# 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
  - Soil-structure interaction problems
    - Shallow foundations (e.g. bearing capacity, deformation)
    - 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, record results, perform the analysis, etc.

## Outline

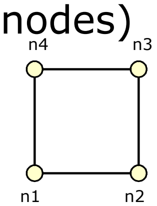
- Finite Elements (for solids)
  - Single-phase
  - Multi-phase (coupled) finite elements
  - Zero length element
- Material Models
  - Elastic
  - Elasto-plastic Continuum Models
  - Elasto-plastic Uniaxial models
- Boundary Conditions
  - Equal DOF
  - Absorbent boundaries

# Finite Elements (solids)

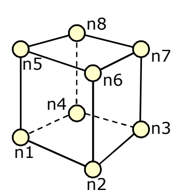
- Single-phase formulation
  - To capture the response of dry soils →need one single phase
    - Phase 1 – soil skeleton
- Multi-phase formulation
  - To capture the response of saturated soils → need two phases
    - Phase 1 → Soil skeleton
    - Phase 2 → pore water
- Zero-Length element
  - To capture interface response between solid and beam elements

# 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)

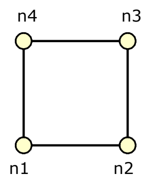



**quad** (4 node)




**stdBrick** (8 node)

## **quad** element definition




**quad** (4 node)

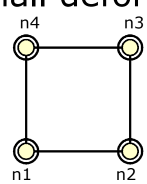
**element quad** $eleTag  $n1 $n2 $n3 $n4  $thick $type $matTag <$press $rho $b1 $b2>

Must define first all the required arguments. In particular:
- **Nodes** $n1, $n2, $n3, $n4 and
- **Material type** $matTag

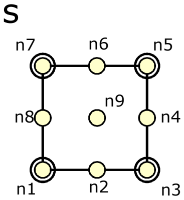
The arguments in <…> are optional

## Multi-Phase Formulations

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



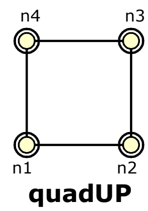

**quadUP**




**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

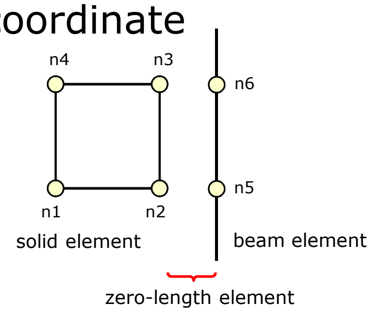



**element quadUP** $eleTag $n1 $n2 $n3 $n4 $thick $type $matTag $bulk $fmass $hPerm $vPerm <$b1 $b2 $t>

$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

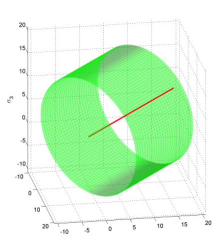
## nDMaterial
Elasto-Plastic (Small Deformations)

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

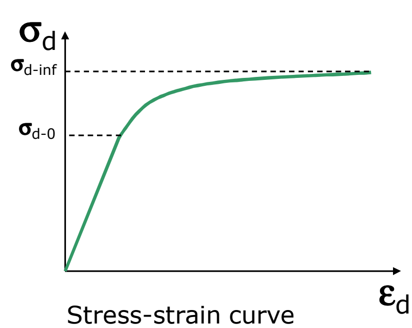
## nDMaterial
## J2Plasticity

- 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**

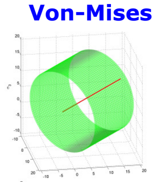
- Developed by Boris Jeremic at UC Davis
  **http://sokocalo.engr.ucdavis.edu/~jeremic**

## nDMaterial
Template Elasto-Plastic Material

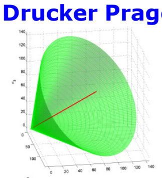
**nDMaterial Template3Dep** $matTag $ElmatTag
**–YS** $ys **–PS** $ps **–EPS** $eps <**-ELS1** $el> <**-ELT1** $et>

**-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)

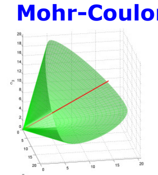
**Von-Mises**



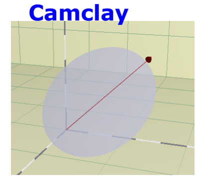
**Drucker Prager**



**Mohr-Coulomb**



**Camclay**



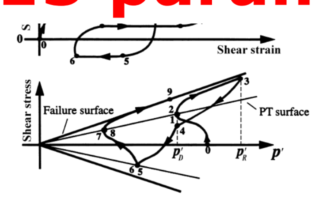
## nDMaterial MultiYield Materials

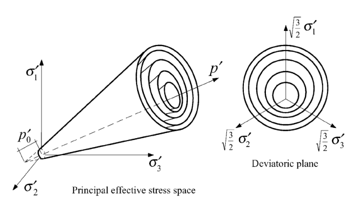
- Material models based on Multiyield Plasticity *(Mroz et al., Prevost et al.)*
- Two types
  - Pressure Independent Multi-yield
  - Pressure Dependent Multiy-ield (captures well the response of liquefiable soils)
  - Material to couple solid &fluid phases
- Developed by Elgamal et al. at UCSD
  **http://cyclic.ucsd.edu/opensees/**

## 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!!??**

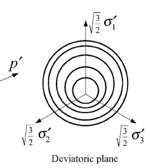


# nDMaterial PressureDependentMultiYield

nDMat ... nd $rho
$refShe ... earStra
$refPre
$contra ... ac3
<$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 |

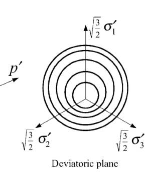



Principal effective stress space

# nDMaterial PressureDependentMultiYield02

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

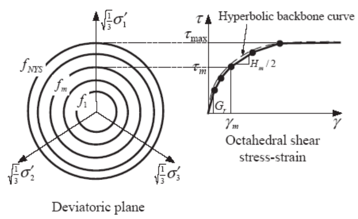
| | Dr=30% | Dr=40% | Dr=50% | Dr=60% | Dr=75% |
|---|---|---|---|---|---|
| *rho (ton/m3)* | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 |
| *refShearModul (kPa, at $p'_r$=80 kPa)* | 6x10$^4$ | 9x10$^4$ | 10x10$^4$ | 11x10$^4$ | 13x10$^4$ |
| *refBulkModu (kPa, at $p'_r$=80 kPa)* | 16x10$^4$ ($K_0$=0.5) | 22x10$^4$ ($K_0$=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 |




Principal effective stress space

## nDMaterial PressureIndependentMultiYield

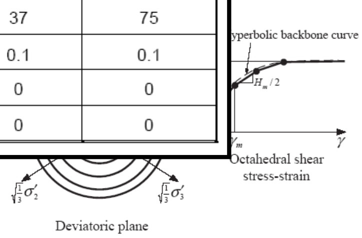
**nDMaterial PressureIndependMultiYield** $matTag $nd $rho $refShearModul $refBulkModul $cohesi $peakShearStra $frictionAng $refPress=101 $pressDependCoe=0. <$noYieldSurf=20 <$r1 $Gs1 …>>




## 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

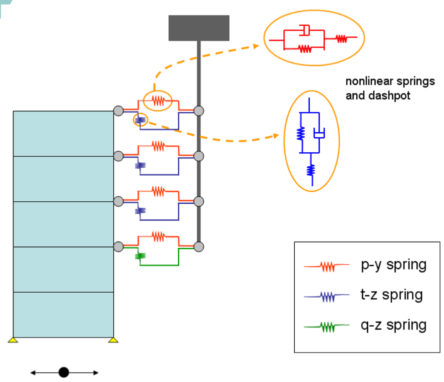
$MatTag → the tag of previously defined material
$sNum → (0 - elastic, 1-plastic, 2 – linear elastic constant **f(**$\sigma_3$**)** )

**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)




PyTzQ Uniaxial Materials

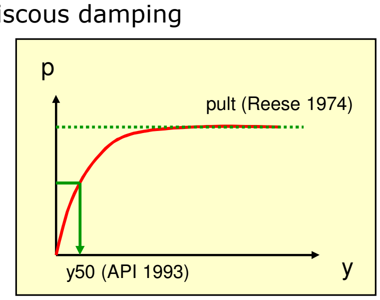
- PySimple1
- TzSimple1
- QzSimple1

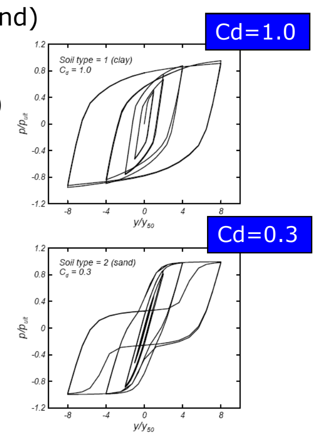
- PyLiq1
- TzLiq1

# 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

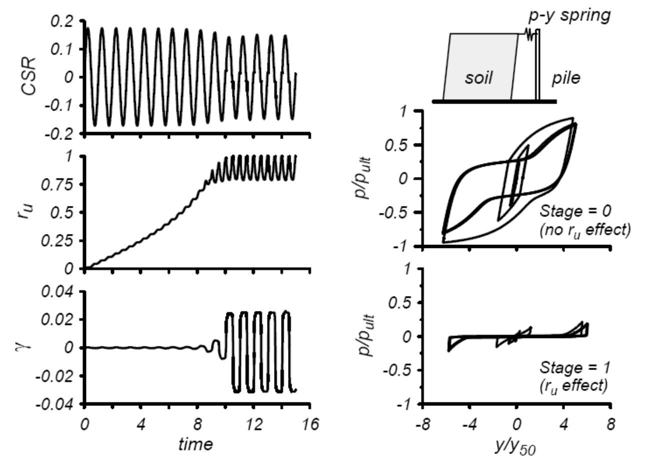


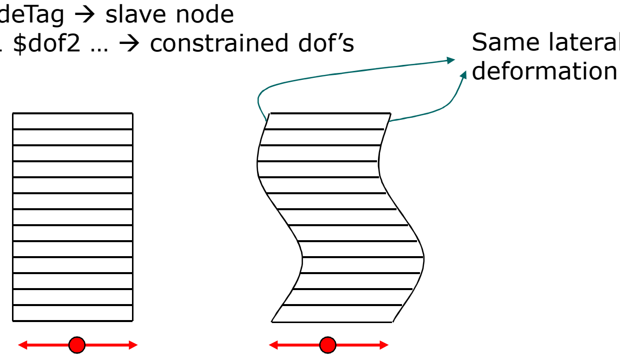

FIG. Example of PyLiq1 behavior during liquefaction without lateral spreading.

# Boundary Conditions

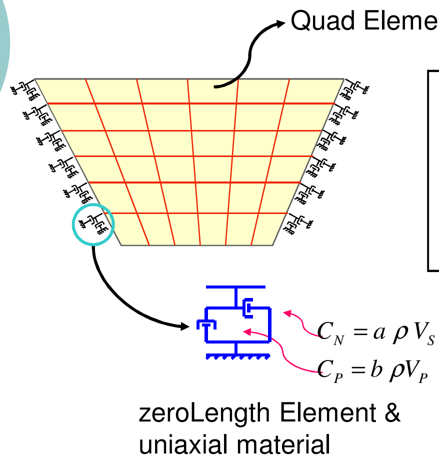
- EqualDof

**equalDOF** $rNodeTag $cNodeTaga $dof1 $dof2 …

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



## Absorbent Boundaries
**Lysmer (1969)**




```
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
```

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Many more capabilities currently under development!!