OpenSeesPL – 3D Pile-Ground Interaction

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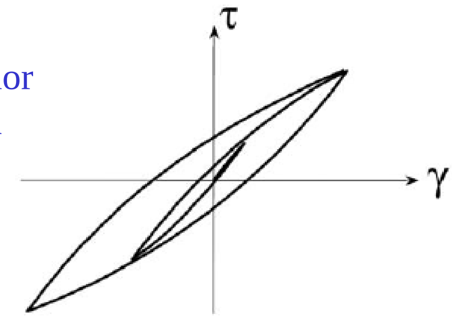
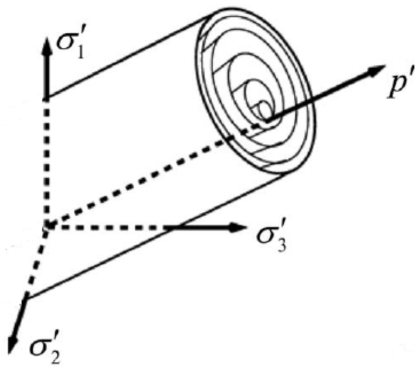
Outline

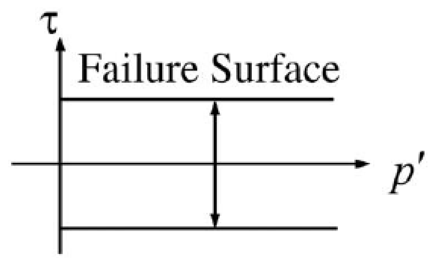
- Soil constitutive models
- Solid-fluid fully-coupled elements
- OpenSeesPL graphical user interface
- Examples of using OpenSeesPL
- Ongoing research projects

Pressure-Independent Material

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







PressureIndependMultiYield

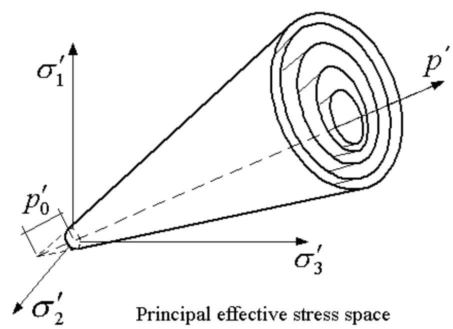
```
nDmaterial PressureIndependMultiYield $tag $nd  $rho  $refShearModul
$refBulkModul $cohesi  $peakShearStra  <$frictionAng=0.  $refPress=100.
$pressDependCoe=0.  $noYieldSurf=20  <$r1 $Gs1 …>  >
```

Suggested parameter values:

	Soft Clay	Medium Clay	Stiff Clay
rho	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
refShearModul	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
refBulkModul	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
cohesi	18 kPa or 2.611 psi	37 kPa or 5.366 psi	75 kPa or 10.878 psi
peakShearStra	0.1	0.1	0.1

Pressure-Dependent Material

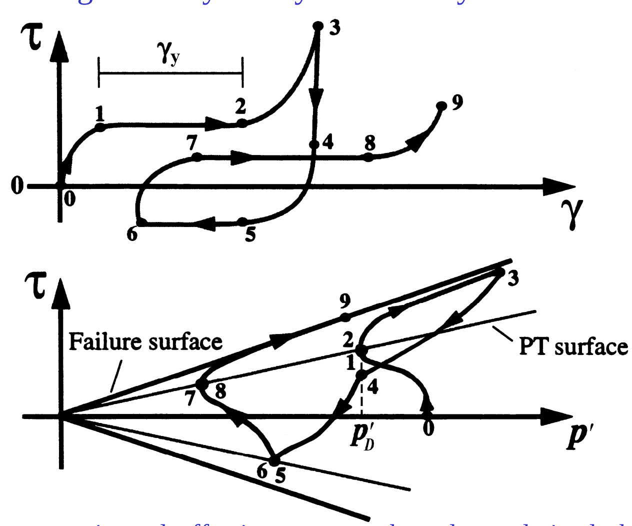
- Multi-yield surface plasticity model (based on Prevost 1985)



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>>

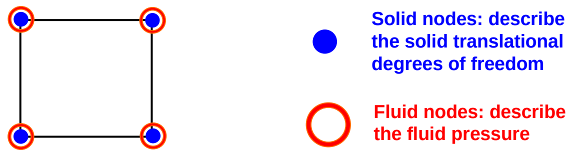
Suggested parameter values:

	Loose Sand (15%-35%)	**Medium Sand (35%-65%)**	**Medium-dense Sand (65%-85%)**	**Dense Sand (85%-100%)**
rho	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
refShearModul (at p'_r=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
refBulkModu (at p'_r=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
frictionAng	29	33	37	40
peakShearStra (at p'_r=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



quadUP

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

Recorder examples:

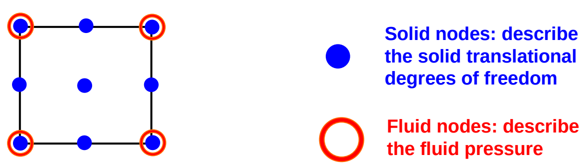
Pore water pressure:

```
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

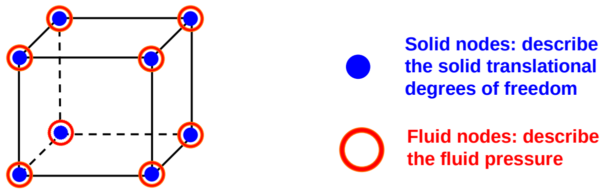


9_4_quadUP

```
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)

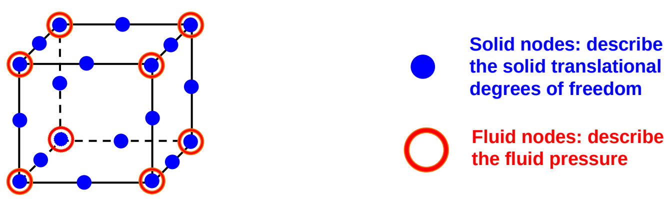
3D Solid-Fluid Coupled Brick Element



brickUP

```
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

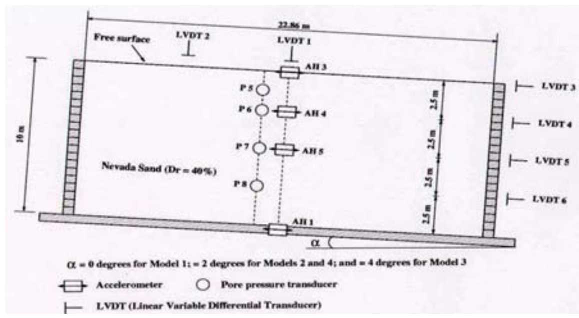
```
element 20_8_BrickUP $eleTag  $Node1  … $Node20 $matTag  $bulk
$fmass  $PermX  $PermY $PermZ <$bX=0  $bY=0 $bZ=0>
```

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

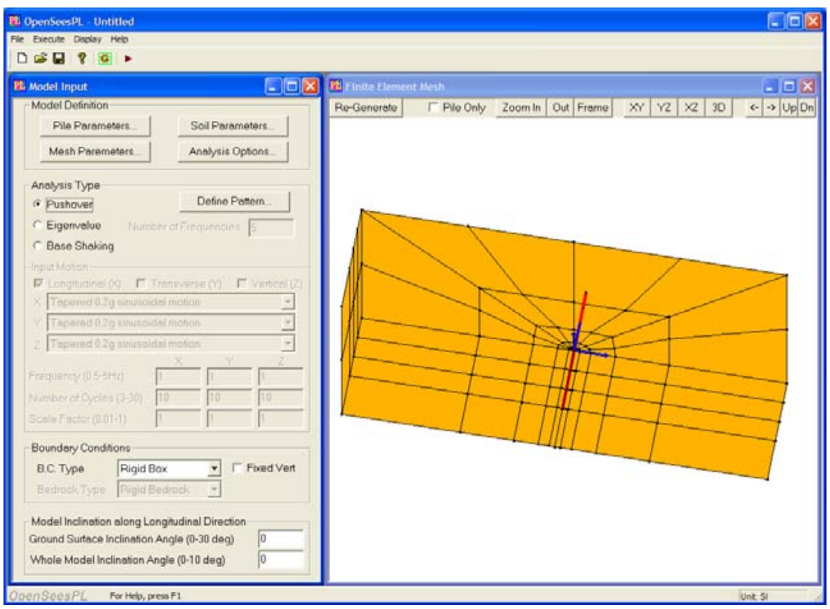
Soil Model Calibration

- 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)

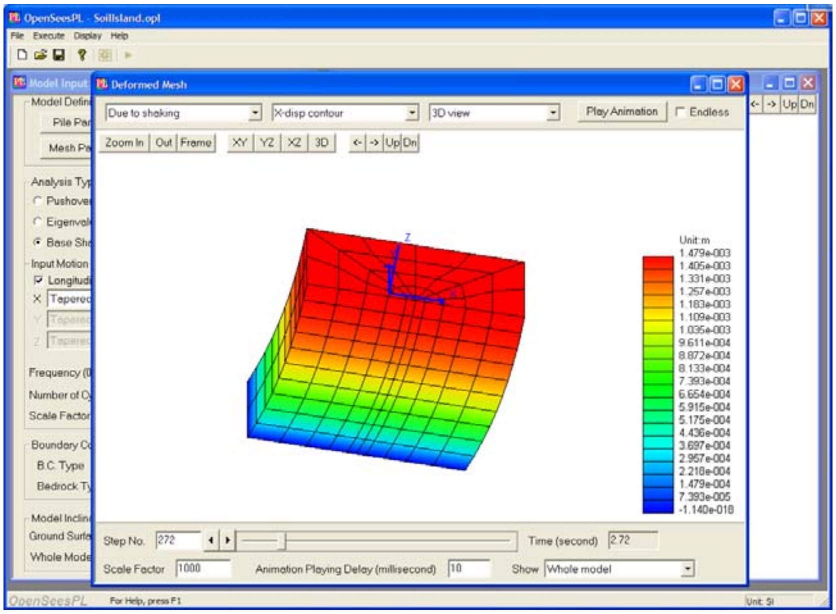
VELACS Models



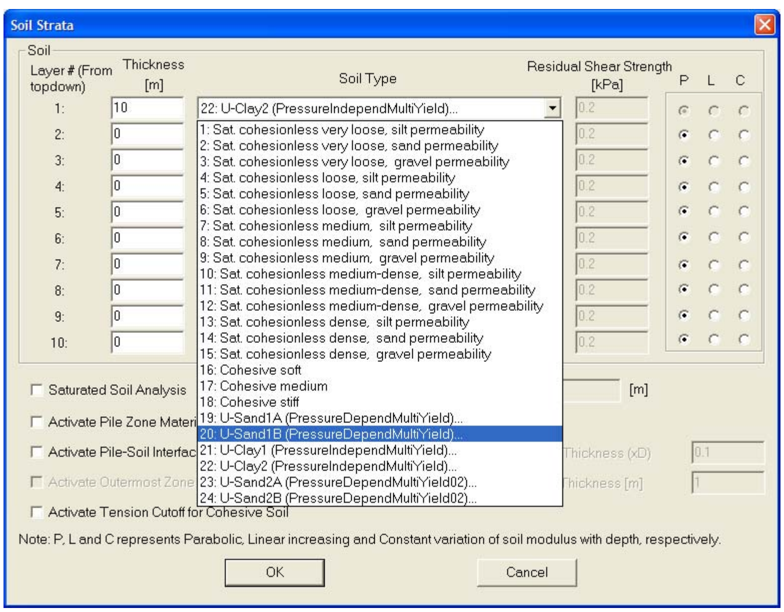
OpenSeesPL Graphical User Interface



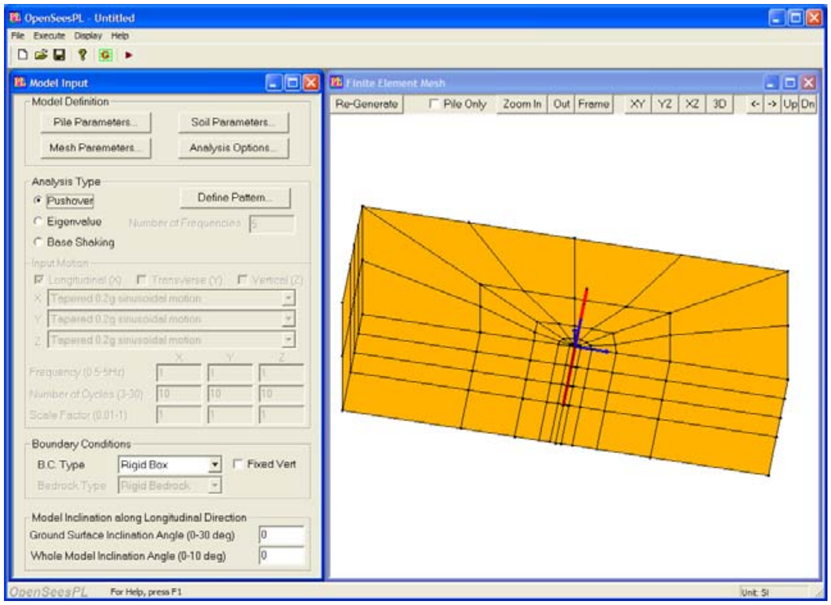
“Soil Island” (Soil Strata Only)



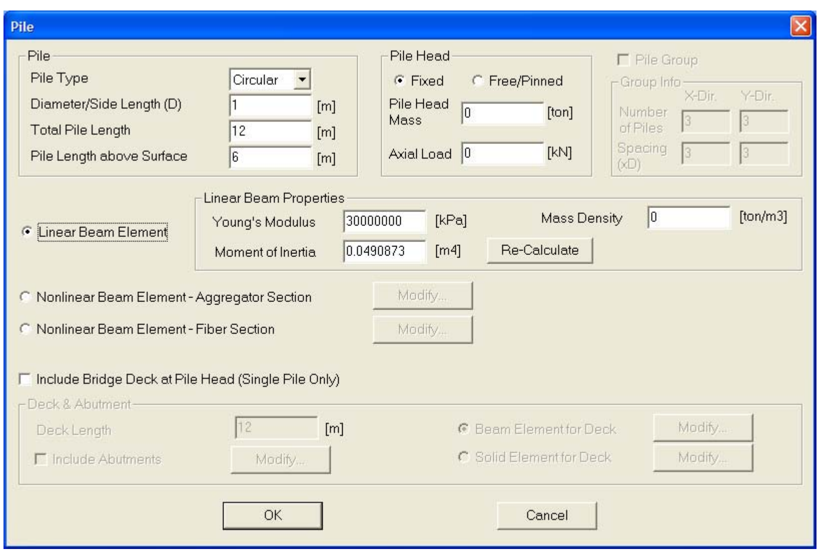
List of Soil Types



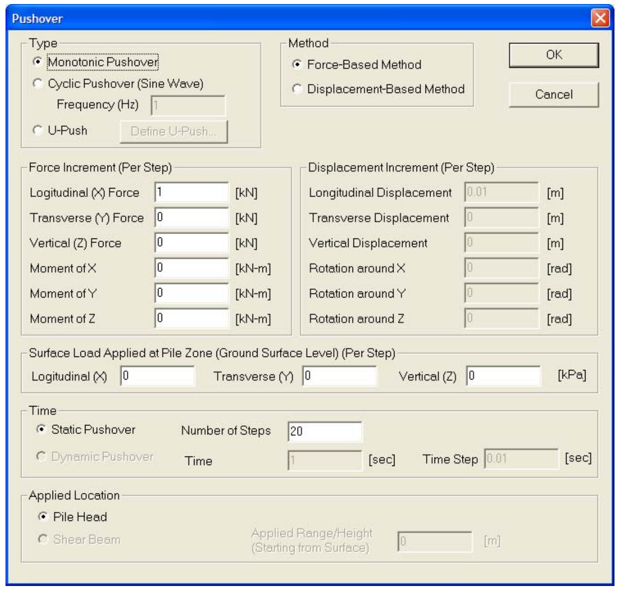
Pile in Soil Layers



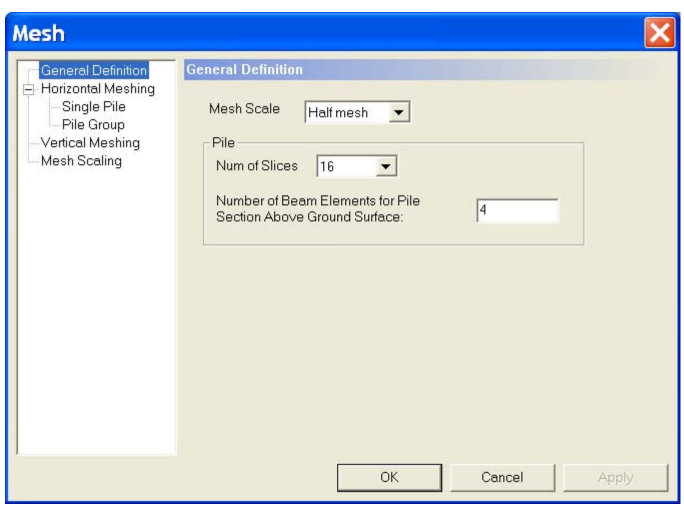
Pile Properties



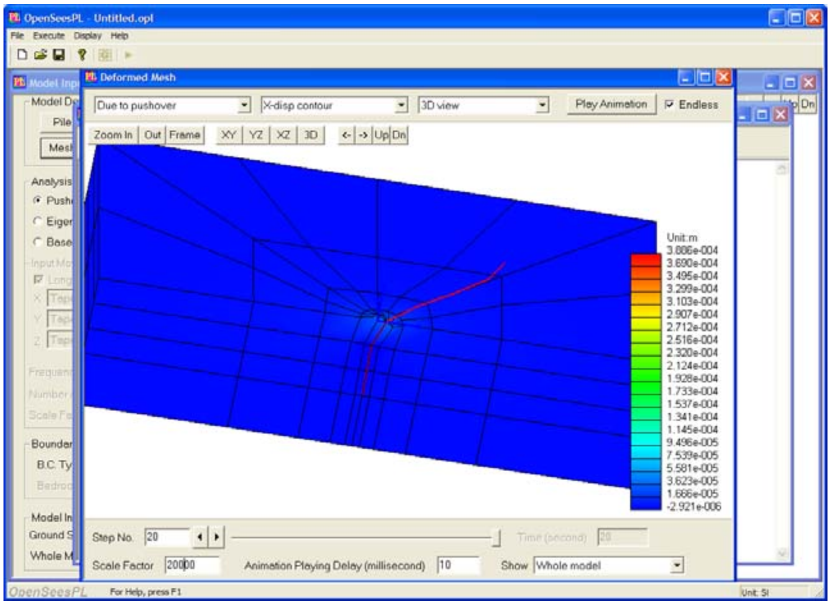
Pushover Analysis



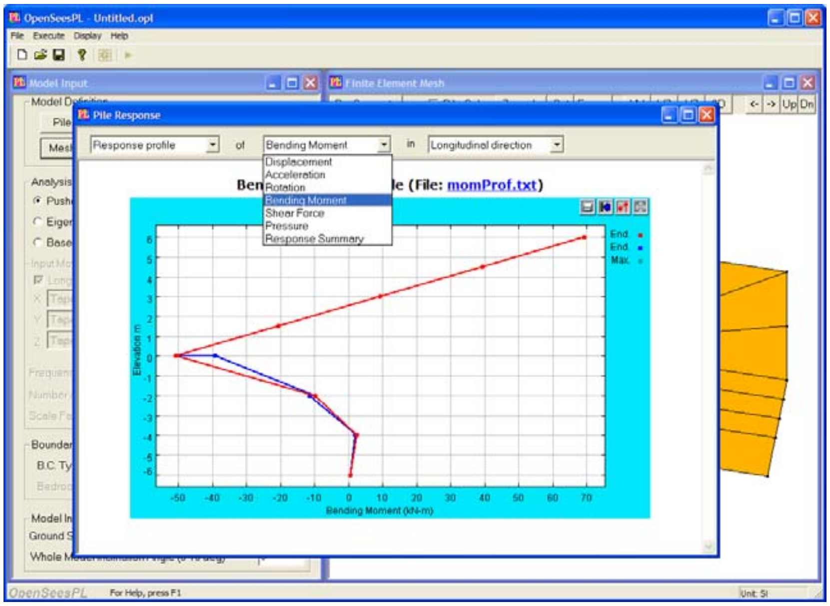
Mesh Generation



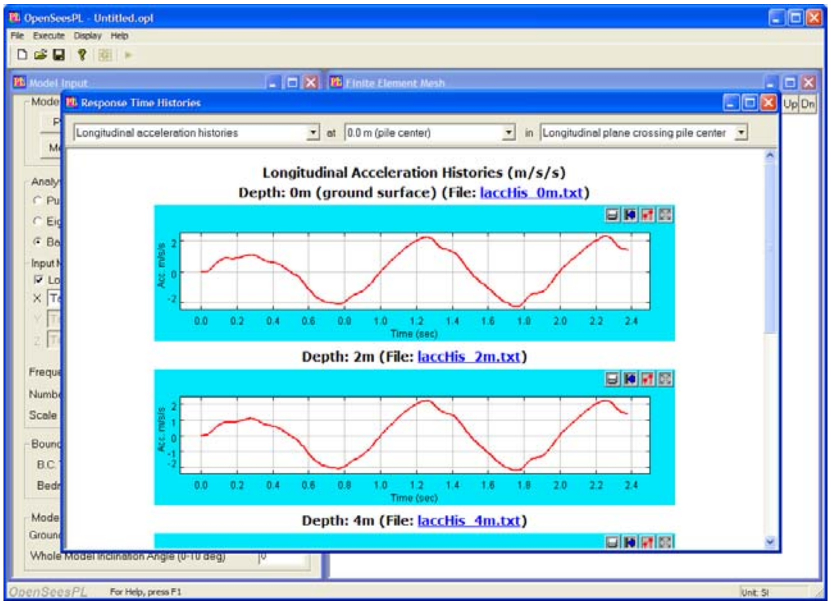
Deformed Mesh



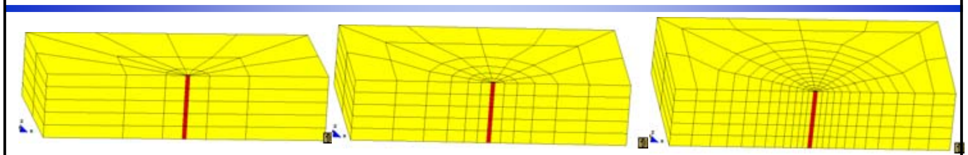
Pile Response Profiles & Time Histories



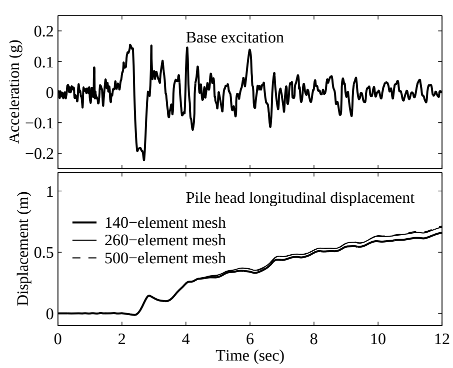
Soil Response Time Histories

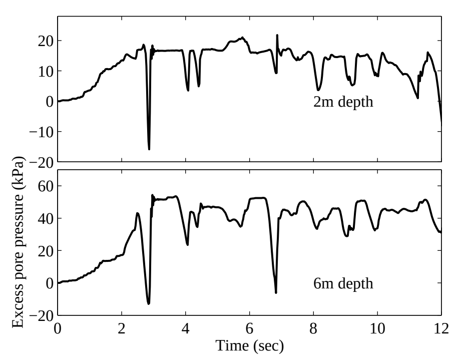


Example 1: Pile in Liquefied Soil



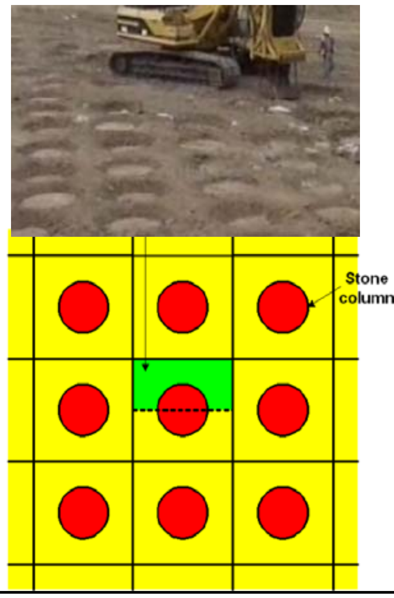
a) 140-element mesh b) 260-element mesh c) 500-element mesh

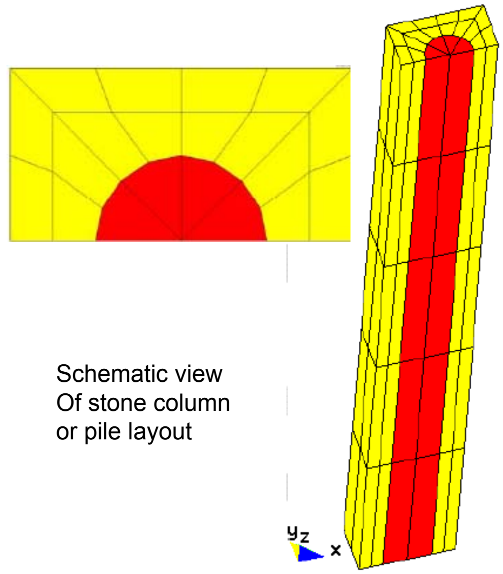




Excess pore pressure time histories in the free-field (500-element mesh)

Example 2: Stone Column Ground Modification





Schematic view
Of stone column
or pile layout

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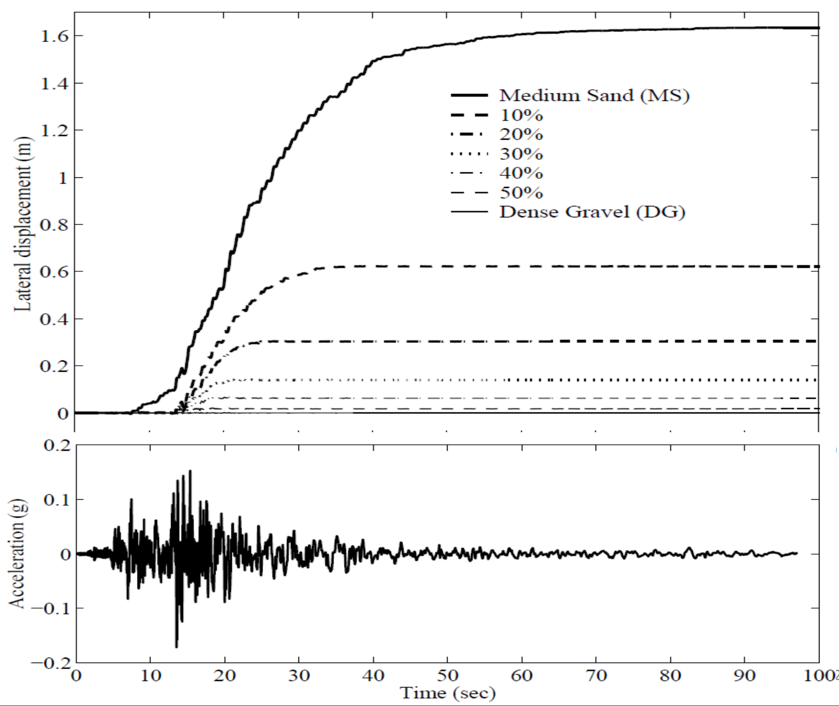

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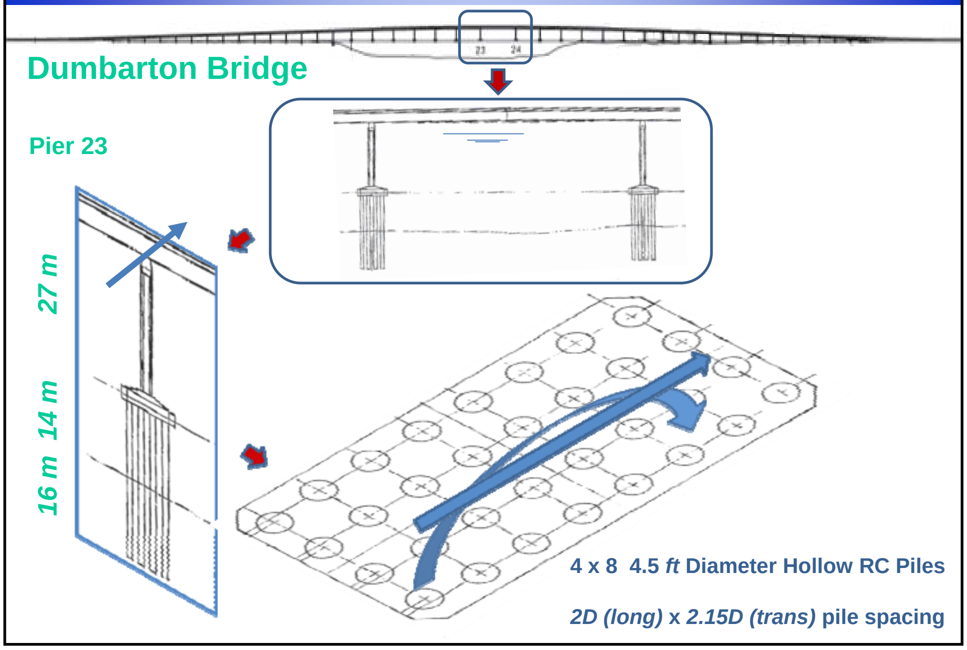
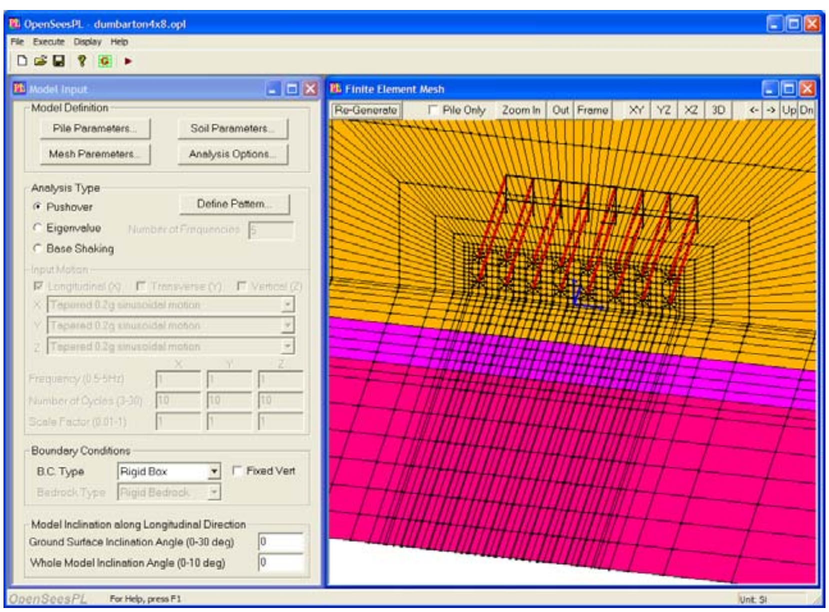
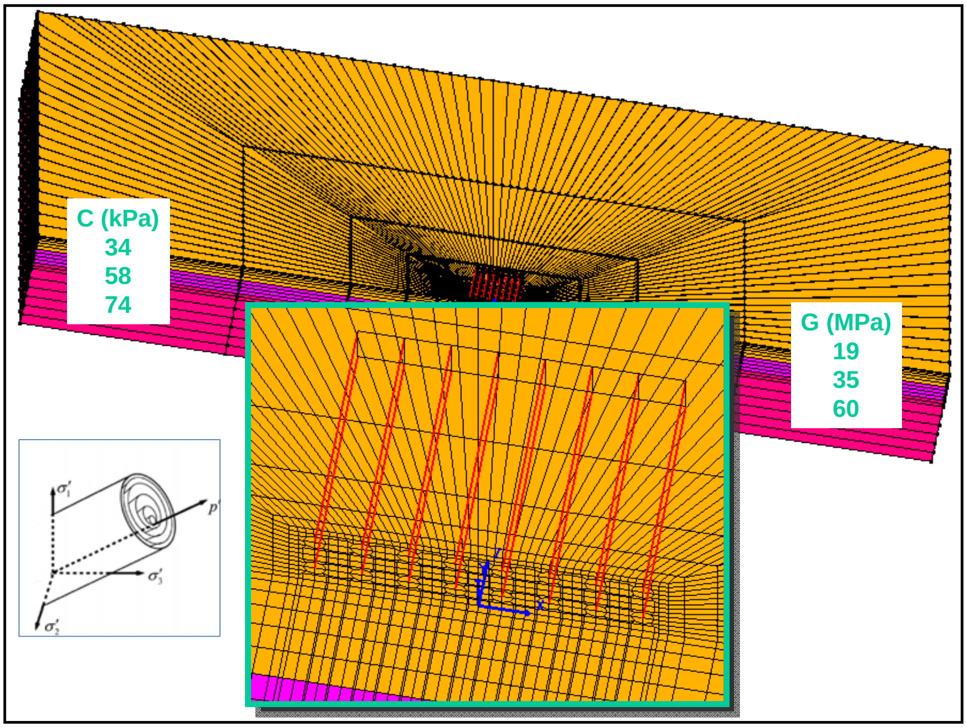
Example 3: Large Pile Group



8 x 4 Pile Group in Half Mesh

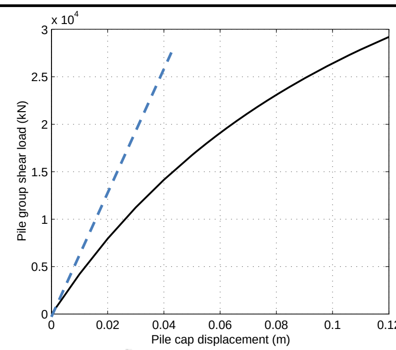


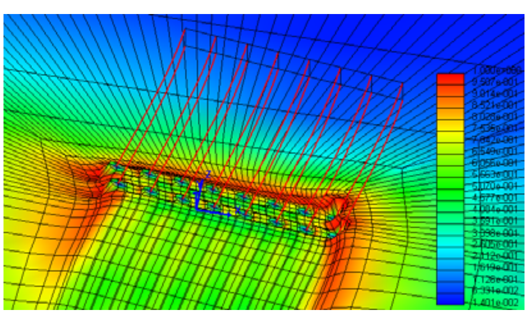


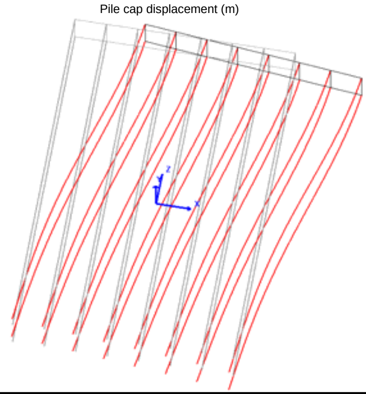
Applied Loads

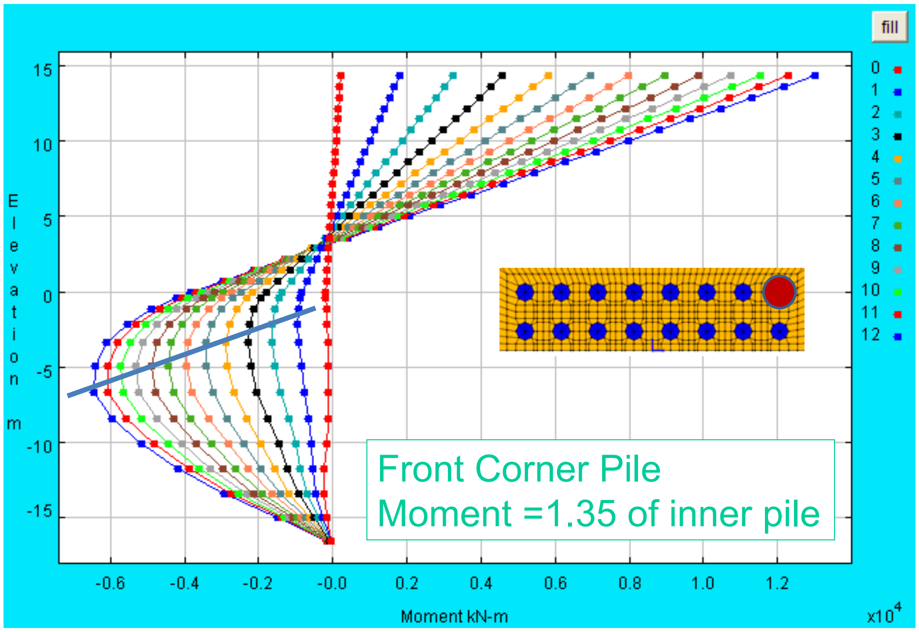
1. Bridge Own weight

2. Pushover analysis (1 g)

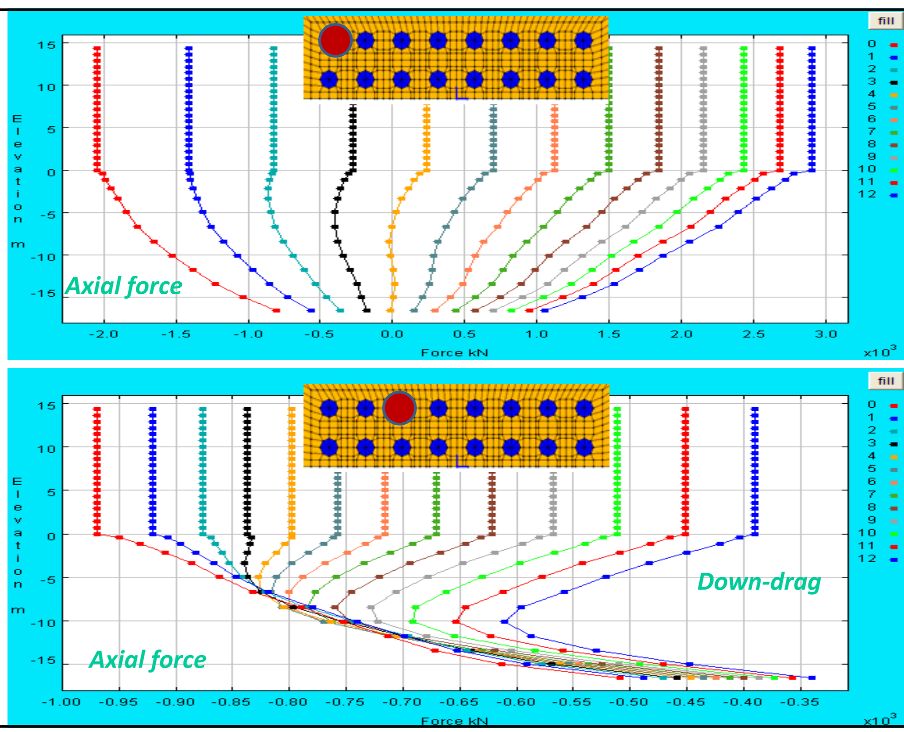








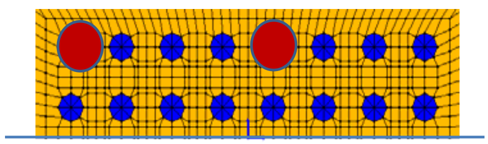
Case of force only



Summary for Pile Group Study

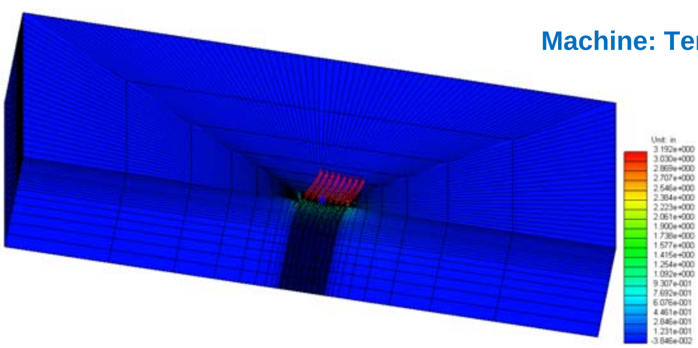
For the employed *cohesive soil* scenario:

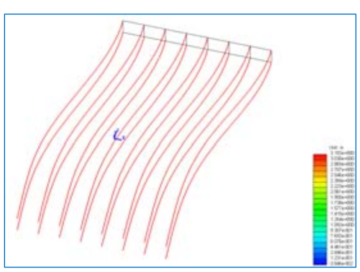
- Corner piles are most vulnerable
- Edge piles carry much more axial load than inner piles
- Axial response and skin friction (t-z springs) may play a critical role
- Pile tensile forces may be quite significant and affect RC response (connection to pile-cap, reduction in confinement)

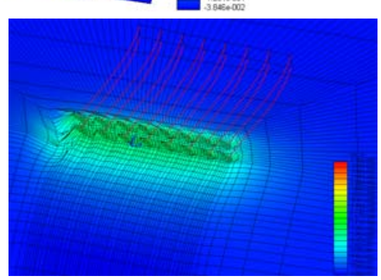


Parallel Computing on Supercomputer

Machine: Teragrid IA-64

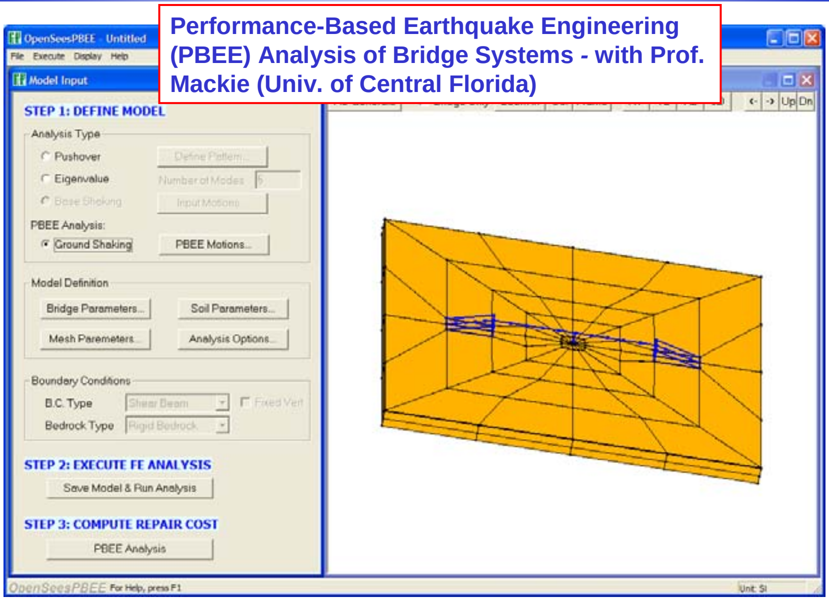




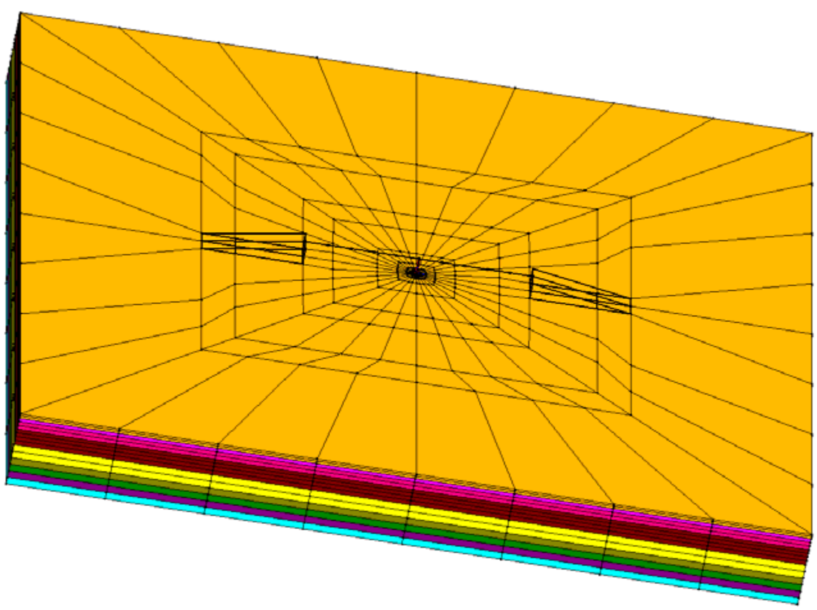


Ongoing Project: OpenSeesPBEE

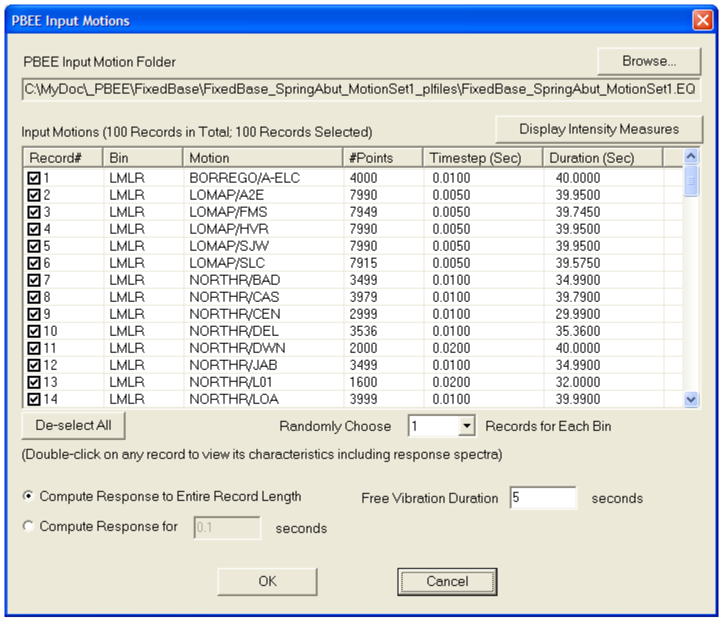
Performance-Based Earthquake Engineering (PBEE) Analysis of Bridge Systems - with Prof. Mackie (Univ. of Central Florida)



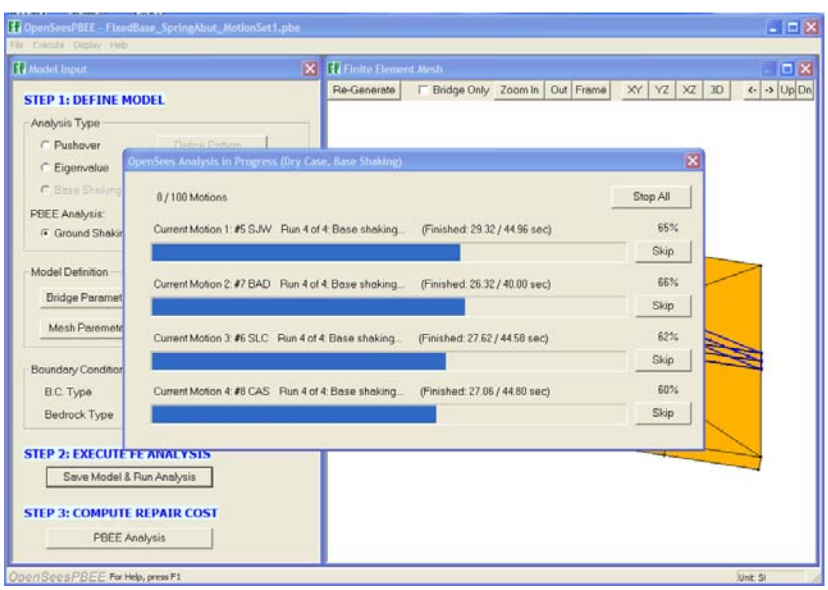
Bridge and Ground Model



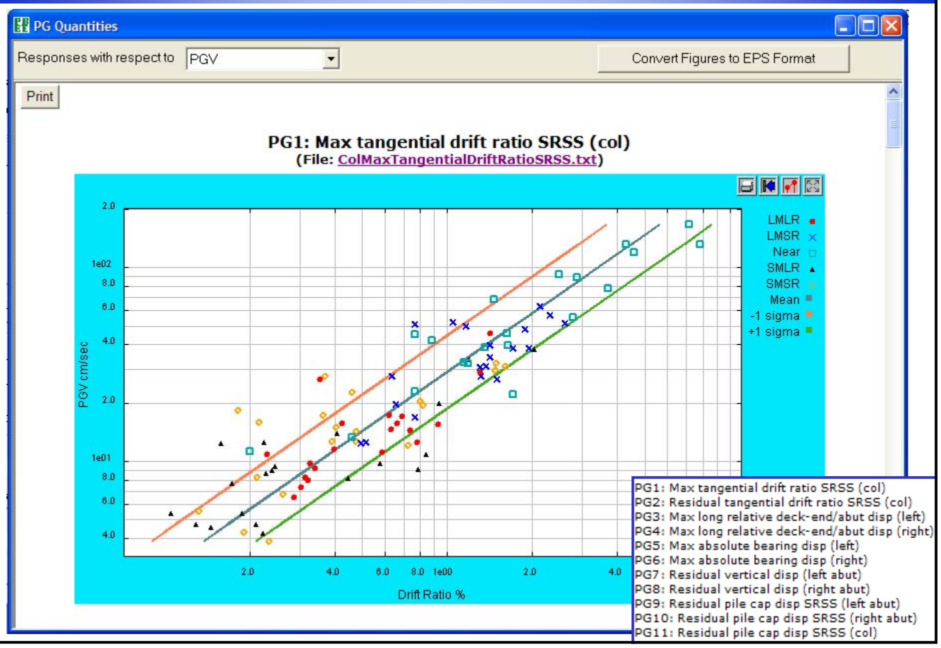
Input Motions



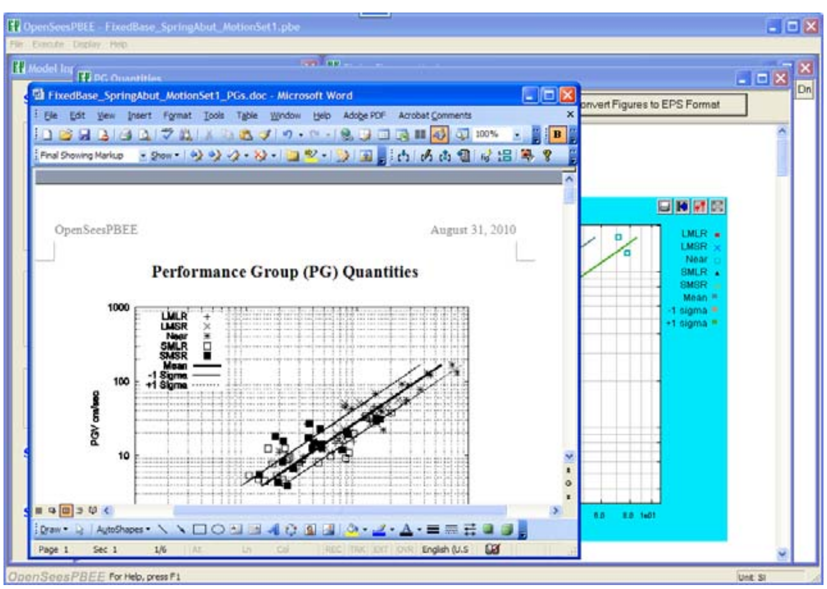
Concurrent Execution for Multiple Records



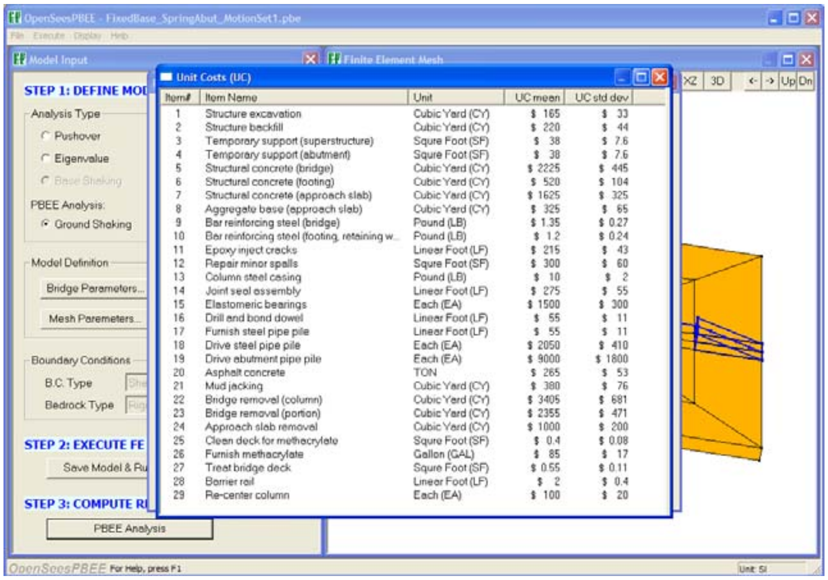
Performance Group (PG) Quantities



Report Generator



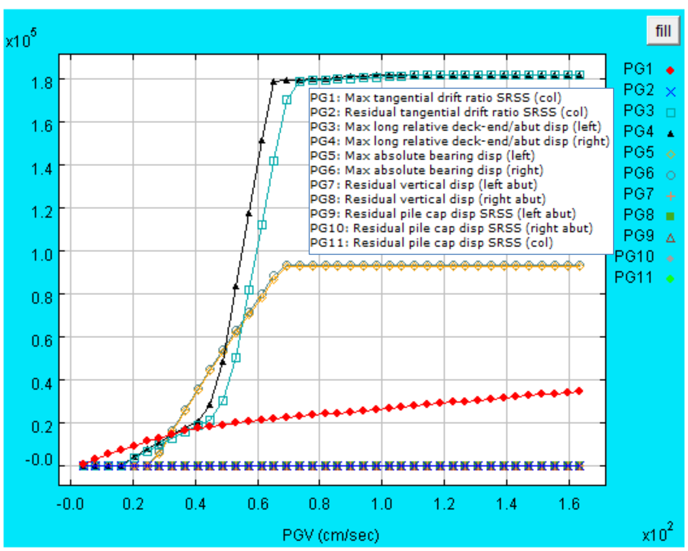
Unit Costs



Item#	Item Name	Unit	UC mean	UC std dev
1	Structure excavation	Cubic Yard (CY)	$ 165	$ 33
2	Structure backfill	Cubic Yard (CY)	$ 220	$ 44
3	Temporary support (superstructure)	Squre Foot (SF)	$ 38	$ 7.6
4	Temporary support (abutment)	Squre Foot (SF)	$ 38	$ 7.6
5	Structural concrete (bridge)	Cubic Yard (CY)	$ 2225	$ 445
6	Structural concrete (footing)	Cubic Yard (CY)	$ 520	$ 104
7	Structural concrete (approach slab)	Cubic Yard (CY)	$ 1625	$ 325
8	Aggregate base (approach slab)	Cubic Yard (CY)	$ 325	$ 65
9	Bar reinforcing steel (bridge)	Pound (LB)	$ 1.35	$ 0.27
10	Bar reinforcing steel (footing, retaining w...	Pound (LB)	$ 1.2	$ 0.24
11	Epoxy inject cracks	Linear Foot (LF)	$ 215	$ 43
12	Repair minor spalls	Squre Foot (SF)	$ 300	$ 60
13	Column steel casing	Pound (LB)	$ 10	$ 2
14	Joint seal assembly	Linear Foot (LF)	$ 275	$ 55
15	Elastomeric bearings	Each (EA)	$ 1500	$ 300
16	Drill and bond dowel	Linear Foot (LF)	$ 55	$ 11
17	Furnish steel pipe pile	Linear Foot (LF)	$ 55	$ 11
18	Drive steel pipe pile	Each (EA)	$ 2050	$ 410
19	Drive abutment pipe pile	Each (EA)	$ 9000	$ 1800
20	Asphalt concrete	TON	$ 265	$ 53
21	Mud jacking	Cubic Yard (CY)	$ 380	$ 76
22	Bridge removal (column)	Cubic Yard (CY)	$ 3405	$ 681
23	Bridge removal (portion)	Cubic Yard (CY)	$ 2355	$ 471
24	Approach slab removal	Cubic Yard (CY)	$ 1000	$ 200
25	Clean deck for methacrylate	Squre Foot (SF)	$ 0.4	$ 0.08
26	Furnish methacrylate	Gallon (GAL)	$ 85	$ 17
27	Treat bridge deck	Squre Foot (SF)	$ 0.55	$ 0.11
28	Barrier rail	Linear Foot (LF)	$ 2	$ 0.4
29	Re-center column	Each (EA)	$ 100	$ 20

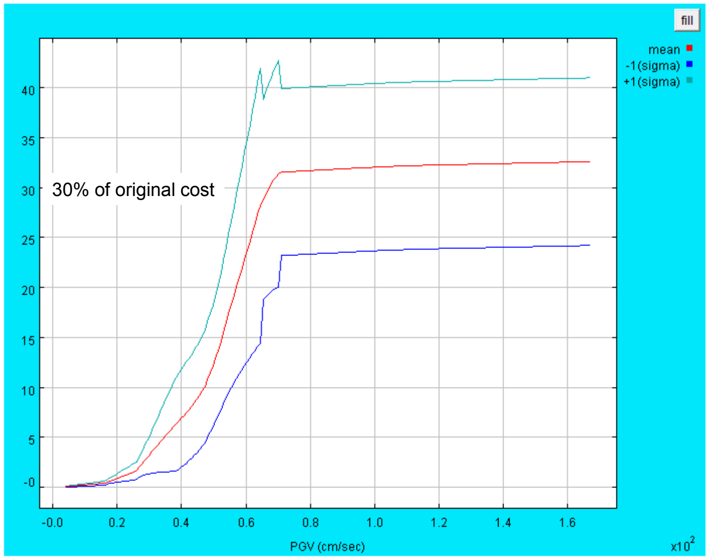
PBEE Outcome: Repair Cost

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)