Exploring the Dynamics of Thin Layer Cap Stability in a Freshwater Industrial Harbour

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October 23, 2012
Goal of this Study

1. Examine the site specific shear stresses expected at the Randle Reef Sediment Remediation project area and

2. Relate these to the estimated critical shear stress of the proposed thin layer capping design as pure sand, a mixture of sand and silty mud (Hamilton Harbour sediments) and with the development of a biofilm layer.
Structure of the Talk

• Background on Site
• Thin Layer Capping Basics
• Methods of the Study
• Results
• Discussion
• Conclusions
Randle Reef Sediment Remediation Project
Hamilton Harbour, Lake Ontario, Canada
Randle Reef = Legacy Site

Contamination is a result of multiple sources over a period of more than 150 years.

• Coal Gasification
• Petroleum Refining
• Steel Making
• Municipal Waste
• Sewage effluent
Randle Reef Statistics

- Approximately 675,000 m³ of contaminated sediment (PAHs & metals);
- Avg total PAH ~5,000 mg/kg
- Max~ 73,000 mg/kg.
- Site Area: ~60 ha (148 acres)
- Depth of Water: ~4 m to 12 m
- Sediment Thickness: ~0.1 m to >3 m
Summary of Project Plan

- Construct a 7.5 hectare (18.5 acres) Engineered Containment Facility (ECF) over the most highly contaminated sediment (130,000 m$^3$ *in-situ*);
- Using primarily hydraulic and some mechanical dredging, remove 500,000 m$^3$ and place within ECF;
- Cap U.S. Steel Intake/Outfall Channel (5,000 m$^3$) to isolated contaminated sediment;
- **Thin Layer Cap ~40,000 m$^3$ of marginally contaminated sediment that will not fit within the ECF**
- **Thin Layer Cap residuals where concentration exceeds site specific criteria**
- Install engineered Cap on top of ECF and construct a port facility and open green space.
Project Area and Dredging Plan
Thin Layer Capping Rationale for Use

• Environmental Dredging will result in residual contamination which requires management

• Residuals are generally not amenable to removal by additional dredging passes unless specialty equipment is used

• Also applicable for sediments of marginal contamination
Thin Layer Capping – How it Works

• Thin layer caps are not intended to isolate contaminants by a physical barrier

• Remediation is expected to be achieved by reducing the overall surface concentrations

• In many cases, with the passage of time, new sediment will be deposited by natural processes. The final result could be an enhanced substrate.
Thin Layer Caps – Design Considerations

• Should consider the amount of cap (thickness) required to manage the expected levels of contamination incorporating:
  • mixing on contact with underlying contaminated sediments
  • subsequent mixing and integrity of the cap over the long term.

• Disturbances (storm generated waves, currents propelled wash) have the potential to severely erode a thin layer cap depending on their intensity.
Thin Layer Caps – Design Considerations

• Important to strike the best balance between stability of capping materials versus habitat considerations of the benthic community

• Should also consider impact velocity by larger grains sizes and subsequent re-suspension
Randle Reef Thin Layer Cap

• The *Randle Reef Sediment Remediation Project* has a Mortar Sand (referencing the Ontario Provincial Standard Specifications (OPSS)) specified as the capping material:

<table>
<thead>
<tr>
<th>OPSS Sieve size</th>
<th>OPSS Spec</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.75mm</td>
<td>100%</td>
</tr>
<tr>
<td>2.36mm</td>
<td>95-100%</td>
</tr>
<tr>
<td>1.18mm</td>
<td>60-100%</td>
</tr>
<tr>
<td>0.6mm</td>
<td>35-80%</td>
</tr>
<tr>
<td>0.3mm</td>
<td>15-50%</td>
</tr>
<tr>
<td>0.15mm</td>
<td>2-15%</td>
</tr>
<tr>
<td>0.075mm</td>
<td>0-5%</td>
</tr>
</tbody>
</table>

• This cap is to be placed in lifts of 8 cm (~3”) to a maximum predicted thickness of 16 cm (~6”)
Methods - Critical Shear Stress from Grain Size

da Silva and Bolisetta (2000) developed an approximate analytical expression for the Sheilds' diagram:

\[ \tau_\ast = 0.13d\ast^{-0.392} \exp(-0.015d\ast^2) + 0.045(1 - \exp(-0.068d\ast)) \]

Where:

\[ d\ast = d \left[ \left( \frac{\gamma_s}{\gamma} - 1 \right) g \right]^{1/3} \]

and

\[ \tau_\ast = \frac{\tau}{(\gamma_s - \gamma)d} \]

\( \tau = \) critical shear stress for erosion

\( \tau_\ast = \) mobility number (critical)

\( d = \) median grain size

\( \gamma_s = \) specific weight of sediment

\( \gamma = \) specific weight of water

\( \varrho = \) kinematic viscosity of water

\( g = \) acceleration due to gravity
Methods – Bottom Shear Stress from Vessels


\[ V_b = \frac{C_1 \times D_o \times C_2}{H_o} \left( \frac{P_d}{D_p^2} \right)^{1/3} \]

Where:

- \( V_b \) = maximum bottom velocity (feet per second [ft/s])
- \( C_1 \) = an empirical constant (0.22 for a non-ducted propeller and 0.3 for a ducted)
- \( D_o \) = propeller diameter (feet [ft])
- \( C_2 \) = an empirical constant (9.72 for a non ducted propeller and 7.68 for a ducted)
- \( P_d \) = applied engine power (horsepower [Hp])
- \( H_o \) = distance from the propeller shaft to the channel bottom (feet [ft])
- \( D_p \) = propeller diameter (feet [ft])
Methods – Bottom Shear Stress from Weather Events (Modeling & Site Specific Monitoring)

• MIKE 3, a general 3D free surface flow model applicable to the simulation of flows, cohesive sediment transport

• Simulates unsteady 3D flows, taking into account density variation, bathymetry and external forces arising from meteorology, water elevations, currents and other hydrographic conditions.

• The mathematical foundation in MIKE 3 is the mass conservation equation, the Reynolds-averaged Navier-Stokes equations in 3D including the effects of turbulence and variable density, together with the conservation equations for salinity and temperature.
Methods – Bottom Shear Stress from Weather Events (Modeling & Site Specific Monitoring)

• 4 Acoustic Doppler Current Profilers (ADCPs) deployed in 2 locations from November 2011 to April 2012.

• Model results were re-scaled by comparing with ADCP measurements to obtain realistic bottom flow conditions.

• The rescaled bottom flow speeds were used to calculate bottom shear stress distributions in the MIKE 3 model by the quadratic friction law:

\[ \tau_b = \rho_b c_f u_b |u_b| \]
Methods – Bottom Shear Stress from Weather Events (Modeling & Site Specific Monitoring)

• Bottom Shear Stress (BSS) was also calculated at the ADCP locations using the measured velocity data based on logarithmic-profile method (law of the wall) for re-scaling and comparison:

\[ u(z) = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \]
Results – Critical Shear Stress For Erosion

• Analytical Expression
  (median grain size of 0.5 mm) = 0.24 Pa

• Flume:
  pure sand = 0.13 Pa
  Sand / fine sediment mix = >0.33 Pa
  With Biofilm = n/a
# Results – BSS from Ships

## BSS for the Large Cargo Vessel (35439 DWT)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Shear Stress (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum hp / loaded</td>
<td>15.7</td>
</tr>
<tr>
<td>Maximum hp / empty</td>
<td>8.4</td>
</tr>
<tr>
<td>Minimum hp / loaded</td>
<td>11.2</td>
</tr>
<tr>
<td>Minimum hp / empty</td>
<td>6</td>
</tr>
</tbody>
</table>

## BSS for a Tug

<table>
<thead>
<tr>
<th>Condition</th>
<th>Shear Stress (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum hp / Pier 14</td>
<td>0.48</td>
</tr>
<tr>
<td>Maximum hp / Pier 15</td>
<td>0.2</td>
</tr>
<tr>
<td>Minimum hp / Pier 14</td>
<td>0.23</td>
</tr>
<tr>
<td>Minimum hp / Pier 15</td>
<td>0.09</td>
</tr>
</tbody>
</table>

## Critical Shear Stress

<table>
<thead>
<tr>
<th>Type</th>
<th>Value (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empirical</td>
<td>0.24</td>
</tr>
<tr>
<td>Flume (sand)</td>
<td>0.13</td>
</tr>
<tr>
<td>Flume (sand and Fine sed)</td>
<td>&gt;0.34</td>
</tr>
</tbody>
</table>
Results – BSS from Weather (max modelled)
Results – Bathymetry of the Area

Reef
Results – BSS from Weather (Time-averaged)
Discussion – BSS Created by Vessels

• The short time frame, varying position with each vessel passage and other disturbance events and sediment movement as a “mass” may limit the actual extent and amount of erosion to local movement.
• The heavy erosive forces are confined to the shipping lanes

From the Literature:
• Irvine et.al. (1997) estimated the extent of erosion from the single passage of large cargo ship in Hamilton Harbour at ~1mm
• Amos and Droppo (1996) - erosion typically associated with a large cargo ship in other areas of Hamilton Harbour on the order of 7 to 8 mm /passage.
*these erosional depths correspond to existing sed and not placed caps
Discussion – BSS Created by Weather Events

BSS due to Weather During Study Period (% of Remediation Area)

- 60% (BSS Max (>0.40 Pa))
- 30% (BSS (0.04 to 0.4 Pa))
- 10% (BSS (<0.04 Pa))

Critical Shear Stress (0.13 to 0.34 Pa)
Discussion - BSS created by Weather

- The area where highest BSS is expected is relatively small (~10%). So concern of majority of the cap being removed is not justified. However, larger storms than those utilized during the study period can be expected.

- Concern with the shallow area of high BSS partially mitigated by:
  1. Dredging in this area (~1m of removal)
  2. Removal of contaminated sediment to native layer
  3. “BSS Model run with out the ECF in-place.
  4. Opportunity to adjust grain size within the proposed specs

- Despite all of this, consideration to a larger grain size for the shallow reef areas may be warranted. Important for storm conditions exceeding what was experienced in the 6 month study period.
Conclusions & Recommendations

• This Study gives us an idea of the BSS stresses that may be experienced at the project site in comparison to the critical shear stress that the capping materials can handle.
• Capping materials can be altered to be more conservative in the areas of potential concern.
• Speed and power restrictions on vessels should be considered

Recommend:

• Running model with ECF in Place
• Predicting the likelihood and frequency of exceeding the conditions that lead to the maximum BSS observed during the study period.