Geotechnical Elements and Models in **OpenSees**

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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

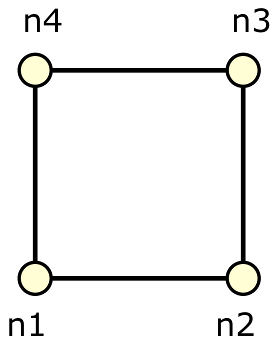
- **Finite Elements** (for solids)
  - Single-phase
  - Multi-phase (coupled) finite elements
  - Zero length element
  - Contact element
- **Material Models**
  - Elastic
  - Elasto-plastic Continuum Models
  - Elasto-plastic Uniaxial models
- **Boundary Conditions**
  - Equal DOF
  - Absorbent boundaries

Finite Elements (solids)

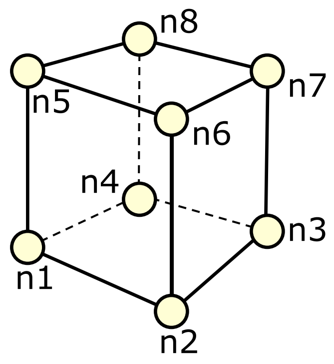
- **Single-phase formulations**
  - To capture the response of dry soils (or total stress analysis) →need one single phase
    - Phase 1 – soil skeleton
- **Multi-phase formulations**
  - To capture the response of saturated soils (effective stress analysis) → need two phases
    - Phase 1 → soil skeleton
    - Phase 2 → pore water
- **Zero-Length & contact elements**
  - 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)

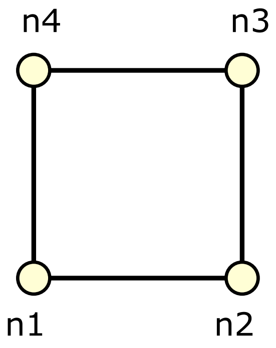


quad (4 node)



stdBrick (8 node)

quad element definition



quad (4 node)

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

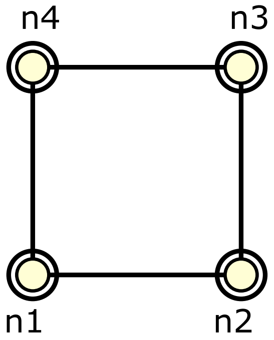
Must define first all the required arguments. In particular:

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

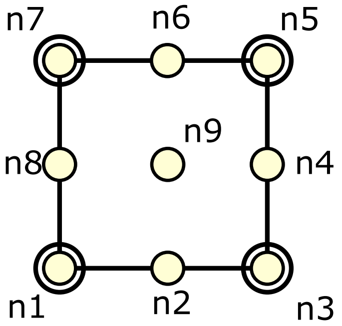
The arguments in <…> are optional

Multi-Phase Formulations

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



quadUP

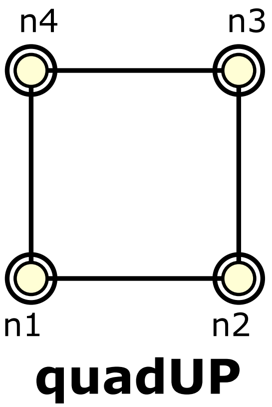


9_4_quadUP

Degrees of Freedom (DOFs) are:

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

quadUP element definition

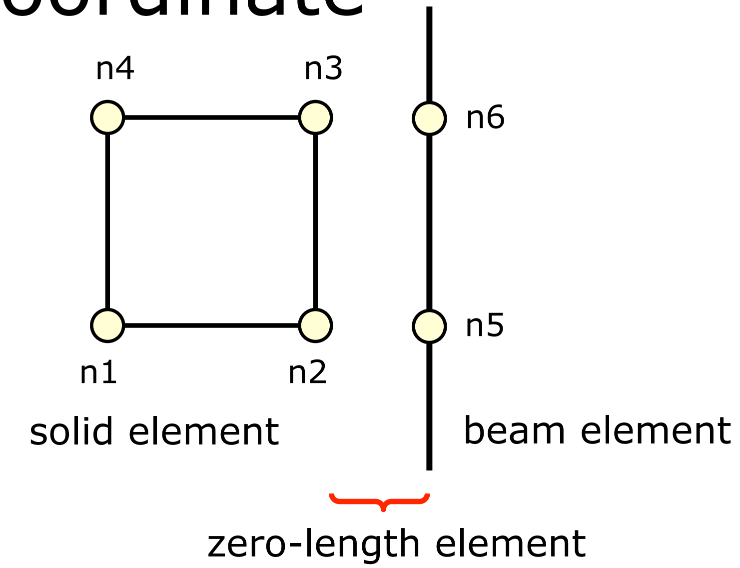


element quadUP $eleTag $n1 $n2 $n3 $n4 $thick $type $matTag $bulk $fmass $hPerm $vPerm <$b1 $b2 $t>

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

zerolength element

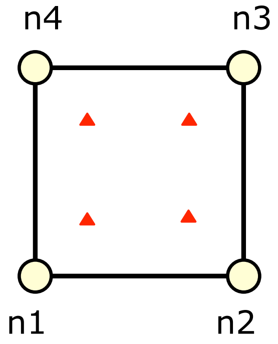
- Connects two points at the same coordinate



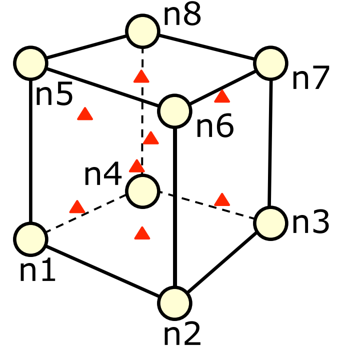
element zeroLength $eleTag $n1 $n2 **–mat** $matTag1 $matTag2 …
-dir $dir1 $dir2 … <**-orient** $x1 $x2 $x3 $yp1 $yp2 $yp3>

Recent Developments at UW

Standard 2D and 3D solid Elements

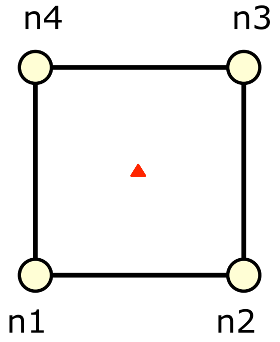


quad (4 node)

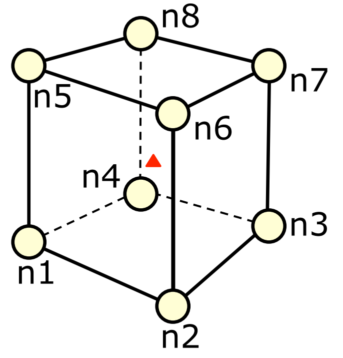


stdBrick (8 node)

Stabilized Single Point 2D and 3D Solid Elements



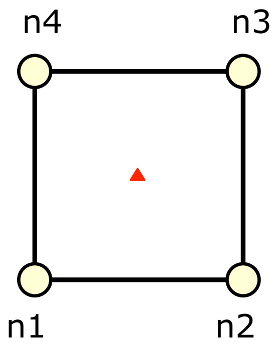
SSPquad (4 node)



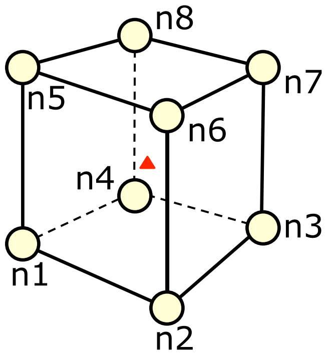
SSPBrick (8 node)

Recent Developments at UW

Stabilized Single Point 2D and 3D Solid Elements

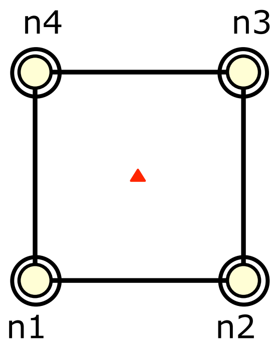


SSPquad (4 node)

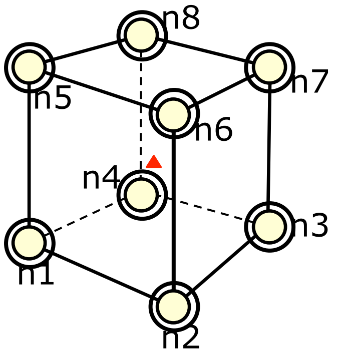


SSPBrick (8 node)

UP - Stabilized Single Point 2D and 3D Solid Elements



SSPquad-up (4 node)



SSPBrick-up (8 node)

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

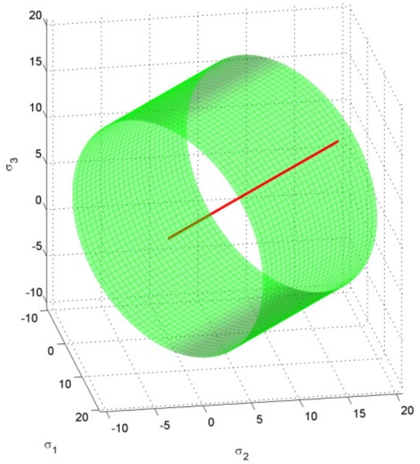
Elasto-Plastic (Small Deformations)

- J2-Plasticity Material (von Mises)
- Drucker-Prager Material (UW)
- Cam-Clay Material (Berkeley, UW)
- MutiYield Materials (San Diego)
- Manzari-Dafalias ***(new)*** (UW)

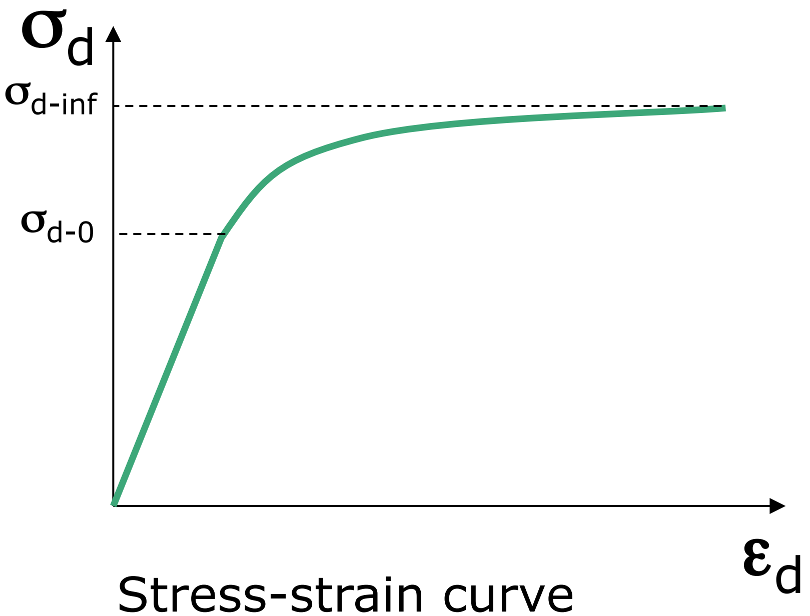
nDMaterial J2Plasticity

- 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)

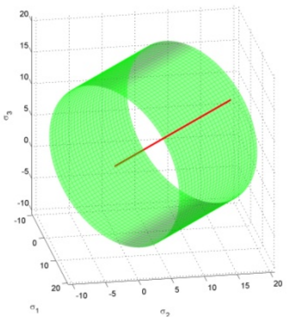
-PS → Plastic potentials (von Mises, Drucker-Prager Mohr-Coulomb, Camclay, Leon)

-EPS → Initial state of stress

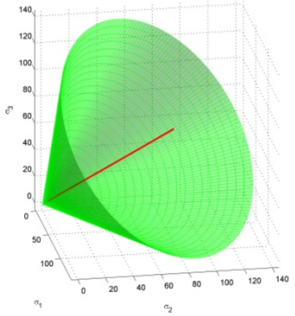
-ELS1 → Scalar evolution laws for isotropic hardening (linear, nonlinear Camclay)

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

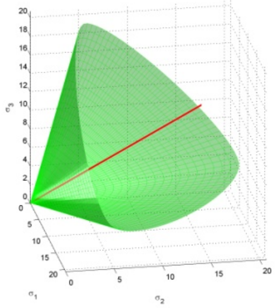
Von-Mises



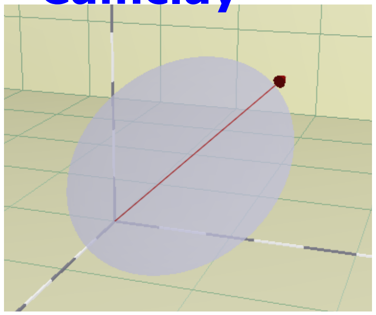
Drucker Prager



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)

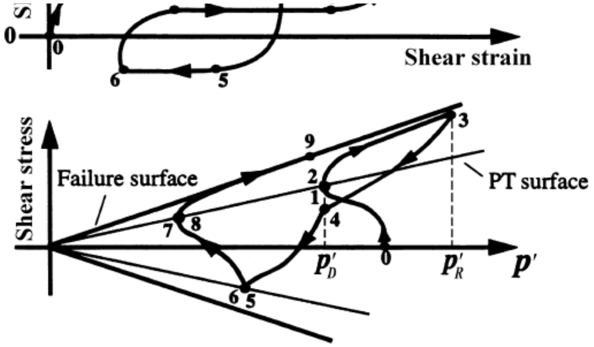
- Developed by Elgamal et al. at UCSD

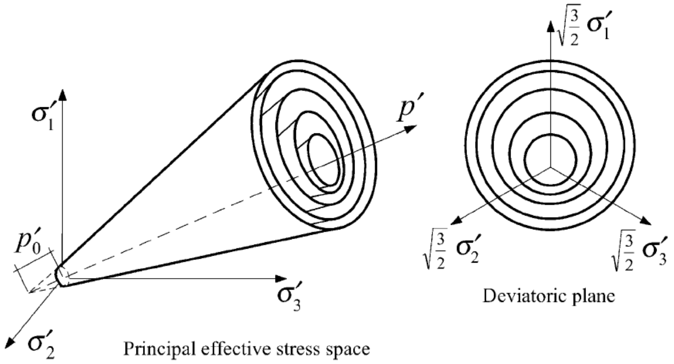
  http://cyclic.ucsd.edu/opensees/

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!!??



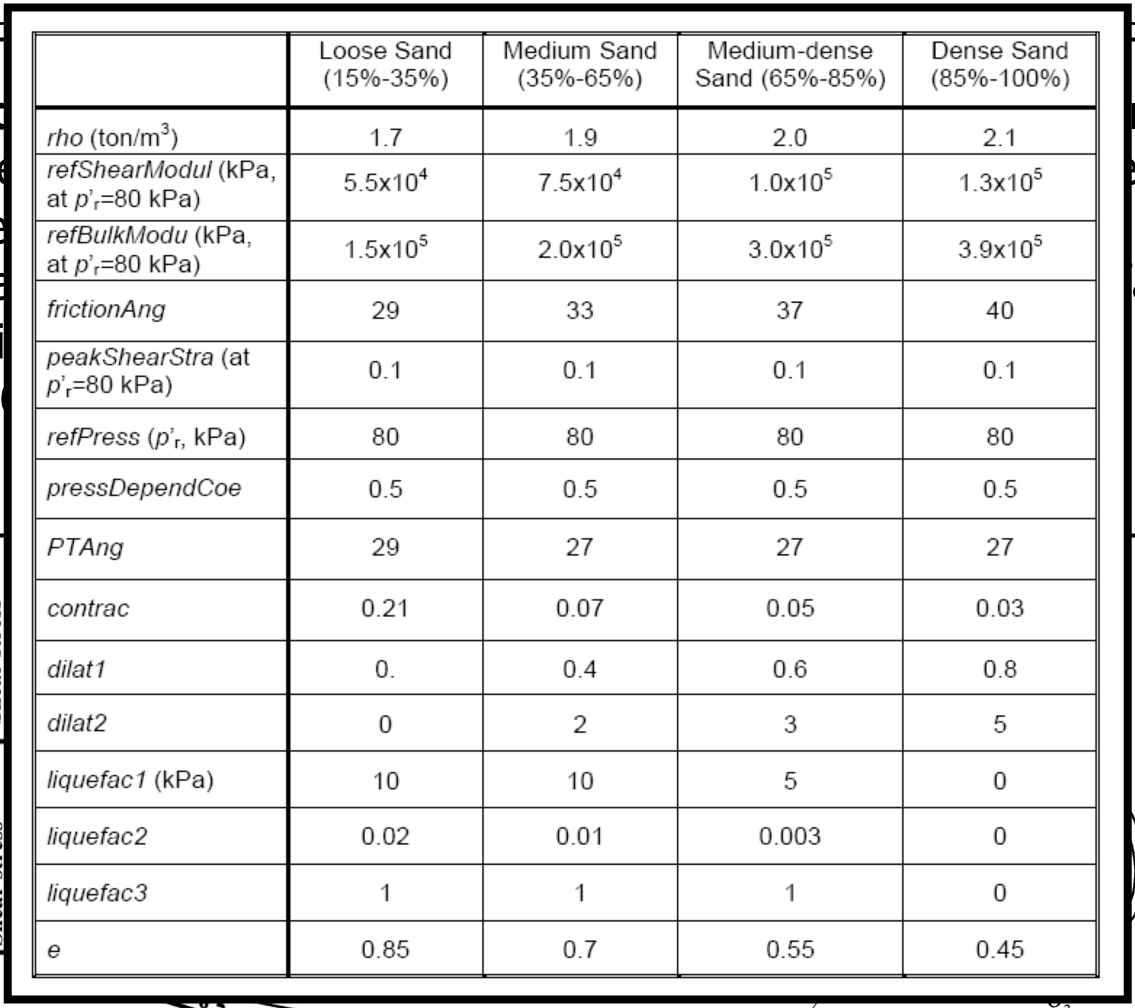


nDMaterial PressureDependentMultiYield

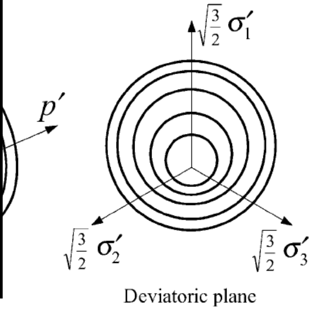
nDMat
$refShe
$refPre
$contra
<$noYi
$e=0.

nd $rho
earStra

ac3



	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)	5.5x10^4	7.5x10^4	1.0x10^5	1.3x10^5
refBulkModu (kPa, at p'_r=80 kPa)	1.5x10^5	2.0x10^5	3.0x10^5	3.9x10^5
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



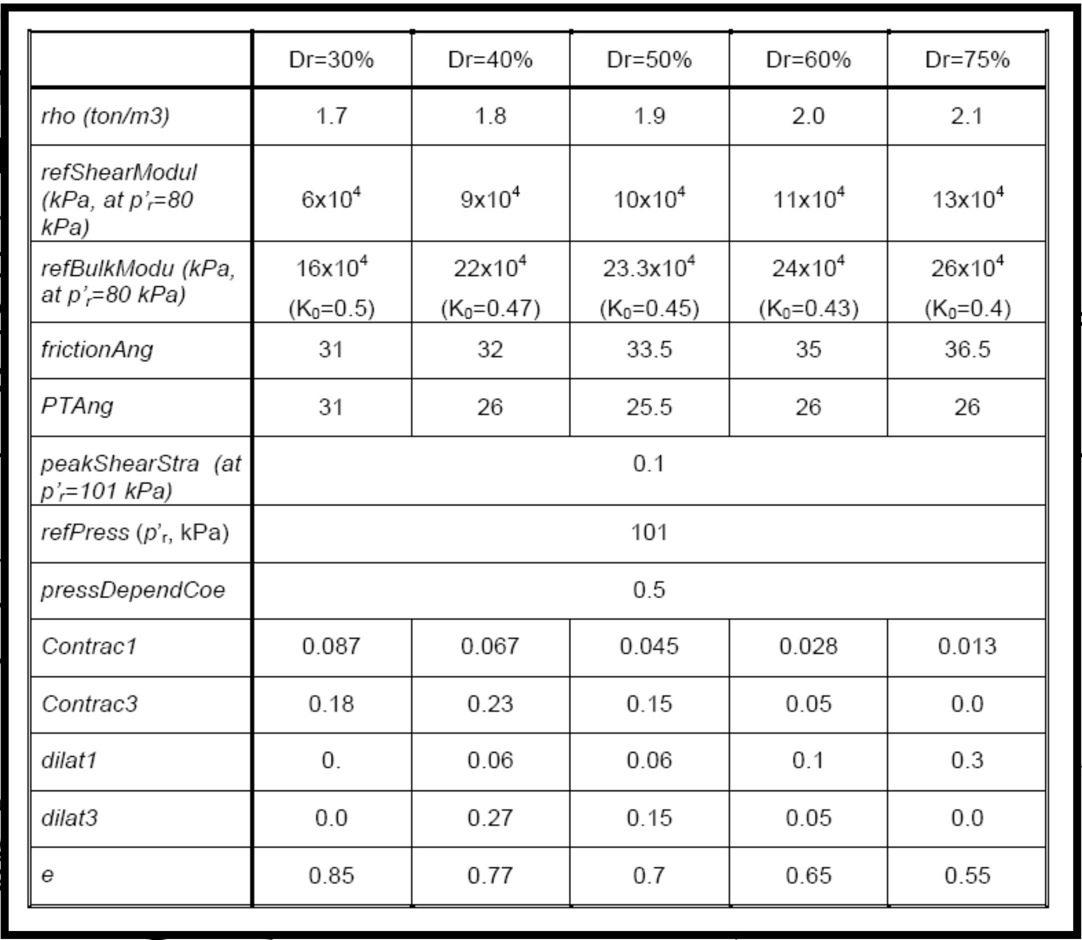
Deviatoric plane

σ'_2

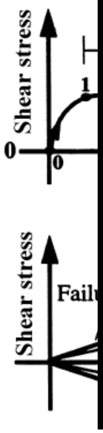
Principal effective stress space

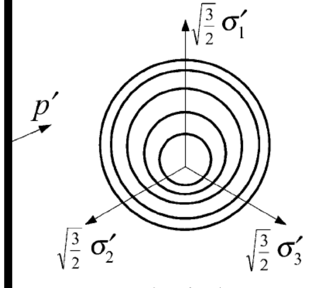
nDMaterial PressureDependentMultiYield02

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



	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





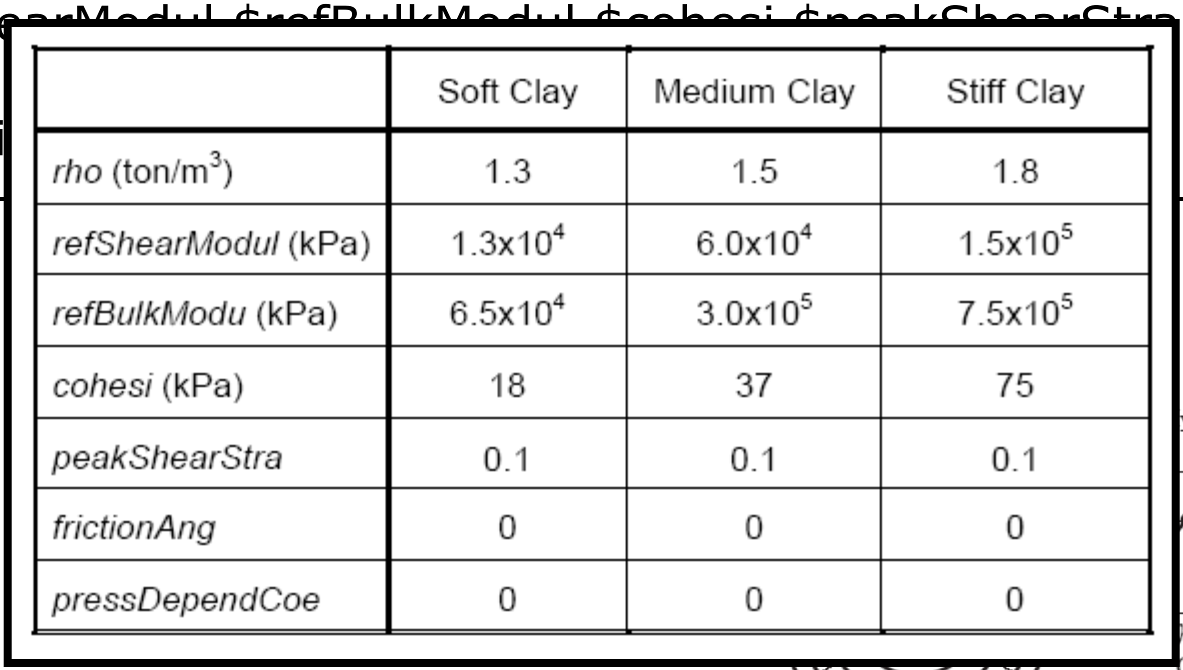
Deviatoric plane

σ'_2

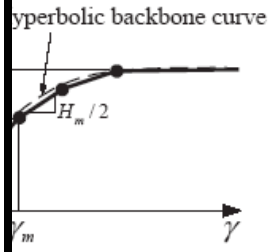
Principal effective stress space

nDMaterial PressureIndependentMultiYield

nDMaterial PressureIndependMultiYield $matTag $nd $rho
$refShearModul $refBulkModul $cohesi $peakShearStra
$frictio
<$noYi



	Soft Clay	Medium Clay	Stiff Clay
rho (ton/m^3)	1.3	1.5	1.8
refShearModul (kPa)	1.3x10^4	6.0x10^4	1.5x10^5
refBulkModu (kPa)	6.5x10^4	3.0x10^5	7.5x10^5
cohesi (kPa)	18	37	75
peakShearStra	0.1	0.1	0.1
frictionAng	0	0	0
pressDependCoe	0	0	0



Octahedral shear stress-strain

Deviatoric plane

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

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
```

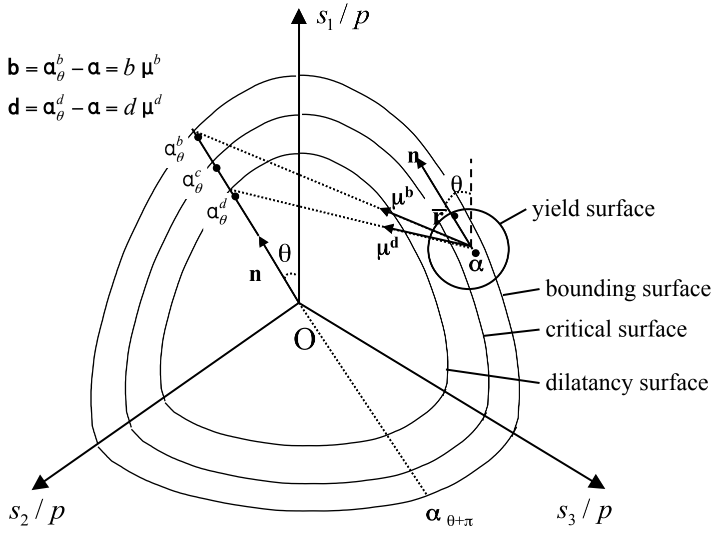
$MatTag → the tag of previously defined material
$sNewVal → new parameter value

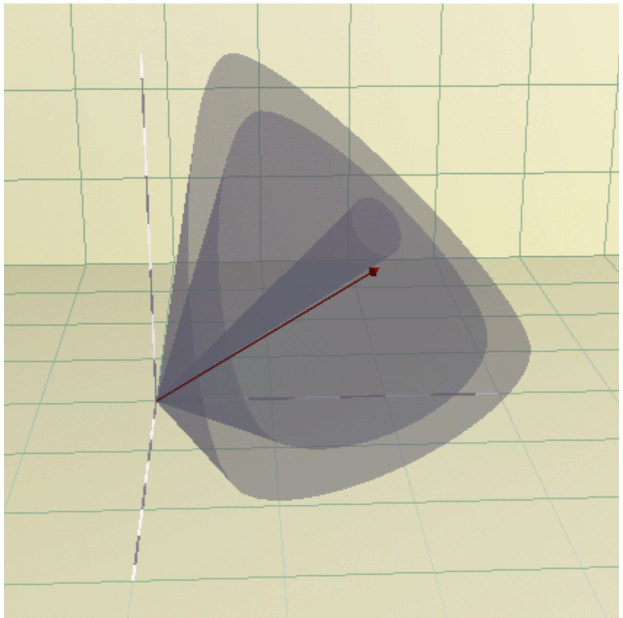
nDMaterial
Other Models under development

nDMaterial BoundingCamClay → (Clays)

nDMaterial Manzari-Dafalias → (Sands)

Bounding Surface Model

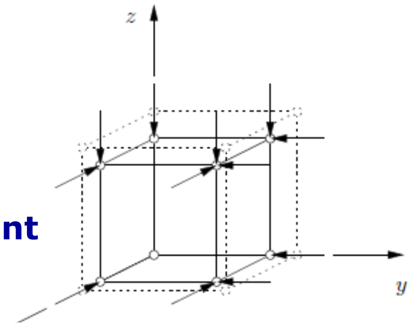




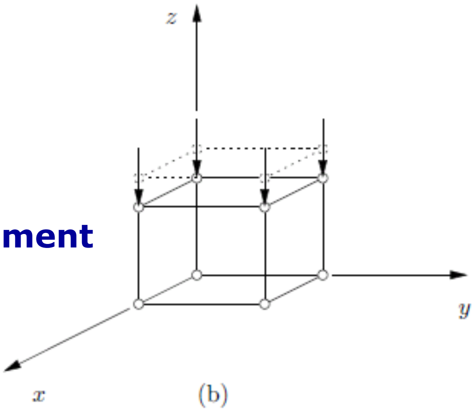
nDMaterial
Manzari-Dafalias (2004)

Conventional Triaxial Test
CTC Undrained

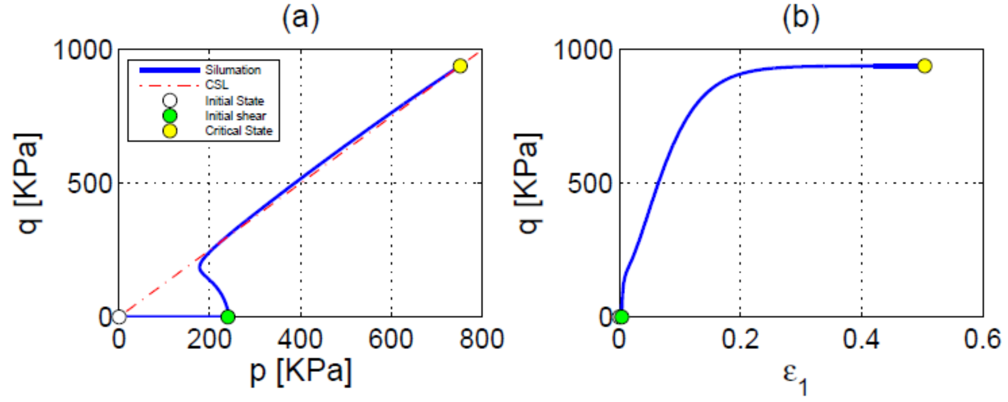
Confinement



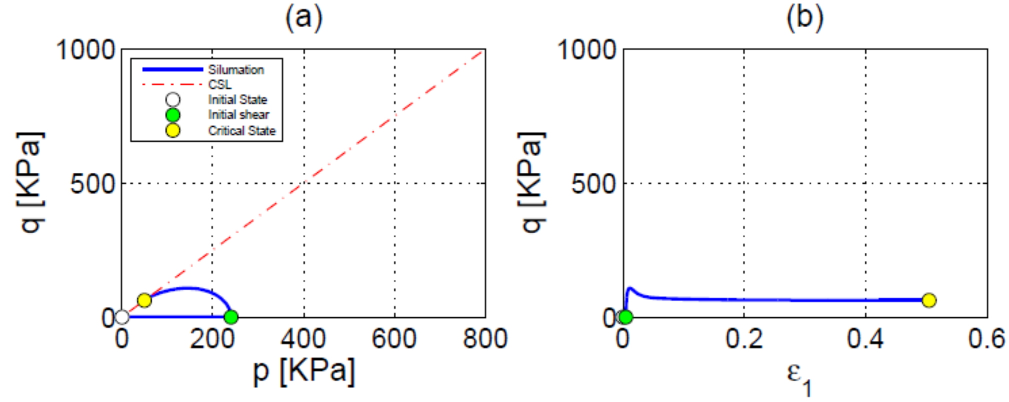
Displacement



Dense Sand



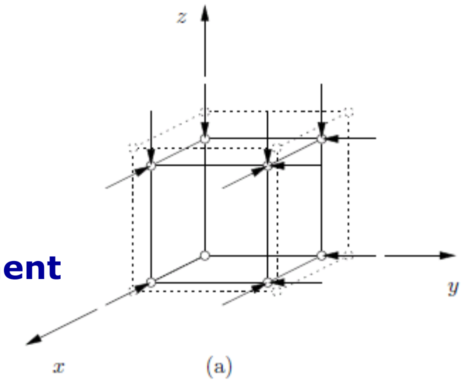
Loose Sand



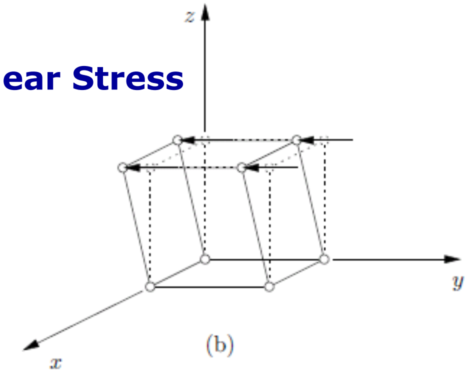
nDMaterial
Manzari-Dafalias (2004)

Cyclic Constant Mean Stress
TC Undrained

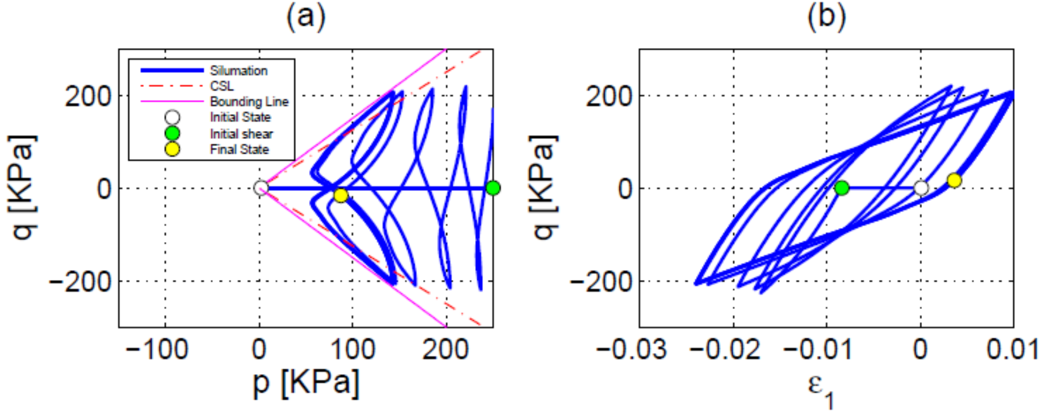
Confinement



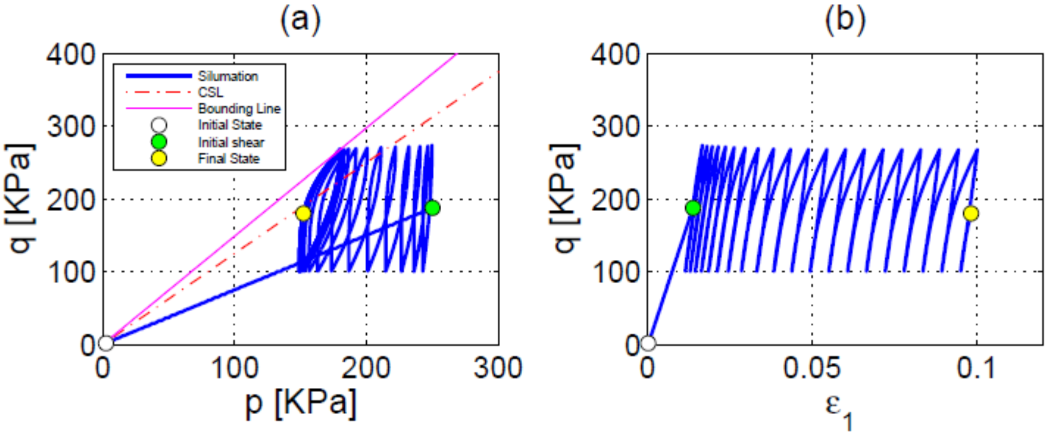
Cyclic Shear Stress



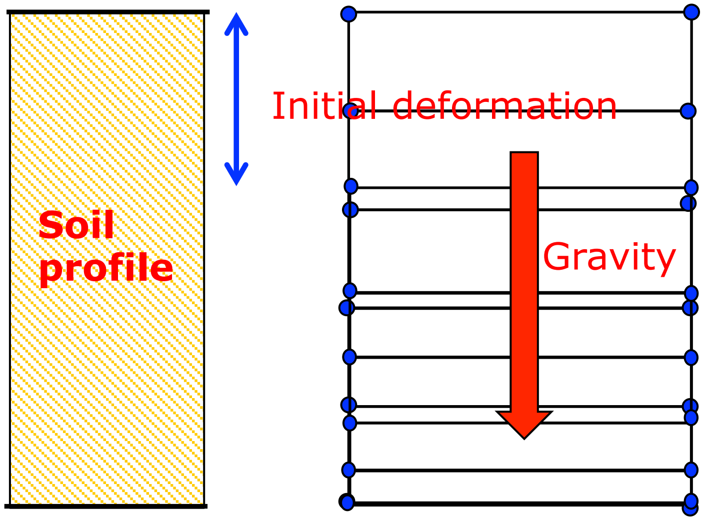
Kα=0



Kα=Ko



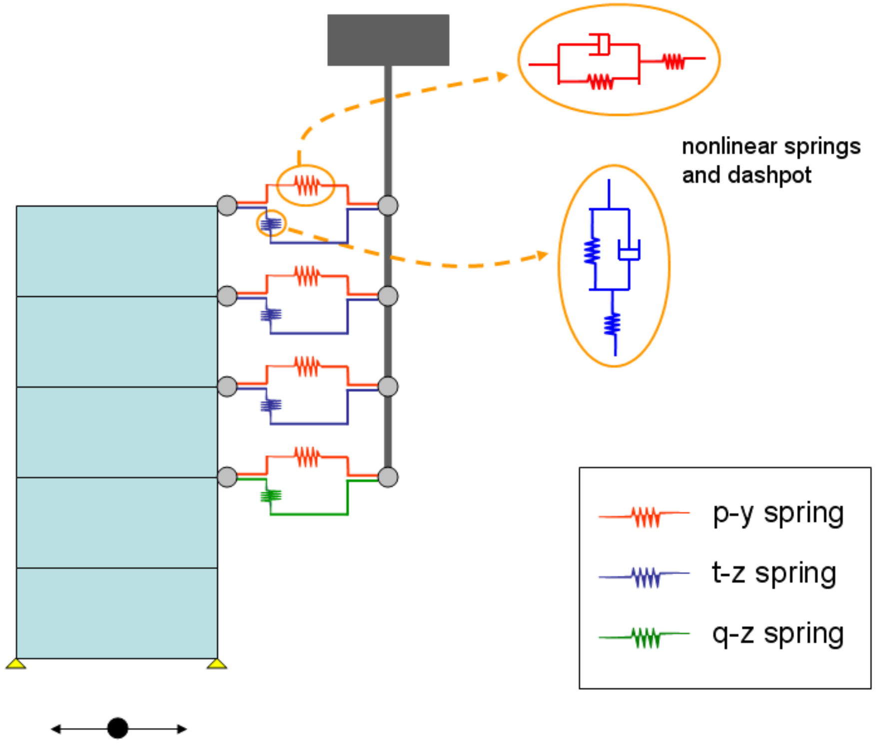
Initial State for Geotechnical Problems



```
# 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

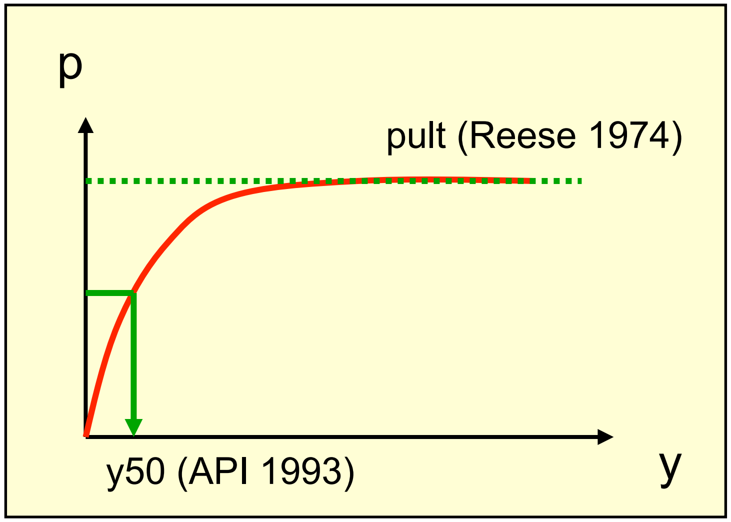
- PySimple1
- TzSimple1
- QzSimple1

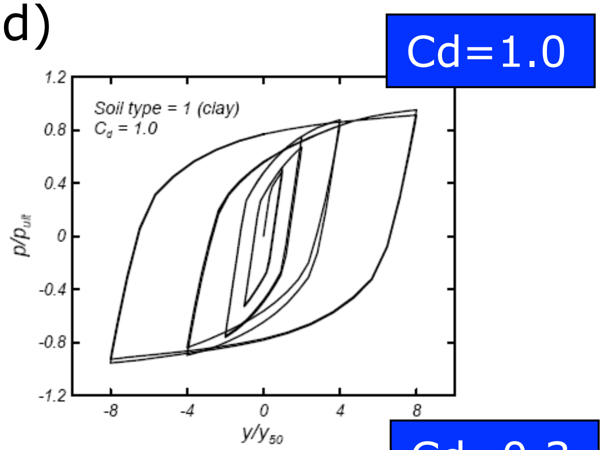
- PyLiq1
- TzLiq1

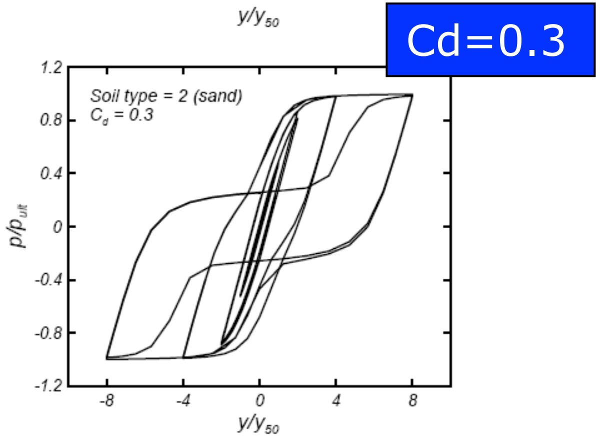
uniaxialMaterial PySimple1

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

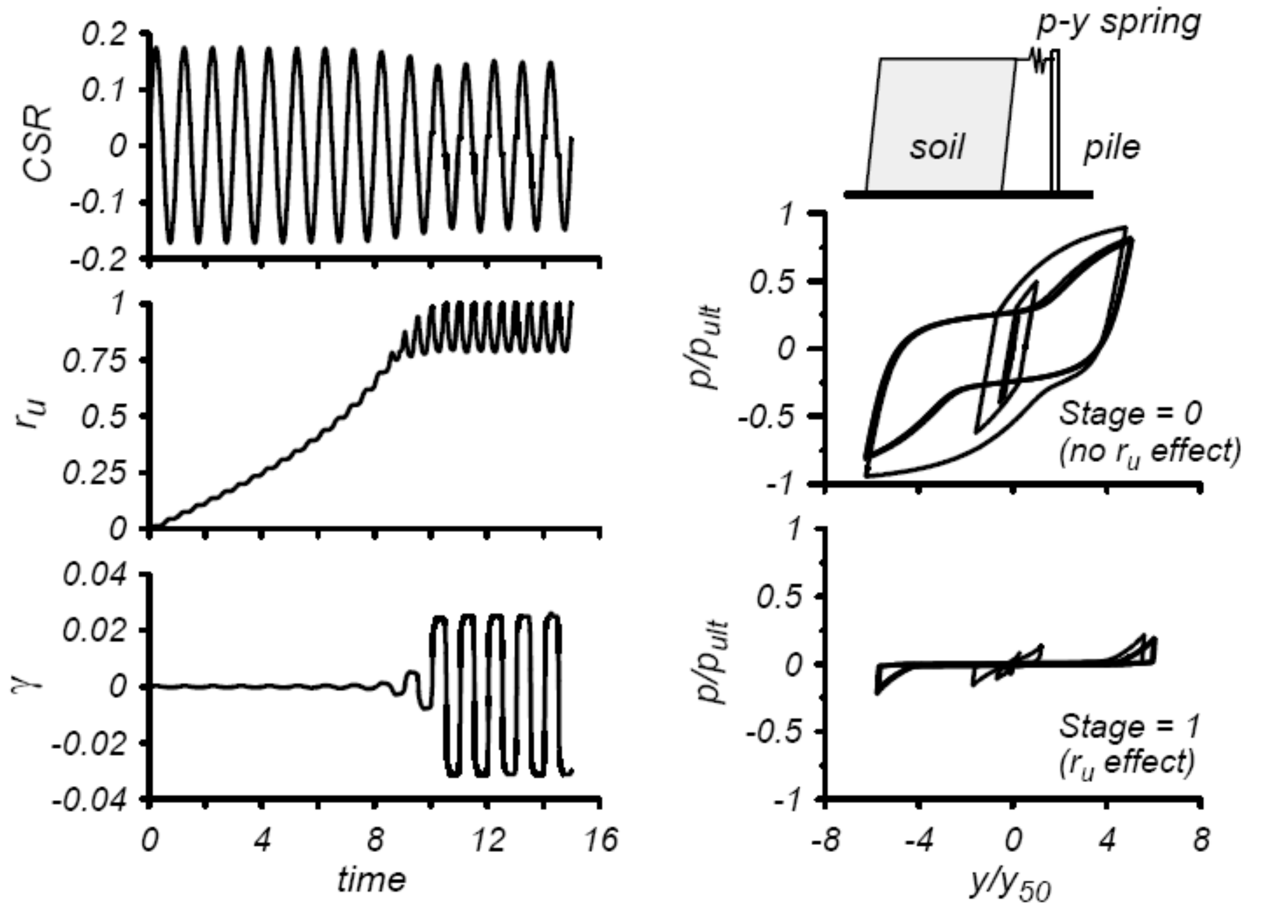


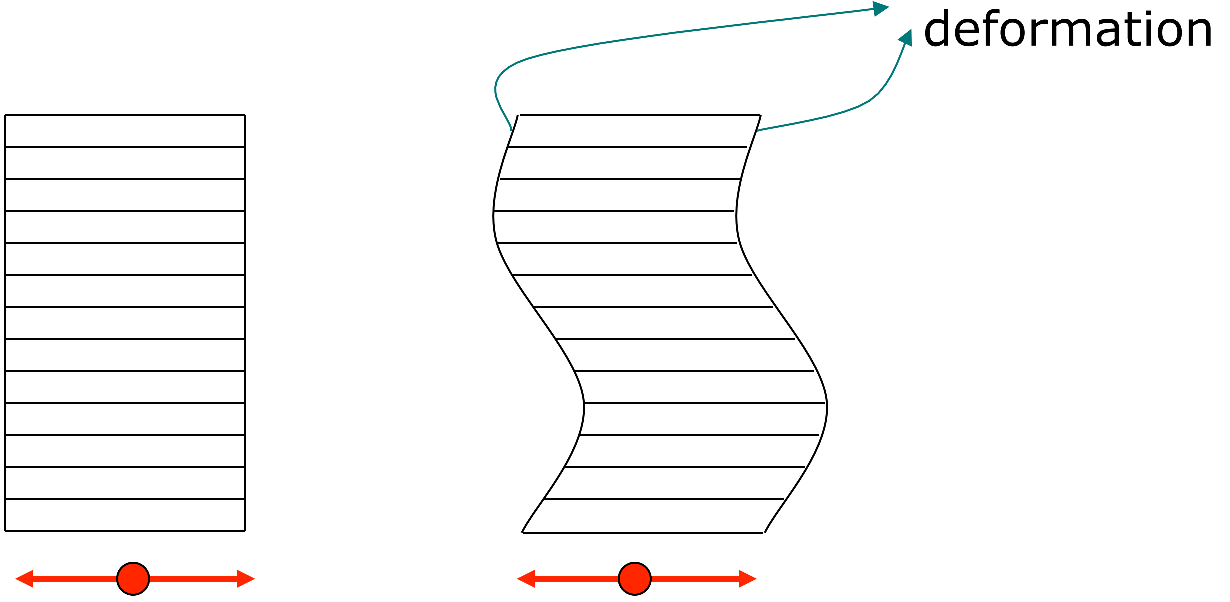
FIG. Example of PyLiq1 behavior during liquefaction without lateral spreading.

Boundary Conditions

- EqualDof

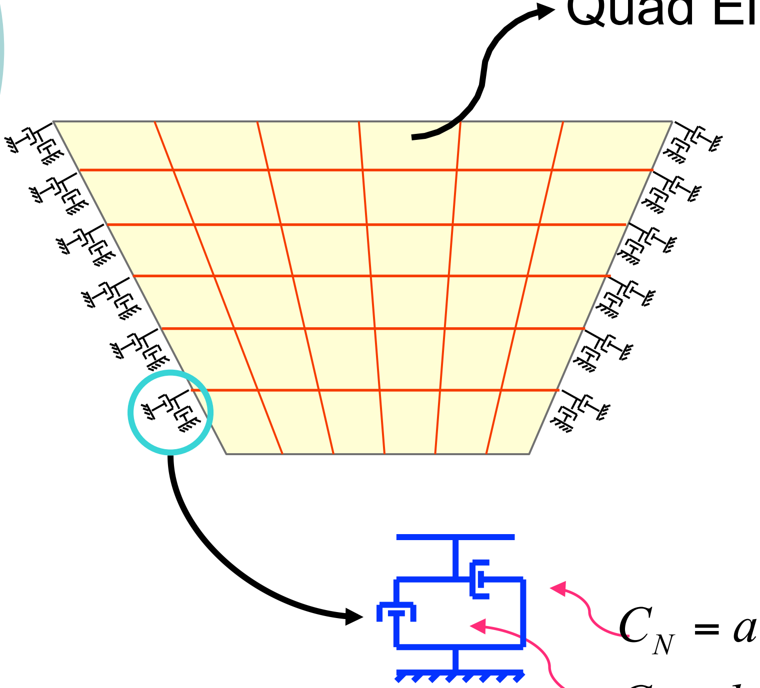
```
equalDOF $rNodeTag $cNodeTag $dof1 $dof2 …
```

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



Same lateral deformation

Absorbent/transmitting Boundaries
Lysmer (1969)



Quad Element

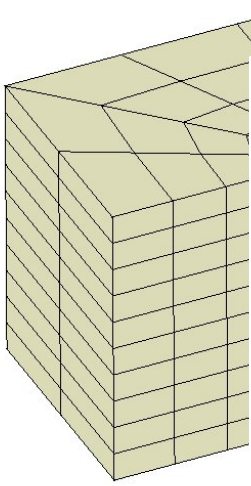
$$C_N = a\,\rho\,V_S$$

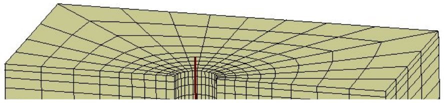
$$C_P = b\,\rho V_P$$

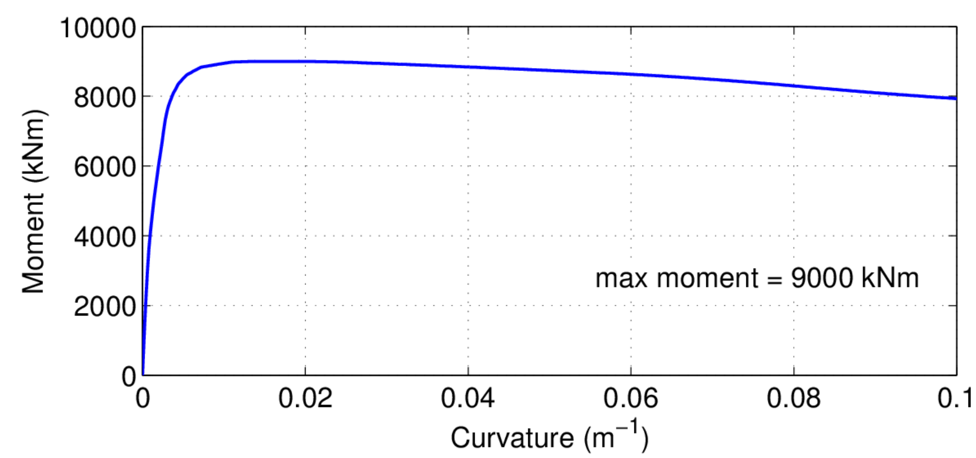
zeroLength Element &
uniaxial material

```
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

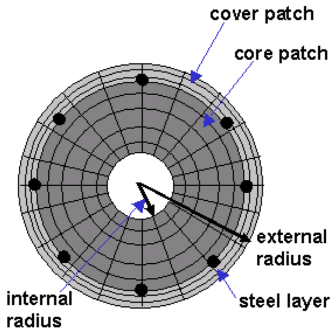






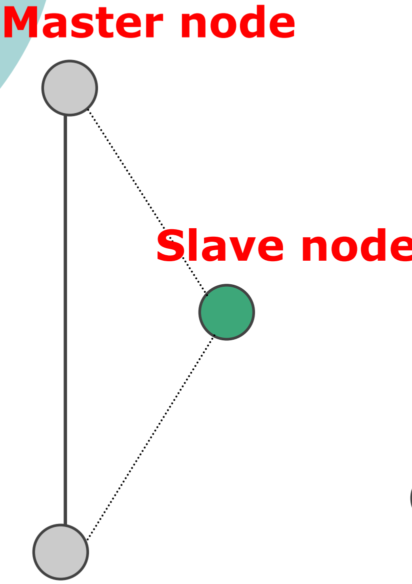
Solid-

Moment curvature response for single shaft

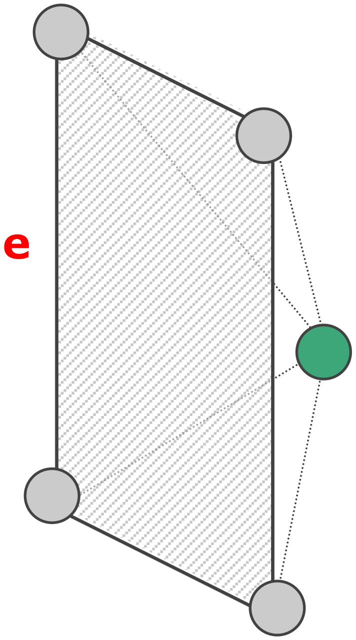


Fiber element

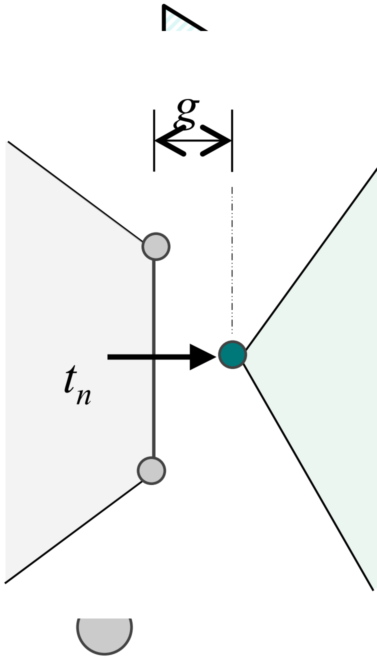
Contact Elements available in OpenSees



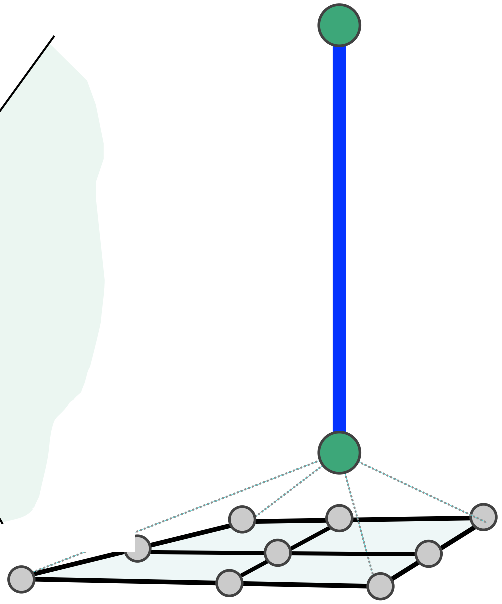
2D Node-to-Line Element



3D Node-to-Surface Element



3D Beam-to-Solid Element

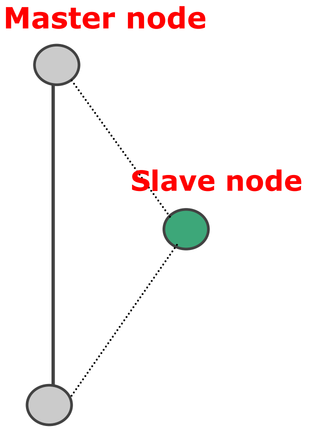


3D End-Beam-to-Solid Element

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!!