On the role of flocculation, hindered settling and sediment-induced damping of turbulence in trapping sediment in estuaries, with focus on the North Passage, Yangtze Estuary

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Introduction to the North Passage

Map of the Yangtze Estuary (YE)

training walls and groins

Tidal mean suspended sediment concentration (SSC, kg/m$^3$) distribution in the North Passage (NP) (Jiang et al., 2013)

note the trapping of sediment
Context

1. Research questions
2. Methodology
3. Results
4. Discussion
5. Conclusions
1 Research questions

the sensitivity of location and intensity of estuarine turbidity maximum (ETM) to
1) **flocculation** and hindered settling of fine sediment
2) sediment-induced damping of turbulence.

Sketch of aggregation of cohesive sediment particles or flocs (aggregation=flocculation) Mehta et al. (2008)

Dependence of sediment settling velocity on concentration Mehta et al. (2008)
2 Methodology

A width-averaged process-based model that describes tides, residual currents and sediment transport in an estuarine channel was developed.

Analytical Solutions

- eddy viscosity/diffusivity coefficients, slip parameter
- tidal flow
- residual flow
- river flow
- density driven flow
- settling velocity
- bottom shear stress
- sediment transport
2 Methodology

Parametrization of sediment settling velocity

settling velocity assumed to be a function of subtidal near-bed sediment concentration (Wan, 2014, Mehta et al., 2008)

\[
ws = \begin{cases} 
ws_0, & c \leq c_0 \\
\frac{\alpha (\frac{c}{c_0})^{1.1}}{(\frac{c}{c_0})^2 + c^*^2}, & c > c_0 
\end{cases}
\]

- \(c_0 = 0.5 \text{ kg.m}^{-3}\)
- \(ws_0 = 0.0001 \text{ m.s}^{-1}\)
- \(\alpha = 0.125 \text{ m.s}^{-1}\)
- \(\hat{c} = 1 \text{ kg.m}^{-3}\)
- \(c^* = 5.5\)

\(ws\): settling velocity
\(c\): bottom concentration
\(c_0\): critical bottom concentration when flocculation process starts
\(ws_0\): particle free settling velocity
2 Methodology

Parametrization of sediment-induced turbulence damping

- **eddy viscosity coefficient** (modification of Munk&Anderson, 1948)

\[ A_v = \left( k u_{bed} (H + \eta) F(\overline{Ri}) \right) \quad F(\overline{Ri}) = \left( 1 + 10 \overline{Ri} \right)^{1/2} \]

- **eddy diffusivity coefficient** (modification of Munk&Anderson, 1948)

\[ K_v = \left( k \frac{u_{bed} (H + \eta) G(\overline{Ri})}{\sigma_p} \right) \quad G(\overline{Ri}) = \left( 1 + 3.33 \overline{Ri} \right)^{3/2} \]

\( k \): drag coefficient, determined according to (Bowden, 1953),
\( \sigma_p \): Prandtl-Schmidt number,
\( \overline{Ri} \): depth-averaged gradient Richardson number.

\[ \overline{Ri} = - g \beta_c \frac{dc}{dz} \left( \frac{du}{dz} \right)^2 + \left( \frac{du}{dz} \right)_{\min}^2 \]

\[ \beta_c = 1 - \rho_o / \rho_s \]

\( \rho_o \): clear-water density, 1000 kg/m³
\( \rho_s \): dry sediment density, 2650 kg/m³

\( \left( \frac{du}{dz} \right)_{\min} \): background shear
2 Methodology

Parametrization of sediment-induced turbulence damping

- bed shear stress (modification of Dijkstra et al., 2019)
  \[ \tau_b = s \, u_{bed} \]

  slip parameter
  \[ s = \langle c_v \, c_D \, u_{bed} \rangle \]

  \( c_v \): drag coefficient, determined according to (Soulsby 1997)

- reduced-drag coefficient
  \[ c_D = (1 + A \langle Rf_{bed} \rangle)^{-2} \]

  \( A \): empirically determined parameter, 5.5

- flux Richardson number near the bed
  \[ Rf_{bed} = \frac{K_v}{A_v} \, Ri_{bed} \]
2 Methodology

Application to the North Passage

Model parameters for the North Passage

<table>
<thead>
<tr>
<th>parameter</th>
<th>description</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>channel length</td>
<td>Low C. 57 km, High C. 57 km</td>
</tr>
<tr>
<td>$B$</td>
<td>channel width</td>
<td>Low C. 5 km, High C. 5 km</td>
</tr>
<tr>
<td>$H$</td>
<td>channel depth</td>
<td>Low C. 12.5 m, High C. 12.5 m</td>
</tr>
<tr>
<td>$K_h$</td>
<td>horizontal eddy diffusivity</td>
<td>100 m$^2$/s</td>
</tr>
<tr>
<td>$Q$</td>
<td>net water transport</td>
<td>750 m$^3$/s</td>
</tr>
<tr>
<td>$Z_0$</td>
<td>$M_2$ tidal amplitude at seaward end</td>
<td>Low C. 1.29 m, High C. 1.6 m</td>
</tr>
<tr>
<td>$Z_L$</td>
<td>$M_2$ tidal amplitude at riverine entrance</td>
<td>Low C. 1.21 m, High C. 1.5 m</td>
</tr>
<tr>
<td>$\varphi_L$</td>
<td>$M_2$ tidal phase at landward boundary</td>
<td>0.873 radian</td>
</tr>
<tr>
<td>$d_s$</td>
<td>sediment particle diameter</td>
<td>10 μm</td>
</tr>
<tr>
<td>$a^*$</td>
<td>reference erosion coefficient</td>
<td>Low C. 0.0001, High C. 0.0002</td>
</tr>
</tbody>
</table>

Low concentration cases

<table>
<thead>
<tr>
<th>cases</th>
<th>flocculation</th>
<th>damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>L2</td>
<td>x</td>
<td>v</td>
</tr>
<tr>
<td>L3</td>
<td>v</td>
<td>x</td>
</tr>
<tr>
<td>L4</td>
<td>v</td>
<td>v</td>
</tr>
</tbody>
</table>

High concentration cases

<table>
<thead>
<tr>
<th>cases</th>
<th>hindered settling</th>
<th>damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>H2</td>
<td>x</td>
<td>v</td>
</tr>
<tr>
<td>H3</td>
<td>v</td>
<td>x</td>
</tr>
<tr>
<td>H4</td>
<td>v</td>
<td>v</td>
</tr>
</tbody>
</table>
3 Results  Low concentration cases

<table>
<thead>
<tr>
<th>cases</th>
<th>flocculation</th>
<th>damping</th>
<th>ETM</th>
<th>((c_b)_{\text{max}})</th>
<th>(x_{(c_b)_{\text{max}}}(\text{km}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L2</td>
<td>×</td>
<td>√</td>
<td>√</td>
<td>1.55</td>
<td>31.4</td>
</tr>
<tr>
<td>L3</td>
<td>√</td>
<td>×</td>
<td>√</td>
<td>1.7</td>
<td>16</td>
</tr>
<tr>
<td>L4</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>1.7</td>
<td>14.8</td>
</tr>
</tbody>
</table>

Maximum bottom concentration (kg/m³)

Location of \((c_b)_{\text{max}}\) (km)

Along-channel SSC distribution in the NP in different cases

constant \(w_s\)

variable \(w_s\)
3 Results  Low concentration cases

- Effects of flocculation of fine sediment

<table>
<thead>
<tr>
<th>cases</th>
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<th>((c_b)_{\text{max}})</th>
<th>(x_{(cb)\text{max}})</th>
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<tbody>
<tr>
<td>L2</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>1.55</td>
<td>31.4</td>
</tr>
<tr>
<td>L4</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>1.7</td>
<td>14.8</td>
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</table>

Flocculation:
- Rapid settling of floci
- More stratified vertical distribution of SSC

Seaward transport ability due to density driven flow
- Landward transport ability due to net water transport
- Landward shift and intensification of the ETM

Bottom concentration & settling velocity

Net sediment transport
('+' seaward transport, '-' landward transport)

Tr\(_d\): net sediment transport due to density driven flow
Tr\(_q\): net sediment transport due to net water transport
Tr\(_\text{diff}\): net sediment transport due to diffusion
3 Results

Low concentration cases

- Effects of sediment-induced damping of turbulence

<table>
<thead>
<tr>
<th>Cases</th>
<th>Flocculation</th>
<th>Damping</th>
<th>ETM</th>
<th>((c_b)_{\text{max}})</th>
<th>(x_{(cb)_{\text{max}}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3</td>
<td>√</td>
<td>✗</td>
<td>√</td>
<td>1.7</td>
<td>16</td>
</tr>
<tr>
<td>L4</td>
<td>√</td>
<td>√</td>
<td>√</td>
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</table>

- Damping of turbulence
  - Decrease in \(A_v\), \(K_v\) and \(s\)
  - Increase in density driven flow
  - Decrease in bottom erosion
  - Increase in landward sediment transport ability
  - Decrease in sediment availability

Who wins?

- Landward shift of the ETM
3 Results

High concentration cases

<table>
<thead>
<tr>
<th>cases</th>
<th>damping hindered settling</th>
<th>ETM</th>
<th>( (c_b)_{\text{max}} )</th>
<th>( x_{(cb)\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>( \times )</td>
<td>( \times )</td>
<td>6.7</td>
<td>19.4</td>
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<tr>
<td>H2</td>
<td>( \sqrt{\ } )</td>
<td>( \times )</td>
<td>5.9</td>
<td>13.1</td>
</tr>
<tr>
<td>H3</td>
<td>( \times )</td>
<td>( \sqrt{\ } )</td>
<td>7.3</td>
<td>23.1</td>
</tr>
<tr>
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<td>( \sqrt{\ } )</td>
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Maximum bottom concentration (kg/m³)

Location of \( (c_b)_{\text{max}} \) (km)

Along-channel SSC distribution in the NP in different cases

constant \( w_s \)

variable \( w_s \)
3 Results  High concentration cases

- Effects of hindered settling of fine sediment

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</tr>
<tr>
<td>H4</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>5.7</td>
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</tbody>
</table>

Bottom concentration & settling velocity

Net sediment transport ('+' seaward transport, '-' landward transport)

- Hindered settling
- Decrease in settling velocity
- More uniform vertical distribution of SSC
- Seaward transport ability due to density driven flow
- Landward transport ability due to net water transport
- Seaward shift and attenuation of the ETM
3 Results  High concentration cases

- Effects of sediment-induced damping of turbulence

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<th>$x(\text{cb})\text{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3</td>
<td>$\times$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>7.3</td>
<td>23.9</td>
</tr>
<tr>
<td>H4</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>5.7</td>
<td>14.3</td>
</tr>
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damping of turbulence

- decrease in $A_v$, $K_v$ and $s$
- increase in density driven flow
- decrease in bottom erosion
- increase in landward sediment transport ability
- decrease in sediment availability
- landward shift of the ETM
- attenuation of the ETM
4 Discussion

• Key point:
Study on sensitivity of location and intensity of ETM to flocculation and hindered settling of fine sediment as well as sediment-induced damping of turbulence by applying a process-based 2D model to the North Passage, Yangtze Estuary.

• Results compare well with other studies (Van Maren et al, 2015; Winterwerp et al., 2013), that flocculation and sediment-induced damping are important for sediment trapping in the North Passage. Hindered settling, which is significant for hyperturbid estuaries (Dijkstra et al, 2018, 2019), doesn’t have much effect in the North Passage, which has tidal mean concentration lower than 10 kg/m$^3$ during calm weather.

• Model limitations:
Only accounts for sediment transport due to gravitational circulation and turbulent diffusion. Tidal pumping, tidal straining, tidal rectification, lateral processes a.o. not taken into account.
4 Conclusions

Flocculation regime

Flocculation regime

Hindered settling regime

Hindered settling regime
Thanks for your attention!
Feedback is appreciated!