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)

![quad (4 node)](image1)

![stdBrick (8 node)](image2)
quad element definition

\[\text{quad (4 node)}\]

\[
\text{element quad eleTag n1 n2 n3 n4 thick type matTag}
<\text{press rho b1 b2}>
\]

Must define first all the required arguments. In particular:

- **Nodes** $n1, n2, n3, n4$ and
- **Material type** $\text{matTag}$

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

Degrees of Freedom (DOFs) are:
- \( u \) → solid displacement, on
- \( P \) → pore fluid pressures, on
- \( U \) → pore fluid displacements, on
quadUP element definition

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

$\text{bulk } \rightarrow \text{combined undrained bulk modulus } B_c = B_f/n$

$\text{fmass } \rightarrow \text{fluid mass density}$

$\text{hperm } \& \text{vperm } \rightarrow \text{horiz. And vert. permeability}$
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)
zero-length element

- Connects two points at the same coordinate

```
element zeroLength $eleTag $n1 $n2 -mat $matTag1 $matTag2 ...
-dir $dir1 $dir2 ...
-oorient $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 state

- 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)
- FluidSolidPorous Material (San Diego)
nDMaterial J2Plasticity

- von-Mises type

\[
\sigma_d \quad \sigma_{d-inf} \quad \sigma_{d-0}
\]

Von-Mises Yield Surface  Stress-strain curve

\text{nDMaterial J2Plasticity} \quad \text{matTag} \quad K \quad G \quad \text{sig0} \quad \text{sigInf} \quad \delta \quad H
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/](http://cyclic.ucsd.edu/opensees/)
**nDMaterial PressureDependentMultiYield**

```
**nDMaterial PressureDependMultiYield** $matTag $nd $rho $refShearModul $refBulkModul $frictionAng $peakShearStrea $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!!??

![Diagram of stress-strain relationship]

![Diagram of principal effective stress space]
### nDMaterial
#### PressureDependentMultiYield

<table>
<thead>
<tr>
<th></th>
<th>Loose Sand (15%-35%)</th>
<th>Medium Sand (35%-65%)</th>
<th>Medium-dense Sand (65%-85%)</th>
<th>Dense Sand (85%-100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>rho (ton/m³)</td>
<td>1.7</td>
<td>1.9</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>refShearModul (kPa, at $p'_c=80$ kPa)</td>
<td>$5.5 \times 10^4$</td>
<td>$7.5 \times 10^4$</td>
<td>$1.0 \times 10^5$</td>
<td>$1.3 \times 10^5$</td>
</tr>
<tr>
<td>refBulkModul (kPa, at $p'_c=80$ kPa)</td>
<td>$1.5 \times 10^5$</td>
<td>$2.0 \times 10^5$</td>
<td>$3.0 \times 10^5$</td>
<td>$3.9 \times 10^5$</td>
</tr>
<tr>
<td>frictionAng</td>
<td>29</td>
<td>33</td>
<td>37</td>
<td>40</td>
</tr>
<tr>
<td>peakShearStra (at $p'_c=80$ kPa)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>refPress ($p'_c$, kPa)</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>pressDependCoe</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>PTAng</td>
<td>29</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>contrac</td>
<td>0.21</td>
<td>0.07</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>dilat1</td>
<td>0</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>dilat2</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>liquefac1 (kPa)</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>liquefac2</td>
<td>0.02</td>
<td>0.01</td>
<td>0.003</td>
<td>0</td>
</tr>
<tr>
<td>liquefac3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>e</td>
<td>0.85</td>
<td>0.7</td>
<td>0.55</td>
<td>0.45</td>
</tr>
</tbody>
</table>

---

*Principal effective stress space*
nDMaterial
PressureDependentMultiYield02

<table>
<thead>
<tr>
<th></th>
<th>Dr=30%</th>
<th>Dr=40%</th>
<th>Dr=50%</th>
<th>Dr=60%</th>
<th>Dr=75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>rho (ton/m³)</td>
<td>1.7</td>
<td>1.8</td>
<td>1.9</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>refShearModul (kPa, at p'=80 kPa)</td>
<td>6x10⁴</td>
<td>9x10⁴</td>
<td>10x10⁴</td>
<td>11x10⁴</td>
<td>13x10⁴</td>
</tr>
<tr>
<td>refBulkModul (kPa, at p'=80 kPa)</td>
<td>16x10⁴ (K₀=0.5)</td>
<td>22x10⁴ (K₀=0.47)</td>
<td>23.3x10⁴ (K₀=0.45)</td>
<td>24x10⁴ (K₀=0.43)</td>
<td>26x10⁴ (K₀=0.4)</td>
</tr>
<tr>
<td>frictionAng</td>
<td>31</td>
<td>32</td>
<td>33.5</td>
<td>35</td>
<td>36.5</td>
</tr>
<tr>
<td>PTAng</td>
<td>31</td>
<td>26</td>
<td>25.5</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>peakShearStra (at p'=101 kPa)</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>refPress (p', kPa)</td>
<td>101</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pressDependCoe</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contrac1</td>
<td>0.087</td>
<td>0.067</td>
<td>0.045</td>
<td>0.028</td>
<td>0.013</td>
</tr>
<tr>
<td>Contrac3</td>
<td>0.18</td>
<td>0.23</td>
<td>0.15</td>
<td>0.05</td>
<td>0.0</td>
</tr>
<tr>
<td>dilat1</td>
<td>0</td>
<td>0.06</td>
<td>0.06</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>dilat3</td>
<td>0.0</td>
<td>0.27</td>
<td>0.15</td>
<td>0.05</td>
<td>0.0</td>
</tr>
<tr>
<td>e</td>
<td>0.85</td>
<td>0.77</td>
<td>0.7</td>
<td>0.65</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Deviatoric plane
Principal effective stress space
nDMaterial
PressureIndependentMultiYield

nDMaterial PressureIndependentMultiYield $matTag $nd $rho
$refShearModul $refBulkModul $cohesi $peakShearStrain
$frictionAng $refPress=101 $pressDependCoe=0.
<$noYieldSurf=20 <$r1 $Gs1 ...>>
nDMaterial
FluidSolidPorousMaterial

- Couples the response of two phases (i.e., 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 $f(\sigma_3)$ )

**updateParameter** -material $matTag -refG $newVal

$MatTag → the tag of previously defined material
$sNewVal → new parameter value
Initial State for Geotechnical Problems

Soil profile

Initial deformation

Gravity

# 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 off 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

---

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

**FIG. Example of PyLiq1 behavior during liquefaction without lateral spreading.**
Boundary Conditions

- **EqualDof**

  \[ \text{equalDOF } \text{rNodeTag } \text{cNodeTag } \text{dof1 } \text{dof2 } \ldots \]

  - `$\text{rNodeTag}$ → master node
  - `$\text{cNodeTag}$ → slave node
  - `$\text{dof1 } \text{dof2 } \ldots$ → constrained dof’s

  Same lateral deformation
Absorbent/transmitting 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

\[ C_N = a \rho V_s \]
\[ C_P = b \rho V_P \]
Contact Elements available in OpenSees
Contact Elements available in OpenSees

Master node

Slave node

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

```plaintext
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!!