Micro and Macro-Mechanics of Granular Media including Crushing

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Problem Statement

Compaction characteristics of granular media can be significantly influenced by crushing.

Shear strength characteristics of granular media is also influenced by crushing.
Objectives of the Study

Macro
- Triaxial Test

DEM
- Visualize particle to particle contact forces
- Shear banding

Micro
- Imaging using the XCT to understand particle packing and crushing
Outline

• **Literature Review**
• Triaxial Compression Test
• Discrete Element Modeling (DEM) using PFC2D
• X-Ray Computed Tomography (XCT) Imaging
Literature Review

- Critical State Line and Shear Strength of Soils
- Granular Crushing
- 2-D and 3-D Imaging using XCT
- Discrete Element Modeling
Factors Influencing Shear Strength of Sands

Inherent Particle Characteristics
- Hardness and Specific Gravity Distribution
- Shape, Angularity, Surface Roughness
- Particle Size and Size Distribution

Geologic Factors
- Age, stress history, natural cementation
- Depositional conditions, initial relative density and fabric
- Initial mean effective normal and shear stress levels

Environmental Factors
- Drained Loading, monotonic stress path and stress level
- Undrained Loading, monotonic stress path and stress level, cyclic stress path, stress level, frequency and duration
Critical State Line (CSL)

- Initially suggested by Poulos, 1971. Definition provided by Coop (2004) - Particles eventually reach a stable gradation, the volume decrease will cease at this point.
Critical State Lines

- Soga (2005) - The critical state is used to characterize strength and deformation properties of a soil. A soil will have a tendency to contract during shearing when it is above the critical state line, and oppositely will have a dilative tendency when it is below the critical state line.
Influence of Crushing on Critical State Lines

- **Schofield (1992)** - CSL when plotted on a volume versus strength plot demonstrate that loose and wet samples plot higher than dry and dense ones. Thus when crushing occurs, the CSL will shift due to a change in volume while testing.
Shear Strength of Soils

- **Bolton (1986)** - Peak friction angle is dependent on the confining stress. A sand sample will fail at a lower friction angle at higher confining stresses due to suppression of dilatancy. Figure below shows Mohr circles created for dense sand tested at both low and high confining stresses.
Shear Strength of Soils

- **Elmamlouk (2013)** - The liquefaction susceptibility of calcareous sand was tested using cyclic undrained triaxial tests. The calcareous sand was less susceptible to liquefaction compared to silica due to the angularity of the calcareous sand particles.
Crushing

- **Nguyen (2015)** - Investigated shear strength of sands with different silt percentages, higher percentages shift CSL downwards.

- **McDowell (1998)** - When a grain breaks, they new grains will have fractal geometry to the original; the grain strength of a particle governs the strength and dilatancy of a crushable soil.

Nguyen (2015)
Imaging

- **Garboczi (2002)** - X-ray Imaging can be used to mathematically characterize the shape of random particles and build image databases.
- **Kawakata (1997)** - X-ray CT used to monitor the faults in Westerly granite sand. The faults began just after peak stress.
Imaging

• **Kawakata (1999)** - Three-dimensional observations of faulting process in Westerly granite under uniaxial and triaxial conditions by X-ray CT. Was able to catch a complete image of the fault system.

Kawakata (1996)
Imaging (cont.)

- Sufian (2013) - Reconstructed void space and solid space in order to calculate void ratio
Discrete Element Modeling

- **Fu, Dafalias (2010)** - Used DEM to monitor the shear deformations. The CS was reached regardless of their initial states.

- **Chang, Bolton (2005)** - Modeled particle breakage by bonding several spheres into a single particle. This was used to simulate soil plasticity.
Discrete Element Modeling

• **McDowell (2014)** - Used DEM to check viability of modeling high pressure triaxial tests using a flexible membrane model.

• **Belheine (2008)** - Used triaxial data to determine contact model properties and captured angularity by varying rolling friction values.

![Diagram of discrete element modeling](image-url)
Outline

• Literature Review
• **Triaxial Compression Test**
• Discrete Element Modeling (DEM) using PFC2D
• X-Ray Computed Tomography (XCT) Imaging
Triaxial Compression Tests

- Vertical stress and controlled horizontal stresses to simulate different depths in the ground
- Shear stress may lead to failure in the sample, in a shear plane
- Shear parameters can be determined
- Consolidated Drained (CD), Consolidated Undrained (CU), and Unconsolidated Undrained (UU) triaxial tests can be performed
Procedure
Measured Triaxial Test Parameters

\[ B = \frac{u_c}{\sigma_3} \]

\[ p' = \frac{\sigma'_1 + \sigma'_3}{2} \]

\[ q' = \frac{\sigma'_1 - \sigma'_3}{2} \]
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• **Discrete Element Modeling (DEM) using PFC2D**
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PFC2D Modeling

• Ran sample codes using about 500 particles
• Simulated a direct shear test on glass beads and Daytona Beach sand
• Overlapping Discrete Element Clusters (ODEC) were used to simulate angular particles
PFC2D Modeling (cont.)

Glass Beads

Daytona Beach Sand
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XCT Imaging using the Skyscan 1172

Material Testing Stage

Skyscan set up
Particle Crushing of Concrete Sand

Load (N) vs. Displacement (mm) graph showing:
- A peak load of 94 N
- A load of 37 N at a displacement of 0.17 mm
- A load of 63.15 N at a displacement of 0.34 mm
- A load of 125.31 N at a displacement of 0.52 mm

Images of crushed concrete sand particles are shown on the right side of the page.
Particle Crushing of Calcareous Sand

0.9 N

35 N
Pluviated Reconstruction Procedure

- Pluviate calcareous sand sample into MTS
- Scan sample with the X-Ray CT
- Reconstruct scans with NRecon software
- Analyze images/models to determine void ratio of sample
  - CTan, CTVox, CTVol
2D Reconstructions
3D Models Using CT Vox
Conclusions

• Conducted a thorough literature review on crushing of granular media
• Learned to use the triaxial apparatus, conduct a CU test and analyze the data
• Learned PFC 2D and conducted some preliminary Discrete Element Modeling
• Learned to use the SkyScan 1172 to crush granular media, and determine the pluviated void ratio
Future Work

**Conduct triaxial tests** at different confining pressures to determine the CSL for the following materials:

- Calcareous Sand
  - Can study the influence of crushing on the CSL
- Glass Beads
  - Idealized material with no angularity and are perfectly spherical
- Transparent Soils
  - Allows shear banding to be seen
- **DEM** of a biaxial test
- Determine crushing strength and pluviated void ratio of materials tested using **XCT**
References


Questions?