Soil and Rock Properties

- Preamble -

J. Carlos Santamarina
KAUST
1. Classification ➔ Properties
2. Permeability
3. Compressibility
4. Coupling
5. Stiffness: $G_{\text{max}} \leftrightarrow G_{\text{tan}}$ ... Oedometer
6. Shear Strength - Localization
7. Repetitive Loads
8. Properties: Database & IT tool
1. Classification ➔ Properties
2. Permeability
3. Compressibility
4. Coupling
5. Stiffness: $G_{\text{max}} \leftrightarrow G_{\text{tan}}$ ... Oedometer
6. Shear Strength - Localization
7. Repetitive Loads
8. Properties: Database & IT tool
<table>
<thead>
<tr>
<th>COARSE</th>
<th>Gravel</th>
<th>Sand</th>
<th>Low Plasticity</th>
<th>High Plasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>R &gt; 50%</td>
<td>R &gt; 50%</td>
<td>P &gt; 50%</td>
<td>LL &lt; 50</td>
<td>LL &gt; 50</td>
</tr>
<tr>
<td>#4</td>
<td>% fines</td>
<td>% fines</td>
<td>CL</td>
<td>CH</td>
</tr>
<tr>
<td>#200</td>
<td>&gt; 12% fines</td>
<td>&gt; 12% fines</td>
<td>OH or MH</td>
<td>OH</td>
</tr>
</tbody>
</table>

**Plasticity Index**

- **CL**: Low Plasticity
- **CH**: High Plasticity
- **OH or MH**: High Plasticity

**Liquid Limit**

- **OL**: Low Plasticity
- **ML**: High Plasticity
- **CH**: High Plasticity
- **OH**: High Plasticity

**Soil Types**

- **GW**: Gravel with C_u > 4, 1 ≤ C_c ≤ 3
- **GP**: Gravel with C_u ≤ 6, 1 ≤ C_c ≤ 3
- **GM**: Gravel with C_u ≤ 6, C_c ≤ 3
- **GC**: Gravel with C_u > 4, C_c > 3
- **SW**: Sand with C_u > 6, 1 ≤ C_c ≤ 3
- **SP**: Sand with C_u ≤ 6, 1 ≤ C_c ≤ 3
- **SM**: Sand with C_u ≤ 6, C_c ≤ 3
- **SC**: Sand with C_u > 4, C_c > 3
- **ML**: Low Plasticity
- **CL**: Low Plasticity
- **OL**: Low Plasticity
- **MH**: High Plasticity
- **OH or MH**: High Plasticity
- **CH**: High Plasticity
Coarse

Porosity

Shear wave velocity [m/s]

Permeability [cm/s]

Friction angle
Fines:

Electrical Sensitivity $S_{E\%}$

- high
- intermediate (interm.)
- low

Plasticity $LL_{brine}$

- non
- low
- intermediate (int.)
- high

$S_{E} = \sqrt{\left(\frac{LL_{DW}}{LL_{brine}} - 1\right)^2 + \left(\frac{LL_{ker}}{LL_{brine}} - 1\right)^2}$
1. Classification
2. Permeability

Leonardo's Parachute

Leonardo da Vinci's sketch of a parachute, showing the concept of using air resistance to slow a fall.
Hydraulic Conductivity: **Physics**

**Physics-inspired:**

*Hagen–Poiseuille*

*Kozeny-Carman*

\[
k = \frac{cg \frac{\rho_{fl}}{\mu_{fl}} \left( \frac{1}{S_s} \right)^2 e^3}{1 + e}
\]
Hydraulic Conductivity: Data

Hydraulic conductivity $k$ [cm/s]

Void ratio $e$

- Sands
- Silts
- Clays

Specific surface
Hydraulic Conductivity: Data

Reference $k_0$ at void ratio $e_0=1$

Hydraulic conductivity $k$ [cm/s]

Void ratio $e$

\[
\frac{k}{k_0} = \left(\frac{e}{e_0}\right)^b
\]
Exponent $b$

Specific surface $S_s$ [m$^2$/g]

Coarse-grained sediments

Fine-grained sediments

$log \left[ \frac{k_0}{\text{cm/s}} \right] = 10^{-5} \left( \frac{\text{m}^2}{\text{g}} \right)^{1.8}$
Hydraulic Conductivity

Physics-inspired:

Hagen–Poiseuille
Kozeny-Carman

\[ k = \frac{c g \rho_{fl}}{\mu_{fl} \rho_m} \left( \frac{1}{S_s} \right)^2 \frac{e^3}{1 + e} \]

Data-driven:

\[ \frac{k}{k_0} = \left( \frac{e}{e_0} \right)^b \]

\[ k_0 = 10^{-5} \left( \frac{m^2}{g} \right)^{1.8} \quad \text{(for water)} \]

Robust model

\[ \frac{k}{cm/s} = 10^{-5} \left( \frac{m^2}{g} \right)^{1.8} e^b \quad \text{(for water)} \]
Hydraulic Conductivity

**Physics-inspired:**

*Hagen–Poiseuille*  
*Kozeny-Carman*

\[ k = \frac{cg}{\mu_{fl} \rho_m} \left( \frac{1}{S_s} \right)^2 \frac{e^3}{1 + e} \]

**Data-driven:**

\[ \frac{k}{k_0} = \left( \frac{e}{e_o} \right)^b \]

\[ k_0 \left( \frac{cm}{s} \right) = 10^{-5} \left( \frac{m^2}{g} \right)^{1.8} \]

(for water)

\[ \frac{k}{k_0} \left( \frac{cm}{s} \right) = 10^{-5} \left( \frac{m^2}{g} \right)^{1.8} e^b \]

(for water)
### Pore Network

<table>
<thead>
<tr>
<th></th>
<th>COV(R²)=0.49</th>
<th>COV(R²)=1.26</th>
<th>COV(R²)=1.95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrelated</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Correlated</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>

preferential flow along interconnected large pores
 Hydraulic Conductivity: Fractured Rocks

Marcellus shale outcrop

Don Duggan-Haas

Aperture coefficient of variation COV

90% of the flow
1. Classification
2. Permeability
3. Compressibility
$k_o$ Compression: Data

Data (Mesri and Olson, 1971)
\( k_0 \) Compression: Model

Data (Mesri and Olson, 1971)

\[ e = e_{1kPa} - C_e \log \left( \frac{\sigma'}{\sigma' = 1kPa} \right) \]
$k_0$ Compression: Model

**Low-stress $e$-asymptote:**
* suspension-skeleton transition

**High-stress $e$-asymptote:**
* shales $\Rightarrow e > 0$

\[
e = e_{1kPa} - C_e \log \left( \frac{\sigma'}{\sigma' = 1kPa} \right)
\]
Compression: Data

Data (Mesri and Olson, 1971)

Boyle-Mariotte

\[ P \cdot V = \alpha \]

van der Waals

\[ (\sigma' + \sigma_A - \sigma_R)(V_t - V_s) = \alpha \]
<table>
<thead>
<tr>
<th>Semi-log</th>
<th>Classical</th>
<th>$e = e_{ref} - C_c \log \left( \frac{\sigma'}{\sigma'_{ref}} \right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubic (3rd order)</td>
<td>$e = e_{ref} - \alpha \cdot \log \left( \frac{\sigma'}{\sigma'<em>{ref}} \right) + \beta \cdot \left[ \log \left( \frac{\sigma'}{\sigma'</em>{ref}} \right) \right]^3$</td>
<td></td>
</tr>
<tr>
<td>Modified</td>
<td>$e = e_c - C_c \log \left( \frac{1 \text{kPa}}{\sigma'<em>{L}} + \frac{1 \text{kPa}}{\sigma'</em>{H}} \right)$</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>From gas to soil</td>
<td>$e = e_H + (e_L - e_H) \left( \frac{\sigma'+\sigma_c'}{\sigma_c'} \right)^{-\beta}$</td>
</tr>
<tr>
<td>Exponential</td>
<td>Gompertz function</td>
<td>$e = e_H + (e_L - e_H) \cdot \exp \left( \frac{(\sigma')^\beta}{\sigma_c'} \right)$</td>
</tr>
<tr>
<td>Hyperbolic</td>
<td>Hyperbolic function (classical hyp: $\beta=1$)</td>
<td>$e = e_L - (e_L - e_H) \frac{1}{1 + \left( \frac{\sigma_c'}{\sigma'} \right)^\beta}$</td>
</tr>
<tr>
<td>Arctangent</td>
<td>S-shaped function</td>
<td>$e = e_L + \frac{2}{\pi} (e_L - e_H) \arctan \left[ -\left( \frac{\sigma'}{\sigma_c'} \right)^\beta \right]$</td>
</tr>
</tbody>
</table>

Terzaghi & Peck (1948)  
Schofield & Wroth (1968)  
Burland (1990)  
Hansen (1969)  
Butterfield (1979)  
Juárez-Badillo (1981)  
Houlsby & Wroth, (1991)  
Pestana & Whittle (1995)  
Gregory et al. (2006)  
Cargill (1984 – $\beta=1$)  

SH Chong
1. Classification
2. Permeability
3. Compressibility
4. Coupling - Implications
Compressibility + Permeability: Coupled HM

\[ e = e_H + (e_L - e_H) \left( \frac{\sigma' + \sigma'_c}{\sigma'_c} \right)^{-\beta} \]

\[ \frac{k}{k_o} = \left( \frac{e}{e_o} \right)^b \]

Oedometer
Compressibility + Permeability: Coupled HM

\[
e = e_H + (e_L - e_H) \left( \frac{\sigma' + \sigma'_c}{\sigma'_c} \right)^{-\beta}
\]

\[
\frac{k}{k_o} = \left( \frac{e}{e_o} \right)^b
\]

suction caissons
cake formation &
borehole stability
seafloor & pumping

![Diagram showing invasion of mud and cake formation with depth.](image)
Compressibility + Permeability: Hydro-Frac.
Compressibility + Permeability: Hydro-Frac.
Hydraulic Fracture: FEM

(MCC - no cohesion)
HF in Soils: *ab initio*

Soil is in compression EVERYwhere
HF in Pre-structured Media (Shales)

**opening**

**closing**

*Self-propping*
HF in Pre-structured Media (Shales)
1. Classification
2. Permeability
3. Compressibility
4. Coupling
5. Stiffness: \( G_{\text{max}} \leftrightarrow G_{\text{tan}} \) ... Oedometer
\( k_0 \) Loading

- Back-calculated from building settlement

![Graph showing compression ratio against soil units]
Oedometer: Improvements

In-Shelby

Displacement [mm] vs. Time [sec]
Sampling effect

biased sampling? 

compaction

Sandy soils

Clayey soils

Highly cemented soils/rocks

Field S-wave velocity $V_F$ [m/s]

Relative velocity $V_{lab}/V_F$
Oedometer?

In situ $V_s$ vs Oedometer

Strain

$10^{-5}$  $10^{-4}$  $10^{-3}$  $10^{-2}$  $10^{-1}$

\[ \frac{\Delta e}{1 + e_o} = C_c \log \left( \frac{\sigma'_o + \Delta \sigma'}{\sigma'_o} \right) \]
Small Strain Stiffness

\( k_0 \) Loading: Fabric change

\[ V_S = \alpha \left( \frac{\sigma'_x + \sigma'_y}{2P_a} \right)^\beta \]

sand – no cement

\( \sigma' \) increases

\( \sigma' \) decreases

\( \sigma' = 1.4 \)
\( \sigma' = 10.1 \)
\( \sigma' = 27.4 \)
\( \sigma' = 62.1 \)
\( \sigma' = 131.5 \)
\( \sigma' = 270.3 \)
\( \sigma' = 409.1 \)
\( \sigma' = 603.9 \)
\( \sigma' = 798.8 \)
\( \sigma' = 1062.5 \)
\( \sigma' = 798.8 \)
\( \sigma' = 603.9 \)
\( \sigma' = 409.1 \)
\( \sigma' = 270.3 \)
\( \sigma' = 131.5 \)
\( \sigma' = 62.1 \)
\( \sigma' = 27.4 \)
\( \sigma' = 10.1 \)
\( \sigma' = 1.4 \)

\( \sigma' \) decreases

Frocht
$C_c \leftrightarrow \alpha \beta$ parameters

$V_s = \alpha \left( \frac{\sigma'_x + \sigma'_y}{2P_a} \right)^\beta$

![Graphs showing the relationship between compression index $C_c$ and α, β parameters](image)

- **Compression index $C_c$**
  - **α-factor [m/s]**
  - **β-exponent**

- **Materials:**
  - **Cemented**
  - **Sand**
  - **Clay**
Velocity-Stress: Soils

\[ V_S = \alpha \left( \frac{\sigma_x' + \sigma_y'}{2P_a} \right)^\beta \]

\[ \beta = 0.73 - 0.27 \log \left( \frac{a}{\text{m/s}} \right) \]
Velocity-Stress: Fractured Rock

\[ V_S = \alpha \left( \frac{\sigma_\perp}{P_a} \right)^\beta \]
1. Classification
2. Permeability
3. Compressibility
4. Coupling
5. Stiffness: $G_{\text{max}} \leftrightarrow G_{\text{tan}} \ldots$ Oedometer
6. Shear Strength - Localization
Sediment Response During Shear

- Shear
- Confinement
- Axial strain
- Volume
- Critical state

Diagram shows the relationship between shear, confinement, axial strain, and volume, with critical state indicated on the graph.
**Plane Strain**

*Contractive sample:* \( \text{rnd}(e) = 0.92 - 1.02 \)  (Note: \( e_{cs} = 0.82 \) )

\[ \delta\text{-fields @ } \varepsilon_z = 20\% \]
Sediment Response During Shear

\[ \phi_r, \phi_{cv}, \phi_p, \psi \]

- shear
- confinement
- axial strain
- volume
**Plane Strain**

*At Critical State*: \( \text{rnd}(\varepsilon) = 0.77 - 0.87 \)  
(Note: \( e_{cs} = 0.82 \))

\[ \delta \text{-fields @ end of test} \]

---

**Graphs**

1. **Vertical stress [kPa]**
   - Red: Hetero(10cm\times10cm)
   - Blue: Hetero(10cm\times20cm)
   - Black: Hetero(20cm\times20cm)
   - Cyan: Hetero(5cm\times5cm)
   - Dotted: Homogeneous

2. **Void ratio**
   - Color scale: 0.78 to 0.82

---

H. Shin – Ulsan Univ.
Localization?

- Strain localization
  - shear band
  - compaction band

- Grains migration
  - clogging
  - piping erosion
  - erosion
  - sand production

- Fluids
  - viscous fingering
  - density tears

- Fluid-driven
  - desiccation cracks
  - gas or oil-driven
  - hydraulic fracture

- Lenses
  - ice & hydrate

- Dissolution
  - shear in contraction
  - piping & wormholes
1. Classification
2. Permeability
3. Compressibility
4. Coupling
5. Stiffness: $G_{\text{max}} \leftrightarrow G_{\text{tan}}$ ... Oedometer
6. Shear Strength - Localization
7. Repetitive Loads
Stress - Strain - Void Ratio

First Cycle
Stress - Strain - Void Ratio  \( N^{th} \) Cycle

\[\varepsilon_1, q, \varepsilon, e, p'\]

\( e_0 \)

\[ \text{M} \]

\( \text{Stress} - \text{Strain} - \text{Void Ratio} \)
Stress - Strain - Void Ratio  \( N^{th} \) Cycle

\[ \varepsilon_1 \quad e \quad e_0 \quad e_{\text{ter}} \quad q \quad p' \]

Terminal void ratio

\[ e \rightarrow e_{\text{ter}} \rightarrow q \rightarrow e \]
Stress - Strain - Void Ratio

N<sup>th</sup> Cycle

- ratcheting
- terminal void ratio

\[ e_{\text{ter}} \]

\[ e_0 \]

\[ e \]

\[ p' \]

\[ \varepsilon_1 \]
Stress - Strain - Void Ratio

N\textsuperscript{th} Cycle

\textit{shakedown}

terminal void ratio
Settlement $k_0$ Conditions (coarse sand)

**Loose specimen**

**Dense sample**
Eugenia Canyon
Grand Canyon Skywalk
Delphi - Greece
Lavrion (Greece)
Brezno (Czech Republic)
Brezno (Czech Republic)
1. Classification
2. Permeability
3. Compressibility
4. Coupling
5. Stiffness: $G_{\text{max}} \leftrightarrow G_{\text{tan}}$ ... Oedometer
6. Shear Strength - Localization
7. Repetitive Loads
8. Properties: Database & IT tool
Properties: IT Tool

Soils: Dr. M. Terzariol (KAUST)  Fractured rocks: Dr. L.G. Cruz (U. Cauca)

- Undisturbed specimens
- Remolded Specimens (index props)
- In-situ

Database & IT tool

Geotech Design
Closing Thoughts

Geotech 100 yrs: comprehensive revision + pruning + expansion (starting with classification)

Models & correlations: physics inspired… data driven
geo-databases: ready for a global community effort

Properties: revolution in experimental methods
boundaries, variability and internal scales
what we want to measure … what we think we measure

Coupled HTCBM: complex … even $\sigma'$ (the most common HM)

Repetitive loading: ubiquitous … fertile territory for research

Localizations: ubiquitous and problematic
Characterization, Modeling, Monitoring, and Remediation of FR Actured ROCK

This presentation and support information:

(1) egel@kaust.edu.sa
or uperc.kaust.edu.sa

(2) egel@kaust.edu.sa
or uperc.kaust.edu.sa
Reason for 3 great geo-conferences in Argentina
An invitation to “care for our common home”

*how can we -GeoEngineers- contribute?*
An invitation to “care for our common home”

how can we -GeoEngineers- contribute?

Soil & rock = terroir (latin)

in Argentina ➔ Malbec, Torrontes…
An invitation to “care for our common home”

*how can we -GeoEngineers- contribute?*

Soil & rock = terroir (latin)

*in Argentina ➔ Malbec, Torrontes…*

We did **not** develop TRUBALL (DEM)

*we developed GREATBALL!*

Reason for 3 great geo-conferences in Argentina
An invitation to “care for our common home”

*how can we -GeoEngineers- contribute?*

Soil & rock = terroir (latin)

*in Argentina ➔ Malbec, Torrontes…*

We did **not** develop TRUBALL (DEM)

*we developed GREATBALL !*

It takes two to tango

*enjoy wonderful colleagues !*

**Welcome to Argentina !!**