping
- Strength
Bounding Surface Cyclic Soil Model (R. Borja) --- Hardening Rule

Constitutive Eqn.

\[ \dot{o} = K \tau \dot{\varepsilon} + 2\mu \left( 1 + \frac{3\mu}{H} \right)^{-1} \dot{\varepsilon}' \]

\[ H' = H_0 \]

\[ H' = h \kappa^m + H_0 \]

\[ \kappa = \frac{\dot{o}' - o'}{o' - o'_0} \]
Bounding Surface Cyclic Soil Model
--- Loading/Unloading Criterion
Bounding Surface Cyclic Soil Model
--- Unloading
Bounding Surface Cyclic Soil Model
--- Hardening of the Bounding Surface
nDMaterial MultiaxialCyclicPlasticity
$matTag$rho$v$G_{max}$Su$Ho$h$m$beta$Ko

- $matTag$: Material ID
- $rho$: Soil density
- $v$: Poisson’s ratio
- $G_{max}$: Small strain shear modulus
- $Su$: Undrained shear strength
- $Ho$: Hardening modulus of bounding surface
- $h$: Exponential hardening parameter
- $m$: Exponential hardening parameter
- $beta$: Integration parameter (0.5)
Parameter Determination

- Material Density

- Elastic Parameters
  
  \[ G_{max} = \rho V_s^2 \]
  
  Vs: shear wave velocity profile

  \[ \nu \]
  
  Poisson’s ratio

- Undrained Shear Strength

  \[ S_u \]

  From Unconfined Compression Test
  
  or SPT correlation

- Hardening Parameters

  \[ h, m \]

  Fit modulus reduction curves

  \[ H_0 \]

  Fit tangential shear modulus at large strain
Fit Modulus Reduction Curves

$G = 1.67 \times 10^5$ KPa

$\nu = 0.49$  $m = 0.8$

$Su = 100$ KPa

$h/G_{max} = 0.3$

$h/G_{max} = 0.7$

$h/G_{max} = 1.0$

$h/G_{max} = 2.0$

$h/G_{max} = 10$

$m = 0.8$

$G = 1.67 \times 10^5$ KPa

$\nu = 0.49$  $h/G_{max} = 0.3$

$Su = 100$ KPa

$\tau$

$\gamma$

$10^{-4}$  $10^{-3}$  $10^{-2}$  $10^{-1}$  $10^0$

$0.1$  $0.2$  $0.3$  $0.4$  $0.5$  $0.6$  $0.7$  $0.8$  $0.9$  $1.0$

$1.5 \times 10^5$

$10^{-0.01}$  $10^{-0.005}$  $0.005$  $0.01$

$-1.5$  $-1$  $-0.5$  $0.5$  $1$  $1.5$

OPENSEES DEVELOPER SYMPOSIUM
Dynamic Pier Load Test (PLT)
PLT Test

- Force Pile head Disp.
- PLT Test
- Spring
- Pile head Disp.
- Load Cell
- Pile
- time

OPENSEES DEVELOPER SYMPOSIUM
PLT Test and Static Compression (Pier A1-19)
Comparison of Dynamic and Static Stiffness

![Graph showing comparison between dynamic and static stiffness](image)

- **Static**
- **Dynamic**

Axial Load (kips) vs. Displacement (inch)
Axially Loaded Pier in Nonlinear Soil
Shear Wave Velocity Profiles
Undrained Shear Strength Profile
Modulus Reduction Curves

![](image)

- **Modulus Ratio G/Gmax**
- **Shear Strain \( \gamma \) [%]

- Static
- Dynamic

- \( P_l = 30 \)
- \( P_l = 15 \)
- \( P_l = 0 \)
Finite Element Simulation (Pier A1-19 PLT)

- System stiffness
- Dynamic capacity
- Energy dissipation
- Permanent disp.

Displacement (inch) vs. Axial Load (kips) graph with markers for Finite Element and PLT Test.
Finite Element Simulation (Pier A1-19 PLT)

Top Node Reaction

A Sample Element Reaction
Finite Element Simulation (Pier A1-20A PLT)

Displacement (inch) vs. Axial Load (kips)
Finite Element Simulation (Pier A1-19 Static Compression Test After PLT)
Vertical Displacement Field

Deformed Mesh (× 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/
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OPENSEES -- OPEN SYSTEM FOR EARTHQUAKE ENGINEERING SIMULATION
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