Quantifying Scour

Overview:
CFD
• Sea state is treated as the superposition of two monochromatic waves
• Can spatially map shear stress around the device, but cannot directly quantify scour
• Different device geometries can be treated
• Can identify shear stress hotspots due to certain elements of geometry

Empirical Formulations
• Sea state is treated as a uniform monochromatic wave
• Cannot spatially map shear stress around the device, but can quantify a general scour depth
• Simple geometries only
  • Global formulations are derived from studies on cylindrical piles
  • Local formulations not yet addressed here

Deployment observations
• Limited to 2-3 qualitative assessments by divers over the 2 week deployment
• Scour noted to beginning shortly after deployment
• Greatest scour in the latter days of deployment (Regime 4)
• Scour was confined to the the device ends and under the caissons at depths of ~ 15 cm
• Accretion was noted in the mid section along the edges ~15cm
Plan for Quantifying Scour

**Aim:** Build on Ryan’s analysis

Correlate CFD with empirical formulations
- Check that methods are consistent in estimating shear stress associated with undisturbed flow
- Global Scour/Shear stresses
  - Empirical formulations for block geometry
  - CFD for block geometry
- Relate CFD shear stress output to scour potential
  - CFD for caisson geometry (accounts for shear stresses that may cause local scour)
  - Local scour formulations using a characteristic element (like horizontal pipe in Ryan’s analysis)
- Verify results are consistent with deployment observations
  - determine whether scour was more likely due to local, global, or both scour processes
  - determine appropriate empirical formulations for general application

Apply empirical formulations to 2014 conditions
- Identify some representative nominal and extreme 2014 conditions based on empirical scour results
- Employ CFD to provide corresponding shear stress estimates
- Infer scour potential from shear stress mapping
Empirical Formulations

- Formulations based on undisturbed flow properties (nearby seabed) estimated using: $H_{rms}$, $T_p$, $u_m$, $d_{50}$, $s$, $v$, $h$, $\alpha$
- Valid for live-bed conditions ($\theta > \theta_{cr}$) when undisturbed seabed velocities can cause sediment motion and contribute to the filling of scour holes downstream

Shields parameter under waves:

$$\theta = \frac{u_{fm}^2}{(s-1)gd_{50}} = \frac{\tau_b/\rho}{(s-1)gd_{50}}$$

Friction velocity:

$$u_{fm} = \sqrt{\frac{f_w}{2}} u_m$$

Wave friction factor (p. 201, text):

$$f_w = 0.035(Re)^{-0.16}$$

Boundary-layer Reynolds number:

$$Re = \frac{a u_m}{\nu}$$

Amplitude of orbital velocity

$$a = \frac{H_{rms}}{2} \left( \frac{1}{\sinh (k_p h)} \right)$$
Empirical Formulations (Global Scour)

• Empirical formulations were derived from those for cylindrical piles under waves.
• K factors expand formulation to account for sediment size, device shape, alignment with respect to waves, finite device height, and sea state exposure time.
• This multistep approach is supported in text, p.192

1. Scour under constant current:
   \[
   \frac{S_c}{D} = K_I K_\delta K_d K_s K_a K_h 
   \]
   \(K_I = 2.4\) (initial factor: live-bed scour, uniform sediment size)
   \(K_\delta = 1\) (boundary layer factor, NA – river flow)
   \(K_d = 1\) (sediment size factor, fig. 3.27 with \(D/d_{s0} = 2.5/0.2E-03 = 1.3E04\))
   \(K_s = 1.11\) (shape factor, rectangle with Length/Width = 9/2.5 = 3.6, Table 3.1)
   \(K_a = \) case specific, \(\sim 2 - 3.7\) for Sept 2014 (alignment factor, fig. 3.29)
   \(K_h = 0.19\) (finite device height factor, fig. 3.28 with \(h/D = 1.0/2.5\))

2. Scour depth (vertical pile/waves only, Myrhaug/Ong 2013*, also p. 192 text):
   \[
   \frac{S}{D} = \frac{S_c}{D} \left(1 - \exp \left[-0.019(KC - 3)\right]\right); KC \geq 3, \ 45^\circ \text{ square cross section}
   \]

3. *Time-scale of scour (Petersen, Sumer and Fredsoe, 2012), substituting \(S\) from step 2 for \(S_0\) below and \(t = 0.5\) hrs:
   \[
   S_t = S_0 \left(1 - \exp \left(-\frac{t}{\tau}\right)\right)
   \]
   \[
   \tau = \frac{D^2}{\sqrt{g(s-1)d_{s0}^3}} \times 10^{-6} \left(\frac{KC}{\theta}\right)^3 \left(\frac{1 \text{ hr}}{3600 \text{ s}}\right)
   \]

for \(KC < O(10)\) scour is due to lee-wake vortex shedding with an onset dependent upon KC and device geometry.
Empirical Estimates for September 2014
APEX deployment site and “block” geometry

Text recommends using $u_m$:

$$u_m = \sqrt{2} \sigma_u = \sqrt{2} u_{rms}$$

$$\sigma_u^2 = \int_0^\infty S_u(f)df$$

But since bimodal wave superposition occasionally results in greater seabed velocities, also considered using $u_{sig}$:

$$u_{sig} = 2\sigma_u = 2 u_{rms}$$
Empirical Estimates for September 2014
APEX deployment site

Assuming “block” geometry

\[ u_m = \sqrt{2} \sigma_u = \sqrt{2} u_{rms} \]

\[ \sigma_u^2 = \int_0^\infty S_u(f) df \]
Possible Alternative
\( u_{\text{sig}} \) instead of \( u_m \)

Assuming “block” geometry

\[ u_{\text{sig}} = 2\sigma_u = 2u_{\text{rms}} \]

* bimodal maximum seabed velocity is at times closer to \( u_{\text{sig}} \)
  
  \( u_{\text{sig}} = 0.52 \text{ m/s for Regime 4} \)
CFD for September 17 (Regime 4)
APEX deployment site and “block” geometry
Empirical Formulation

Shields Parameters

Above:
\[ H_{rms} = 1.2 \text{ m} \]
\[ T_p = 13.1 \text{ s} \]
\[ u_m = 0.37 \text{ m/s} \]
\[ f_w = 0.0047 \]
\[ u_{fm} = 0.018 \text{ m/s} \]
\[ \tau_w = u_{fm}^2 = 0.32 \times 10^{-3} \text{ m}^2/\text{s}^2 \]
\[ Sh = 0.10 \]
\[ KC = 1.9 < 3, \text{ no scour} \]

CFD (sampled undisturbed seabed)
\[ u_m \sim 0.44 \text{ m/s} \ (3\text{cm above floor}) \]
\[ \tau_w \sim 0.35 \times 10^{-3} \text{ m}^2/\text{s}^2 \]
\[ u_{fm} = \sqrt{\tau_w} = 0.019 \text{ m/s} \]
What would be the more appropriate way to define $U_m$ for empirical estimates?

- With respect to $H_{rms}$ (since recommended by text assuming single-mode spectra)
- With respect to $H_{sig}$ (since bimodal spectra result in occasional higher maxima than would be seen for single-mode)
CFD sampling of undisturbed seabed

\( u_m \sim 0.44 \text{ m/s (3cm above floor)} \)

\( t = 19 \text{ s} \)
max shear stress at device

\( \tau_w \sim 0.35 \times 10^{-3} \text{ m}^2/\text{s}^2 \)
\( u_{fm} = \sqrt{\tau_w} = 0.019 \text{ m/s} \)

\( \tau_w \sim 0.4 \times 10^{-3} \text{ m}^2/\text{s}^2 \)
\( u_{fm} = \sqrt{\tau_w} = 0.02 \text{ m/s} \)

Regime 4
Sept 17, 2014

sampling along line
CFD

Undisturbed Flow Maxima
$t = 20$ s

Empirical Formulation

Shields Parameters

Regime 4
Sept 17, 2014

(Cylindrical pile, Ryan):
$H_s = 1.66$ m
$T_p = 13.1$ s
$*u_m = 0.6$ m/s
$*f_w = 0.0022$
$*u_{fm} = 0.02$ m/s
$u_{fm}/u_m = 0.033$
$\tau_w = u_{fm}^2 = 0.4\times10^{-3} \text{ m}^2/\text{s}^2$
$Sh = 0.13$
$KC = 3.2 < 6$, no scour

Alternative (Above, but $u_m = u_s$):
$H_s = 1.66$ m
$T_p = 13.1$ s
$u_m = 0.52$ m/s
$f_w = 0.0042$
$u_{fm} = 0.024$ m/s
$u_{fm}/u_m = 0.046$
$\tau_w = u_{fm}^2 = 0.65\times10^{-3} \text{ m}^2/\text{s}^2$
$Sh = 0.18$
$KC = 2.7 < 3$, no scour

Above (Sept 17):
$H_{rms} = 1.2$ m
$T_p = 13.1$ s
$u_m = 0.37$ m/s
$f_w = 0.0047$
$u_{fm} = 0.018$ m/s
$u_{fm}/u_m = 0.046$
$\tau_w = u_{fm}^2 = 0.32\times10^{-3} \text{ m}^2/\text{s}^2$
$Sh = 0.10$
$KC = 1.9 < 3$, no scour

CFD (sampled undisturbed maxima)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$t = 20$ s</th>
<th>$t = 19$ s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_m$ (m/s)</td>
<td>$\approx 0.47$</td>
<td>$\approx 0.44$</td>
</tr>
<tr>
<td>$\tau_w$ (m$^2$/s$^2$)</td>
<td>$\approx 0.40 \times 10^{-3}$</td>
<td>$\approx 0.35 \times 10^{-3}$</td>
</tr>
<tr>
<td>$u_{fm}$ (m/s)</td>
<td>$\approx 0.020$</td>
<td>$\approx 0.019$</td>
</tr>
<tr>
<td>$u_{fm}/u_m$</td>
<td>$\approx 0.043$</td>
<td>$\approx 0.043$</td>
</tr>
<tr>
<td>$Sh$</td>
<td>$\approx 0.13$</td>
<td>$\approx 0.11$</td>
</tr>
</tbody>
</table>
Scour was noted by divers for caisson geometry, especially for Regime 4 conditions

- How do we relate empirical scour estimates to shear stress map?

Notable hotspots from
- Plunging over the caissons
- Interior caisson corners (interior vortex?)
CFD: Average shear stress of caisson geometry versus block geometry

- Since shear stresses are generally smaller for caisson geometry, could we infer that local scour would be less significant than global scour in this instance?
- Or perhaps things would look different if we averaged shear stress components instead of overall magnitudes

Caisson geometry
(local and global shear stress)

Block geometry
empirical global scour estimates apply

Regime 4
Sept 17, 2014