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

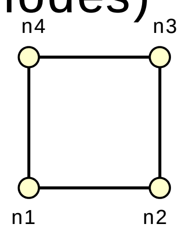
- Finite Elements (for solids)
  - Single-phase
  - Multi-phase (coupled) finite elements
  - Zero length element
- Material Models
  - Elastic
  - Elasto-plastic Continuum Models
  - Elasto-plastic Uniaxial models
- Boundary Conditions
  - Equal DOF
  - Absorbent boundaries

Finite Elements (solids)

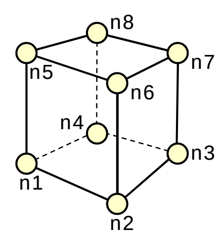
- Single-phase formulations
  - To capture the response of dry soils (or total stress analysis) →need one single phase
    - Phase 1 – soil skeleton
- Multi-phase formulations
  - To capture the response of saturated soils (effective stress analysis) → need two phases
    - Phase 1 → Soil skeleton
    - 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)

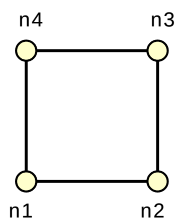


quad (4 node)



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:

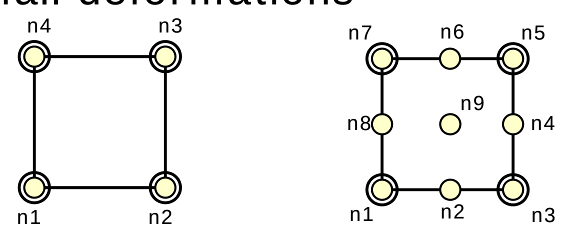
Nodes $n1, $n2, $n3, $n4 and

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

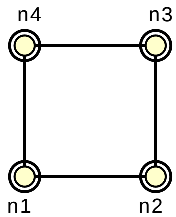


quadUP **9_4_quadUP**

Degrees of Freedom (DOFs) are:

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

quadUP element definition



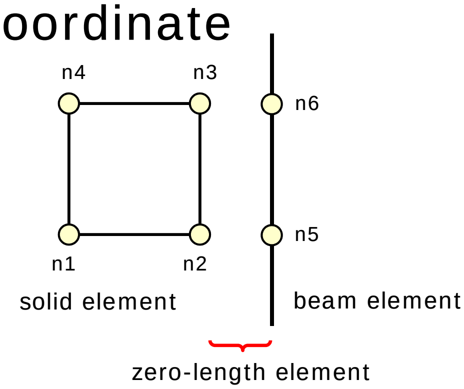
quadUP

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
```

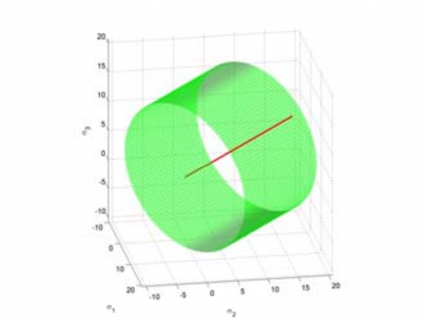
nDMaterial
Elasto-Plastic (Small Deformations)

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

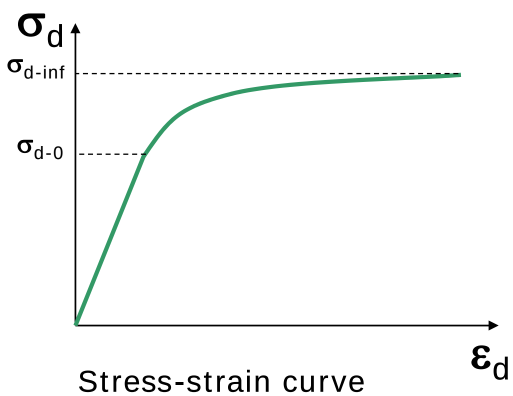
nDMaterial
J2Plasticity

- 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**

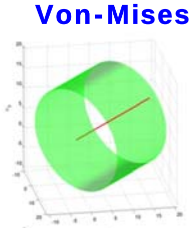
- Developed by Boris Jeremic at UC Davis
  http://sokocalo.engr.ucdavis.edu/~jeremic

nDMaterial
Template Elasto-Plastic Material

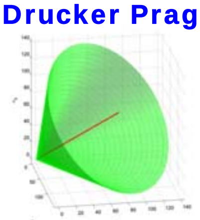
nDMaterial Template3Dep $matTag $ElmatTag
–YS $ys **–PS** $ps **–EPS** $eps <**-ELS1** $el> <**-ELT1** $et>

-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)

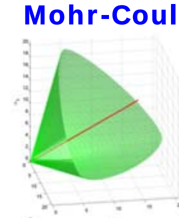
Von-Mises



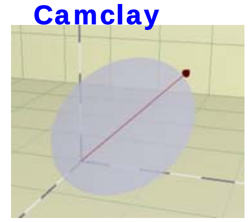
Drucker Prager



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)

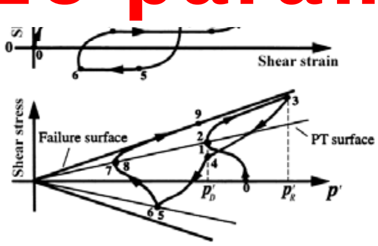
  - Fluid-solid porous material (Material to couple solid &fluid phases)

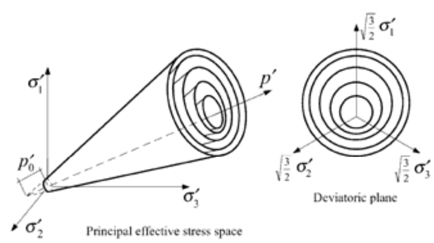
- Developed by Elgamal et al. at UCSD
  http://cyclic.ucsd.edu/opensees/

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>
```

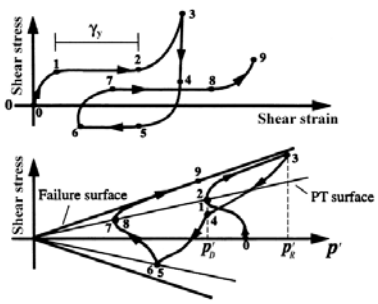
15 parameters!!??

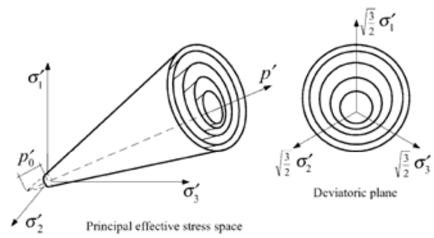




nDMaterial PressureDependentMultiYield

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>

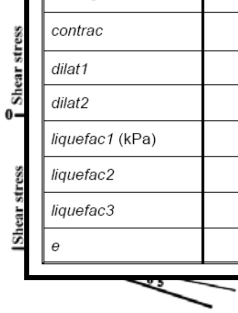


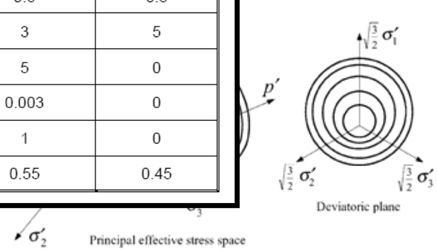


nDMaterial PressureDependentMultiYield

nDMat … nd $rho
$refShe … earStra
$refPre
$contra … ac3
<$noYi
$e=0.

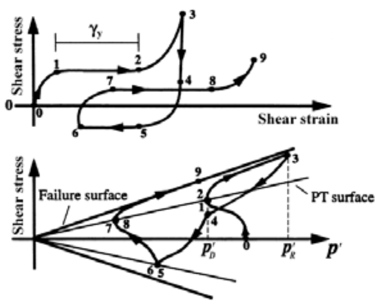
	Loose Sand (15%-35%)	Medium Sand (35%-65%)	Medium-dense Sand (65%-85%)	Dense Sand (85%-100%)
rho (ton/m^3)	1.7	1.9	2.0	2.1
refShearModul (kPa, at p'_r=80 kPa)	5.5x10^4	7.5x10^4	1.0x10^5	1.3x10^5
refBulkModu (kPa, at p'_r=80 kPa)	1.5x10^5	2.0x10^5	3.0x10^5	3.9x10^5
frictionAng	29	33	37	40
peakShearStra (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

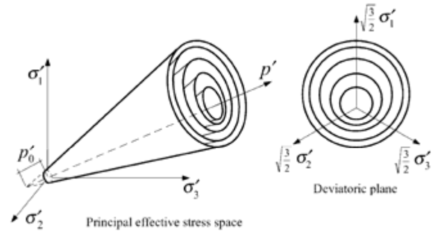




nDMaterial PressureDependentMultiYield02

nDMaterial PressureDependMultiYield02 $matTag $nd $rho
$refBulkModul $frictionAng $peakShearStra $refPress
$pressDepenCoe $PTAng
$contrac1 $contrac3 $dilat1 $dilat3
<$noYieldSurf=20 <$r1 $Gs1 …>
$contrac2=5.0 $dilat2=3.0 $liquefac1=1.0 $liquefac2=0.0
$e=0.6 $cs1=0.9 $cs2=0.02 $cs3=0.7 $pa=101>

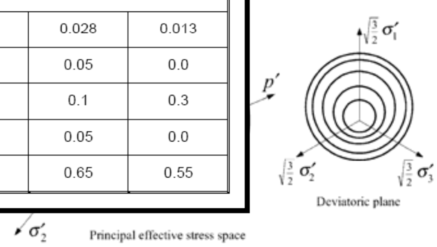




nDMaterial PressureDependentMultiYield02

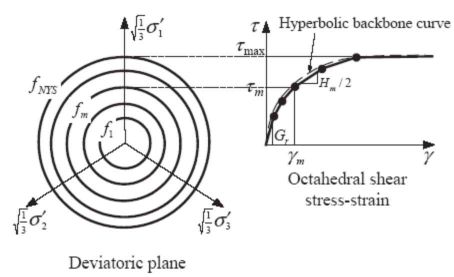
nDMater … $nd $rho
$refBulkM
$pressDe
$contrac1
<$noYield
$contrac2 … =0.0
$e=0.6 $

	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)	6x10⁴	9x10⁴	10x10⁴	11x10⁴	13x10⁴
refBulkModu (kPa, at p'r=80 kPa)	16x10⁴ (K0=0.5)	22x10⁴ (K0=0.47)	23.3x10⁴ (K0=0.45)	24x10⁴ (K0=0.43)	26x10⁴ (K0=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

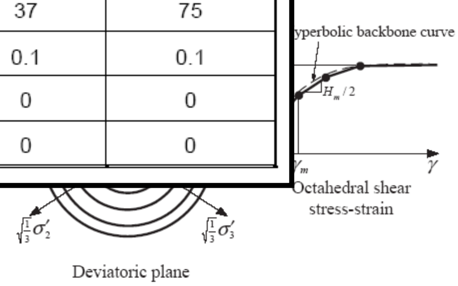
nDMaterial PressureIndependMultiYield $matTag $nd $rho $refShearModul $refBulkModul $cohesi $peakShearStra $frictionAng $refPress=101 $pressDependCoe=0. <$noYieldSurf=20 <$r1 $Gs1 …>>



nDMaterial PressureIndependentMultiYield

nDMaterial PressureIndependMultiYield $matTag $nd $rho $refShe… $frictio… <$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



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

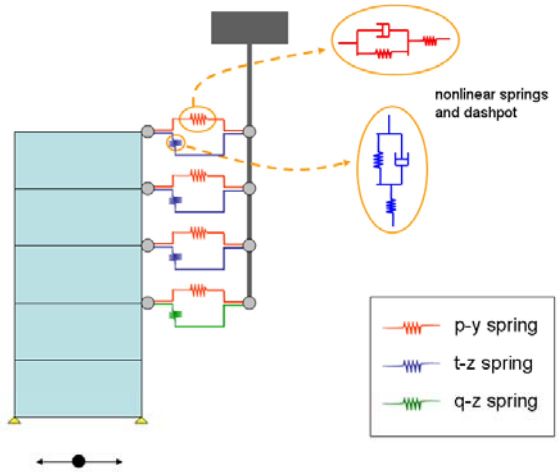
$MatTag → the tag of previously defined material
$sNum → (0 - elastic, 1-plastic, 2 – linear elastic constant **f(σ_3)**)

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

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

Elasto-plastic Uniaxial models

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



Py Tz Qz Uniaxial Materials

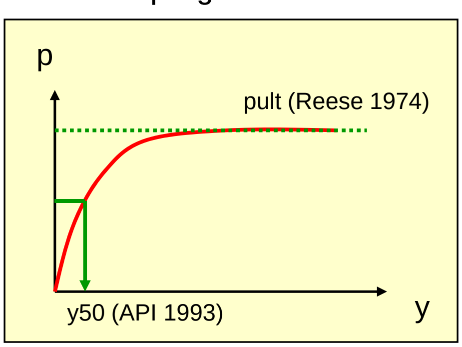
- PySimple1
- TzSimple1
- QzSimple1

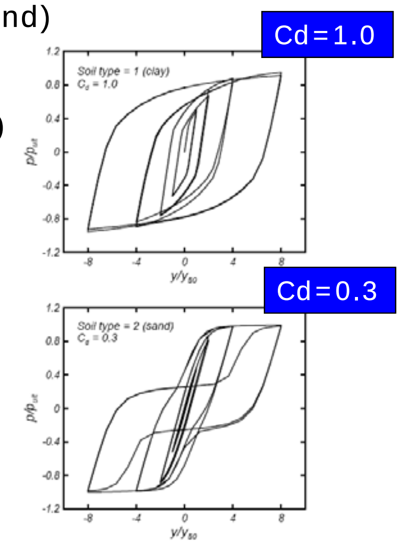
- PyLiq1
- TzLiq1

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

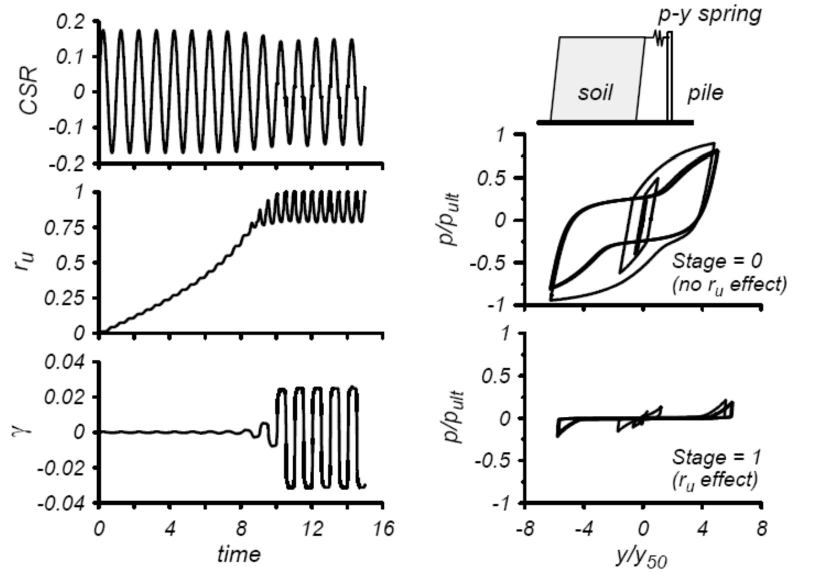


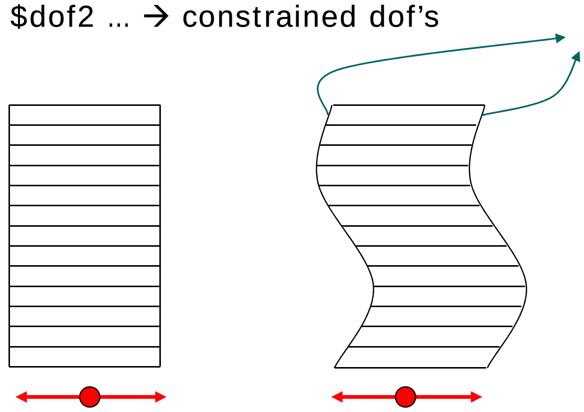
FIG. Example of PyLiq1 behavior during liquefaction without lateral spreading.

Boundary Conditions

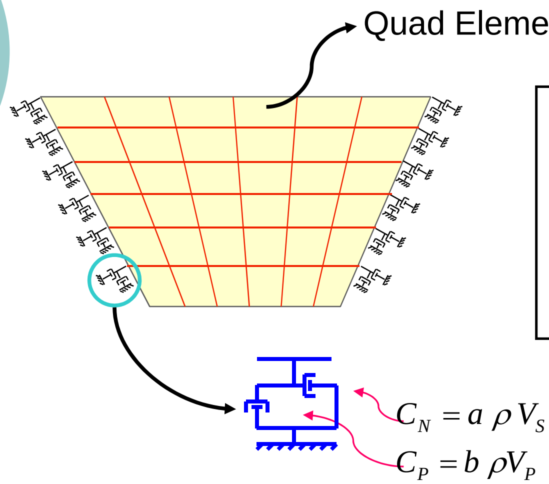
- EqualDof

equalDOF \$rNodeTag \$cNodeTag \$dof1 \$dof2 ...

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



Absorbent Boundaries
Lysmer (1969)



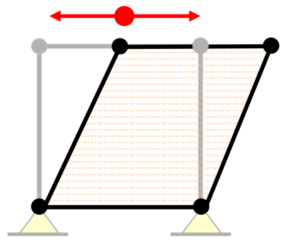
zeroLength Element & uniaxial material

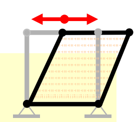
```
1. set DampP 755
2. set DampN 1216
3. uniaxialMaterial Elastic  1  0 $DampP
4. uniaxialMaterial Elastic  2  0 $DampN
5. node 1 16.0 0.0
6. node 2 16.0 0.0
7. element zeroLength 1 1  2  -mat 1  2
   -dir 1 2 –orient 1 –2 0 2 1 0
```

Many more capabilities currently under development!!

Basic Example

- Response of saturated soil element to harmonic excitation

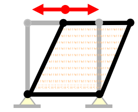




```
#Created by Zhaohui Yang (zhyang@ucsd.edu)
#plastic pressure dependent material
#plane strain,  single element,  dynamic analysis (input motion: sinusoidal acceleration at base)
#SI units (m, s, KN, ton)
#
#       4    3
#       -------
#       |     |
#       |     |
#       |     |
#      1-------2   (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 ptfangle 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 basic variables using good names!!!

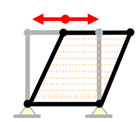
Define model geometry, materials & fixities



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

##############################################################
#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!!!



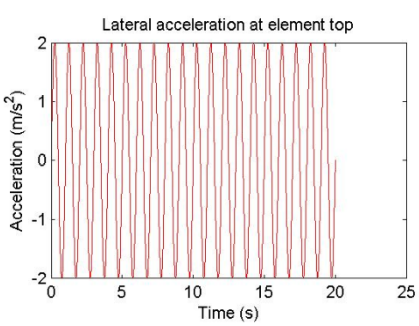
```
##############################################################
# GRAVITY APPLICATION (elastic behavior)
# create the SOE, ConstraintHandler, Integrator, Algorithm and Numberer
system ProfileSPD
test NormDispIncr 1.D-12 25 0
constraints Transformation
integrator LoadControl 1 1 1 1
algorithm Newton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

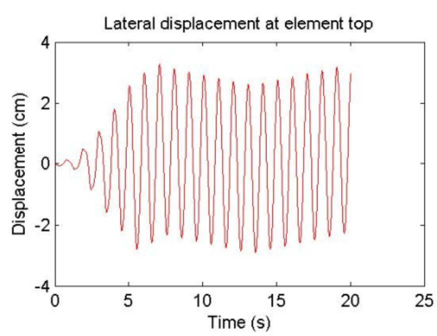
```
################################################################
# NOW APPLY LOADING SEQUENCE AND ANALYZE (plastic)

# 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
```

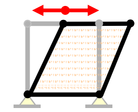
Plot Results

Input Accel time history



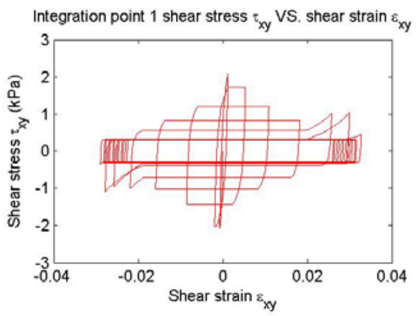
Output displ. time history

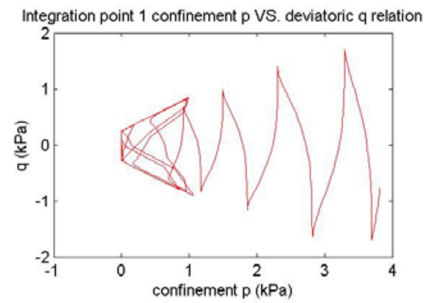




Plot results

Stress-strain & stress path





Pore pressures