Visualising internal erosion mechanisms using transparent soil

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Contents

• Internal erosion via Skempton & Brogan (1984) experiments
• Experimental techniques
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Internal erosion (or suffusion) responsible for ~50% of embankment dam failures globally

- Predominantly a problem in older or smaller earthworks
- Work focused on establishing erosion criteria
- Work focused on understanding mechanisms of internal erosion

Gap-graded soil in which fine particles can migrate through voids = suffusion (Rosenbrand, 2011)
Skempton & Brogan (1994) experiments

- Performed tests on internally unstable sandy gravels to compare theoretical value of critical hydraulic gradient at which piping occurs \( i_c \) under an upward flow (according to Terzaghi, 1925) with the actual hydraulic gradient \( i_{cr} \).

- Proposed that the erodible fine grains carry some (reduced) proportion of the overburden load.

- The critical gradient for piping in the fine grains is then:

  \[
  i_{cr} = \alpha \left( \frac{\gamma'}{\gamma_w} \right) \quad \text{or} \quad i_{cr} = \alpha i_c
  \]

  where \( i_{cr} \) is the critical hydraulic gradient observed in the test.

- From this: a larger \( \alpha \) will yield a greater resistance to the onset of seepage-induced instability.
## Visualising internal erosion

### Laboratory based
- Using a box-shaped permeameter
  - Initial experiments based on Skempton & Brogan (1994) design
- Glass particles and optically matched immersion oil
  - Replicating soil and water
- Variable particle grading and hydraulic head
- Refractive index matching (RIM) & planar laser induced fluorescence (PLIF) techniques
- (High) speed imaging
- Image processing
Refractive Index Matching & seepage scaling

<table>
<thead>
<tr>
<th>Material</th>
<th>Refractive Index at 589.3 nm</th>
<th>Density at 25 °C (g/cm³)</th>
<th>Kinematic Viscosity at 25 °C (cSt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrocarbon Oil</td>
<td>1.4715</td>
<td>0.846</td>
<td>16</td>
</tr>
<tr>
<td>Duran Glass</td>
<td>1.4718</td>
<td>2.23</td>
<td>-</td>
</tr>
</tbody>
</table>

Matched!

Ratio $G_s = 2.65!$

Scale particles ~4 times up!
Transparent materials
  – Solids & fluid with same refractive index (RIM)

Planar laser induced fluorescence (PLIF)
  – Fluorescent dye in fluid
  – ~1mm thick laser sheet (532nm) to illuminate plane
  – Particles appear dark against bright fluid background
Particles used

Duran® borosilicate glass, irregular shape:

- Cut / crushed rods (4mm to 30mm)
- Crushed tubes (4mm to 150μm)
Sample preparation

Crushing / breaking & sieving
Saturating with immersion oil

Careful placement into permeameter (no air bubbles!)
Skempton & Brogan (1994) permeameter method
Gap graded susceptible soil – Grading “A”
Test results – hydraulic gradient vs seepage velocity

Skempton & Brogan (1994), sample A
Critical hydraulic gradient = 0.2; Alpha factor = 0.18

Critical hydraulic gradient = 0.25; Alpha factor = 0.21
Refractive Index Matching

Flow Velocity, $v$ (cm/s) vs. Average hydraulic gradient, $i_{av}$

- Slight general movement: $i_{cr} = 0.248$
  - Slight movement of fines in voids and along glass walls: $k = 0.26$ cm/s
- Moderately strong piping: $k = 1.6$ cm/s
- Strong general piping: $k = 3.3$ cm/s

- Refractive Index Matching:
  a) $i_{av} = 0$
  b) $i_{av} = 0.153$
  c) $i_{av} = 0.248$
  d) $i_{av} = 0.286$
  e) $i_{av} = 0.381$
Test suite - PSDs

Grain Size D (mm)

Passing by mass (%)
## Test results – comparison with soil

<table>
<thead>
<tr>
<th>Glass – oil tests</th>
<th>GS&amp;B-A</th>
<th>GS&amp;B-B</th>
<th>GS&amp;B-D</th>
<th>G-G4-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>0.27</td>
<td>0.27</td>
<td>0.29</td>
<td>0.266</td>
</tr>
<tr>
<td>$k_{\text{initial}}$ (cm/s)</td>
<td>0.30</td>
<td>1.00</td>
<td>0.18</td>
<td>0.02</td>
</tr>
<tr>
<td>$i_c$</td>
<td>1.19</td>
<td>1.16</td>
<td>1.16</td>
<td>1.20</td>
</tr>
<tr>
<td>$i_{cr}$</td>
<td>0.25</td>
<td>0.300 / 1.01</td>
<td>1.31</td>
<td>0.72</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.21</td>
<td>0.26 / 0.85</td>
<td>1.13</td>
<td>0.60</td>
</tr>
<tr>
<td>Failure mode</td>
<td>Piping</td>
<td>Piping / heave</td>
<td>Heave</td>
<td>Piping with suffusion / volume change</td>
</tr>
</tbody>
</table>

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<tr>
<th>Soil - water tests</th>
<th>S&amp;B-A</th>
<th>S&amp;B-B</th>
<th>S&amp;B-D</th>
<th>G4-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>0.34</td>
<td>0.37</td>
<td>0.365</td>
<td>0.24</td>
</tr>
<tr>
<td>$k_{\text{initial}}$ (cm/s)</td>
<td>0.45</td>
<td>0.84</td>
<td>1.80</td>
<td>0.022</td>
</tr>
<tr>
<td>$i_c \text{ or } i_{gc}$</td>
<td>1.09</td>
<td>1.04</td>
<td>1.05</td>
<td>53</td>
</tr>
<tr>
<td>$i_{cr} \text{ or } i_{gcr}$</td>
<td>0.20</td>
<td>0.34</td>
<td>1.0</td>
<td>9.1, 8.0</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.18</td>
<td>0.33</td>
<td>0.95</td>
<td>0.34, 0.30</td>
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</table>
“Suffusion”: Internal erosion without structure collapse
Internal erosion sequence

Pipe formation:
Glass S&B – grading “A”
“Suffosion”:
Suffusion leading to structure collapse

Fannin & Moffat (2006)
Material Glass “4C”
Image issues: degradation with laser / image depth

- Loss of brightness along laser due to mismatched RI and impurities
- Loss of overall clarity with depth due to mismatched RI and impurities (dirt, air bubbles etc)
Quantitative image analysis of “open” void space

(a) Original image  (b) $\frac{1}{2}$ image  (c) Divisions

(a) Original image  (b) Large particles  (c) Large void space
Void space analysis: GS&B – A/B results

1. Upward seepage velocity vs hydraulic gradient
2. Open void vertical migration with hydraulic gradient

Flow velocity, v (cm/s)

Average hydraulic gradient, \( i_{av} \)

Percentage area of open voids (%)

Phase

- Minor movement of fines along glass edge \( k = 0.033 \text{cm/s} \)
- Slight-moderate movement of fines throughout \( k = 0.042 \text{cm/s} \)
- Moderate movement of fines; minor movement of smaller, coarse particles throughout \( k = 0.072 \text{cm/s} \)
- Initiation of piping along glass wall. Washing out of fines between clasts \( k = 0.142 \text{cm/s} \)

\( n = 28.2\% \)

\( (H/F)_{min} = 0.27 \)
Conclusions => “Seeing is believing”

Transparent soil permeameters

- Allow internal erosion mechanisms to be visualised, internal to the transparent soil
- Similar results to those on real soil
- Image analysis on particle fabric shows fines migration

References
Hunter, RP & Bowman, ET “Visualisation of seepage induced suffusion and suffosion within internally erodible granular media” submitted to Géotechnique

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Future work

Transparent soil **rigid permeameter** (with Jonathan Black and Nicoletta Sanvitale)
- Further work to refine equipment and methods
  - Precision slices using stage micrometer
- Further work on material behaviour
  - Compare behaviour of spherical and angular particles (compare to DEM)
  - Fluid tracking using neutrally buoyant particles (PIV)

Transparent soil **triaxial permeameter** (with Fahed Gaber, Jonathan Black and Nicoletta Sanvitale)
- More complex stress states
  - Influence of erosion on strength / deformation
- Visualisation of erosion