Geotechnical Elements and Models in **OpenSees**

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OpenSees Days 2011,

OpenSees User Workshop, Monday August 22, 2011

Type of Geotechnical Problems that can be solved using **OpenSees**

- Static Problems
  - Deformation analyses (1D, 2D, or 3D)
  - Consolidation problems (diffusion problems)
  - Soil-structure interaction problems
    - Shallow foundations (e.g. bearing capacity, settlements)
    - Pile foundations (e.g. vertical and lateral capacity)

- Dynamic (earthquake problems)
  - Free-field analysis
  - Liquefaction induced problems
  - Soil structure interaction problems (e.g. response of pile foundations, bridge bents, or complete structures embedded in soils to earthquake excitations)

What do we need??

- Solid **elements** to characterize the soil domain (continuum).
- Appropriate **boundary conditions** to accurately represent the soil domain boundaries.
- Robust **constitutive models** to characterize the soil stress-strain response under monotonic and cyclic loading conditions
- **Interface elements** to capture the interaction between the soil and adjacent structures.
- **Everything else** you are learning in this workshop (i.e., how to create beam elements, apply loads and boundary conditions, record results, perform the analysis, etc.

Outline

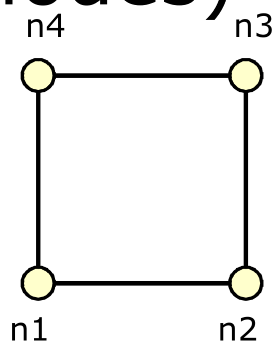
- **Finite Elements** (for solids)
  - Single-phase
  - Multi-phase (coupled) finite elements
  - Zero length element
- **Material Models**
  - Elastic
  - Elasto-plastic Continuum Models
  - Elasto-plastic Uniaxial models
- **Boundary Conditions**
  - Equal DOF
  - Absorbent boundaries

Finite Elements (solids)

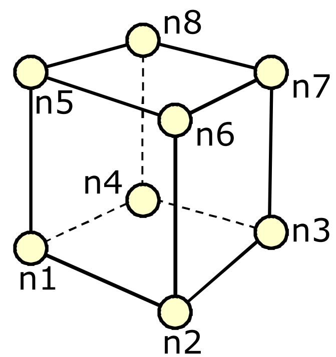
- **Single-phase formulations**
  - To capture the response of dry soils (or total stress analysis) →need one single phase
    - Phase 1 – soil skeleton
- **Multi-phase formulations**
  - To capture the response of saturated soils (effective stress analysis) → need two phases
    - Phase 1 → Soil skeleton
    - Phase 2 → pore water
- **Zero-Length element**
  - To capture interface response between solid and beam elements, and to apply absorbent boundary conditions

Single Phase Formulations

- Small deformation solid elements
  - 2-D quadrilateral elements (4, 9 nodes)
  - 3-D solid elements, brick (8, 20 nodes)
- Large deformation (total Lagrangian) solid elements, bricks (20 nodes)

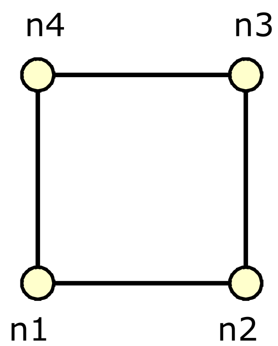


quad (4 node)



stdBrick (8 node)

quad element definition



quad (4 node)

element quad $eleTag $n1 $n2 $n3 $n4 $thick $type $matTag
<$press $rho $b1 $b2>

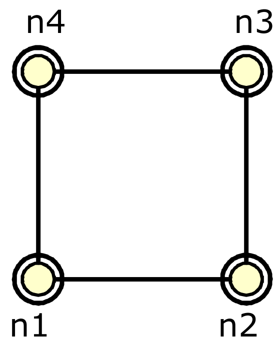
Must define first all the required arguments. In particular:

- **Nodes** $n1, $n2, $n3, $n4 and
- **Material type** $matTag

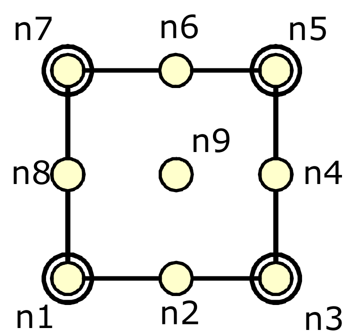
The arguments in <…> are optional

Multi-Phase Formulations

- Fully coupled u-p elements (2D & 3D)
- Fully coupled u-p-U elements (3D) for small deformations



quadUP

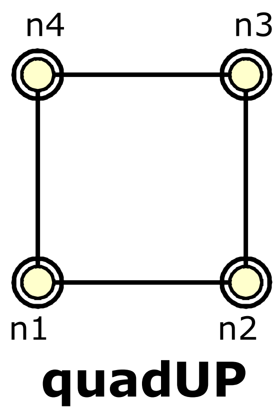


9_4_quadUP

Degrees of Freedom (DOFs) are:

- u → solid displacement, on
- P → pore fluid pressures, on
- U → pore fluid displacements, on

quadUP element definition

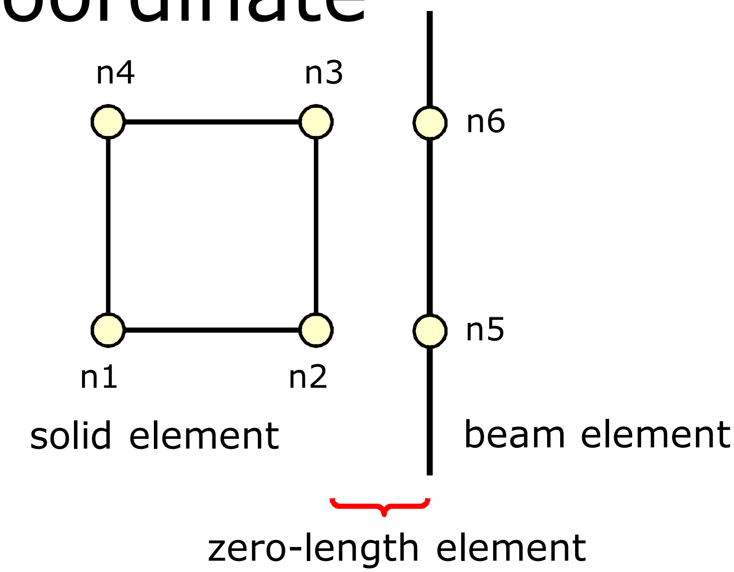


element quadUP $eleTag $n1 $n2 $n3 $n4 $thick $type $matTag
$bulk $fmass $hPerm $vPerm <$b1 $b2 $t>

$bulk → combined undrained bulk modulus $B_c = B_f/n$
$fmass → fluid mass density
$hperm & $vperm → horiz. And vert. permeability

zerolength element

- Connects two points at the same coordinate



element zeroLength $eleTag $n1 $n2 **–mat** $matTag1 $matTag2 …
-dir $dir1 $dir2 … <**-orient** $x1 $x2 $x3 $yp1 $yp2 $yp3>

Material Models

- Linear Elastic Material model (**nDMaterial**)
  - To characterize the response of the soil (or other continuum) in its elastic regime
- Elasto-Plastic Material models (**nDMaterial**)
  - To characterize the nonlinear stress-strain response of soils
- Elasto-plastic Uniaxial models
  - To characterize the interface response between soil and structural elements (**uniaxialMaterial**).

nDMaterial Elastic

- Small deformation elasticity
  - Linear isotropic
  - Nonlinear isotropic
  - Cross anisotropic

- Elastic Isotropic Material

```
nDMaterial ElasticIsotropic $matTag $E $v
```

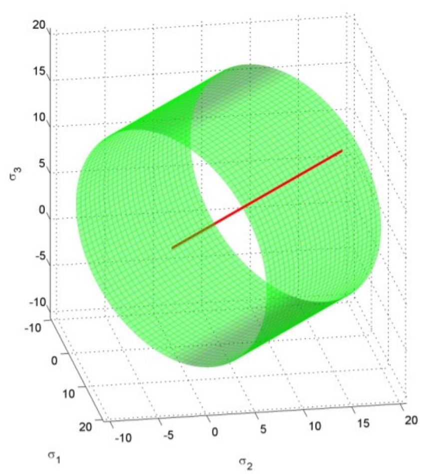
nDMaterial
Elasto-Plastic (Small Deformations)

- J2-Plasticity Material (von Mises)
- Drucker-Prager Material (UW)
- Template Elasto-Plastic Material (UC Davis)
- Cam-Clay Material (Berkeley, UW)
- MutiYield Materials (San Diego)
- FluidSolidPorous Material(SanDiego)

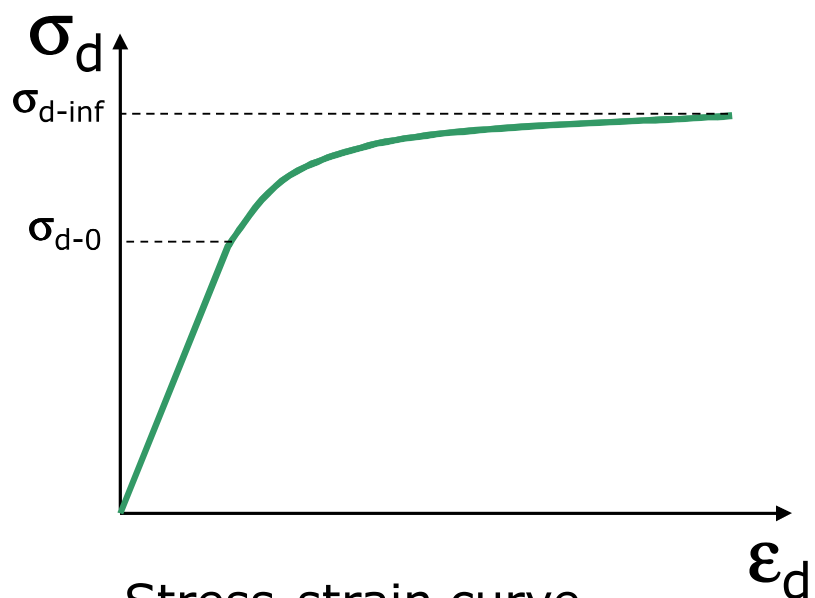
nDMaterial J2Plasticity

- von-Mises type

nDMaterial J2Plasticity $matTag $K $G $sig0 $sigInf $delta $H



Von-Mises Yield Surface



Stress-strain curve

nDMaterial
Template Elasto-Plastic Material

- Versatile tool to generate multiple types of elasto-plastic materials by combining **yield surfaces**, **plastic potentials** and **evolution laws**

- Developed by Boris Jeremic at UC Davis
  `http://sokocalo.engr.ucdavis.edu/~jeremic`

nDMaterial
Template Elasto-Plastic Material

nDMaterial Template3Dep $matTag $ElmatTag
–YS $ys **–PS** $ps **–EPS** $eps <**-ELS1** $el> <**-ELT1** $et>

-YS → Yield surfaces (von Mises, Drucker Prager, Mohr-Coulomb, Camclay)

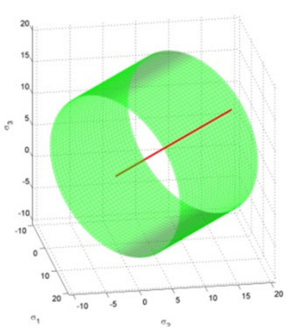
-PS → Plastic potentials (von Mises, Drucker-Prager Mohr-Coulomb, Camclay, Leon)

-EPS → Initial state of stress

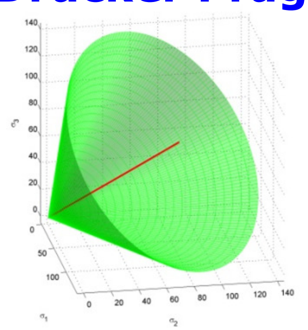
-ELS1 → Scalar evolution laws for isotropic hardening (linear, nonlinear Camclay)

-ELT1 → Tensorial evolution laws for Kinematic hardening (linear, nonlinear Armstrong-Frederick)

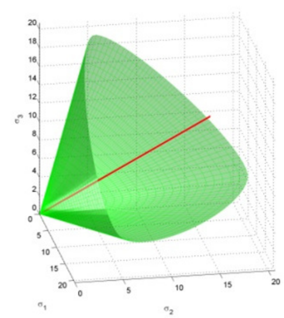
Von-Mises



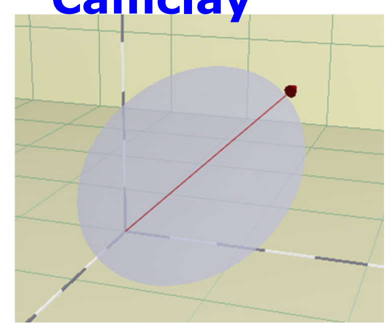
Drucker Prager



Mohr-Coulomb



Camclay



nDMaterial
MultiYield Materials

- Material models based on Multiyield Plasticity *(Mroz et al., Prevost et al.)*

- Two types
  - Pressure Independent Multi-yield (for total stress analysis)
  - Pressure Dependent Multi-yield (captures well the response of liquefiable soils)

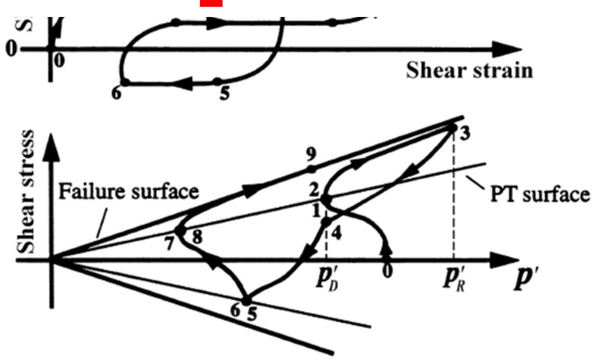
  - Fluid-solid porous material (Material to couple solid &fluid phases)

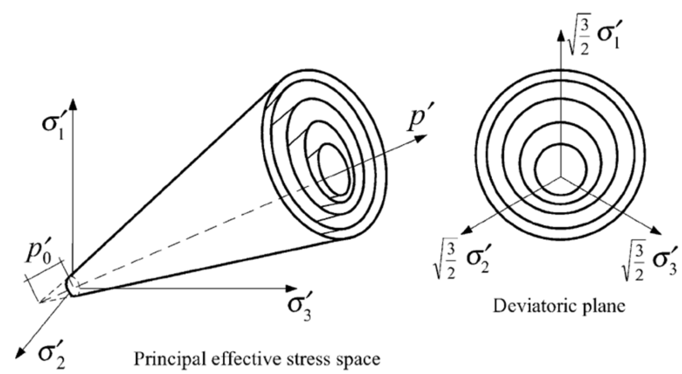
- Developed by Elgamal et al. at UCSD
  http://cyclic.ucsd.edu/opensees/

nDMaterial PressureDependentMultiYield

```
nDMaterial PressureDependMultiYield $matTag $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>
```

15 parameters!!??

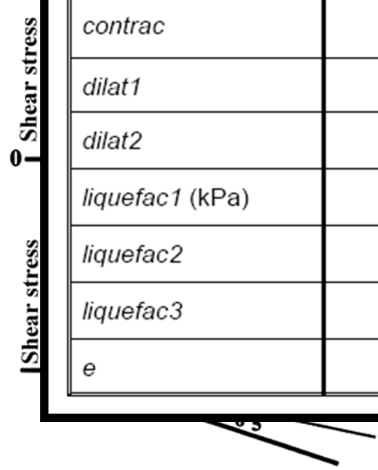


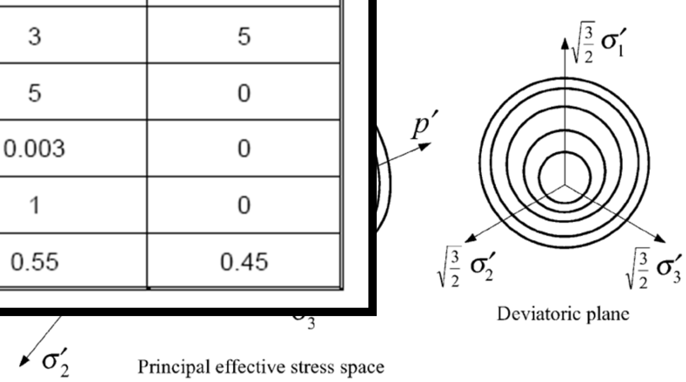


nDMaterial PressureDependentMultiYield

nDMat … nd $rho
$refShe … earStra
$refPre
$contra … fac3
<$noYi
$e=0.(

	Loose Sand (15%-35%)	Medium Sand (35%-65%)	Medium-dense Sand (65%-85%)	Dense Sand (85%-100%)
rho (ton/m^3)	1.7	1.9	2.0	2.1
refShearModul (kPa, at p'_r=80 kPa)	5.5×10^4	7.5×10^4	1.0×10^5	1.3×10^5
refBulkModu (kPa, at p'_r=80 kPa)	1.5×10^5	2.0×10^5	3.0×10^5	3.9×10^5
frictionAng	29	33	37	40
peakShearStra (at p'_r=80 kPa)	0.1	0.1	0.1	0.1
refPress (p'_r, kPa)	80	80	80	80
pressDependCoe	0.5	0.5	0.5	0.5
PTAng	29	27	27	27
contrac	0.21	0.07	0.05	0.03
dilat1	0.	0.4	0.6	0.8
dilat2	0	2	3	5
liquefac1 (kPa)	10	10	5	0
liquefac2	0.02	0.01	0.003	0
liquefac3	1	1	1	0
e	0.85	0.7	0.55	0.45

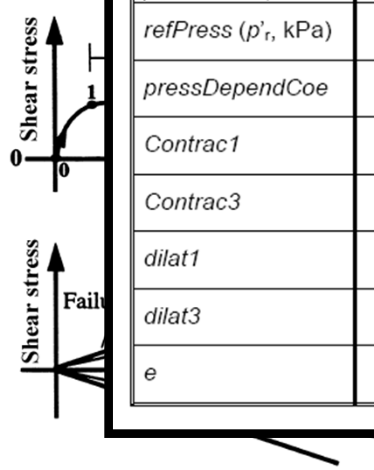


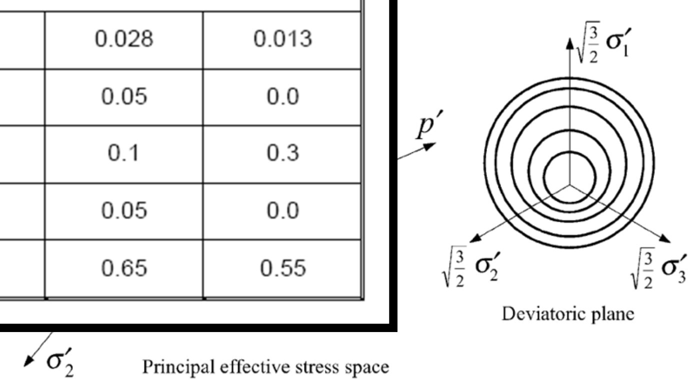


nDMaterial PressureDependentMultiYield02

nDMater $nd $rho
$refBulkM
$pressDe
$contrac1
<$noYield
$contrac2 =0.0
$e=0.6 $

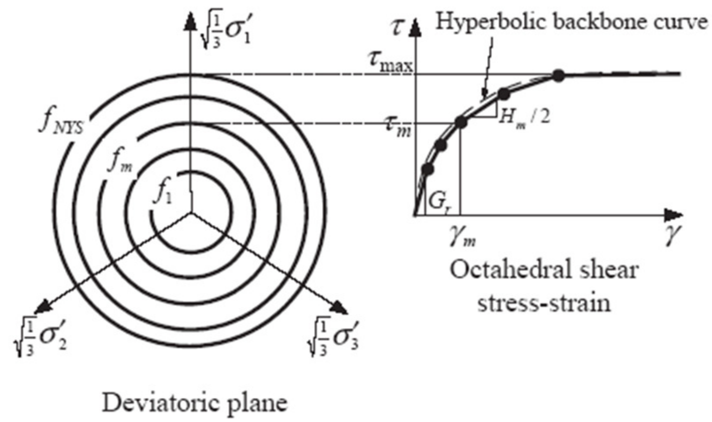
	Dr=30%	Dr=40%	Dr=50%	Dr=60%	Dr=75%
rho (ton/m3)	1.7	1.8	1.9	2.0	2.1
refShearModul (kPa, at p'$_r$=80 kPa)	6x10^4	9x10^4	10x10^4	11x10^4	13x10^4
refBulkModu (kPa, at p'$_r$=80 kPa)	16x10^4 (K_0=0.5)	22x10^4 (K_0=0.47)	23.3x10^4 (K_0=0.45)	24x10^4 (K_0=0.43)	26x10^4 (K_0=0.4)
frictionAng	31	32	33.5	35	36.5
PTAng	31	26	25.5	26	26
peakShearStra (at p'$_r$=101 kPa)	0.1				
refPress (p'$_r$, kPa)	101				
pressDependCoe	0.5				
Contrac1	0.087	0.067	0.045	0.028	0.013
Contrac3	0.18	0.23	0.15	0.05	0.0
dilat1	0.	0.06	0.06	0.1	0.3
dilat3	0.0	0.27	0.15	0.05	0.0
e	0.85	0.77	0.7	0.65	0.55





nDMaterial PressureIndependentMultiYield

nDMaterial PressureIndependMultiYield $matTag $nd $rho $refShearModul $refBulkModul $cohesi $peakShearStra $frictionAng $refPress=101 $pressDependCoe=0. <$noYieldSurf=20 <$r1 $Gs1 …>>



nDMaterial FluidSolidPorousMaterial

- Couples the response of two phases:fluid and solid – developed to simulate the response of saturated porous media

nDMaterial FluidSolidPorousMaterial $matTag $nd $soilMatTag $combinedBulkModul

$soilMatTag → the tag of previously defined material
$combinedBulkModul → combined undrained bulk modulus, Bc=Bf/n

nDMaterial FluidSolidPorousMaterial

- Couples the response of two phases:fluid and solid – developed to simulate the response of saturated porous media

nDMaterial FluidSolidPorousMaterial $matTag $nd
$soilMatTag $combinedBulkModul

$soilMatTag → the tag of previously defined material
$combinedBulkModul → combined undrained bulk modulus, Bc=Bf/n

nDMaterial
Other Models under development

nDMaterial BoundingCamClay

nDMaterial Manzari-Dafalias

Additional commands for **multiyield** materials

- Help perform stage analysis

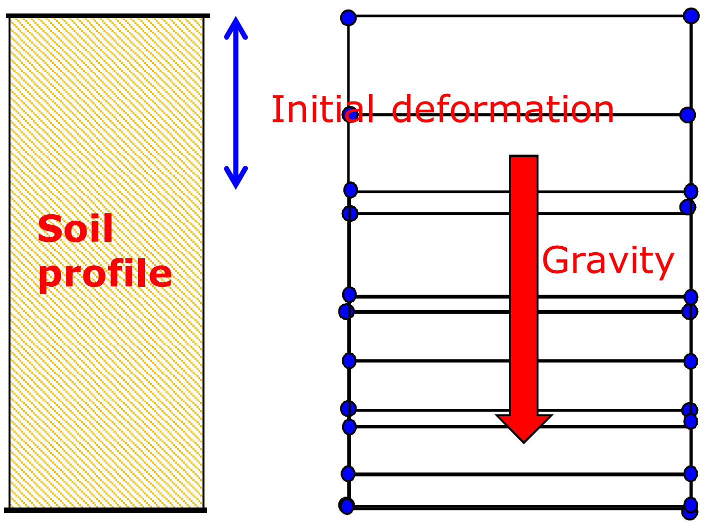
updateMaterialStage –material \$matTag **–stage** \$sNum

\$MatTag → the tag of previously defined material
\$sNum → (0 - elastic, 1-plastic, 2 – linear elastic constant **f(σ_3)**)

updateParameter –material \$matTag **–refG** \$newVal

\$MatTag → the tag of previously defined material
\$sNewVal → new parameter value

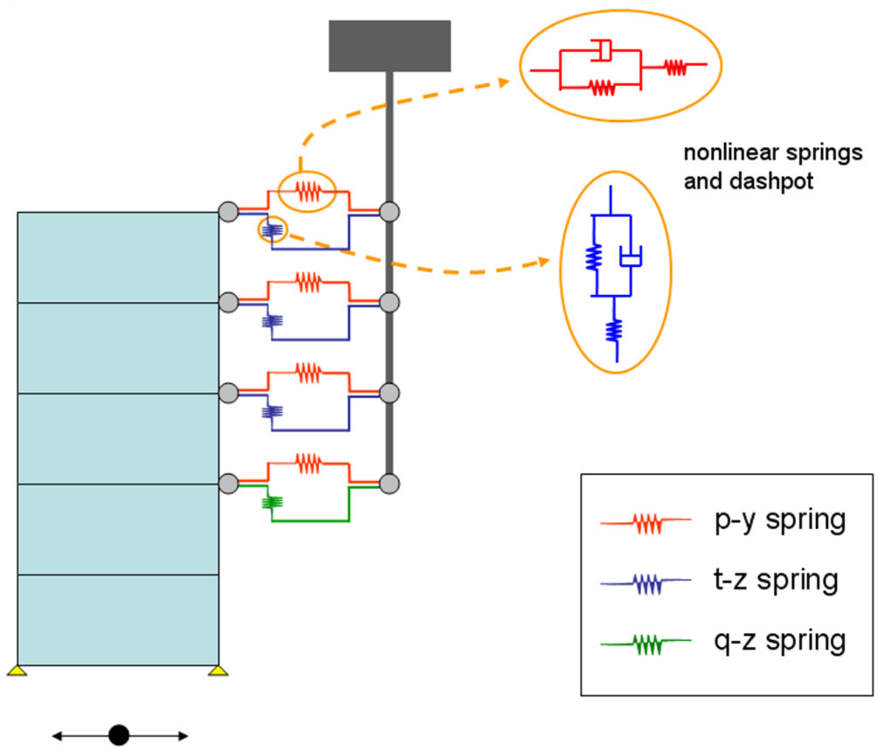
Initial State for Geotechnical Problems




```
# turn on initial state analysis feature
InitialStateAnalysis on

# create incremental gravity load
pattern Plain 3 {Series -time {0 10 10000} -values {0 1 1} -factor 1} {
    eleLoad -ele 1 -type –selfWeight
    eleLoad -ele 2  -type –selfWeight
    .
    .
    .
}

  analysis steps …

# turn on initial state analysis feature
InitialStateAnalysis off
```

Elasto-plastic Uniaxial models

- To capture interface response between solid (soil) and beam elements (pile)



Py Tz Qz Uniaxial Materials

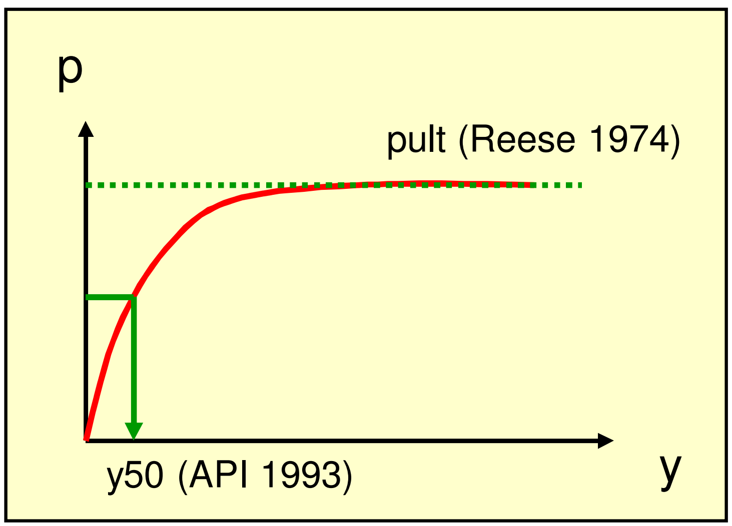
- PySimple1
- TzSimple1
- QzSimple1

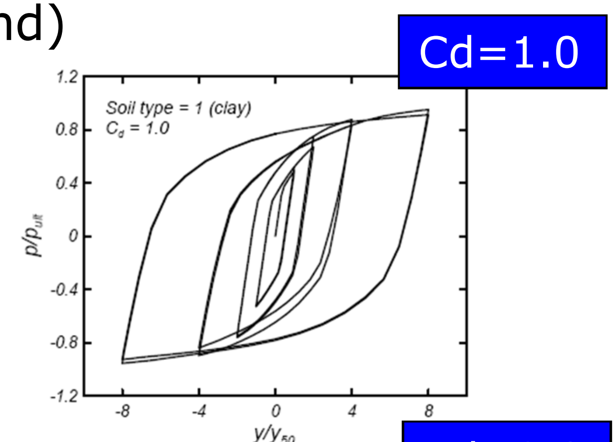
- PyLiq1
- TzLiq1

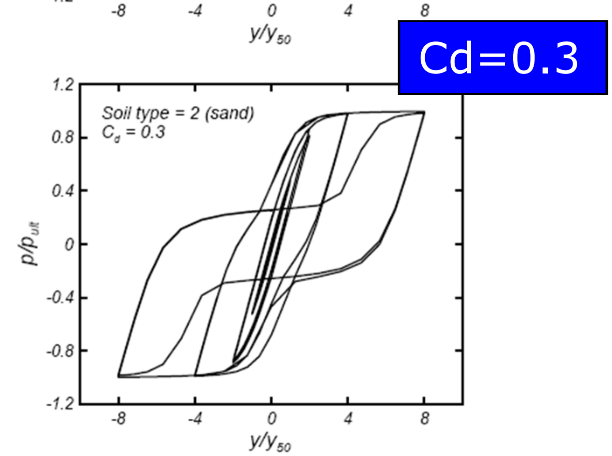
uniaxialMaterial PySimple1

uniaxialMaterial PySimple1 matTag $soilType $pult $Y50 $Cd <$c>

$soilType → =1 Matlock (clay), =2 API (sand)
$pult → ultimate capacity of p-y material
$Y50 → displ. @ 50% of pult
Cd → drag resistance (=1 no gap, <1 gap)
$c → viscous damping







uniaxialMaterial TzSimple1 & QzSimple1

uniaxialMaterial TzSimple1 matTag $tzType $tult $z50 <$c>

$tzType→ =1 Reese & O'Neill (clay), =2 Mosher (sand)
$tult → ultimate capacity of t-z material
$z50 → displ. @ 50% of tult
$c → viscous damping

uniaxialMaterial QzSimple1 matTag $qzType $qult $z50 <$suction $c>

$qzType→ =1 Reese & O'Neill (clay), =2 Vijayvergiya (sand)
$qult = ultimate capacity of q-z material
$z50 = displ. @ 50% of qult
$suction → uplift resistance = suction*qult
$c viscous damping

uniaxialMaterial PyLiq1

uniaxialMaterial PyLiq1 $matTag $soilType $pult $Y50 $Cd $c $pRes $solidElem1 $solidElem2

$soilType → =1 Matlock (clay), =2 API (sand)
$pult → ultimate capacity of p-y material
$Y50 → displ. @ 50% of pult
Cd → drag resistance (=1 no gap, <1 gap)
$c → viscous damping
$pRes → residual (minimum) p-y resistance as r_u=1.0
$solidElem1 & $solidElem2 → solid elements from which PyLiq1 will obtain effective stresses and pore pressures

uniaxialMaterial PyLiq1

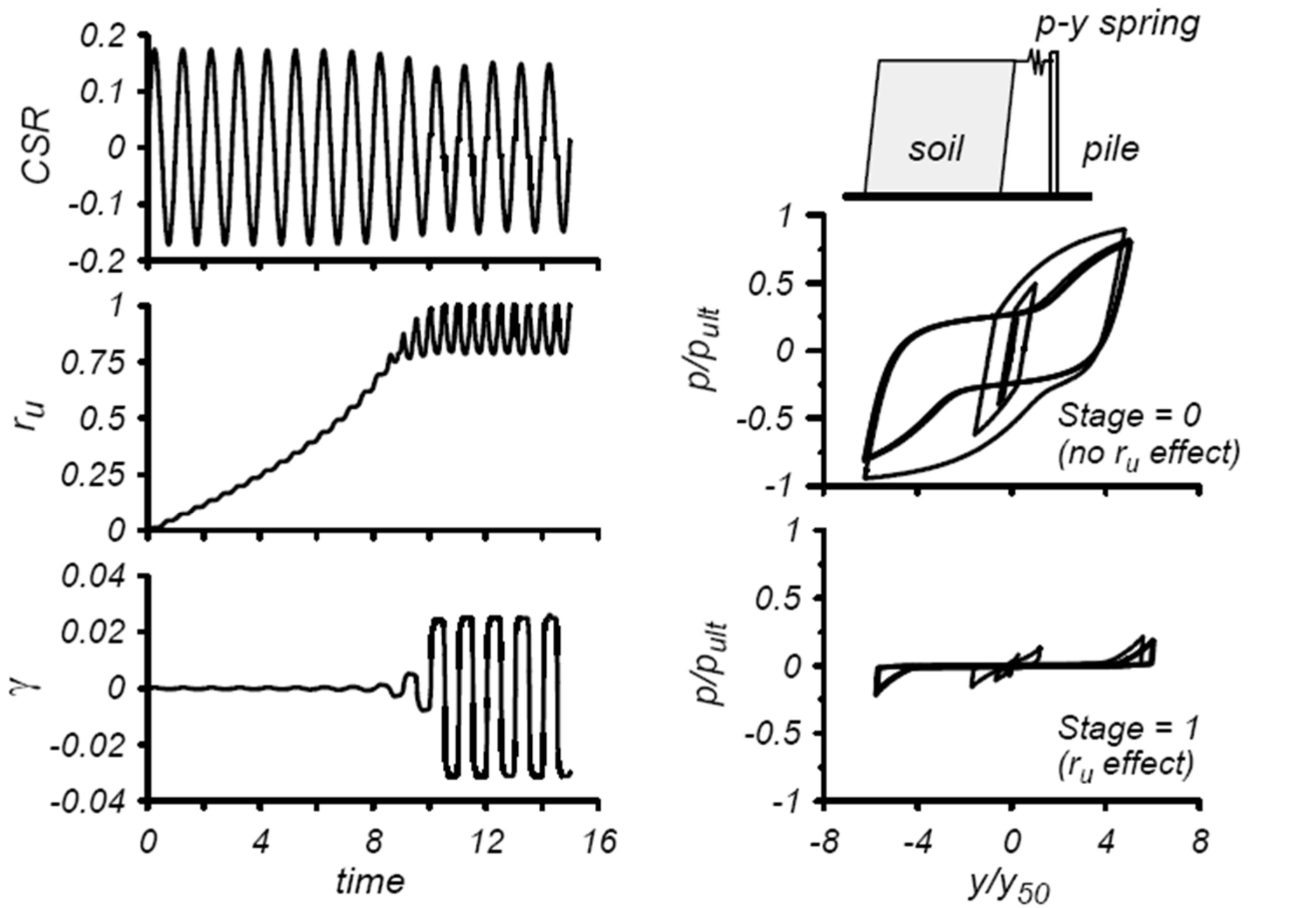


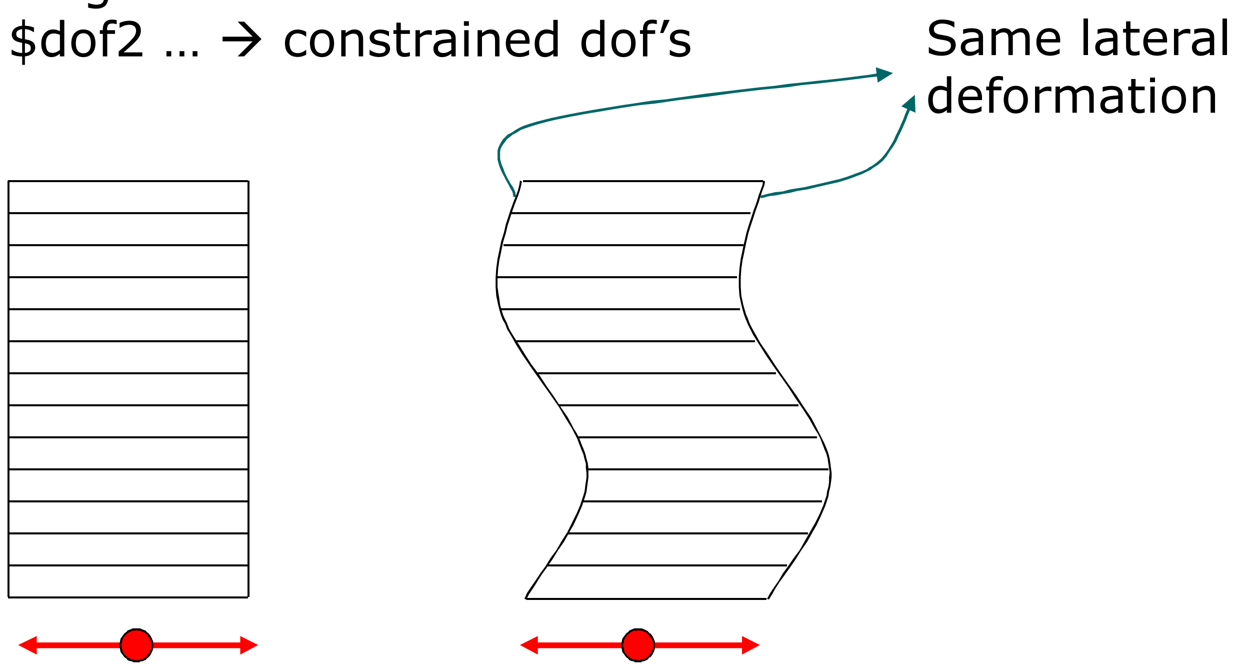
FIG. Example of PyLiq1 behavior during liquefaction without lateral spreading.

Boundary Conditions

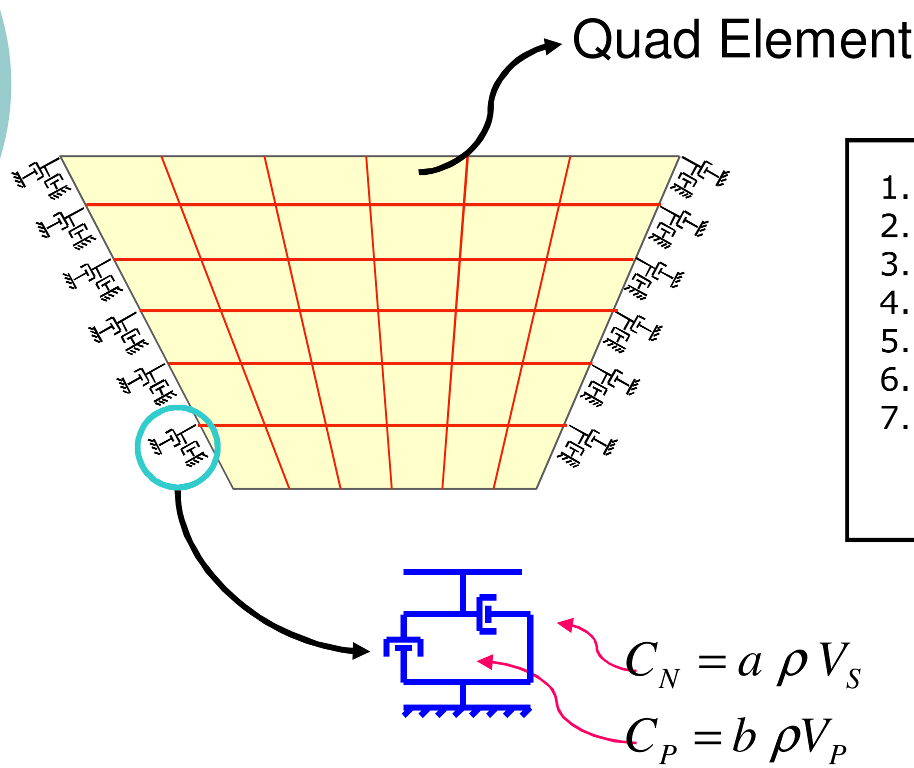
- EqualDof

equalDOF $rNodeTag $cNodeTag $dof1 $dof2 …

$rNodeTag → master node
$cNodeTag → slave node
$dof1 $dof2 … → constrained dof's



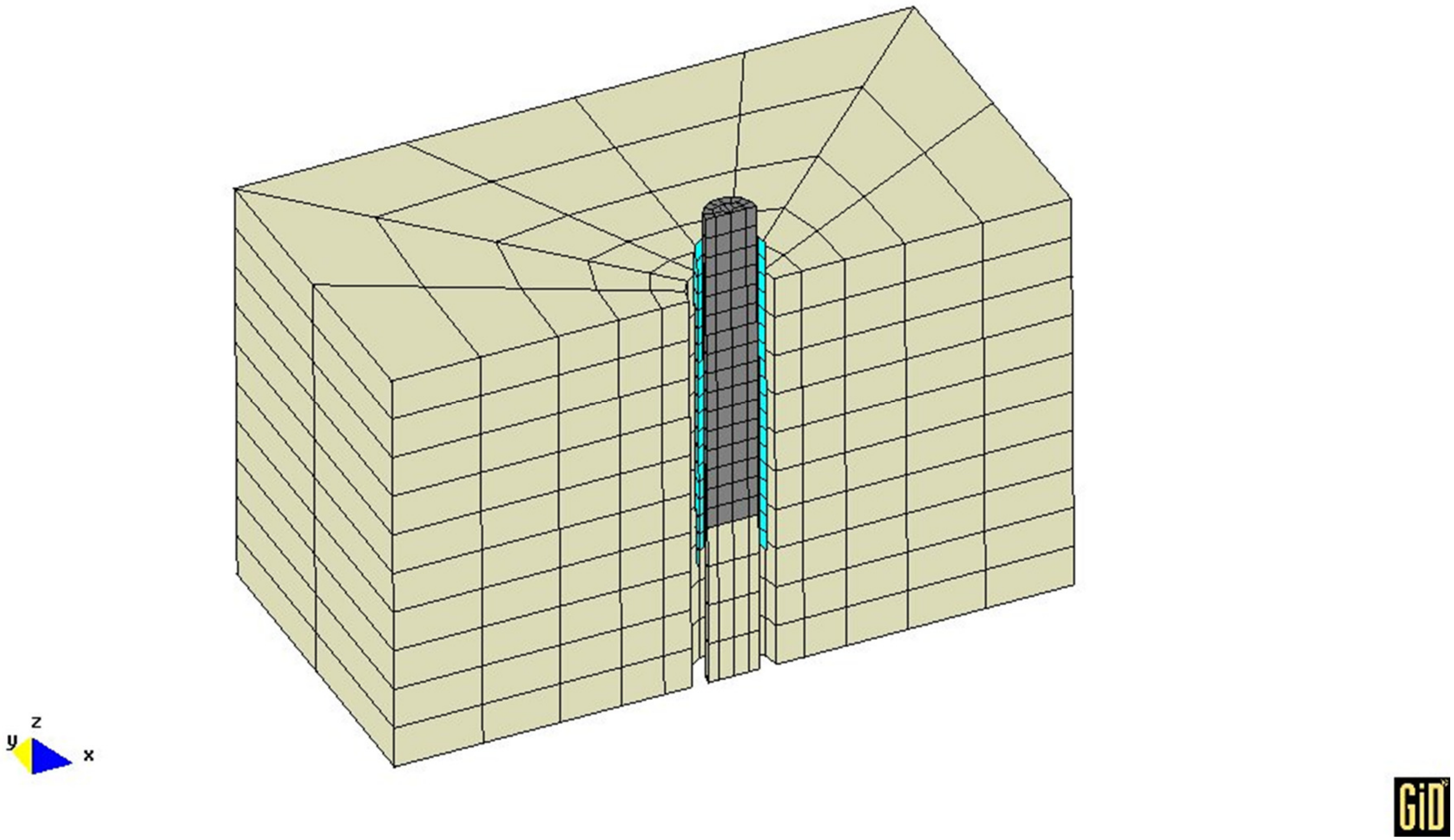
Absorbent/transmitting Boundaries
Lysmer (1969)



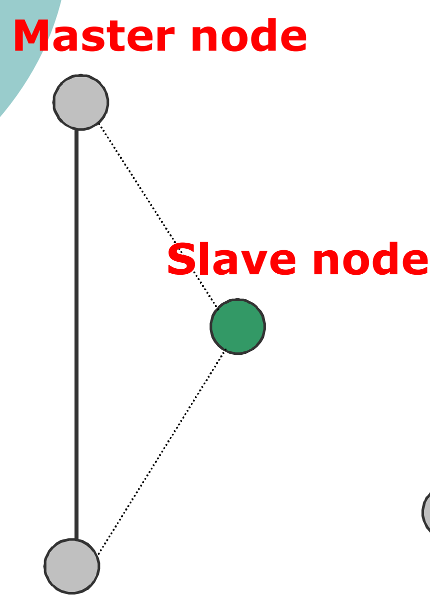
zeroLength Element &
uniaxial material

```
1. set DampP 755
2. set DampN 1216
3. uniaxialMaterial Elastic   1  0 $DampP
4. uniaxialMaterial Elastic   2  0 $DampN
5. node 1 16.0 0.0
6. node 2 16.0 0.0
7. element zeroLength 1 1  2  -mat 1  2
    -dir 1 2 –orient 1 –2 0 2 1 0
```

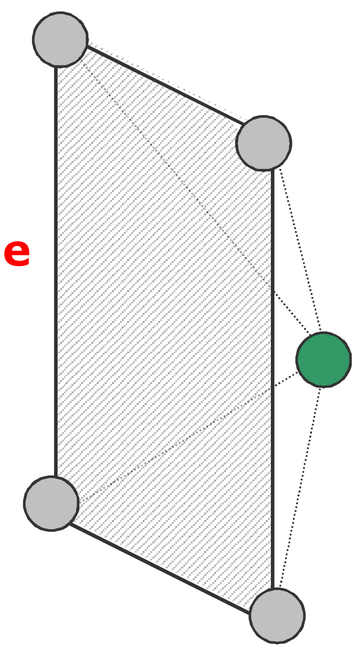
Contact Elements available in OpenSees



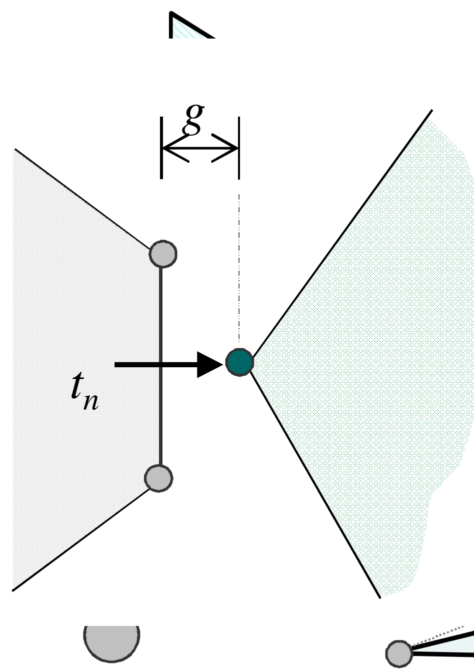
Contact Elements available in OpenSees



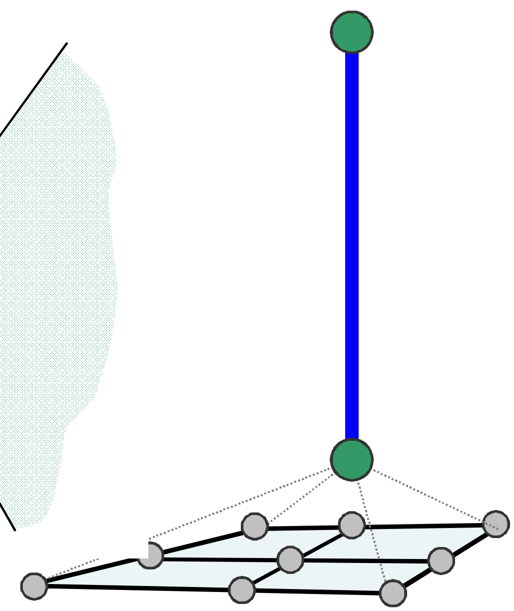
2D Node-to-Line Element



3D Node-to-Surface Element



3D Beam-to-Solid Element

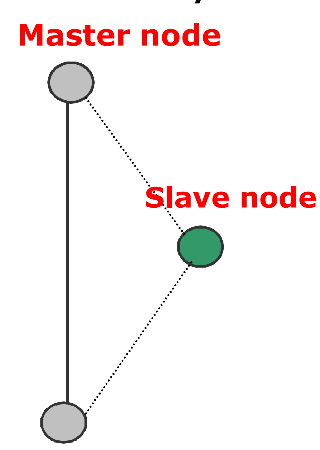


3D End-Beam-to-Solid Element

Contact Elements available in OpenSees

element SimpleContact2D $eleTag $iNode $jNode $sNode $lNode $matTag $gTol $fTol

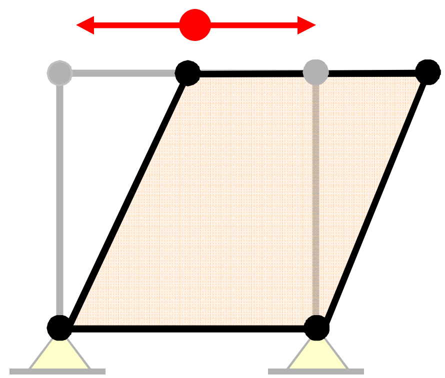
$eleTag → unique integer tag identifying element object
$iNode $jNode → master nodes
$sNode → slave node
$lNode → Lagrange multiplier node
$matTag → unique integer tag associated with previously-defined nDMaterial object
$gTol → gap tolerance
$fTol → force tolerance

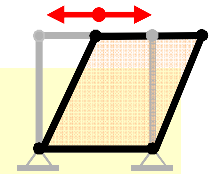


Many more capabilities currently under development!!

Basic Example

- Response of saturated soil element to harmonic excitation

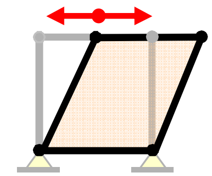




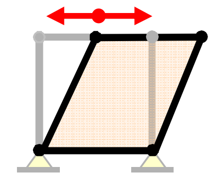
Define basic variables using good names!!!

```
#Created by Zhaohui Yang (zhyang@ucsd.edu)
#plastic pressure dependent material
#plane strain,  single element,  dynamic analysis (input motion: sinusoidal acceleration at base)
#SI units (m, s, KN, ton)
#
#        4     3
#        -------
#        |     |
#        |     |
#        |     |
#       1-------2   (nodes 1 and 2 fixed)
#        ^     ^
#         <--> input motion: sinusoidal acceleration at base
wipe
#

#some user defined variables
#
set accMul   2          ;# acceleration multiplier
set massDen  2.0      ;# solid mass density
set fluidDen 1.0       ;# fluid mass density
set massProportionalDamping   0.0 ;
set stiffnessProportionalDamping 0.001 ;
set fangle 31.40        ;#friction angle
set ptangle 26.50        ;#phase transformation angle
set E      90000.0      ;#shear modulus
set poisson 0.40 ;
set G [expr $E/(2*(1+$poisson))] ;
set B [expr $E/(3*(1-2*$poisson))] ;
set press   0.0 ;# isotropic consolidation pressure on quad element(s)
set deltaT   0.010   ;# time step for analysis
set numSteps 2000   ;# Number of analysis steps
set gamma    0.600    ;# Newmark integration parameter
set period   1      ;# Period of applied sinusoidal load
set pi 3.1415926535     ;
set inclination 0       ;
set unitWeightX [expr  ($massDen-$fluidDen)*9.81*sin($inclination/180.0*$pi)] ;# unit weight in X direction
set unitWeightY [expr -($massDen-$fluidDen)*9.81*cos($inclination/180.0*$pi)] ;# unit weight in Y direction
```

Define model geometry, materials & fixities



```
############################################################

############################################################

#create the ModelBuilder
model basic -ndm 2 -ndf 2

# define material and properties
nDMaterial PressureDependMultiYield 2 2 $massDen $G $B  $fangle .1 80 0.5 \
                        $ptangle 0.17 0.4 10  10 0.015 1.0
nDMaterial FluidSolidPorous 1 2 2 2.2D+6

updateMaterialStage -material 1 -stage 0
updateMaterialStage -material 2 -stage 0

# define the nodes
node 1   0.0D0 0.0D0
node 2   1.0D0 0.0D0
node 3   1.0D0 1.0D0
node 4   0.0D0 1.0D0

# define the element     thick  material     maTag   press    mDensity   gravity
element quad  1  1 2 3 4  1.0   "PlaneStrain"    1   $press     0.      $unitWeightX  $unitWeightY

# fix the base
fix 1 1 1
fix 2 1 1

#tie nodes 3 and 4
equalDOF 3 4   1 2
```

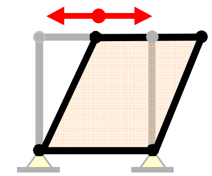


Define gravity step

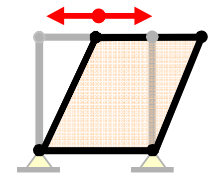
VERY IMPORTANT!!!

```
##################################################################
# GRAVITY APPLICATION (elastic behavior)
# create the SOE, ConstraintHandler, Integrator, Algorithm and Numberer
system ProfileSPD
test NormDispIncr 1.D-12 25 0
constraints Transformation
integrator LoadControl 1 1 1 1
algorithm Newton
numberer RCM

# create the Analysis
analysis Static

#analyze
analyze 2

# switch the material to plastic
updateMaterialStage -material 1 -stage 1
updateMaterialStage -material 2 -stage 1
updateParameter -material 2 -refB [expr $G*2/3.];

#analyze
analyze 1
```

Define dynamic step

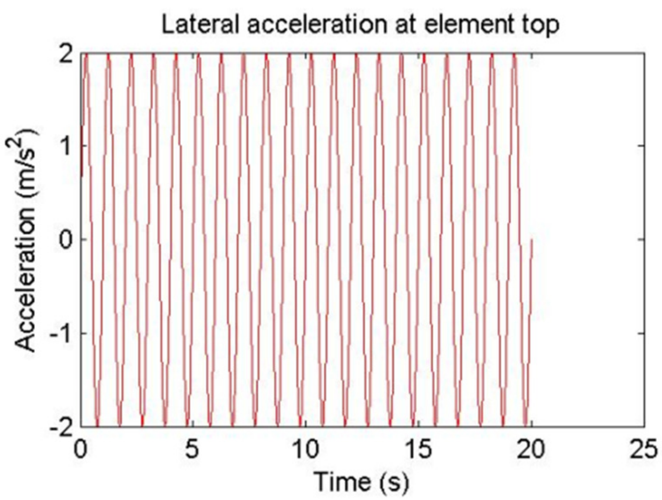


```
##################################################
# NOW APPLY LOADING SEQUENCE AND ANALYZE (plastic)

# rezero time
setTime 0.0
wipeAnalysis

#create loading pattern
pattern UniformExcitation 1 1 -accel "Sine 0 1000 $period -factor $accMul"

# create the Analysis
constraints Transformation;
test NormDispIncr 1.D-12 25 0
algorithm Newton
numberer RCM
system ProfileSPD
integrator Newmark $gamma  [expr pow($gamma+0.5, 2)/4]  \
               $massProportionalDamping 0.0 $stiffnessProportionalDamping 0.0
analysis VariableTransient

#create Recorders
recorder Node -file disp.out   -time  -node 1 2 3 4 -dof 1 2 -dT  0.01 disp
recorder Node -file acce.out  -time  -node 1 2 3 4 -dof 1 2 -dT 0.01 accel
recorder Element -ele 1 -time -file stress1.out material 1 stress -dT 0.01
recorder Element -ele 1 -time -file strain1.out material 1 strain -dT 0.01
recorder Element -ele 1 -time -file stress3.out material 3 stress -dT 0.01
recorder Element -ele 1 -time -file strain3.out material 3 strain -dT 0.01
recorder Element -ele 1 -time -file press1.out material 1 pressure -dT 0.01
recorder Element -ele 1 -time -file press3.out material 3 pressure -dT 0.01

#analyze
set startT [clock seconds]
analyze $numSteps $deltaT [expr $deltaT/100] $deltaT 10
set endT [clock seconds]
puts "Execution time: [expr $endT-$startT] seconds."

wipe  #flush ouput stream
```

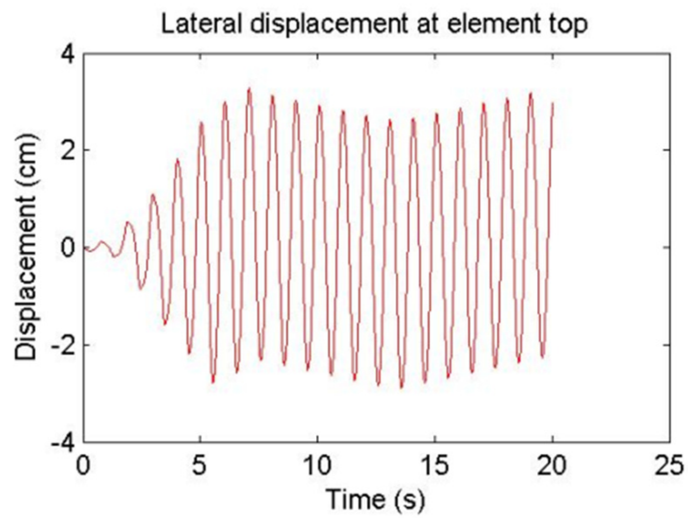


Plot Results

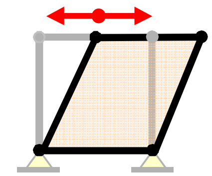
Input Accel time history



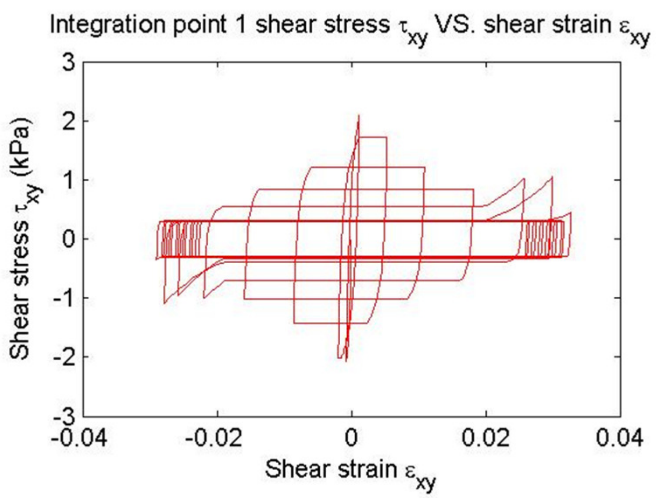
Output displ. time history

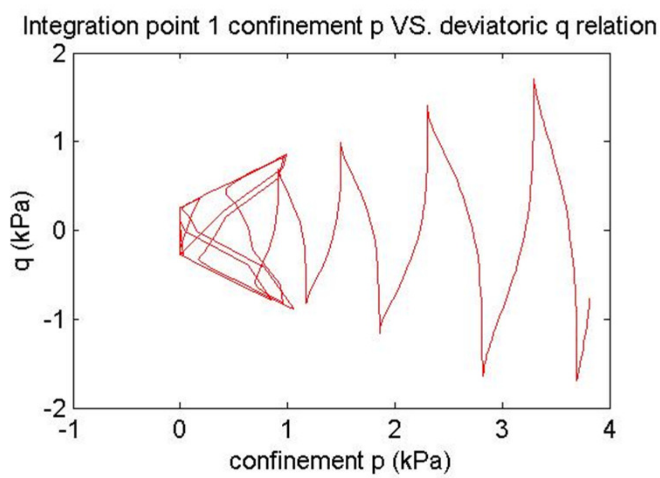


Plot results



Stress-strain & stress path





Pore pressures