Increased Bed Erosion Due to Ice

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What Happened?
Open Water

Stationary-Floating Cover

Fixed Cover

\[ Q_{\text{ow}} \]
\[ d_{\text{ow}} \]
\[ Q_{\text{ice}} = Q_{\text{ow}} \]
\[ d_{\text{ice}} > d_{\text{ow}} \]

\[ Q'_{\text{ice}} > Q_{\text{ow}} \]
\[ d'_{\text{ice}} > d_{\text{ow}} \]
Ice Cover Effects on Narrow Rivers
Initial Water Level

60 m 60 m
Ice Cover Effects on Narrow Rivers
Rising Water Level

Characteristic length \( l \) for 50 cm ice thickness \( h \)
Approximated by \( 16h^{3/4} \), \( l = 9.5 \, \text{m} \)
Radius of Influence \((5\times l)\) is \(>>\) Half the Span
General Background

- Field Measurements
  - Scour probes using Time-Domain Reflectometry-independent of surface conditions
  - Stage must increase 2-4 times the ice thickness before break-up
  - Ice cover does not immediately respond to changes in stage
  - Increases above the freeze-up discharge but below the break-up threshold → increases in mean velocity
TDR Scour Probes
Ice Cover Rt. 5 Bridge
Scour Under an Ice Cover
Initial Stage of Breakup

- Restrained Ice Cover
- Ice Collar
- Pier
- Armoring Layer
- TDRs
- Footing

US Army Corps of Engineers
Scour Under an Ice Cover Immediately Following Breakup
Scour Under an Ice Cover
High Water Following Breakup

- Ice Collar
- Pier
- Gravel Wedge
- Armoring Layer
- TDRs
- Footing
- River Bed
Fort Peck Reach of Missouri River

Five sites with periodic and continuous monitoring along the 170 mile reach

US Army Corps of Engineers
Culbertson, Montana
January
Culbertson, Montana

April
Milltown Dam located 120 miles downstream of historic Butte and Anaconda copper mining operations.
Testing Parameters

- Clear Water Scour
- Cylindrical Pier
- Smooth & Rough Cover
- One type of Uniform Sediment ($d_{50} = 0.13$ mm)
- Two Pressure Conditions
  - 3” of head
  - 6” of head
Effect of Flow Intensity: $V/V_c$

- Clear-water Scour- no sediment transport on the bed

$$V_c > V \geq 0.5 V_c$$

- Live-bed Scour- sediment transport on the bed

$$V \geq V_c$$

- For the sediment in this study, $V_c = 0.9$ fps
## Test Conditions

<table>
<thead>
<tr>
<th>Number of Tests</th>
<th>Cover Condition</th>
<th>Relative Cover Roughness</th>
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<tbody>
<tr>
<td>6</td>
<td>Open Water/Free Surface</td>
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<tr>
<td>5</td>
<td>Floating</td>
<td>Smooth</td>
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<tr>
<td>1</td>
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<td>2</td>
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Velocity 1.96 cm/s, $\frac{V_{avg}}{V_c} = 0.8589$
Velocity 1.96 cm/s, $V_{avg}/V_c = 0.8589$

- Open Water (A2)
- Floating Smooth (B2)
- Fixed Smooth 7.6 cm hydrostatic pressure (C5)
- Fixed Smooth 15.2 cm hydrostatic pressure (C6)
Velocity 1.96 cm/s, $V_{avg}/V_c = 0.8589$

- **Open Water (A2)**
- **Fixed Smooth 7.6 cm Hydrostatic Pressure (C5)**
- **Fixed Smooth 15.2 cm Hydrostatic Pressure (C6)**
- **Fixed Rough 7.6 cm Hydrostatic Pressure* (XR1)**
- **Fixed Rough 15.2 cm Hydrostatic Pressure* (XR2)**
Velocity 1.96 cm/s, $V_{avg}/V_c = 0.8589$

- Open Water (A2)
- Floating Rough* (R1)
- Fixed Rough 7.6 cm Hydrostatic Pressure* (XR1)
- Fixed Rough 15.2 cm Hydrostatic Pressure* (XR2)
Sample Scour Hole - Test C5
Sample Scour Hole- Test XR2
Conclusions

Ice Effects on Bed Erosion

- Ice cover can be a major factor in sediment transport and stability of contaminated sediment.
- Pressurized flow due to ice significantly increases mean velocity and the scour potential.
- Ice cover roughness increases turbulence, distorts the vertical velocity profile and increases bed shear.
- Existing theory and models do not adequately explain these field observations and flume experiments.
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### Summary Results Grouped by $V_{avg}$

<table>
<thead>
<tr>
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<td><strong>0.650 fps; $V_{avg}/V_c = 0.7222$</strong></td>
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<tr>
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# Summary Results Grouped by $V_{\text{avg}}$

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**0.773 fps; $V_{\text{avg}}/V_c = 0.8589$**

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</table>

**0.835 fps; $V_{\text{avg}}/V_c = 0.9278$**

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US Army Corps of Engineers
Velocity Profile Comparisons - Summary

• Open water - logarithmic as expected
• Covered flows -
  • Zero velocity at boundaries (no slip condition)
  • Maximum velocity location is a function of-
    • Flow depth
    • Roughness of boundaries
    • Viscosity of fluid
  • Maximum velocity located near the middle for floating smooth cover → similar boundary roughness
  • Larger maximum velocity for rough cover → live-bed
• Pressurized flows - velocity shifts toward smoother boundary
  • Less scour for pressurized smooth cover → shifts toward cover
  • More scour for pressurized rough cover → shifts toward bed
  • Shifts more pronounced for larger $V_{\text{avg}}/V_c$ and larger pressure head
  • Pressurized flows - $V_{\text{avg}}$ not acceptable indicator for live-bed scour

• Combined effect of roughness and pressure flow