Time Development of Scour by Circular by Wall Jets in Cohesive Soils at Varied Scale

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Background

- Stream boundaries in Canada typically a thin layer of alluvial material overlying highly consolidated, clayey sediments.
- Seeking to better understand time development of scour below culverts in clayey soils.
- Modelled as scour by circular wall jets.
Past Work - Abt (1980)

• Large scale experiments in 30.5 m long, 6.1 m wide, 2.4 m deep flume.
• One soil (58 % sand, 28 % clay, 14 % silt).
• Three culvert diameters (273, 356, or 457 mm).
• Tailwater at 45 % of diameter.
• Measure scour hole at 31.6, 100, 316, and 1000 min.
Experimental Setup
Measurements

• Stopped test at times of 10 min, 20 min, 30 min, 1 h, 2 h, 4 h, 8 h then at 8 h intervals.
• Tests run for 36 to 84 h.
• Cross-sections of scour hole taken using laser displacement meter at every interval.
## Details of Experiments

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Jet Velocity (m/s)</th>
<th>Test Duration (h)</th>
<th>Clay</th>
<th>Dry Density (kg/m³)</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>PL (%)</th>
<th>LL (%)</th>
<th>$\tau_c$ (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.3</td>
<td>84</td>
<td>M370</td>
<td>1610</td>
<td>0</td>
<td>68</td>
<td>32</td>
<td>13</td>
<td>33</td>
<td>26.1</td>
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<tr>
<td>2</td>
<td>8.3</td>
<td>36</td>
<td>M370</td>
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<tr>
<td>3</td>
<td>8.9</td>
<td>60</td>
<td>M370</td>
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</tr>
<tr>
<td>4</td>
<td>7.0</td>
<td>60</td>
<td>BSC</td>
<td>1560</td>
<td>6.5</td>
<td>69</td>
<td>24.5</td>
<td>14</td>
<td>33</td>
<td>19.9</td>
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</tbody>
</table>
Growth of Scour Hole Profile along Jet Centreline

Test 2

*Eroded by mass erosion.

Abt (1980)
Typical Cross-Sections

Test 2
(after 240 min)

Abt (1980)
(after 31.6 min and 100 min)
Dimensionless Longitudinal Scour Profile

Normalized longitudinal distance, $x/b$

Normalized scour depth, $\varepsilon_{cl}/\varepsilon_{clm}$

Legend:
- Sample 1, 2160 mins
- Sample 2, 20 mins
- Sample 2, 480 min
- Sample 2, 2160 min
- Sample 3, 240 min
- Sample 4, 30 min
- Sample 4, 480 min
- Sample 5, 480 min
- Abt Test 28, 31.6 min
- Abt Test 36, 31.6 min
- Abt Test 35, 100 min
- Abt Test 28, 316 min
- Abt Test 28, 1000 min

Eqn. 1
Dimensionless Cross-Sections

Normalized centreline distance ($y/b_w$)

Normalized scour depth ($\epsilon/\epsilon_c$)

- $x=60mm$ at 10mins
- $x=40mm$ at 20mins
- $x=40mm$ at 30mins
- $x=60mm$ at 30mins
- $x=40mm$ at 60mins
- $x=20mm$ at 240mins
- $x=40mm$ at 240mins
- $x=120mm$ at 240mins
- $x=40mm$ at 480mins
- $x=40mm$ at 480mins
- $x=100mm$ at 480mins
- $x=40mm$ at 960mins
- $x=40mm$ at 2160mins
- $x=120mm$ at 2160mins
Prediction of Scales

• To use dimensionless profiles need to predict at a particular time:
  - maximum depth of scour hole along centreline.
  - half-width of scour hole at a given location.

• Assume:

\[ \varepsilon_{clm} = f \{ U_o, d, \rho, \mu, \tau_c, t \} \]
- Using dimensional analysis:

\[
\frac{\varepsilon_{clm}}{d} = f\left\{\frac{\rho U_o^2}{\tau_c}, \frac{\rho U_o d}{\mu}, \frac{U_o t}{d}\right\}
\]

\[
\tau_o = c_f \rho \frac{U_o^2}{2}
\]

- Rewrite as using excess stress:

\[
\frac{\varepsilon_{clm}}{d} = f\left\{\frac{\tau_o - \tau_c}{\tau_c}, \frac{U_o t}{d}\right\}
\]
- Using multiple linear regression, find:

\[
\frac{\varepsilon_{clm}}{d} = 0.201 \left( \frac{\tau_o - \tau_c}{\tau_c} \right)^{0.613} \left( \frac{U_o t}{d} \right)^{0.0145}
\]

Adjusted \( r^2 = 0.77 \):
Conclusions

• Shape of scour hole in cohesive materials appears to similar at small and large scales.
• Developed a reasonably good relationship for maximum scour depth based on excess shear stress and dimensionless time.
• Prediction of half-width of scour hole more problematic for small scale tests in clay due to mass erosion.
Acknowledgments

• MITACs Globalink program
• Natural Science and Engineering Research Council of Canada