Rapid Characterization of Unsaturated Soils using Simple Equipment

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Outline

- Introduction
- Limitations of suction-controlled triaxial test
- Novel methods for soil characterization and modelling
  - Modified state surface approach (MSSA)
  - Optical method for volume measurement
  - High suction tensiometer for suction measurement
- Undrained tests and data analysis
- Conclusions
GCTS USTX-2000 for Unsaturated Soils

- Independent control: $\sigma_1$, $\sigma_3$, $u_a$, and $u_w$
- Volume measurements: soil skeleton, water and/or air

$\approx$ $100,000-$150,000
Divide-and-Conquer Approach

When a process is influenced by several parameters, to examine the influence of each individual parameter, one has to conduct tests which involve keeping all the influencing parameters constant except for the target parameter.

Varying $p$

Varying $s$

Varying $q$

$(1-3)$ months/test $\times (20-30)$ tests $= 2-5$ years/ soil
Historical Development of Unsaturated Soil Mechanics

- Bishop (1959), Bishop and Donald (1961)
- Jennings and Burland (1962)
- Matyas and Radhakrishna (1968)
- Fredlund and Morgenstern (1976, 1977)
- Alonso et al. (1990)
- Fredlund and Rahardjo (1993)
- Sheng et al. (2008), Alonso et al. (2010), Zhang (2015)
Barcelona Basic Model

- Developed by Alonso, Gens, and Josa in 1990
- The first elasto-plastic model for unsaturated soils
- It is later called the Barcelona Basic Model (BBM)
- The very most cited paper (about 1,700 times) in unsaturated soil community
- Sheng et al. (2004):
  
  All existing models are variants of the BBM
Suction-Controlled Triaxial Tests

- **Advantages**
  - Designed upon Divide-and-Conquer approach
  - Stress path can be controlled: $p$, $q$, $u_a$, and $u_w$
  - Results easy to analyze

- **Disadvantages**
  - Require sophisticated equipment ($60-120K$)
  - Time-consuming (3-5 years/soil)
  - Results theoretically incorrect*

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Failure of Divide-and-Conquer Approach

What is your record?

God’s number = 20

World’s record= 5.25s
Suction-Controlled Isotropic Compression Test

Stress Path

Test Results
Step vs. Continuous Loadings

$C_v = 2 \times 10^{-8} \text{ m}^2/\text{s}$

$u_{\text{max}}$

$H (\text{m})$

$0.05 \text{ m}$

$0.10$

$0.05$

$0$

$p (\text{kPa})$

$50$

$0$

$t (\text{hour})$

$100$

$q_c = 50 \text{ kPa}$
Drained and Undrained Loadings

\[ \ln p \]

\[ l(s_1) \]

\[ k \]

\[ \lambda(s_3) \]

\[ \lambda(s_1) \]

\[ \kappa \]

\[ \kappa_s \]

\[ s \]

\[ O \]

\[ p \]

\[ e \]

\[ s \]

[Diagram showing points A, B, C, D, E, F, G, H, J, J', LC_1, LC_2 on a 3D graph with axes e, s, p and ln p. The graph illustrates the concepts of constant loading (A to B) and unloading (B to C, D).]
Multiple Undrained Tests with Different $\omega$
An Optical Method to Measure Volume
Principle of Photogrammetry-Based Method
Shape Changes in Soil Specimen
Development of Shear Band
High Suction Tensiometer

Ceramic Disc
Water Reservoir
Epoxy
Diaphragm
Housing
EPXO Pressure Transducer
Cables

0.2 mm

EPXO Pressure Transducer
Epoxy
Housing
Ceramic Disc
Stainless Steel Ring

(a) (b) (c) (d)
Reaction Time and Maximum Suction

Reaction time <2 seconds
Maximum Suction = 1100 kPa
Undrained Test Setup

<$1,400

<$1,100
Undrained Test Results

Measured Soil Responses

Measured Stress Paths

\[ v \ln p_l(s_1) \]

\[ l(s_2) \]

\[ l(s_3) \]

\[ A \]

\[ B \]

\[ C \]

\[ D \]

\[ E \]

\[ F \]

\[ G \]

\[ H \]

\[ I \]

\[ *0p \]

\[ *1p \]

\[ *2p \]

\[ s \]

\[ s(s_3) \]

\[ s(s_2) \]

\[ s(s_1) \]

\[ p_0 \]

\[ p_1 \]

\[ p_2 \]

\[ \ln p \]

\[ 0 \]

\[ 15 \]

\[ 0 \]

\[ 150 \]

\[ 300 \]

\[ 450 \]

\[ 0 \]

\[ 1 \]

\[ 1.75 \]

\[ 10 \]

\[ 100 \]

\[ 1000 \]

\[ W = 12.3\% \]

\[ W = 9.9\% \]

\[ W = 8.4\% \]

\[ W = 8.3\% \]

\[ W = 7.3\% \]

\[ W = 6.5\% \]
Calibration of Model Parameters

\[ F(X) = \sum_{i=1}^{n} w_i (v_i - \hat{v}_i)^2 \]

\[ = \sum_{i=1}^{n} w_i \left\{ v_i - \left[ N(0) - \kappa_s \ln \left( \frac{s_i + p_{at}}{p_{at}} \right) - \lambda(0) \ln \left( \frac{p_i}{p^c} \right) \right] \right\}^2 \]

### Table: Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Best Fit</th>
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<tbody>
<tr>
<td>( \kappa_s )</td>
<td>—</td>
<td>0.019</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>—</td>
<td>0.006</td>
</tr>
<tr>
<td>( N(0) )</td>
<td>—</td>
<td>1.663</td>
</tr>
<tr>
<td>( \lambda(0) )</td>
<td>—</td>
<td>0.020</td>
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<tr>
<td>( r )</td>
<td>—</td>
<td>1.599</td>
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<tr>
<td>( \beta )</td>
<td>MPa(^{-1})</td>
<td>1.573</td>
</tr>
<tr>
<td>( p^c )</td>
<td>MPa</td>
<td>113.3</td>
</tr>
<tr>
<td>( p_{at} )</td>
<td>MPa</td>
<td>0.1</td>
</tr>
<tr>
<td>Standard Deviation ( \sigma )</td>
<td>—</td>
<td>0.012</td>
</tr>
<tr>
<td>Correlation Coefficient</td>
<td>—</td>
<td>92.3%</td>
</tr>
</tbody>
</table>
Yield Curve for Compacted Fairbanks Silt

![Graph showing yield curves for different water contents (W) with respect to mean net stress (p) and matric suction (s).]
Experimental vs. Predicted Test Results
Experimental vs. Predicted Test Results
Conclusions

- Suction-controlled triaxial tests cannot produce correct results needed for the constitutive modeling
- MSSA is proposed to study unsaturated soil behavior
- Undrained triaxial tests used for soil characterization to get correct results
- Optical method developed for volume measurements
- High suction tensiometer for direct suction measurements
- Shape of the LC yield curves in the BBM verified
The proposed method is:

- More cost-effective ($2,500 vs. $60-120K)
- More efficient (4-5 hours vs. 1-3 months/test)
- Theoretically correct
- Easy to understand and use