Effect of Proximity of Sheet Pile Walls on the Apparent Capacity of Driven Displacement Piles (BDV31 TWO 977-26)

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Florida Department of Transportation (FDOT)
Gainesville, Florida
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Agenda

- Introduction
- Task 2 Activities
- Preliminary Progress for Task 3
Introduction

- Effect of Sheet Pile Walls in the Vicinity of Driven Piles

What is the effect of sheet pile wall removal on pile capacity?
Introduction: Project Approach

• Identify design-relevant parameters for calculating pile capacities in the vicinity of SPWs

• Develop design charts and/or tabularized matrices for use in calculation of pile-capacity changes

• Methodology:
  • Combined Discrete (soil) and Finite (pile and sheet pile wall) Element Analysis
  • Spectrum of model validation (laboratory and centrifuge testing)
Introduction: Project Approach

• **Phase I (12 months; July 2014 - June 2015)**
  • Task 1. Literature Review, Scenario Identification, and Field-Data Acquisition
  • Task 2. Numerical Modeling Schemes and Granular Soil Units

• **Phase II (18 months; July 2015 - December 2016)**
  • Task 3. Numerical Modeling of Driven foundation in Granular Soils
  • Task 4. Physical Laboratory/Centrifuge Experimentation
  • Task 5. Reporting of Findings and Design-Oriented Recommendations
  • Task 6. Final Report
Task 2. Numerical Modeling of Granular Soils

- **Deliverables**
  - Methodology for modeling direct shear and triaxial compression tests of granular soil
  - Simulation of macroscopic shear strength (Mohr-Coulomb failure envelopes)
  - Creation of standardized DEM “soil-unit” library
Task 2. Numerical Modeling of Granular Soils

• **Activities**
  
  • Scale dependency of friction and “Shear Jamming”
  
  • Contact rheology
  
  • Direct shear test simulation
  
  • Triaxial test simulation
  
  • Soil unit library
Task 2 Activity: Scale Dependency of Friction

- Granular materials have surface texture at multiple scales; the repetitive or randomly-ordered particle arrangement forms 3-D topology of the surface.

Geometrically regular packings: a) Close-packed tetrahedral spheres at the theoretical maximum bulk density of $\pi/(3\sqrt{2})$ (~74%) in a volume; b) An equivalent 2-D planar packing of discs at the theoretical maximum bulk density of $\pi/(2\sqrt{3})$ (~91%) (Israelachvill 2011)
Task 2 Activity: Scale Dependency of Friction

Figure 2.1.2.1. Pictorial surface texture of close-packed spheres: a) Microroughness of a spherical particle; b) Macroroughness of 2-D corrugated surface; c) Representation of a periodic surface with corrugations on the two scales
Task 2 Activity: Scale Dependency of Friction

Figure 2.1.2.4. Idealized macroroughness with periodic corrugation: a) Corrugated surface with intrinsic coefficient of friction, $\mu_0$; b) Free-body diagram of a body on a corrugated surface with coefficient of friction, $\mu_0$

$$ I' : \quad F_N \cos \theta_1 + F \sin \theta_1 = R $$

$$ x' : \quad F_N \sin \theta_1 + \mu_0 R = F \cos \theta_1 \quad \frac{F'}{F_N} = \frac{\mu_0 + \tan \theta_1}{1 - \mu_0 \tan \theta_1} = \frac{\mu_0 + \mu_1}{1 - \mu_0 \mu_1} $$

$$ \mu = \tan \theta = \frac{\sin(\theta_0 + \theta_1)}{\cos(\theta_0 + \theta_1)} = \frac{\sin \theta_0 \cos \theta_1 + \cos \theta_0 \sin \theta_1}{\cos \theta_0 \cos \theta_1 - \sin \theta_0 \sin \theta_1} = \frac{\tan \theta_0 + \tan \theta_1}{1 - \tan \theta_0 \tan \theta_1} = \frac{\mu_0 + \mu_1}{1 - \mu_0 \mu_1} $$

$$ \mu = \tan \left( \sum_i \arctan \mu_i \right) $$
Task 2 Activity: Scale Dependency of Friction

Figure 2.1.5.1. Grain surface topography: SEM (left) and AFM (right) scan size 10 micrometers square. Semi-round grains with characteristic surface fractures (Konopinski et al. 2012)
Task 2 Activity: Scale Dependency of Friction

JKR Theory (Johnson-Kendall-Robertson, 1971)

Figure 2.1.2.5. Dimensional representation of the grain surface (from Konopinski et al. 2012): a) 3-D elevation map of Fig. 2.1.5.1b; b) 3-D representation of the microscopic surface texture of a grain; c) Counting estimate of fractal dimension for a 20 μm AFM scan

\[
\mu_0 \approx 7.8 \left( \frac{d_c}{l} \right)^{8/3} \tan(\langle \theta \rangle_x)
\]

\[
d_c = \left( \frac{3 \gamma_{12}^2 \pi^2 R}{64 (E^*)^2} \right)^{1/3} = \left( \frac{3 (1.2)^2 \pi^2 (0.0015)}{64 (83.5E9)^2} \right)^{1/3} = 5.233 \times 10^{-9} \text{ m} \approx 5.233 \text{ nm}
\]

\[
\mu_0 \approx 7.8 \left( \frac{5.233}{9.37} \right)^{8/3} \tan(\langle \theta \rangle_x) = 1.65 \tan(\langle \theta \rangle_x)
\]
Table 2.1.5.4. Values of microscopic angles of friction for various minerals (Mitchell and Soga 2005)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Type of Test</th>
<th>Conditions</th>
<th>$\phi_{\mu}$ (deg)</th>
<th>Comments</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Quartz</td>
<td>Block over particle set in mortar</td>
<td>Dry</td>
<td>6</td>
<td>Dried over CaCl$_2$ before testing</td>
<td>Tschenbottroff and Welch (1948)</td>
</tr>
<tr>
<td>Quartz</td>
<td>Three fixed particles over block</td>
<td>Moist, Water saturated</td>
<td>24.5</td>
<td>24.5</td>
<td>Hafiz (1950)</td>
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<tr>
<td>Quartz</td>
<td>Block on block</td>
<td>Dry</td>
<td>7.4</td>
<td>Normal load per particle increasing from 1 g to 100 g Polished surfaces</td>
<td>Horn and Deere (1962)</td>
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<tr>
<td>Quartz</td>
<td>Block on block</td>
<td>Variable</td>
<td>0-45</td>
<td>$\phi$ decreasing with increasing particle size Depends on roughness and cleanliness</td>
<td>Bromwell (1966)</td>
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<tr>
<td>Quartz</td>
<td>Particle–particle</td>
<td>Saturated</td>
<td>26</td>
<td>Single-point contact</td>
<td>Proctor and Bartor (1974)</td>
</tr>
</tbody>
</table>

Figure 2.1.5.8. SEM analysis of quartz grains: a) Diameter ~ 0.55 mm (scale bar = 100 $\mu$m ) with rough surface texture (scan size = 10 $\mu$m); b) Diameter ~ 0.8 mm with fairly smooth surface texture; c) Diameter~ 0.6 mm (scale bar = 100 $\mu$m) with smooth surface (scale size = 25 $\mu$m)
Task 2 Activity: Scale Dependency of Friction

Figure 2.1.7.1. Irregularly shaped grains represented by spheroids: a) Circumscribing diameter (note that the volume of the inner sphere drawn on the larger grain is approximately the same as the volume of the particle); b) Equivalent diameters (note that the surface of the sphere drawn on the smaller grain is approximately the same as the surface area of the particle)

Transformation of Angularity (shape effect)
Task 2 Activity: Shear Jamming in Force Chains

(Mair et al. 2002, Bi et al. 2011)

<table>
<thead>
<tr>
<th></th>
<th>US180</th>
<th>PO125</th>
</tr>
</thead>
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<tr>
<td>20.5</td>
<td>31.5</td>
<td></td>
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<tr>
<td>3.46</td>
<td>2.48</td>
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<tr>
<td>3.96</td>
<td>2.96</td>
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<tr>
<td>1.14</td>
<td>1.19</td>
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<tr>
<td>1.1173</td>
<td>1.1618</td>
<td></td>
</tr>
</tbody>
</table>

Weak force chain of uniform size DSE

Smaller particles represent "Spectators."

Larger particles represent "Filters."
Task 2 Activity: Shear Jamming Mechanism (Concept of Liu-Nagel Theory, 1998)

Increase “stick” in tangential sliding motion

Volumetric control in contraction

Frustrated (high $\phi_n$)

Stronger force chain of primary DSEs

Weak force chain of uniform size DSE

Strong force chain of binary mixture

Force chain of Primary DSEs

Primary and Secondary DSEs
Task 2 Activity: Contact Rheology

- Viscoelastic spherical bodies in contact

LS-DYNA DEM Model:

linear damped spring with a sliding friction element

- Hertzian contact theory (normal stiffness)
- Coulombic limits on tangential force and torque
- Natural frequency analysis: critical damping
- Viscous damping in both normal and tangential directions
- Normal and tangential restitution coefficients
- The ratio of normal to tangential stiffness
- Mindlin contact theory (quasi-static tangential stiffness)
**Task 2 Activity: Contact Rheology**

- **Identification of parameter values**
  - Example: Collision test simulation per incidence angles

**Calibration of normal and tangential restitution coefficients**

---

**Diagram**

- Sphere 1
- Sphere 2 (fixed)
- $H_{initial}$
- $g$

**Graph**

- NDAMP = 0.1
- NDAMP = 0.3
- NDAMP = 0.5
- NDAMP = 0.7
- NDAMP = 0.9
Task 2 Activity: Contact Rheology

Sphere 1

$H_{initial}$

Sphere 2 (fixed)

$g$

![Graph showing the relationship between H and g](image)
Task 2 Activity: Contact Rheology

For example:

\[ F_{S, on} = \min \left( k_S \delta_S + v_S \dot{s}, \mu |F_N| \right) \dot{s} \]

- Widely used
- Moderately difficult model to implement
- Does include tangential stiffness ⇒ possible to have velocity reversal
- Dynamics of impact are governed by the ratio of the tangential to normal impact stiffnesses
  - the normal spring sets the contact duration while the tangential response is a function of the tangential spring stiffness
- If the tangential stiffness is large and the sliding friction coefficient is small, then the sliding friction element dominates during most of the contact.
Figure 2.4.5.7. Tangent of effective recoil angle versus tangent of effective incident angle for a ratio of rolling to sliding friction equal to 1.0

\[ y = 1.1041x - 1.1282 \]
\[ y = -0.4001x - 0.0255 \]
Task 2 Activity: Contact Rheology

- **Relationships identified between:**
  - Normal and tangential contact stiffness
  - Normal and tangential contact damping
  - Sliding friction and rolling friction

Inter-relationships identified as well
Task 2 Deliverable: Modeling Direct Shear Tests

- **Model of test apparatus**

  - Extender plates (to prevent particle escape)
  - Top plate
  - Bottom plate
  - Bottom half of apparatus
  - Top half of apparatus

* - Overall dimensions taken from UF lab manual
Task 2 Deliverable: Modeling Direct Shear Tests

- Animation

Contours of XY-displacement
min=0, at node# 7764
max=5.78933e-05, at node# 35446
Task 2 Deliverable: Modeling Direct Shear Tests

- **Validation of direct shear test methodology**
  - Direct shear tests using 1 mm steel spheres

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Normal Stress (kPa)</th>
<th>Peak Shear Stress (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense 1-1</td>
<td>54.5</td>
<td>24.86</td>
</tr>
<tr>
<td>Dense 1-2</td>
<td>54.5</td>
<td>27.23</td>
</tr>
<tr>
<td>Dense 1-3</td>
<td>54.5</td>
<td>19.58</td>
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<tr>
<td>Dense 2-1</td>
<td>109</td>
<td>45.90</td>
</tr>
<tr>
<td>Dense 2-2</td>
<td>109</td>
<td>49.50</td>
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<tr>
<td>Dense 2-3</td>
<td>109</td>
<td>42.75</td>
</tr>
<tr>
<td>Dense 3-1</td>
<td>163.5</td>
<td>83.03</td>
</tr>
<tr>
<td>Dense 3-2</td>
<td>163.5</td>
<td>71.55</td>
</tr>
<tr>
<td>Dense 3-3</td>
<td>163.5</td>
<td>75.15</td>
</tr>
</tbody>
</table>

Three runs at each of three pressure levels
Task 2 Deliverable: Modeling Direct Shear Tests

Peak shear stresses listed in O’Sullivan et al. (2004) for redundant testing of stainless steel spheres
Task 2 Deliverable: Modeling Direct Shear Tests

Benchmark simulation results: 25°

Average from O’Sullivan et al. 2004b: 24.4°

- DEM-FEM Simulation
- O’Sullivan et al. (2004b)
Task 2 Deliverable: Modeling Triaxial Tests

- Model of test apparatus

* Overall dimensions: 102 mm x 203 mm
Task 2 Deliverable: Modeling Triaxial Tests

- **Model of Test Apparatus**
  - Finite element membrane (favors efficiency)

* - Overall dimensions: 102 mm x 203 mm
Task 2 Deliverable: Modeling Triaxial Tests

- **Model of Test Apparatus**
  - Discrete element membrane (favors stability)

* - Overall dimensions: 102 mm x 203 mm
Task 2 Deliverable: Modeling Triaxial Tests

- **Animation**

Contours of XY-displacement
min=0, at node # 70703
max=0.00197909, at node # 206532
Task 2 Deliverable: Modeling Triaxial Tests

- **Validation of triaxial test methodology**
  - *3D Analysis of Kinematic Behavior of Granular Materials in Triaxial Testing using DEM with Flexible Membrane Boundary* (Cil and Alshibli 2014)
  - Triaxial tests using 3.75 mm plastic spheres

<table>
<thead>
<tr>
<th>Table 1 Summary of the experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
</tr>
<tr>
<td>------------</td>
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<tr>
<td>Test 1</td>
</tr>
<tr>
<td>Test 2</td>
</tr>
<tr>
<td>Test 3</td>
</tr>
</tbody>
</table>

One run at each of three pressure levels

Physical test specimen
Task 2 Deliverable: Modeling Triaxial Tests

- Confining pressure

<table>
<thead>
<tr>
<th>Confining Pressure (kPa)</th>
<th>$\eta$</th>
<th>$\tilde{\sigma}_{XX}$ (kPa)</th>
<th>$\tilde{\sigma}_{YY}$ (kPa)</th>
<th>$\tilde{\sigma}_{ZZ}$ (kPa)</th>
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<tbody>
<tr>
<td>25</td>
<td>0.37</td>
<td>-25.0</td>
<td>-25.1</td>
<td>-26.0</td>
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<tr>
<td>50</td>
<td>0.37</td>
<td>-49.6</td>
<td>-49.8</td>
<td>-51.9</td>
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<td>100</td>
<td>0.35</td>
<td>-98.1</td>
<td>-98.8</td>
<td>-106</td>
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</tbody>
</table>
Task 2 Deliverable: Modeling Triaxial Tests

![Graph showing triaxial test results with different stress levels and comparing with Cil and Alshibli (2014) data.](image)
Task 2 Deliverable: Soil Unit Library

- **Triaxial compression tests to assess macro-behaviors**
  - Maintain inter-relationships among rheological parameters for Discrete Spherical Elements (DSEs)
  - Use of uniform size DSEs (Monodisperse system) vs. two various size DSEs (Bidisperse or binary system)

**Binary system:** primary 5 mm dia. and secondary 3 mm dia.

**Monodisperse system (5 mm)**
Task 2 Deliverable: Soil Unit Library

- **Triaxial compression tests to assess macro-behaviors**

  Binary system: primary 5 mm dia. and secondary 3 mm dia.

  - Monosized spheres
  - Rigid funnel
  - Rigid cylindrical container
  - Rigid bottom plate
  - Gravity, g
Task 2 Deliverable: Soil Unit Library

• Rheological parameters calibrated to generate desired macroscopic behaviors

Numerical description of relative density states:

Loose → Dense

Monodisperse system:
- low strength

Monodisperse system w/ high friction:
- medium strength

Binary system:
- w/o shear jamming
- With shear jamming
Task 2 Deliverable: Soil Unit Library

- A range of macroscopic behaviors is simulated

At confining stress of 70 kPa

(Initial) denser state
(Initial) Loose state

(Initial) denser state

(Initial) denser state
Task 2 Deliverable: Soil Unit Library

Simulated volumetric behaviors

Point A of Figure 3.4.2.3a
axial strain = 3.2%

Point B of Figure 3.4.2.3a
axial strain = 4%

Point C of Figure 3.4.2.3a
axial strain = 5.6%

Point D of Figure 3.4.2.3a
axial strain = 12%

Figure 3.4.2.4 Evolution of particle rearrangement and in-plane displacement (top: binary system and bottom: monodisperse system of Figure 3.4.2.3)
Task 2 Deliverable: Soil Unit Library

Simulated volumetric behaviors

Point A of Figure 3.4.2.3a
axial strain = 3.2%

Point B of Figure 3.4.2.3a
axial strain = 4%

Point C of Figure 3.4.2.3a
axial strain = 5.6%

Point D of Figure 3.4.2.3a
axial strain = 12%

Figure 3.4.2.5 Development of force chains (top: binary system and bottom: monodisperse system of Figure 3.4.2.3)
Task 2 Deliverable: Soil Unit Library

Simulated volumetric behaviors

Effective bulk modulus = 2.6 MPa at 70 kPa
Per an average coordination number ~4.4 by Walton’s theory (1987): monodisperse system

The slope of p-q is unity

Volumetric strain

Mean Stress (Pa)

Fringe Levels

3.000e+00
2.900e+00
2.800e+00
2.700e+00
2.600e+00
2.500e+00
2.400e+00
2.300e+00
2.200e+00
2.100e+00
2.000e+00
**Task 2 Deliverable: Soil Unit Library**

<table>
<thead>
<tr>
<th>Density state being modeled:</th>
<th>Loose</th>
<th>Loose-medium</th>
<th>Medium-mono</th>
<th>Medium-binary</th>
<th>Medium-dense</th>
<th>Dense</th>
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<tbody>
<tr>
<td>Particle size distribution:</td>
<td>Mono-spheres</td>
<td>Mono-spheres</td>
<td>Mono-spheres</td>
<td>Binary-spheres</td>
<td>Binary-spheres</td>
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<td>Spherical radius 1 (m)</td>
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<td>0.0025</td>
<td>0.0025</td>
<td>0.0025</td>
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<td>Spherical radius 2 (m)</td>
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<td>-</td>
<td>0.0015</td>
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<td>Number of spheres created:</td>
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<td>1.376E+04</td>
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<td>2.611E+04</td>
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<tr>
<td>Large spheres (nL)</td>
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<td>-</td>
<td>-</td>
<td>1.294E+04</td>
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<td>Small spheres (nS)</td>
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<td>-</td>
<td>1.317E+04</td>
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<td>Void ratio</td>
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<td>Numerical mass density (kg/m³)</td>
<td>1.406E+03</td>
<td>1.456E+03</td>
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<td>1.651E+03</td>
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<td>2.650E+03</td>
<td>2.650E+03</td>
<td>2.650E+03</td>
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<tr>
<td>Young’s modulus 1 (N/m²)</td>
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<td>1.724E+08</td>
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<td>Young’s modulus 2 (N/m²)</td>
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<td>-</td>
<td>-</td>
<td>7.00E+08</td>
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<td>Poisson’s ratio 1</td>
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<td>0.17</td>
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<td>Poisson’s ratio 2</td>
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<td>Rheological model parameters:</td>
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<td>Normal damping</td>
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<td>Tangential damping</td>
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<td>0.4</td>
<td>0.33</td>
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<td>Coefficient of sliding friction</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0(1) &amp; 1.0(2)</td>
<td>1.0(1) &amp; 1.0(2)</td>
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<tr>
<td>Coefficient of rolling friction</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.05</td>
<td>0.2(1) &amp; 0.1(2)</td>
<td>0.2(1) &amp; 0.1(2)</td>
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<td>Coefficient of shear jamming</td>
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<td>1.0</td>
<td>0.0</td>
<td>1.0(1) &amp; 0.0(2)</td>
<td>4.0(1) &amp; 0.0(2)</td>
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<tr>
<td>Normal stiffness factor</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<td>Shear stiffness factor</td>
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<td>0.9</td>
<td>0.5</td>
<td>0.9</td>
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<tr>
<td>Shear behavior under triaxial compression testing (at 140 kPa confinement):</td>
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<td></td>
<td></td>
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<td></td>
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<tr>
<td>Peak shear strength (N/m²)</td>
<td>-</td>
<td>2.14E+05</td>
<td>2.62E+05</td>
<td>2.55E+05</td>
<td>3.57E+05</td>
<td>4.68E+05</td>
</tr>
<tr>
<td>Peak angle of internal friction (°)</td>
<td>-</td>
<td>25.0</td>
<td>28.5</td>
<td>28.0</td>
<td>35.5</td>
<td>38.0</td>
</tr>
<tr>
<td>Ultimate shear strength (N/m²)</td>
<td>1.56E+05</td>
<td>1.61E+05</td>
<td>1.56E+05</td>
<td>1.58E+05</td>
<td>1.61E+05</td>
<td>1.62E+05</td>
</tr>
<tr>
<td>Ultimate angle of internal friction (°)</td>
<td>20.0</td>
<td>21.0</td>
<td>21.0</td>
<td>21.0</td>
<td>21.0</td>
<td>21.0</td>
</tr>
<tr>
<td>Shear behavior under triaxial compression testing (at 70 kPa confinement):</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak shear strength (N/m²)</td>
<td>-</td>
<td>9.53E+04</td>
<td>1.14E+05</td>
<td>1.18E+05</td>
<td>1.70E+05</td>
<td>1.98E+05</td>
</tr>
<tr>
<td>Peak angle of internal friction (°)</td>
<td>-</td>
<td>23.0</td>
<td>26.0</td>
<td>26.0</td>
<td>32.5</td>
<td>35.0</td>
</tr>
<tr>
<td>Ultimate shear strength (N/m²)</td>
<td>7.66E+04</td>
<td>7.64E+04</td>
<td>7.60E+04</td>
<td>7.61E+04</td>
<td>8.42E+04</td>
<td>8.50E+04</td>
</tr>
<tr>
<td>Ultimate angle of internal friction (°)</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>21.0</td>
<td>21.0</td>
</tr>
</tbody>
</table>
Task 2 Deliverable: Soil Unit Library

Confining stress = 140 KPa
Task 2 Deliverable: $K_f$ lines

$$\sin(\phi) = \tan(\psi)$$

\[
\begin{align*}
\text{asin}(0.3723) &= 21.858 \text{ deg} \\
\text{asin}(0.6512) &= 40.632 \text{ deg}
\end{align*}
\]
Task 2 Deliverable: $K_f$ lines

$$\sin(\phi) = \tan(\psi)$$

$$\sin(0.5117) = 30.777 \text{ deg}$$

$$\sin(0.4859) = 29.071 \text{ deg}$$
Task 2 Deliverable: $K_f$ lines

\[ \sin(\phi) = \tan(\psi) \]

\[ \arcsin(0.4559) = 27.123 \text{ deg} \]

\[ \arcsin(0.6183) = 38.192 \text{ deg} \]
Task 2 Deliverable: $K_f$ lines

\[ \sin(\phi) = \tan(\psi) \]

\begin{align*}
\text{asin}(0.3723) &= 21.858 \text{ deg} \\
\text{asin}(0.4559) &= 27.123 \text{ deg}
\end{align*}
Other Studies: Particle size distribution (per Murzenko 1966)

CONTROL_DISCRETE_ELEMENT

$\#$ ndamp tdamp frie frier normk sheark cap mxnsc
0.70000 0.40000 0.48000 0.00010 1.00000 0.900000 0 0

Nspk = 73,453
Porosity=0.34

<table>
<thead>
<tr>
<th>GROUP</th>
<th>Content (%)</th>
<th>Diameter (m)</th>
<th>E (Pa)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6.5</td>
<td>0.005</td>
<td>7.00E+07</td>
<td>0.17</td>
</tr>
<tr>
<td>B</td>
<td>15.5</td>
<td>0.0025</td>
<td>7.00E+08</td>
<td>0.17</td>
</tr>
<tr>
<td>C</td>
<td>63</td>
<td>0.001</td>
<td>7.00E+08</td>
<td>0.17</td>
</tr>
<tr>
<td>D</td>
<td>15</td>
<td>0.0007</td>
<td>7.00E+10</td>
<td>0.17</td>
</tr>
</tbody>
</table>

$E_{cal}$ (Pa) K (Pa) $k_N$ $k_T$ $k_T/k_N$ Ndamp Tdamp
1.72E+08 8.71E+07 2.18E+05 1.96E+05 0.9 0.7 0.4
1.72E+08 8.71E+07 1.09E+05 9.80E+04 0.9 0.7 0.4
3.53E+08 1.78E+08 8.91E+04 8.02E+04 0.9 0.7 0.4
3.53E+08 1.78E+08 6.24E+04 5.61E+04 0.9 0.7 0.4

ASTM D7181-11
Minimum Sample size: 1.3 inch x 2.6 inch (33x66mm)
Section 6.1 “The largest particle size shall be smaller than 1/6 specimen diameter.”
Other Studies: Particle size distribution

The internal friction angle = 34 deg.
Other aspects: Capillary Suction
Apparent cohesion in Pendular regime

Table 3.2.6.2. Direct shear test simulation results

<table>
<thead>
<tr>
<th>Normal stress (kPa)</th>
<th>Shear stress without Capillary Suction (kPa)</th>
<th>Shear stress with capillary suction (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>54.5</td>
<td>22.87</td>
<td>24.59</td>
</tr>
<tr>
<td>109</td>
<td>45.32</td>
<td>48.12</td>
</tr>
<tr>
<td>163.5</td>
<td>68.5</td>
<td>70.5</td>
</tr>
</tbody>
</table>

Figure 3.2.6.2. Direct shear test simulations with and without use of capillary force calculations
Project Approach

• **Phase I (12 months; July 2014 - June 2015)**
  - Task 1. Literature Review, Scenario Identification, and Field-Data Acquisition
  - Task 2. Numerical Modeling Schemes and Granular Soil Units

• **Phase II (18 months; July 2015 - December 2016)**
  - Task 3. Numerical Modeling of Driven foundation in Granular Soils
  - Task 4. Physical Laboratory/Centrifuge Experimentation
  - Task 5. Reporting of Findings and Design-Oriented Recommendations
  - Task 6. Final Report
Task 3. Numerical Modeling of Driven Foundation in Granular Soils

- **Activities**
  - Generation of geostatic stress states in megascopic assemblies
  - Preliminary modeling of pile driving simulations
  - Investigation of upscaling
Task 3. Numerical Modeling of Driven Foundation in Granular Soils

- Generation of geostatic stress states

~1.26 million UDES per assembly
Task 3. Numerical Modeling of Driven Foundation in Granular Soils

- Parametric set of assemblies investigated
Task 3. Numerical Modeling of Driven Foundation in Granular Soils

Stress ratio decreases for increasing friction

X-stress / Z-stress

Friction coefficient

○REV₁ ×REV₂ + REV₃
Task 3. Numerical Modeling of Driven Foundation in Granular Soils

- Preliminary modeling of pile driving

Periodic pulse force applied to induce pile penetration

Megascopic DSE assembly (composed of units with known macroscopic properties)

All perimeter spheres are fully restrained from motion

Pile object (eight-node solid elements)
Task 3. Numerical Modeling of Driven Foundation in Granular Soils

- **Animation (Z-Stresses)**

Contours of Z-stress
min=-1.10679e+06, at node# 528785
max=402876, at node# 452058
Task 3. Numerical Modeling of Driven Foundation in Granular Soils

- Animation (Force Chains)
Task 3. Numerical Modeling of Driven Foundation in Granular Soils

- Resultant vertical forces at tip and sides
Task 3. Numerical Modeling of Driven Foundation in Granular Soils

- Investigation of upscaling

Strong force chains under plane strain condition
(Iwashita and Oda 1998)

Polydisperse assembly is unrestrained from motion
Task 3. Numerical Modeling of Driven Foundation in Granular Soils

- **Animation**

  Contours of XY-displacement
  min=0, at node# 603
  max=0.54149, at node# 2324
Task 3. Numerical Modeling of Driven Foundation in Granular Soils

Force vs displacement

- Multisphere model
- Hertz contact theory
Task 3. Numerical Modeling of Driven Foundation in Granular Soils

• **Next steps**
  - Pile driving simulations: non-reflecting boundary conditions

  [Image of waveforms showing before and after simulations with a URL: http://labman.phys.utk.edu/phys222core/modules/m9/Thin%20films.htm]

• Upscaling: effect on rheology parameters and inter-relationships
Thank You!