

OpenSeesPL – 3D Pile-Ground Interaction

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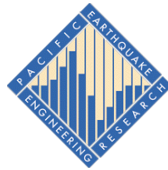
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Zhaohui Yang

Thomas Shantz

September 3, 2010

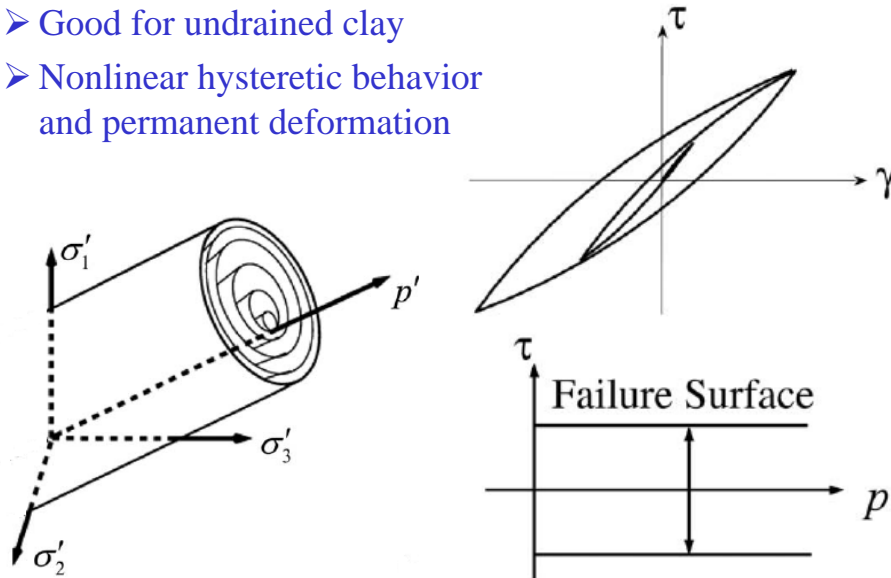


Outline

- Soil constitutive models
- Solid-fluid fully-coupled elements
- OpenSeesPL graphical user interface
- Examples of using OpenSeesPL
- Ongoing research projects

Pressure-Independent Material

- Good for undrained clay
- Nonlinear hysteretic behavior and permanent deformation



PressureIndependentMultiYield

```

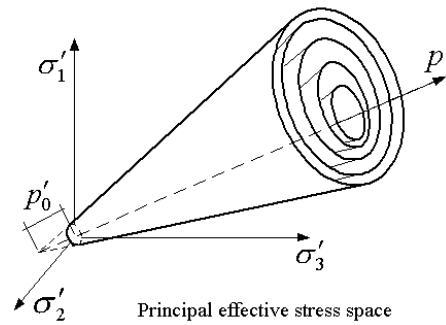
nDmaterial PressureIndependentMultiYield $tag $nd $rho $refShearModul
$refBulkModul $cohesi $peakShearStra <$frictionAng=0. $refPress=100.
$pressDependCoe=0. $noYieldSurf=20 <$r1 $Gs1 ...> >
    
```

Suggested parameter values:

	Soft Clay	Medium Clay	Stiff Clay
<i>rho</i>	1.3 ton/m ³ or 1.217x10 ⁻⁴ (lbf)(s ²)/in ⁴	1.5 ton/m ³ or 1.404x10 ⁻⁴ (lbf)(s ²)/in ⁴	1.8 ton/m ³ or 1.685x10 ⁻⁴ (lbf)(s ²)/in ⁴
<i>refShearModul</i>	1.3x10 ⁴ kPa or 1.885x10 ³ psi	6.0x10 ⁴ kPa or 8.702x10 ³ psi	1.5x10 ⁵ kPa or 2.176x10 ⁴ psi
<i>refBulkModul</i>	6.5x10 ⁴ kPa or 9.427x10 ³ psi	3.0x10 ⁵ kPa or 4.351x10 ⁴ psi	7.5x10 ⁵ kPa or 1.088x10 ⁵ psi
<i>cohesi</i>	18 kPa or 2.611 psi	37 kPa or 5.366 psi	75 kPa or 10.878 psi
<i>peakShearStra</i>	0.1	0.1	0.1

Pressure-Dependent Material

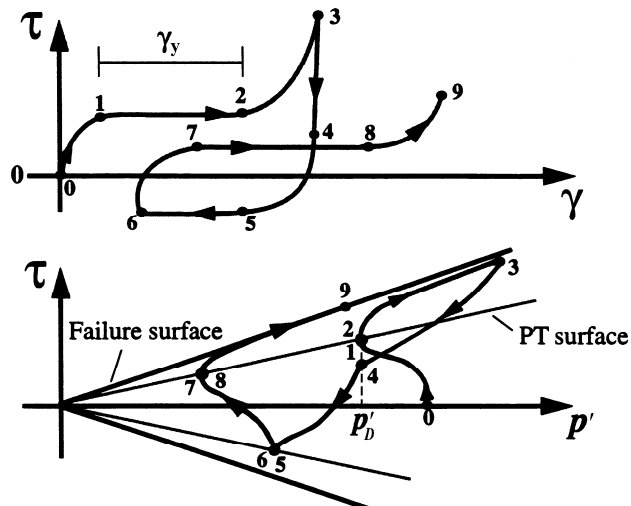
- Multi-yield surface plasticity model (based on Prevost 1985)



Conical yield surfaces for granular soils (Prevost 1985; Elgamal et al. 2003; Yang and Elgamal 2008)

Pressure-Dependent Material (cont)

- Incorporating dilatancy and cyclic mobility effects



Shear stress-strain and effective stress path under undrained shear loading condition (Parra 1996, Yang 2000, Yang and Elgamal 2002)

PressureDependMultiYield

```
nDMaterial PressureDependMultiYield $tag $nd $rho $refShearModul
$refBulkModul $frictionAng $peakShearStra $refPress
$pressDependCoe $PTAng $contrac $dilat1 $dilat2 $liquefac1
$liquefac2 $liquefac3 <$noYieldSurf=20 <$r1 $Gs1 ...> $e=0.6 $cs1=0.9
$cs2=0.02 $cs3=0.7 $pa=101 <$c=0.3>>
```

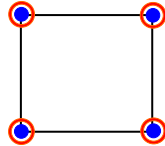
Suggested parameter values:

	Loose Sand (15%-35%)	Medium Sand (35%-65%)	Medium-dense Sand (65%-85%)	Dense Sand (85%-100%)
<i>rho</i>	1.7 ton/m ³ or 1.59x10 ⁻⁴ (lbf)(s ²)/in ⁴	1.9 ton/m ³ or 1.778x10 ⁻⁴ (lbf)(s ²)/in ⁴	2.0 ton/m ³ or 1.872x10 ⁻⁴ (lbf)(s ²)/in ⁴	2.1 ton/m ³ or 1.965x10 ⁻⁴ (lbf)(s ²)/in ⁴
<i>refShearModul</i> (at <i>p'_r</i> =80 kPa or 11.6 psi)	5.5x10 ⁴ kPa or 7.977x10 ³ psi	7.5x10 ⁴ kPa or 1.088x10 ⁴ psi	1.0x10 ⁵ kPa or 1.45x10 ⁴ psi	1.3x10 ⁵ kPa or 1.885x10 ⁴ psi
<i>refBulkModu</i> (at <i>p'_r</i> =80 kPa)	1.5x10 ⁵ kPa or 2.176x10 ⁴ psi	2.0x10 ⁵ kPa or 2.9x10 ⁴ psi	3.0x10 ⁵ kPa or 4.351x10 ⁴ psi	3.9x10 ⁵ kPa or 5.656x10 ⁴ psi
<i>frictionAng</i>	29	33	37	40
<i>peakShearStra</i> (at <i>p'_r</i> =80 kPa)	0.1	0.1	0.1	0.1

Solid-Fluid Fully-Coupled Elements (*u-p* formulation)

- quadUP
- 9_4_QuadUP
- brickUP
- 20_8_BrickUP

2D Solid-Fluid Coupled Element



- Solid nodes: describe the solid translational degrees of freedom
- Fluid nodes: describe the fluid pressure

quadUP

```
element quadUP $eleTag $iNode $jNode $kNode $lNode $thick $matTag
$bulk $fmass $hPerm $vPerm <$b1=0 $b2=0 $t=0>
```

Recorder examples:

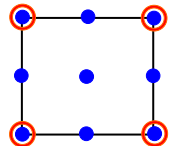
Pore water pressure:

```
recorder Node <-file $fileName> <-time> <-node ($nod1 $nod2 ...)> -dof 3 vel
```

Stress:

```
recorder Element <-file $fileName> <-time> <-ele ($ele1 $ele2 ...)> material 1 stress
```

2D Solid-Fluid Coupled Element



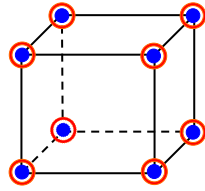
- Solid nodes: describe the solid translational degrees of freedom
- Fluid nodes: describe the fluid pressure

9_4_quadUP

```
element 9_4_QuadUP $eleTag $Node1 $Node2 $Node3 $Node4 $Node5
$Node6 $Node7 $Node8 $Node9 $thick $matTag $bulk $fmass $hPerm
$vPerm <$b1=0 $b2=0>
```

- Recommended to ensure numerical stability in case of liquefaction analyses (Babuska-Brezzi condition)

3D Solid-Fluid Coupled Brick Element

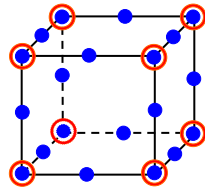


brickUP

- Solid nodes: describe the solid translational degrees of freedom
- Fluid nodes: describe the fluid pressure

```
element brickUP $eleTag $Node1 $Node2 $Node3 $Node4 $Node5
$Node6 $Node7 $Node8 $matTag $bulk $fmass $PermX $PermY
$PermZ <$bX=0 $bY=0 $bZ=0>
```

3D Solid-Fluid Coupled Brick Element



20_8_BrickUP

- Solid nodes: describe the solid translational degrees of freedom
- Fluid nodes: describe the fluid pressure

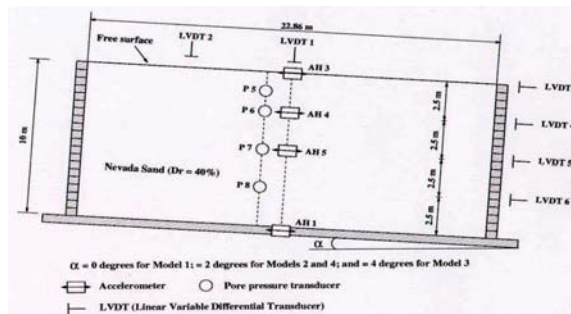
```
element 20_8_BrickUP $eleTag $Node1 ... $Node20 $matTag $bulk
$fmass $PermX $PermY $PermZ <$bX=0 $bY=0 $bZ=0>
```

- 20-node element is recommended to ensure numerical stability in case of liquefaction analyses (Babuska-Brezzi condition)

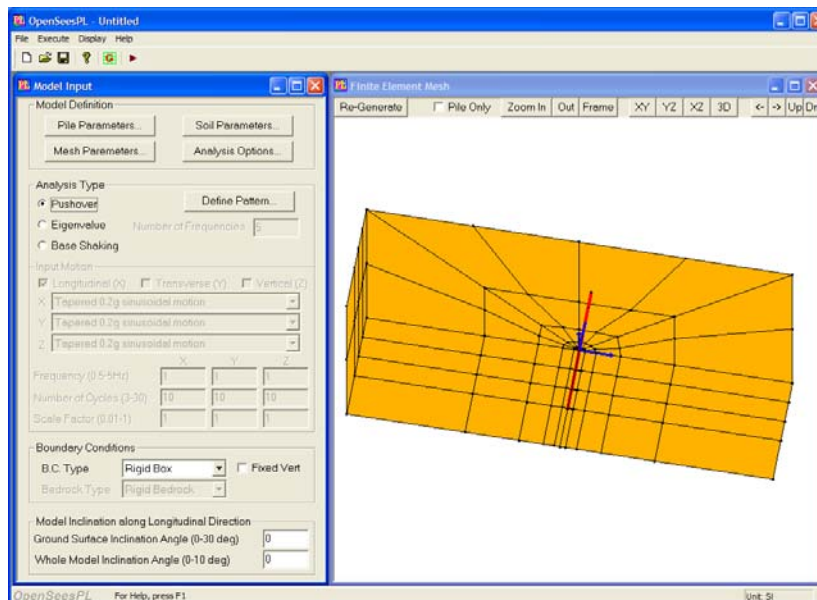
Soil Model Calibration

- The pressure-dependent material model has been extensively calibrated for clean Nevada Sand at $D_r \approx 40\%$ (Parra 1996; Yang 2000)
- Calibration was based on results of:
 - Monotonic and cyclic laboratory tests (Arulmoli et al. 1992)
 - Centrifuge experiments (VELACS Models 1 & 2, Dobry et al. 1995; Taboada 1995)

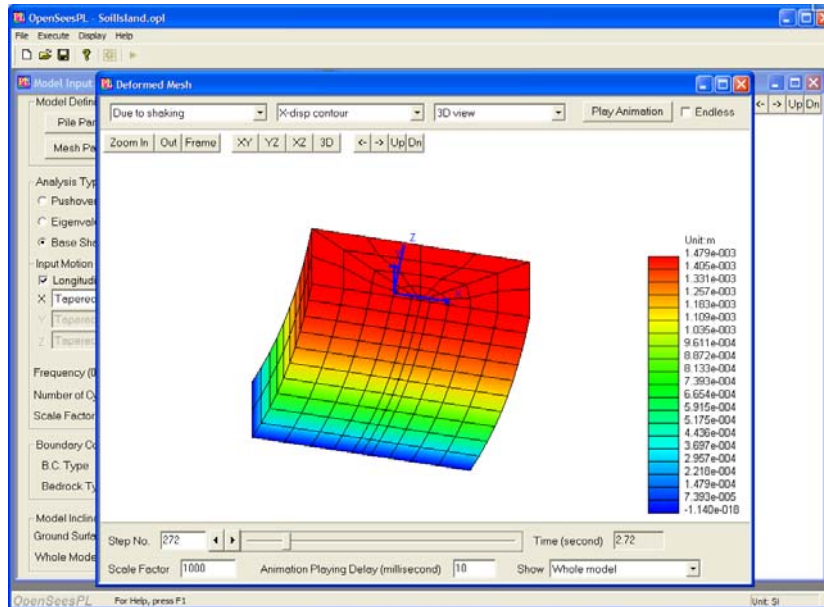
VELACS Models



OpenSeesPL Graphical User Interface



“Soil Island” (Soil Strata Only)



List of Soil Types

Soil	Thickness [m]	Soil Type	Residual Shear Strength [kPa]	P	L	C
1:	10	22: U-Clay2 (PressureIndependentMultiYield)...	0.2	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2:	0	1: Sat. cohesionless very loose, silt permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3:	0	2: Sat. cohesionless very loose, sand permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
4:	0	3: Sat. cohesionless very loose, gravel permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5:	0	4: Sat. cohesionless loose, silt permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
6:	0	5: Sat. cohesionless loose, sand permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
7:	0	6: Sat. cohesionless loose, gravel permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
8:	0	7: Sat. cohesionless medium, silt permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
9:	0	8: Sat. cohesionless medium, sand permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
10:	0	9: Sat. cohesionless medium, gravel permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		10: Sat. cohesionless medium-dense, silt permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		11: Sat. cohesionless medium-dense, sand permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		12: Sat. cohesionless medium-dense, gravel permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		13: Sat. cohesionless dense, silt permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		14: Sat. cohesionless dense, sand permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		15: Sat. cohesionless dense, gravel permeability	0.2	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		16: Cohesive soft		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		17: Cohesive medium		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		18: Cohesive stiff		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		19: U-Sand1A (PressureDependMultiYield)...		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		20: U-Sand1B (PressureDependMultiYield)...		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		21: U-Clay1 (PressureIndependentMultiYield)...		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		22: U-Clay2 (PressureIndependentMultiYield)...		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		23: U-Sand2A (PressureDependMultiYield02)...		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
		24: U-Sand2B (PressureDependMultiYield02)...		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Saturated Soil Analysis

Activate Pile Zone Material

Activate Pile-Soil Interface

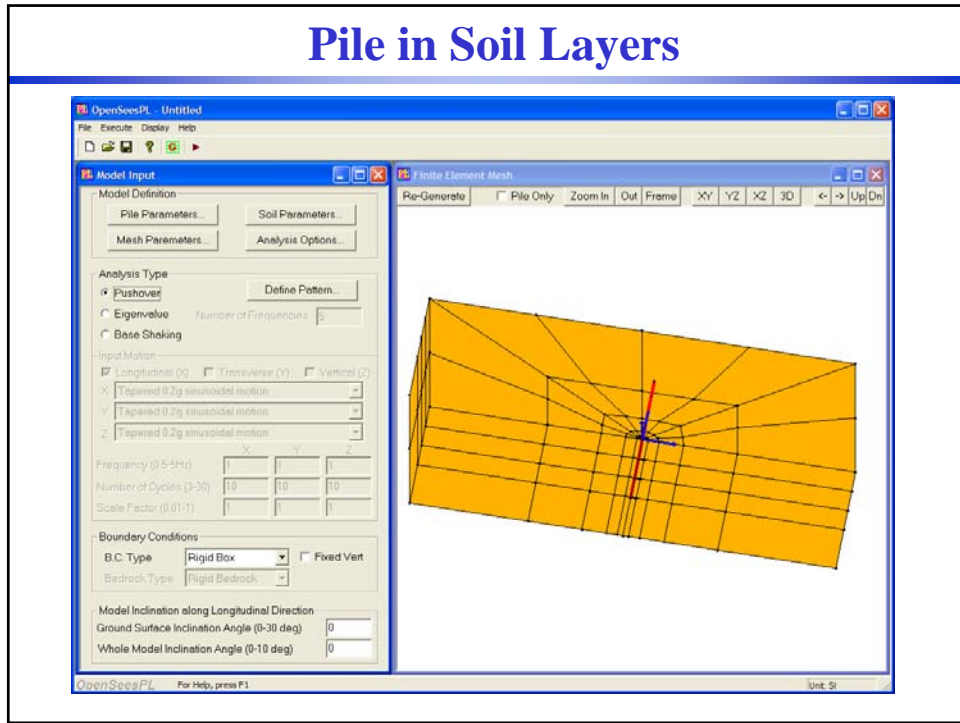
Activate Outermost Zone

Activate Tension Cutoff for Cohesive Soil

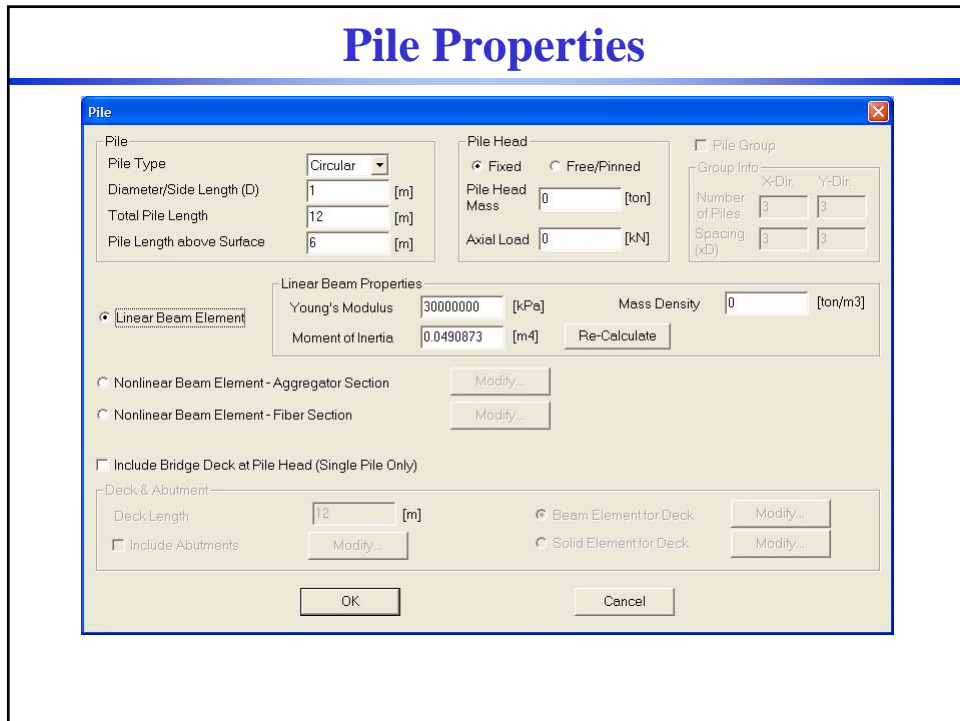
Note: P, L and C represents Parabolic, Linear increasing and Constant variation of soil modulus with depth, respectively.

OK Cancel

Pile in Soil Layers



Pile Properties



Pushover Analysis

Pushover

Type

- Monotonic Pushover
- Cyclic Pushover (Sine Wave)
Frequency (Hz) []
- U-Push [Define U-Push...]

Method

- Force-Based Method
- Displacement-Based Method

OK Cancel

Force Increment (Per Step)

Logitudinal (X) Force [1] [kN]
Transverse (Y) Force [0] [kN]
Vertical (Z) Force [0] [kN]
Moment of X [0] [kN-m]
Moment of Y [0] [kN-m]
Moment of Z [0] [kN-m]

Displacement Increment (Per Step)

Longitudinal Displacement [0.01] [m]
Transverse Displacement [0] [m]
Vertical Displacement [0] [m]
Rotation around X [0] [rad]
Rotation around Y [0] [rad]
Rotation around Z [0] [rad]

Surface Load Applied at Pile Zone (Ground Surface Level) (Per Step)

Logitudinal (X) [0] Transverse (Y) [0] Vertical (Z) [0] [kPa]

Time

- Static Pushover Number of Steps [20]
- Dynamic Pushover Time [] [sec] Time Step [0.01] [sec]

Applied Location

- Pile Head
- Shear Beam

Applied Range/Height (Starting from Surface) [0] [m]

Mesh Generation

Mesh

General Definition

- Horizontal Meshing
 - Single Pile
 - Pile Group
- Vertical Meshing
- Mesh Scaling

General Definition

Mesh Scale [Half mesh]

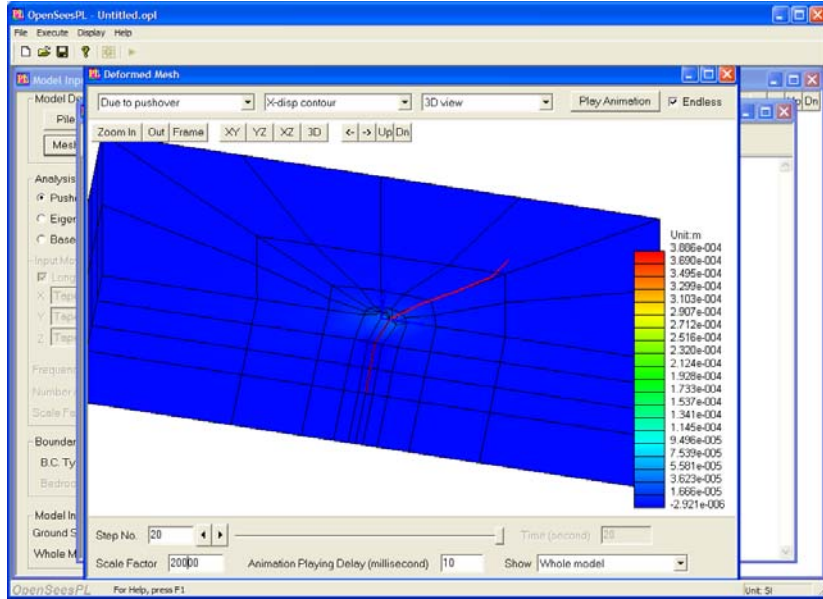
Pile

Num of Slices [16]

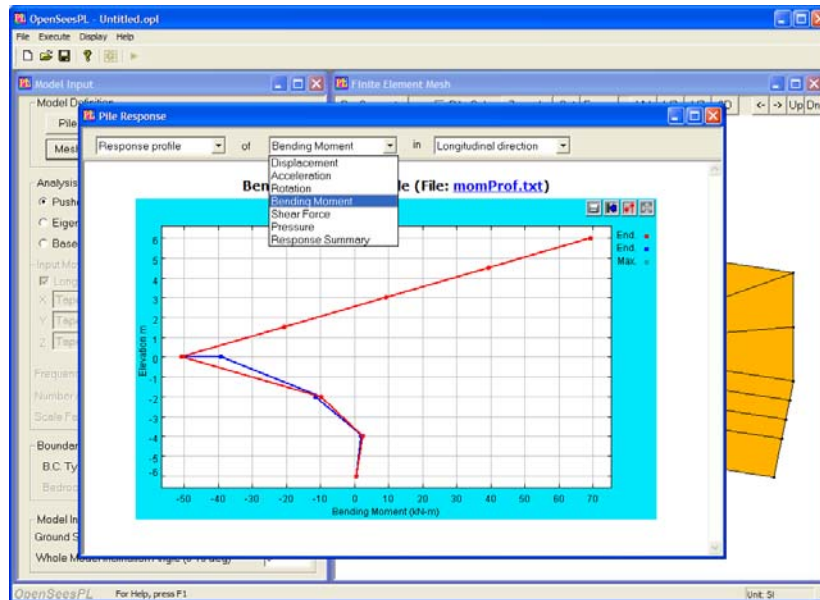
Number of Beam Elements for Pile Section Above Ground Surface: [4]

OK Cancel Apply

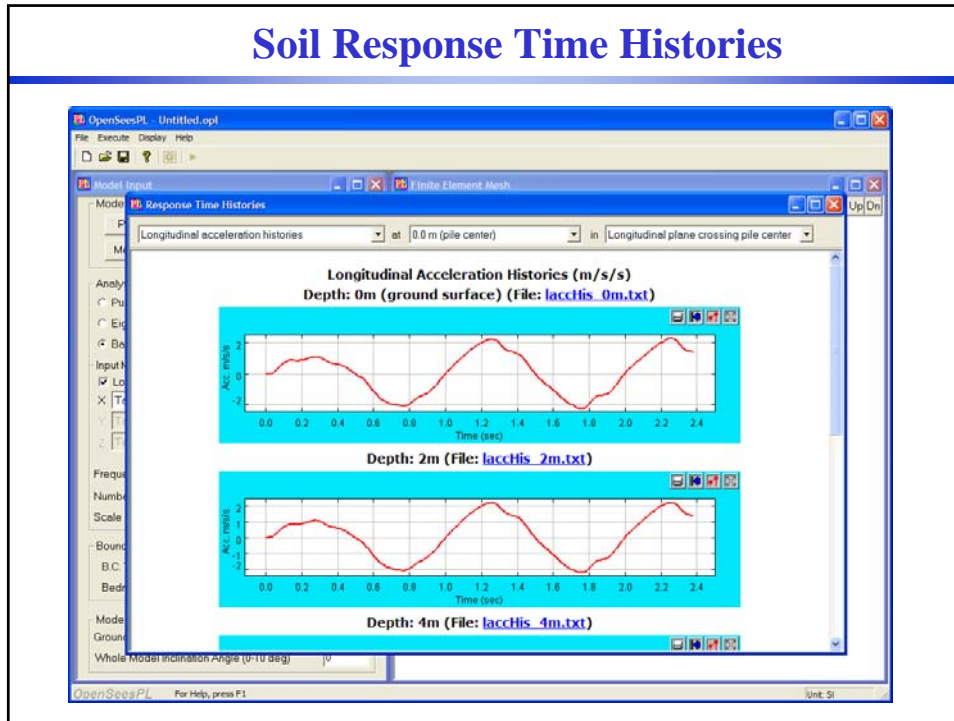
Deformed Mesh



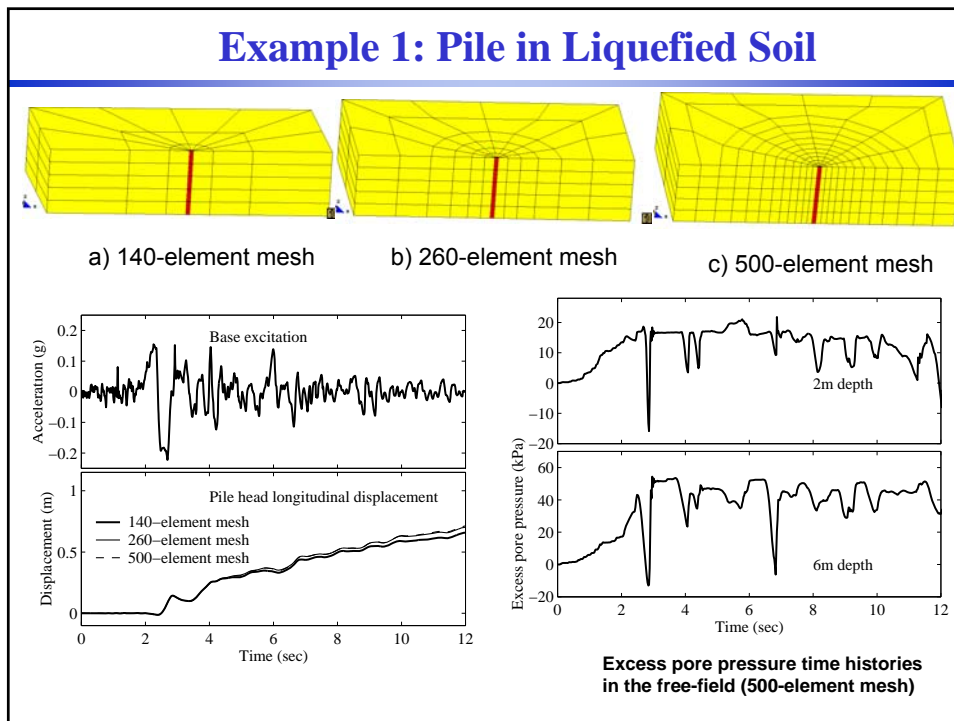
Pile Response Profiles & Time Histories



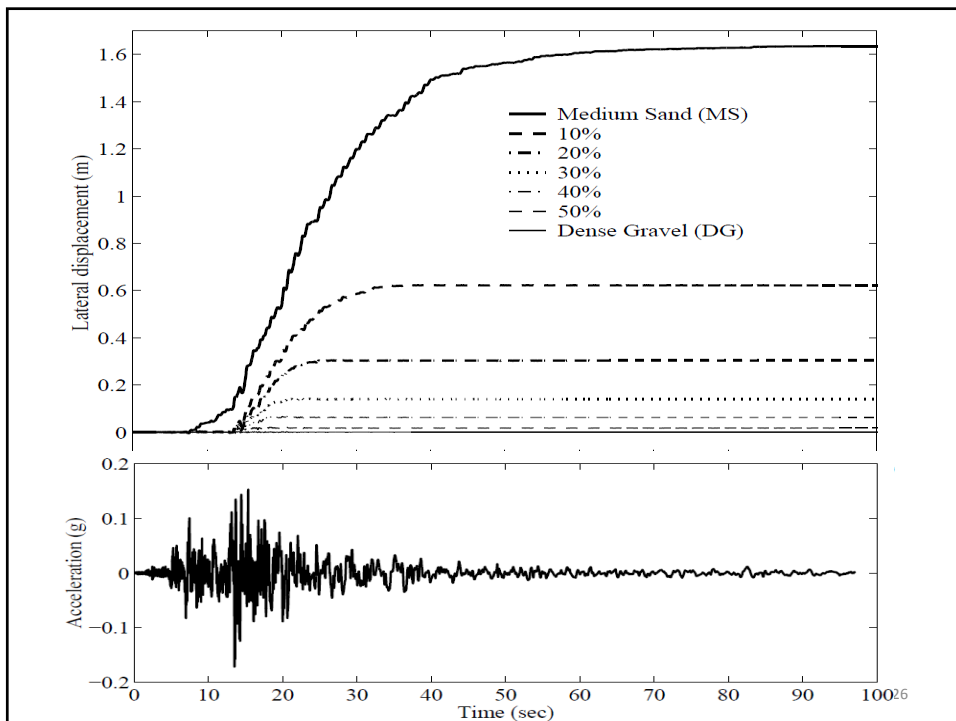
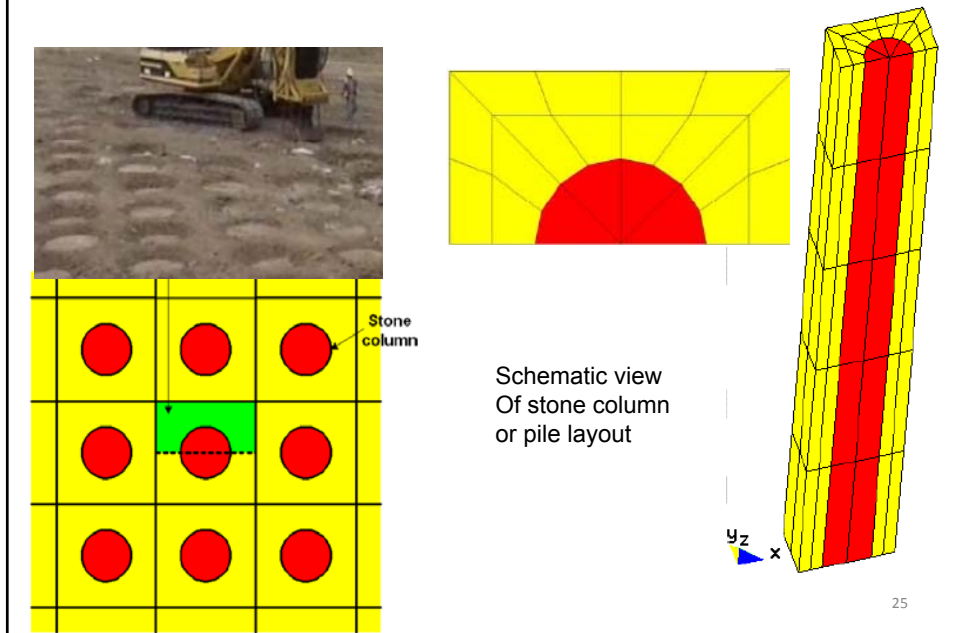
Soil Response Time Histories



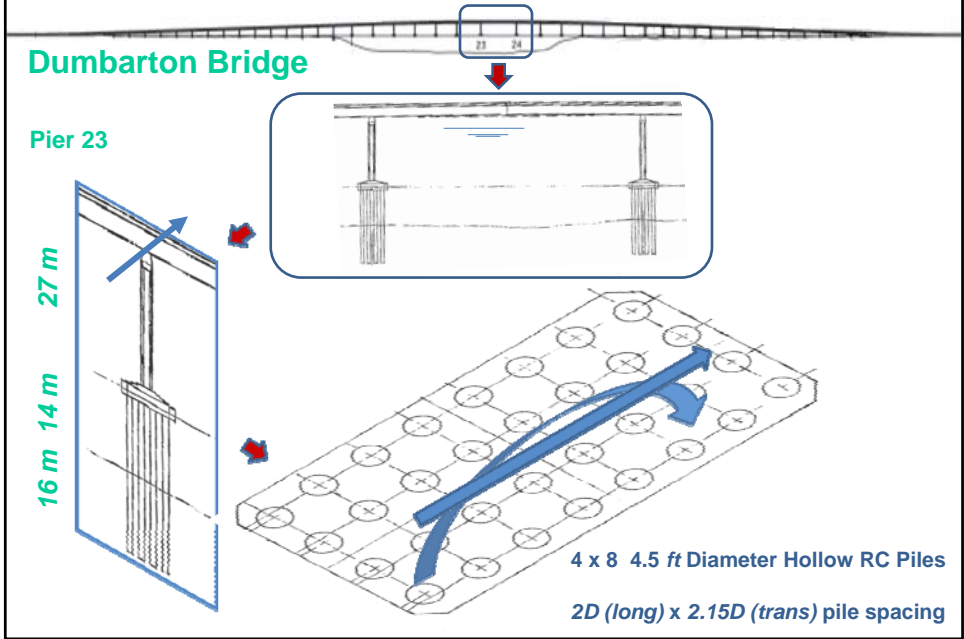
Example 1: Pile in Liquefied Soil



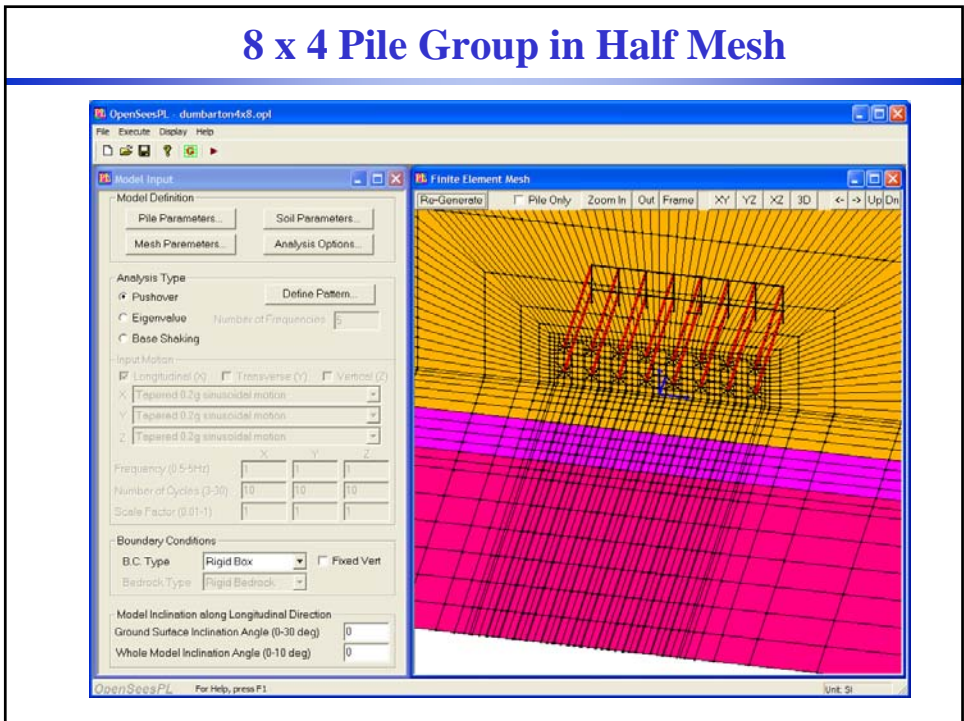
Example 2: Stone Column Ground Modification

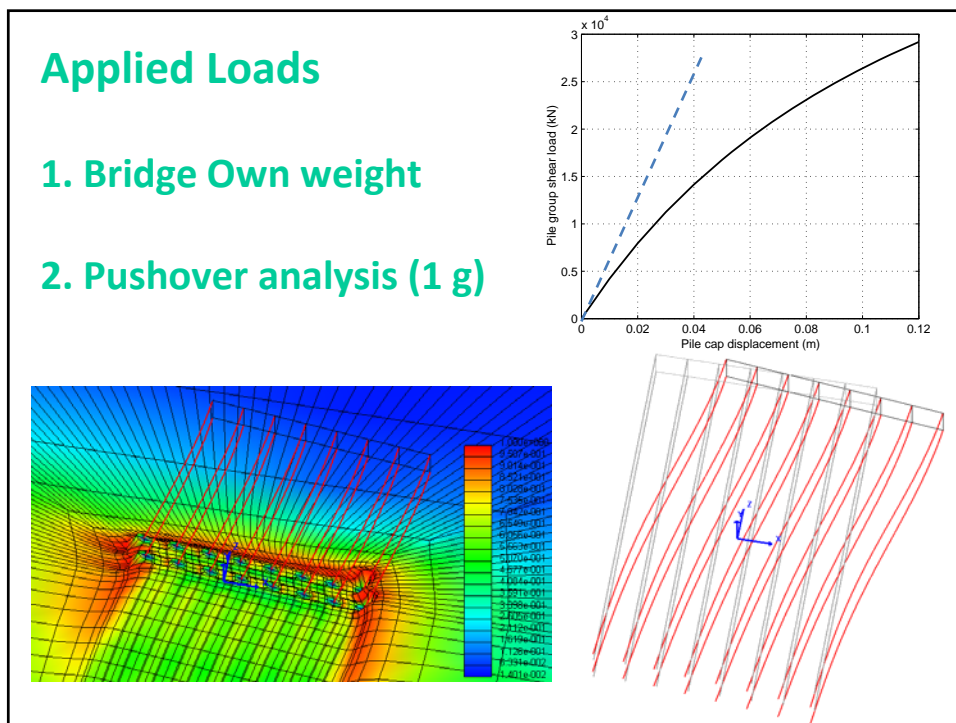
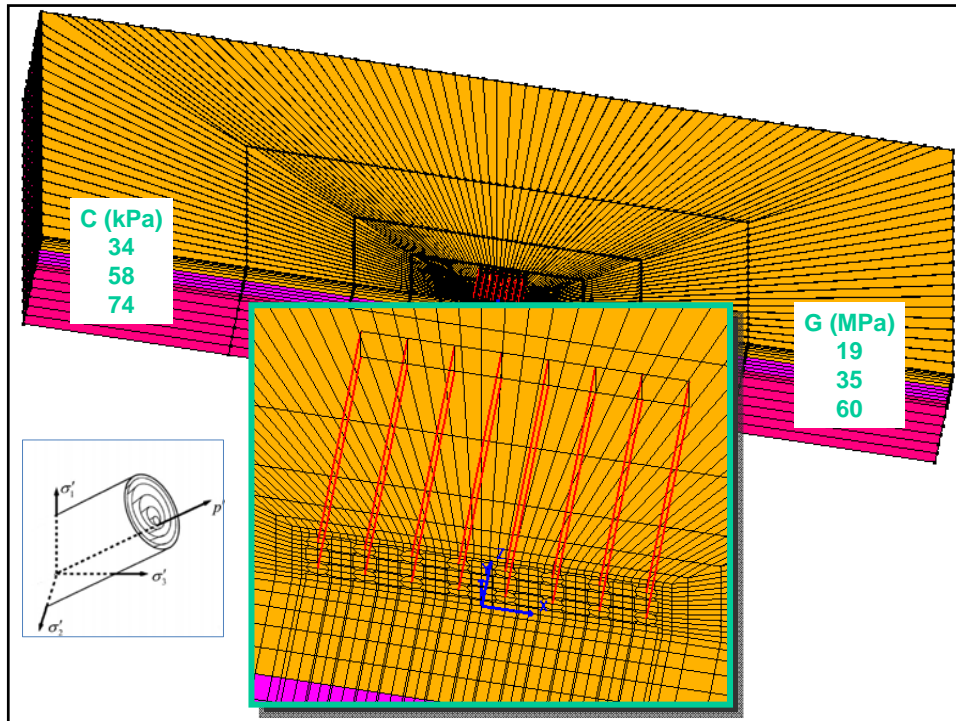


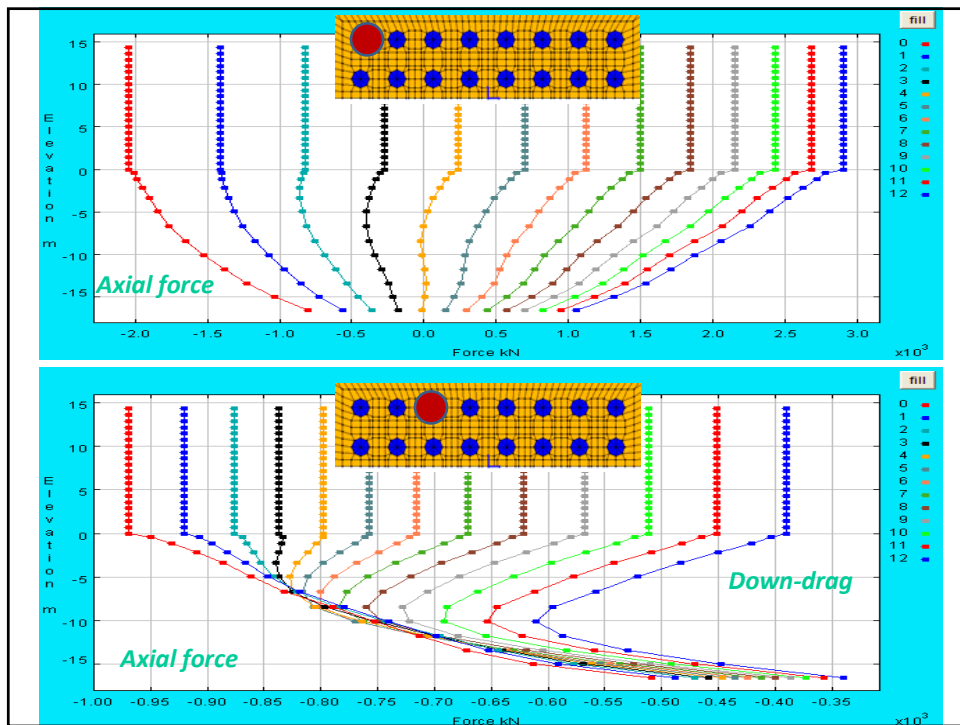
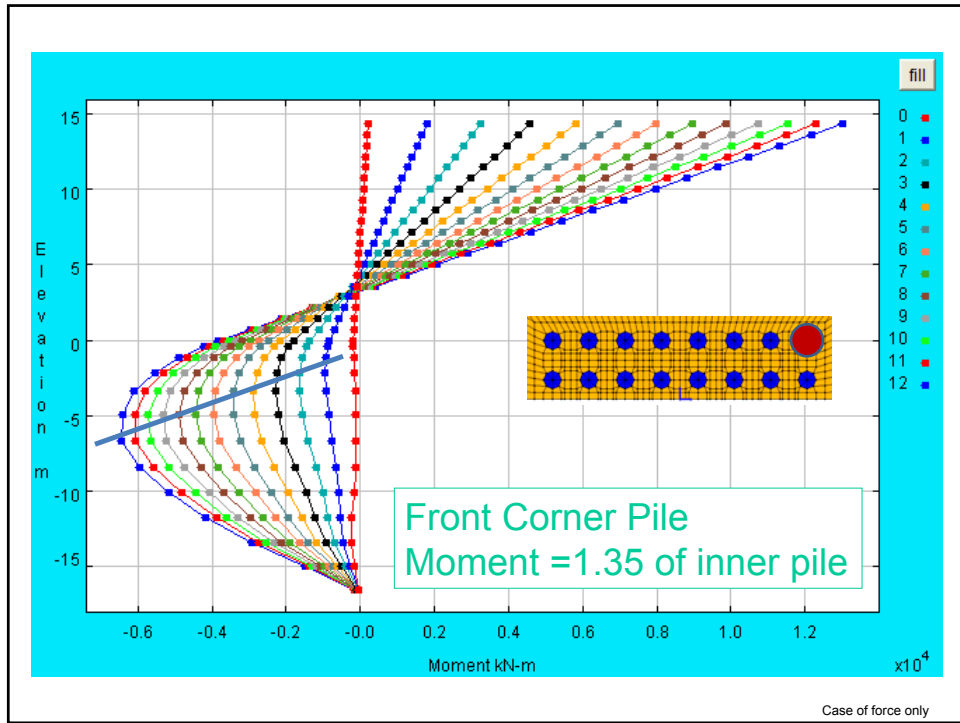
Example 3: Large Pile Group



8 x 4 Pile Group in Half Mesh



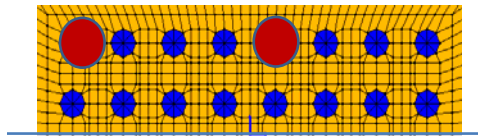




Summary for Pile Group Study

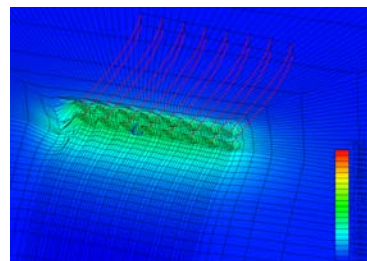
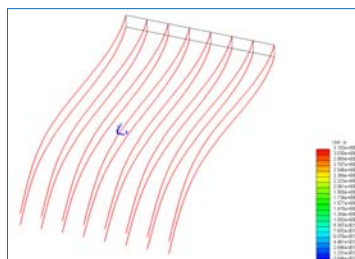
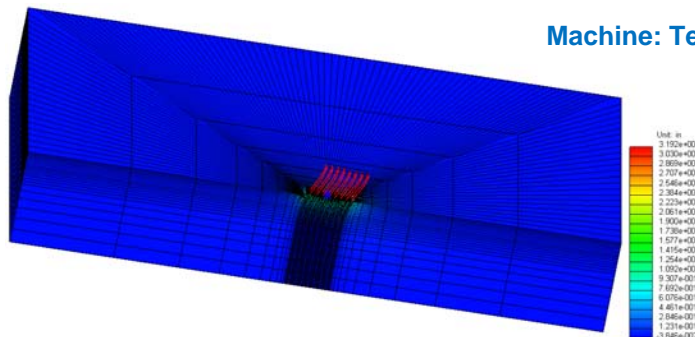
For the employed *cohesive soil* scenario:

- Corner piles are most vulnerable
- Edge piles carry much more axial load than inner piles
- Axial response and skin friction (t-z springs) may play a critical role
- Pile tensile forces may be quite significant and affect RC response (connection to pile-cap, reduction in confinement)



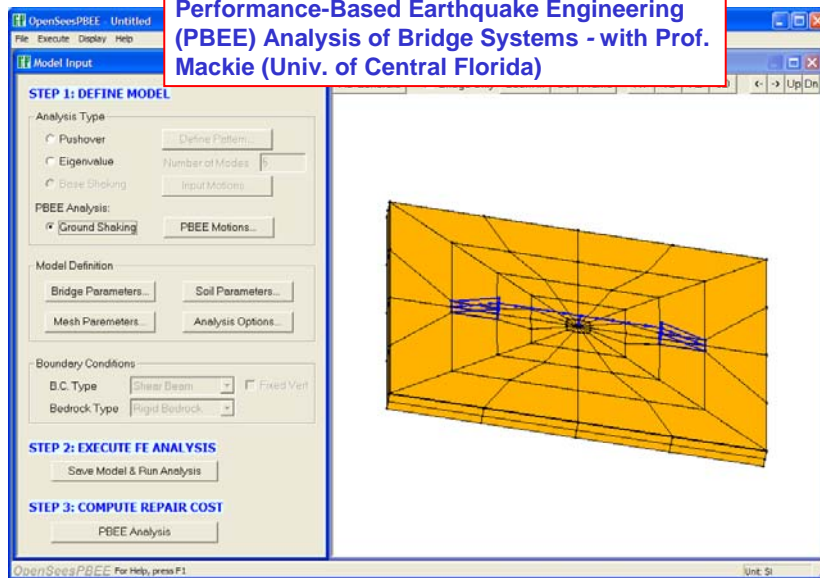
Parallel Computing on Supercomputer

Machine: Teragrid IA-64

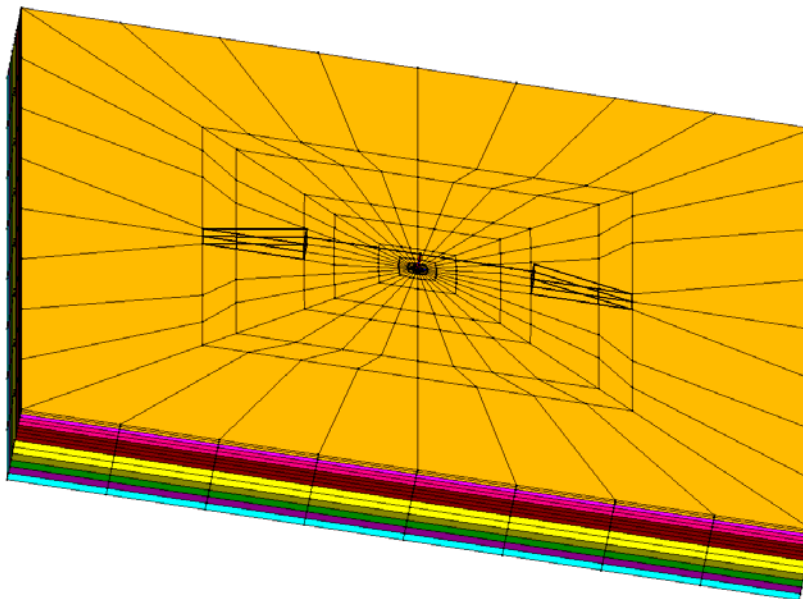


Ongoing Project: OpenSeesPBEE

Performance-Based Earthquake Engineering (PBEE) Analysis of Bridge Systems - with Prof. Mackie (Univ. of Central Florida)



Bridge and Ground Model



Input Motions

PBEE Input Motions

PBEE Input Motion Folder Browse...

C:\MyDoc_PBEE\FixedBase\FixedBase_SpringAbut_MotionSet1_pfiles\FixedBase_SpringAbut_MotionSet1.EQ

Input Motions (100 Records in Total; 100 Records Selected) Display Intensity Measures

Record#	Bin	Motion	#Points	Timestep (Sec)	Duration (Sec)
<input checked="" type="checkbox"/>	LMLR	BORREGO/A-ELC	4000	0.0100	40.0000
<input checked="" type="checkbox"/>	LMLR	LOMAP/AZE	7990	0.0050	39.9500
<input checked="" type="checkbox"/>	LMLR	LOMAP/FMS	7949	0.0050	39.7450
<input checked="" type="checkbox"/>	LMLR	LOMAP/HVR	7990	0.0050	39.9500
<input checked="" type="checkbox"/>	LMLR	LOMAP/SJW	7990	0.0050	39.9500
<input checked="" type="checkbox"/>	LMLR	LOMAP/SLC	7915	0.0050	39.5750
<input checked="" type="checkbox"/>	LMLR	NORTHR/BAD	3499	0.0100	34.9900
<input checked="" type="checkbox"/>	LMLR	NORTHR/CAS	3979	0.0100	39.7900
<input checked="" type="checkbox"/>	LMLR	NORTHR/CEN	2999	0.0100	29.9900
<input checked="" type="checkbox"/>	LMLR	NORTHR/DEL	3536	0.0100	35.3600
<input checked="" type="checkbox"/>	LMLR	NORTHR/DWN	2000	0.0200	40.0000
<input checked="" type="checkbox"/>	LMLR	NORTHR/JAB	3499	0.0100	34.9900
<input checked="" type="checkbox"/>	LMLR	NORTHR/L01	1600	0.0200	32.0000
<input checked="" type="checkbox"/>	LMLR	NORTHR/LOA	3999	0.0100	39.9900

De-select All Randomly Choose 1 Records for Each Bin

(Double-click on any record to view its characteristics including response spectra)

Compute Response to Entire Record Length Free Vibration Duration 5 seconds
 Compute Response for 0.1 seconds

OK Cancel

Concurrent Execution for Multiple Records

OpenSeesPBEE - FixedBase_SpringAbut_MotionSet1.pbe

File Execute Display Help

Model Input **Finite Element Mesh**

Re-Generate Bridge Only Zoom In Out Frame XY YZ XZ 3D <-> Up/Down

STEP 1: DEFINE MODEL

Analysis Type

- Pushover
- Eigenvalue
- Base Shaking

PBEE Analysis:

- Ground Shaking

Model Definition

- Bridge Paramet Skip
- Mesh Paramet Skip
- Boundary Condition
- B.C. Type Skip
- Bedrock Type Skip

STEP 2: EXECUTE FE ANALYSIS

Save Model & Run Analysis

STEP 3: COMPUTE REPAIR COST

PBEE Analysis

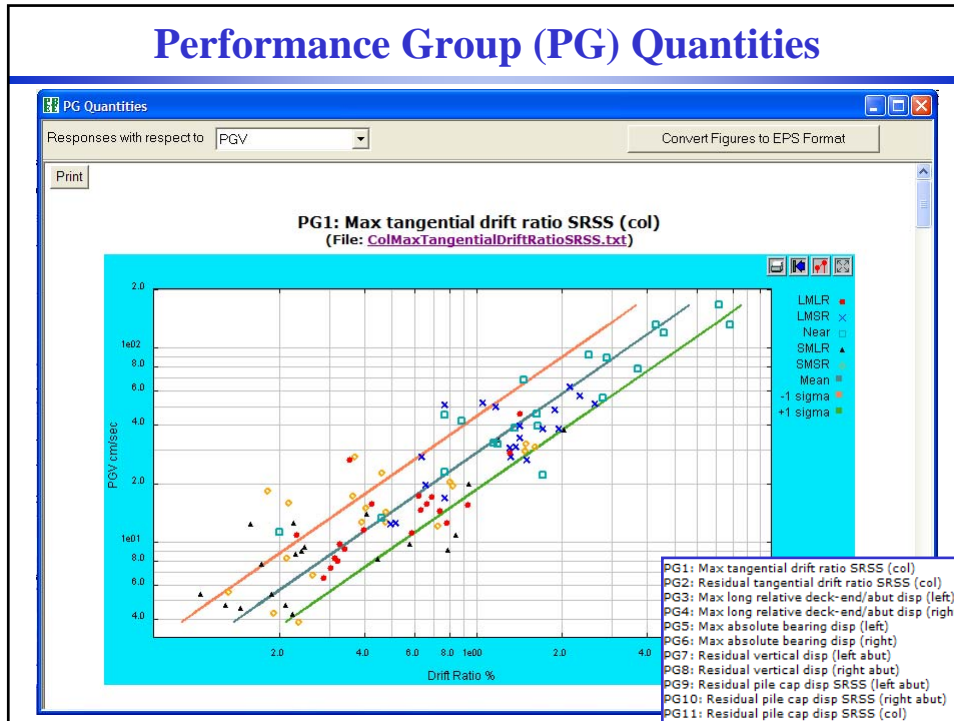
OpenSees Analysis In Progress (Dry Case, Base Shaking)

8 / 100 Motions Stop All

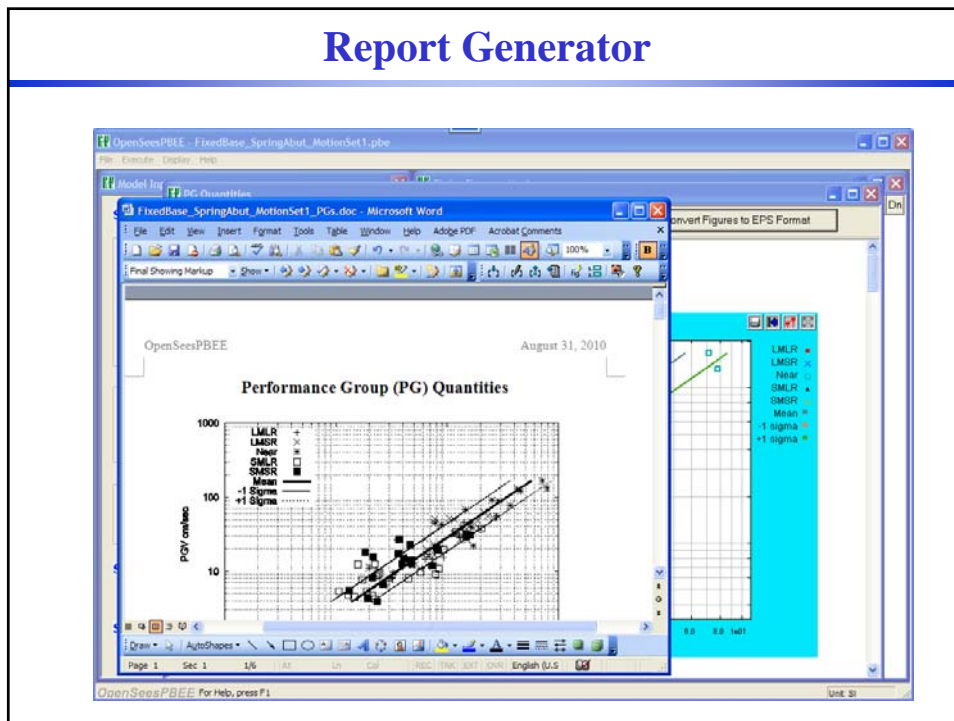
Current Motion 1: #5 SJW Run 4 of 4 Base shaking... (Finished: 29.32 / 44.96 sec)	65%
<div style="background-color: blue; width: 65%; height: 10px;"></div>	Skip
Current Motion 2: #7 BAD Run 4 of 4 Base shaking... (Finished: 26.32 / 40.00 sec)	66%
<div style="background-color: blue; width: 66%; height: 10px;"></div>	Skip
Current Motion 3: #6 SLC Run 4 of 4 Base shaking... (Finished: 27.62 / 44.58 sec)	62%
<div style="background-color: blue; width: 62%; height: 10px;"></div>	Skip
Current Motion 4: #8 CAS Run 4 of 4 Base shaking... (Finished: 27.06 / 44.60 sec)	60%
<div style="background-color: blue; width: 60%; height: 10px;"></div>	Skip

OpenSeesPBEE For Help, press F1 Unit: SI

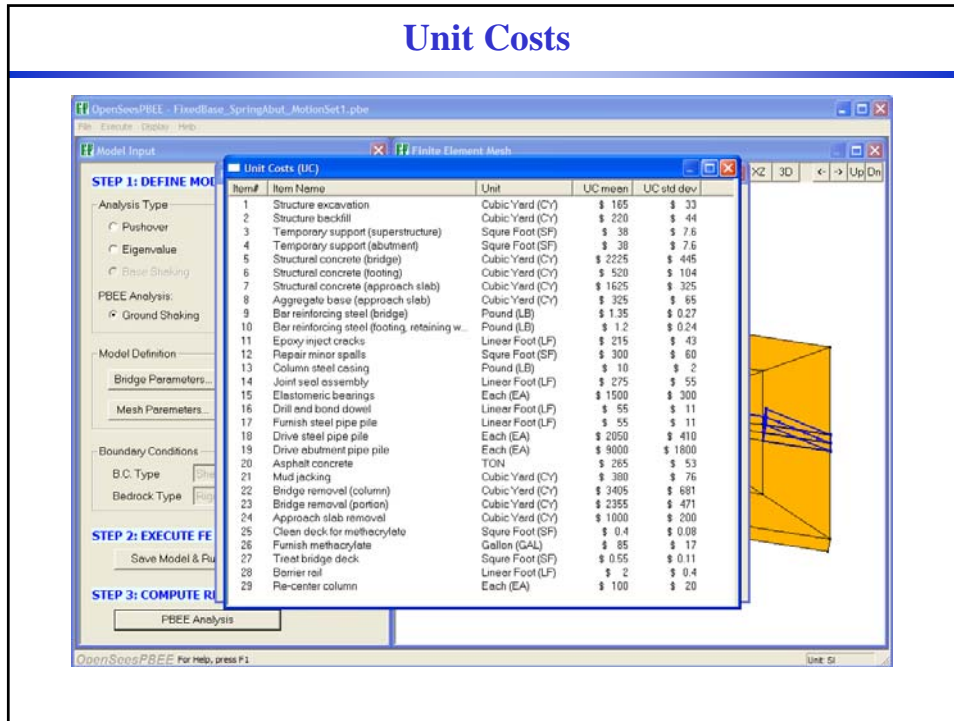
Performance Group (PG) Quantities



Report Generator

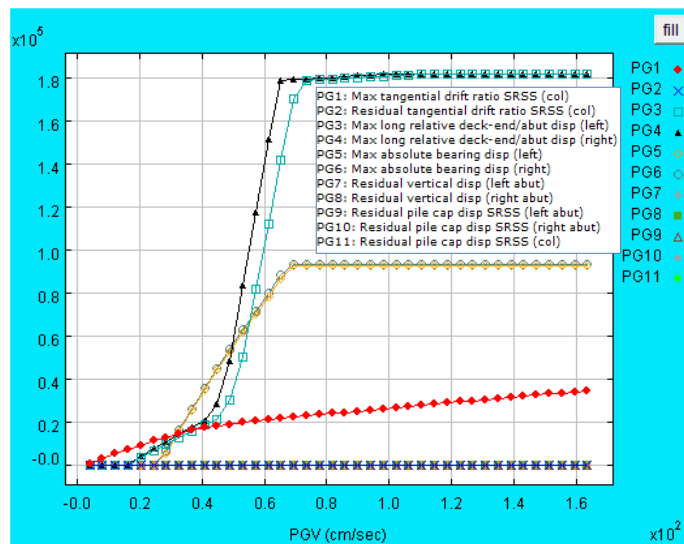


Unit Costs



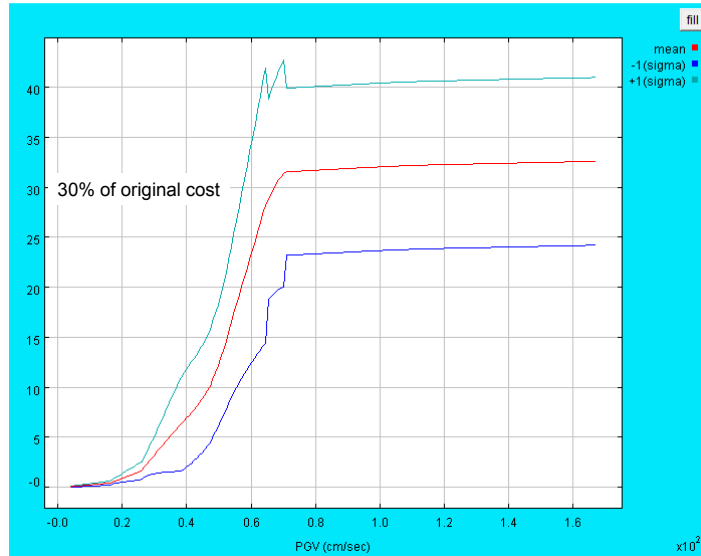
PBEE Outcome: Repair Cost

Contribution to expected repair cost (\$) from each performance group
(File: [PGsens_E.txt](#))



Total Repair Cost Ratio

Total repair cost ratio (%) (File: [RCR_Model.txt](#))



Ongoing Project: Deep Soil Mixing

Joint project with UC Davis (Prof. Boulanger) and Oregon State Univ. (Prof. Ashford)

