State-of-the-art

on

HYDRAULIC TESTING IN UNSATURATED SOIL

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Outline:

1. Water retention characteristics
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2. Water and air permeabilities in unsaturated soils
   K. V. BICALHO

3. Permeability in unsaturated swelling soils
   F. MASROURI
INTRODUCTION

Water Retention Characteristic Curve (WRCC)

- Main drying curve
- Main wetting curve
- Scanning curves
- Air entry value
- Water entry value
WRC DEPENDS ON …

(1) Soil properties
(Particle size distribution, Organic matter content, Mineral composition, etc.)

(2) Conditions
(Void ratio, Temperature, Micro structure, Stress state, etc.)

(3) Suction history
(Drying, Wetting, Initial state ($\rho_d$, s, Sr))
TESTING FOR WRC (1)

(1) Suction measurement
   (Filter paper technique, Tensiometer, Psychrometer, Freezing point depression method, etc.)

(2) Indirect method
   (Mercury intrusion testing, Air intrusion testing)
# (3) Suction Control

<table>
<thead>
<tr>
<th>Technique</th>
<th>Control suction with</th>
<th>Suction range</th>
<th>Suction history</th>
<th>Data continuity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure plate</td>
<td>Air pressure</td>
<td>0 to 1500 (kPa)</td>
<td>Poss.</td>
<td>Fine</td>
</tr>
<tr>
<td>Vapour pressure</td>
<td>Salt solution</td>
<td>4 to 300 (MPa)</td>
<td>Poss</td>
<td>Fine</td>
</tr>
<tr>
<td>Soil column</td>
<td>Water table</td>
<td>0 to 100 (kPa)</td>
<td>Poss.</td>
<td>Good</td>
</tr>
<tr>
<td>Osmotic</td>
<td>Osmotic pressure</td>
<td>0 to 4 (MPa)</td>
<td>Poss</td>
<td>Fine</td>
</tr>
<tr>
<td>Centrifuge</td>
<td>Centrifugal force</td>
<td>High</td>
<td>Imposs.</td>
<td>Fine</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Evaporation</td>
<td>0 to 100 (kPa)</td>
<td>Imposs.</td>
<td>Good</td>
</tr>
</tbody>
</table>
MONITORING METHOD

Water retention characteristics

Rassam & Williams (2000)

Toker et al. (2004)
(1) Soil Properties

- Particle size distribution
  Gupta & Larson (1979), Ghosh (1980)
  Araya et al. (1981), Harverkamp & Patlange (1986),
  Fredlund (1998), Kamiya & Uno (2000), Imre et al. (Experus)
- Mineral composition
  Williams et al. (1983), Bilsel & Öncü (Experus),
  Russo (Experus), Araújo et al. (Experus)
- Organic matter content
(2) Conditions

- **Void ratio**
  Fleureau et al. (1993), Kawai et al. (2000),
  Romero & Vanuat (2000)

- **Temperature**
  Duarte et al. (Experus)

- **Structure**
  Croney & Coleman (1954), Walker et al. (Experus)

- **Stress states**
(1) Experiment

(2) Assuming internal pore structures

(3) Formulating the derivative
   Hanks et al. (1969), Dane & Wierenga (1974), Li (2005)

(4) Similarity between boundary curves and scanning curves
   Rojas (2002), Kawai et al. (2002)
CONCLUDING REMARKS

- Select an appropriate method for soil properties, site, …
- Void ratio strongly influences on WRC.
- Temperature, Stress states, are indirect factors, which change void ratio
- Quantitative evaluation of WRC by fitting to the empirical equation
- To evaluate test results correctly, we have to know how the hysteresis appears
INTRODUCTION:

All macroscopic properties of porous media are influenced by the pore structure

Permeability ($k$): macroscopic pore structure parameter

$k$ (porous media) depends on the permeating fluid and the mechanism of permeation

$k$ is defined by Darcy’s law

Both liquids and gases have been used to measure permeabilities
INTRODUCTION:

\[ k_w \text{(unsaturated soils)} : F \text{(soil structure + saturation)} \]

Highly nonlinear and challenging problem

Sophisticated experimental and analytical tools are needed to address the problem

Most of the existing laboratory methods yield the \( k_w - S_r \) (or \( u_w \)) relationship

Hysteresis (?)
DETERMINATION OF $k_w$ FUNCTIONS:

1. Direct methods (steady and unsteady) (*)
2. Indirect methods (empirical, macroscopic and statistical)
3. Inverse problem solution approach (*)

(*) Laboratory testing
DIRECT LABORATORY METHODS:

1. Steady state
   a) Constant hydraulic gradient
   b) Constant flow rate (flow pump technique)
   c) Centrifuge method

2. Unsteady state
   a) Outflow-inflow methods
   b) Instantaneous profile methods
1. a) **Constant hydraulic gradient**

   Bjerrum & Huder (1957); Corey 1957 (Richards 1931), Mitchell et al. (1965)

1. b) **Constant flow rate (flow pump technique)**

   Saturated $k_w$: Olsen 1966 (fine grained soils),
   Pane et al. 1983, Olsen & Schiffman, 1983
   Aiban & Znidarcic 1989 (Constant head vs flow pump tests)

   Unsaturated $k_w$: Znidarcic et al. 1991
   Bicalho et al. 2000, 2004

   **Experus 2005:** Bicalho, Znidarcic & Ko
   Likos, Lu & Wayllace
1. **a) Constant hydraulic gradient**

**b) Constant flow rate (flow pump technique)**

**Advantages:**

- Simplicity in the result analysis
- Controls of the stress state variables during the testing
- Flow pump provides high level of flow control + short testing time
1. c) **Centrifuge method**
   (centrifugal force + steady flow)

**History** *(Centrifuge modeling)*

- 1930s application to design problems (USSR and USA)
- 1960s research application in Japan and the UK
- 1990s extensive instructional application

Nimmo et al, 1987, 1992; Conca & Wright, 1992; Wright et al., 1994

**Experus 2005:** Caputo & Nimmo *(quasi-steady CM)*
   McCartney & Zornberg
2. a) Outflow-inflow methods

Gardner (1956); Miller & Elrick (1958), Rijtem (1959), Kunze & Kirkham (1962) and others.
Brace et al. (1968) (Pulse test) (very small k values)

2. a.1) Boltzmann transform methods

(based on the transformation of Richard’s equation to a diffusion equation using Boltzmann’s transformation)


Experus 2005: Bulut, Aubeny & Lytton (Unsat. Soil Diffusivity Meas.)
Aubeny, Bulut & Lytton (laboratory vs. field)
2. b) Instantaneous profile methods (IPM)

The IPM consists of inducing transient flow in a long cylindrical sample of soil and then measuring the resulting water content and/or pore water pressure profiles at various time intervals.

Several variations in the method of data analysis have been employed.

Measure: $h_{pw}$ distributions (uss water flow)
Obtain: water content distribution
(from an independently measured or estimated WRC)

History:

Richards & Weeks 1953
Wind 1966 (correction of WRC using the outflow data collected)
Amraoui 1996
INVERSE PROBLEM SOLUTION APPROACH:

Solution of a boundary value problem in which the test results are matched in the numerical analysis

Obtain WRC and k functions from experimental data

**Known:** governing equation + initial and boundary conditions

**Unknown:** material functions + parameters

Parameter estimation technique
History:

**Soil Mechanics:**

Testing technique with the flow control method (flow pump)
The selected flow rate determines how appropriate the stated assumptions in the data interpretation.

**Experus 2005:** Likos, Lu & Wayllace (numerical model)
History:

- Corey (1957) (special permeability device – silty sand)
- Yoshimi & Osterberg (1963)
  (standard oedometer connected to U-shape manometer)
- Delage, Cui & De Laure (1998) ($k_a$ of a low plasticity compacted silt)
- Loiseau, Cui & Delage (2002)
  ($k_a$ heavily compacted sweling clay-sand mixture)

Experus 2005:
Kamiya, Bakrie & Honjo: Test method: $k_a$ – $S_r$ relationship (sandy soils)
Romero, García & Knobelsdorf: Exp. study 80/20 sand/bentonite mixture
  Influence of the hydraulic history and the $V_a/V_s$ on $k_a$
CONCLUDING REMARKS

Unsaturated water and air permeability

Reliable measurements and predictions of unsaturated permeability functions are essential for solving any unsaturated soil problem

Direct measurements of unsaturated k functions should always be preferred over the prediction using models

Need of study comparing different methods (field?)
Most of the existing methods yield the $k_w - S_r$ (or $u_w$) relationships, need of experimental study of $k_w$ (soil structure + $S_r$ (or $u_w$))

Highly nonlinear and challenging problem

Sophisticated experimental and analytical tools are needed to address the problem

Today such tools are available, but a lot of fundamental work still needs to be done (microscopic approach?)
**Introduction:**

**Permeability in unsaturated swelling soils**

Rigid soils:

1. Degree of Saturation - Suction curve $\rightarrow$ (WRC)
2. Unsaturated permeability - Suction curve $\rightarrow$ $k(s)$

Swelling soils:

3. Shrinkage swelling curve $\rightarrow$ (SSC)
   Specific volume - Moisture content

Simultaneous measurement of three functions

Separate experiments (Kim et al. 1993)

*Non linear Hysteresis*
Three different boundary conditions:

- Free Swelling
- Constant Volume
- Oedometric
Different testing methods

**Dual gamma-ray → bulk density \( \rho_d \) & volumetric water content \( \theta \)**

**Tensiometers → suction**
Angulo (1989), Garnier et al. (1997)

**Thermocouple psychrometer → suction**
Bulut et al. (2005)

**Other separate methods**

**Laser spots, laser barriers → swelling rate**
Garnier et al. (1997), Rolland (2002)

**Contact sensors → swelling rate**
Angulo (1989), Kim et al. (1992)
Free Swelling:

Sensivities:
\[ \theta_w \rightarrow \pm 0.04 \, \text{cm}^3/\text{cm}^3 \]
\[ \rho_d \rightarrow \pm 0.04 \, \text{g/cm}^3 \]
\[ w = \pm 3\% \]
\[ d = \pm 3\mu\text{m} \]

Free Swelling:

Apparatus used to determine the hydraulic properties of a sample of swelling soil under evaporation (t = 27 °C)

Garnier et al. (1997)

Sensivities:
- Tensiometers ± 2 cm H_2O
- Laser spot: 2 µm
- Laser barriers: 100 µm
Permeability in unsaturated swelling soils

Constant Volume:

Dual gamma-ray: Tabani (1999), Rolland (2002), Rolland et al. (2005)

Sensivities:

\[ \theta_w \rightarrow \pm 0.04 \text{ cm}^3/\text{cm}^3 \]
\[ \rho_d \rightarrow \pm 0.04 \text{ g/cm}^3 \]
\[ w = \pm 3\% \]
**Permeability in unsaturated swelling soils**

**Governing equations for water flow in swelling soils:**

Swelling → an element in motion in a fluid system

2 distinct approaches to unsteady problems may be used:

**Eulerian**  Spatial coordinates → independent variables (t)
- velocities and pressure heads → dependent variables (t)
  - Prager (1953), Philip (1968), Nakano et al. (1986), Kim et al. (1999)

**Lagrangian**  Spatial (material) coordinates → dependent variables (t)
- Hartley & Crank (1949), Gibson et al. (1967), Smiles & Rosenthal (1968),
  - Philip 1968, Angulo (1986), Nakano et al. (1986), Kim et al. (1999),
Permeability (k) as a function of volumetric water content (θ)

Nakano et al. (1986)
(Japanese Bentonite: Bulk density 0.846 g/cm³)

Kim et al. (1999)
(Compacted mixture of 20% Bentonite and loam)
Permeability in unsaturated swelling soils

Free Swelling test results (Rolland et al. Experus 2005):

<table>
<thead>
<tr>
<th>Soils</th>
<th>( \rho_s ) (g/cm³)</th>
<th>( w_L ) (%)</th>
<th>( w_p ) (%)</th>
<th>( I_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xeuilley Silt</td>
<td>2.67</td>
<td>53</td>
<td>30</td>
<td>23</td>
</tr>
<tr>
<td>Bentonite</td>
<td>2.7</td>
<td>164</td>
<td>64</td>
<td>100</td>
</tr>
</tbody>
</table>

Initial and final profiles:

- Bulk density before and after infiltration test.
- Gravimetric water content before and after infiltration test.
Permeability in unsaturated swelling soils

Free Swelling test results (Rolland et al. Experus 2005):

**HYDRIC TRANSFER**

LAGRANGIAN DESCRIPTION

(Philip, 1969)

\[
\frac{\partial w}{\partial t} = \frac{\partial}{\partial m} \left[ D_m(w) \left( \frac{\partial w}{\partial m} \right) \right] \quad \text{with} \quad \frac{dm}{ds} = dz \quad \text{d}m = 0 \cdot dz
\]

\[m\] is the material coordinate

Boundary Conditions

\[w = w(\text{saturation}) \quad \text{for} \quad m = 0 \quad \text{and} \quad t \geq 0\]

\[w = w(\text{initial}) \quad \text{for} \quad m \rightarrow \infty\]

**BOLTZMANN TRANSFORMATION**

Ordinary differential equation

\[
\frac{d^2w}{d\xi^2} = -\frac{1}{D_m(w)} \left( 1 - \frac{\partial w}{\partial \xi} + \frac{D_m(w)}{dw} \left( \frac{dw}{d\xi} \right)^2 \right)
\]

Boundary Conditions

\[w = w(\text{saturation}) \quad \text{for} \quad \xi = 0\]

\[w = w(\text{initial}) \quad \text{for} \quad \xi \rightarrow \infty\]
Permeability in unsaturated swelling soils

Free Swelling test results (Rolland et al. Experus 2005):

Water content versus boltzmann variable.

GARDNER’S MODEL:

$$D_m(w) = a_m \exp(b_m w)$$

Material diffusivity parameters identified by inverse method.
Free Swelling test results (Rolland et al. Experus 2005):

Water retention curve (osmotic et filter paper methods)
Free Swelling test results (Rolland et al. Experus 2005):

Effect of the mechanical boundary conditions

\[
K_{w/s} = D_m \left[ 1 - \left( \frac{\theta_w}{\theta_s} \right) \left( \frac{d\theta_s}{d\theta_w} \right) \right]^{-1} \left[ \frac{\partial \psi_w}{\partial \theta_w} \theta_s^2 \right]
\]

Hydraulic conductivity

Free swelling
Dynamics of moisture movement is extremely complex in unsaturated swelling-shrinking soils.

Given the complexity of theoretical and analytical methods, rigorous non-linear hysteretic analyses may not always be justified.

The simplified methods in this domain should be developed.
Special thanks to Alessandro

Thank you for your kind attention

Molte Grazie