An Introduction to Sediment Transport in Estuaries

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Outline

• Introduction to basic principles of sediment transport
  – Emphasis on erodibility of muds
• Modes of transport
• Modeling
• High Concentration Suspensions
• Turbidity Maxima


Basic Characteristics of Sediments

• They sink or settle (Latin *sedere*, to sit) and have inertia
  – They don’t move exactly with the water
• There are sources (rivers, shorelines, atmosphere, bottom) and sinks (bottom)
• Particle behavior depends on size, weight, stickiness, and shape
• Biology can affect physics at lowest order
• Other particles (i.e., plankton) can be thought of as sediments with different density and behavior
Global Sediment Sources –
Rivers account for 85% of inputs to global ocean
Estuaries can trap large portions of riverine inputs, can have large internal inputs from shoreline erosion, and can import sediment from the ocean (from Langland and Cronin 2002)

Figure 5.5. Relation between fastland (above tide) erosion and nearshore (below tide) erosion.
The bottom can serve as both source and sink, and often dominates both terms in estuaries and coastal seas.

### Upper Chesapeake Bay Suspended Sediment Mass Balance

- **4,400 MT/d**
- **0 MT/d**

\[
\begin{align*}
90,000 \text{ MT} & \quad 45,000 \text{ MT} \\
\text{resuspended} & \quad \text{background}
\end{align*}
\]

\[= 135,000 \text{ MT}\]

- **180,000 MT/d**
- **184,400 MT/d**

- **4,400 MT/d**

---

Figure 6.5: Comparison of historical (1880-present) and long-term sediment flux at core sites in Chesapeake Bay (determined by methods described in Table 6.1).
What matters the most for sediment transport dynamics? Not minerology, stickiness, or size \textit{per se}, but rather settling speed, remobilization criteria, and deposition criteria.
Background – Classification of Sediment Transport (in decreasing order of understanding)

- **Non-cohesive**
  - > 64 um particle size, including coarse silts, sands, and gravels, interparticle cohesive forces negligible, highly permeable
  - Dominant on energetic inner continental shelves far from sources of fines
  - Previously thought to be biogeochemically boring, under revision …

- **Cohesive**
  - < 64 um particle size, poorly sorted mix of silts, clays, and organics (mud), interparticle cohesive forces dominate, impermeable
  - Dominant in less energetic environments and/or close to sources
  - Strong correlation to transport and fate of POC and associated contaminants
  - Primary determinant of turbidity

- **Mixed**
  - Sands with > 10% mud, muds with > 5-10% sands, essentially impermeable
  - Dominant in all other environments
  - More resistant to erosion than either sand or mud alone (?)
  - Very complex and poorly understood dynamics
What determines the settling velocity of a sediment particle?

At equilibrium (no acceleration), it has reached terminal fall velocity

\[ F_D = F_g \]
\[ F_g = Vol \, (\rho_s - \rho) \, g \]
\[ F_D = \frac{1}{2} \, \rho \, C_D \, A_{normal} \, W_s^2 \]

For spherical particle: \( Vol = \frac{\pi}{6} \, D^3 \) and \( A_{normal} = \frac{\pi}{4} \, D^2 \)

Use spherical results, set \( F_D = F_g \)

\[ W_s = \sqrt{\frac{4}{3} \, g \, D \,(s-1) \, \frac{1}{C_D}} \]

where \( s = \frac{\rho_s}{\rho} \)

typically \( s \approx 2.65 \)

\[ C_D = \text{func}(Re_D); \quad Re_D = \frac{W_s \, D}{v} \]
For \( \text{Re}_D < 1 \), laminar flow around particle. Stokes solved for \( C_D \) for spheres in laminar flow

\[
C_D = \frac{24 \nu}{W_s D} \\
W_s = \frac{1}{18} g (s - 1) \frac{D^2}{\nu}
\]

Examples: \( \nu = 0.01 \text{ cm}^2/\text{s} \)  \
\( \rho = 1 \text{ gm/cm}^3 \)  \
\( \rho_s = 2.65 \text{ gm/cm}^3 \) (sand)

<table>
<thead>
<tr>
<th>Sediment type</th>
<th>D (cm)</th>
<th>( W_s ) (cm/s)</th>
<th>( \text{Re}_D )</th>
<th>( W_s ) (cm/hr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 µm clay</td>
<td>0.0001</td>
<td>(9 \times 10^{-5})</td>
<td>(9 \times 10^{-7})</td>
<td>0.33</td>
</tr>
<tr>
<td>10 µm silt</td>
<td>0.001</td>
<td>(9 \times 10^{-3})</td>
<td>(9 \times 10^{-4})</td>
<td>33</td>
</tr>
<tr>
<td>100 µm sand</td>
<td>0.01</td>
<td>0.9</td>
<td>0.9</td>
<td>3,000</td>
</tr>
</tbody>
</table>
Drag coefficient around a sphere (from ?, one of the general refs, I think)
when Re $>> 1$, fully turbulent,

$$C_D = \text{constant}$$

$$W_s \propto \sqrt{D}$$

someone (Grant & Madsen 1976) has solved for

$$\frac{W_s}{\sqrt{g(s-1)D}} = \text{funct}(S_*)$$

where $S_*$ only dependent on particle properties

$$S_* = \frac{D}{4\nu} \sqrt{g(s-1)D}$$

**Settling velocity for higher Re (larger or more dense)**

Alternative approximation due to Gibbs (1971) as quoted by Wright (1995)

$$w_s = \frac{-3\nu + \left[9\nu^2 + gD^2\left(\frac{\rho_s}{\rho} - 1\right)(0.003869 + 0.02480D)\right]^{1/2}}{0.011607 + 0.07440D}$$
Now, what factors affect remobilization of sediment from the bottom?

- Trade-off between forcing (bottom shear stress) and response (resistance to motion)
- Bottom shear stress important for estuarine sediment transport is some combination of “steady” stress (tidal and longer period forcing) and high frequency oscillatory stress (surface waves)
  - Except for completely smooth bottoms, stress must also be separated into the total stress that affects the flow above the bottom, and the skin friction that affects the sediment bed
- Resistance to motion and transport behavior can be quite different for non-cohesive and cohesive sediments, and in general is much more complex for cohesive sediments
Separation of total stress and skin friction for quasi-steady flows
(not the most sophisticated technique, but has been used previously [Glenn and Grant, 1987; Grant and Madsen, 1982] and is simple)

Assume we have a reasonable estimate of the total stress bottom roughness parameter $z_{0T}$ from model calibration or direct stress measurements in the log layer. Then the log layer velocity law (as ably explained by Steve Monismith) gives

$$u(z_1) = \frac{u_*}{\kappa} \ln \left( \frac{z_1}{z_{0T}} \right)$$

where $u(z_1)$ is the velocity at height $z_1$, $u_*$ is the total stress shear velocity, and $\kappa=0.4$ is von Karman’s constant. This can be solved for the total hydrodynamic bottom stress as

$$\tau_T = \rho u_*^2 = \rho C_d u(z_1)^2$$

where

$$C_d = \left( \frac{\kappa}{\ln \frac{z_1}{z_{0T}}} \right)^2$$
Now write a new law of the wall for the skin friction shear velocity $u_*$ in terms of $u(z_1)$ determined above and the skin friction roughness parameter $z_{0s}$

$$u_* = \left( \frac{\kappa}{\ln \frac{z_1}{z_{0s}}} \right) u(z_1) = u_* T \left( \frac{\ln \frac{z_1}{z_{0T}}}{\ln \frac{z_1}{z_{0s}}} \right) = \sqrt{C_d} u(z_1) \left( \frac{\ln \frac{z_1}{z_{0T}}}{\ln \frac{z_1}{z_{0s}}} \right)$$

And the ratio of the skin friction $\tau_s$ to the total stress $\tau_T$ is

$$\frac{\tau_s}{\tau_T} = \left( \frac{\ln \frac{z_1}{z_{0T}}}{\ln \frac{z_1}{z_{0s}}} \right)^2$$

Ratio of skin friction to total stress for $kb,tot = 3$ cm, $kb,skin=0.3$ mm, 10 sigma layers
Surface gravity waves (only most important aspects for sediment transport)

**Kinematic Relationships**

H: wave height  
\( a: \text{amplitude} = \frac{1}{2} \, H \)  
C: phase speed  
T: wave period = time for one wave to pass  
C=L/T units of velocity  
K=2\( \pi \)/L wave number, units of length\(^{-1} \)

\( \sigma, \omega = 2\pi/T \) radian frequency, time\(^{-1} \)

f = common frequency = 1/T unit Hz, time\(^{-1} \) (1Hz=1cycle/sec)

\[
\eta(x,t) = \text{instantaneous sea surface elevation : shape of the wave}
\]

\[
= \frac{1}{2} H \sin(kx - \omega t)
\]
Wave Dynamics
Solution of equation of motion (linearized), derive a Dispersion Relationship between L & T, or between C and L

\[ \omega^2 = gk \tanh(kd) \]

g=9.81m^2/sec
d:water depth
tanh: hyperbolic tangent.
In nature \( \omega \) is conserved (stays the same) and \( k \) changes in response to changing depth.
Deep water waves for \( d/L > 0.5 \), \( \tanh(kd) \approx 1 \), then dispersion relationship becomes

\[
\omega^2 = gk
\]

\[
C = \frac{L}{T} = \frac{\omega}{k} = \sqrt{\frac{g}{k}} = \frac{gT^2}{2\pi} = \sqrt{\frac{gL}{2\pi}}
\]

\[
L_0 = \frac{gT^2}{2\pi} = \text{deep water wavelength}
\]

because \( C \) depends on \( L \), longer waves travel faster and waves of different length disperse – separate as they travel.

Shallow water waves \( d/L < 1/25 \), then \( \tanh(kd) \approx kd \), the dispersion relationship becomes

\[
\omega^2 = gk \cdot kd = gk^2d
\]

\[
\frac{\omega^2}{k^2} = c^2 = gd
\]

\[
c = \sqrt{gd}
\]

\( u_b \) is the amplitude of the near bottom velocity fluctuations.

\( u_b = 0 \)

\( u_b = \frac{a}{h} \sqrt{gh} \)
Table 1
Properties of Linear Gravity Waves

<table>
<thead>
<tr>
<th>Property</th>
<th>General Expression</th>
<th>Deep Water (h/L &gt; 0.5; Short Waves)</th>
<th>Shallow Water (h/L &lt; 0.05; Long Waves)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity potential, ( \phi )</td>
<td>( \phi = a \frac{g}{\omega} \cosh \frac{k(z + h)}{\cosh kh} \sin(kx - \omega t) )</td>
<td>( \phi = a \frac{g}{\omega} e^{\imath \omega t} \sin(kx - \omega t) )</td>
<td>( \phi = a \frac{g}{\omega} \sin(kx - \omega t) )</td>
</tr>
</tbody>
</table>
| Phase speed, \( C \)          | \( C = \frac{\omega}{k} = \frac{L}{T} = \frac{g}{\omega} \tanh kh \) | \( C_s = \frac{g}{\omega} = \frac{T}{2\pi} \) | \( C = (gh)^{1/3} \) |}
| Wave length, \( L \)         | \( L = g \frac{T^2}{2\pi} \tanh kh \) | \( L_s = g \frac{T_s^2}{2\pi} \) | \( L = T(gh)^{1/3} \) |
| Group velocity, \( C_g \)     | \( C_g = C_n = C \frac{1}{2} \left[ 1 + \frac{2kh}{\sinh 2kh} \right] \) | \( C_{\rho\omega} = \frac{1}{2} C_w \) | \( C_s = C = (gh)^{1/3} \) |
| Pressure, \( p_{\omega} \)    | \( p_{\omega} = \rho g a \cosh \frac{k(z + h)}{\cosh kh} \cos(kx - \omega t) \) | \( p_{\omega} = \rho gae^{\omega t} \cos(kx - \omega t) \) | \( p_{\omega} = \rho g \eta \) |
| Horizontal orbital velocity, \( \tilde{u}_x \) | \( \tilde{u}_x = a\omega \cosh \frac{k(z + h)}{\sinh kh} \cos(kx - \omega t) \) | \( \tilde{u}_x = a\omega e^{\omega t} \sin(kx - \omega t) \) | \( \tilde{u}_x = \frac{Ca}{h} \cos(kx - \omega t) \) |
| Vertical orbital velocity, \( \tilde{w}_x \) | \( \tilde{w}_x = a\omega \sinh \frac{k(z + h)}{\sinh kh} \sin(kx - \omega t) \) | \( \tilde{w}_x = a\omega e^{\omega t} \cos(kx - \omega t) \) | \( \tilde{w}_x = 0 \) |
| Energy density, \( E \)       | \( E = \frac{1}{2} \rho g a^2 \) | \( E = \frac{1}{2} \rho g a^2 \) | \( E = \frac{1}{2} \rho g a^2 \) |
| Energy flux, \( E_j \)        | \( E_j = E C_s \) | \( E_j = E C_s \) | \( E_j = E C_s \) |
| Radiation stress, \( S_{\alpha\alpha} \) | \( S_{\alpha\alpha} = E \left[ \frac{1}{2} + \frac{2kh}{\sinh 2kh} \right] \) | \( S_{\alpha\alpha} = \frac{3}{2} E \) | \( S_{\alpha\alpha} = E \sin \alpha \cos \alpha \) |
| Radiation stress, \( S_{\alpha\beta} \) | \( S_{\alpha\beta} = E \left[ \frac{kh}{\sinh 2kh} \right] \) | \( S_{\alpha\beta} = 0 \) | \( S_{\alpha\beta} = \frac{1}{2} E \) |
| Radiation stress, \( S_{\beta\beta} \) | \( S_{\beta\beta} = E \left[ \frac{1}{2} \left( 1 + \frac{2kh}{\sinh 2kh} \right) \sin \alpha \cos \alpha \right] \) | \( S_{\beta\beta} = \frac{1}{2} E \sin \alpha \cos \alpha \) | \( S_{\beta\beta} = E \sin \alpha \cos \alpha \) |

* \( n \) is defined by Equation 8 in Chapter II.
As a deep water wave moves into shallower water, it first becomes a transitional wave and eventually a shallow water wave. “Deep” is defined relative to wavelength (or period), however, and it is different in different environments. Wave base refers to the depth at which typical waves in that environment first begin to significantly influence the bottom.
Oscillatory boundary layers and wave friction factors

Oscillatory boundary layers have an inherent vertical length scale associated with the diffusion limit for turbulence in one cycle,

\[ \delta_w \propto u_{*w} / \omega \]

Wave bbls are typically cms thick, which greatly enhances shear and turbulent stress.

This leads to much larger drag coefficients \( f_w \)

\[ \tau_{bw} = \frac{1}{2} \rho f_w u_b^2 \]

When compared to quasi-steady drag coefficients \( C_d \)

Figure 2.3.7  Wave friction coefficient for hydraulic smooth and rough conditions (Jonsson, 1966)
So surface gravity wave forcing can play a dominant role in sediment transport in shallow, microtidal environments (Nakagawa, Sanford, and Halka 2000)

Simulated significant wave height (m)  
Estimated bottom shear stress (Pa)

Simulated wave height and wave induced bottom shear stress for a 15 m s$^{-1}$ wind from the northwest in Baltimore Harbor, Maryland, USA
Figure 3 – Time series observations of mud resuspension before, during and after a storm, from a site in upper Chesapeake Bay, Maryland, USA. (Sanford in press)
Resistance to remobilization of bottom sediments: 

*Critical Stress*

A threshold value of the applied skin friction below which there is no (or negligible) transport of bottom sediments

For non-cohesive sediments, the stabilizing force $F_g$ is the submerged weight of the particle

$$F_g = \text{Vol} \left( \rho_s - \rho \right) g \propto D^3$$

Destabilizing forces

$$F_L = \rho C_L U^2 A \propto D^2$$
$$F_D = \tau_b A = \rho C_D U^2 A \propto D^2$$

Ratio of Destabilizing/Stabilizing

$$\Psi \propto \frac{\tau_b}{\rho (s-1) D}$$
Shield’s parameter $\Psi$ determines whether a particle will move. For any given particle $(s, D)$, there is a critical value of $\Psi$ above which sediment motion occurs called the critical Shield’s parameter $\Psi_c$.

$\Psi_c$ often plotted as a function of $(Re* = u*kb/\nu)$. For a flat sediment bed, $kb \sim D_{50}$ = median diameter of the sediment grains, so

$\Psi_c = func\left(\frac{u* D_{50}}{\nu}\right)$

The value of $\Psi_c$ must be empirically determined, resulting in Shield’s Diagram:

![Figure III-6-7. Shields diagram for initiation of motion in steady turbulent flow (from Raudkivi (1967))](image)
This is inconvenient because both axes are a function of $u^*$, so derive a modified Shields diagram (Madsen and Grant 1976); also valid for waves

$$\Psi_c = \text{funct}(S_*)$$

where

$$S_* = \frac{D_{s0}}{4\nu} \sqrt{g(s-1)}D_{s0}$$
A simpler, but much less general way to present this information is to assume quartz grains with a fixed drag coefficient, and derive a relationship for motion in terms of grain size and current speed (at right). This is sometimes referred to as a Hjulstrom diagram.

This diagram also indicates a fixed erosion threshold for silts and clays, which is overly simplistic, and a general behavior known as exclusive deposition, which is not universally accepted.

From Waves, Tides, and Shallow Water Processes (1999)
Erosion/Resuspension of silt/clay mixtures (muds)

• Resistance of the bed a function of cohesion, water content, grain size distribution and density. Often expressed as erodibility, parameterized by critical stress $\tau_c$ and erosion rate $E$.

• In general, mud erodibility is not predictable \emph{a priori} and at least some measurements are required
Partial list of factors affecting fine sediment erodibility

<table>
<thead>
<tr>
<th>Factor</th>
<th>Sense of effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content</td>
<td>+</td>
</tr>
<tr>
<td>Percent sand</td>
<td>-</td>
</tr>
<tr>
<td>Percent clay</td>
<td>-</td>
</tr>
<tr>
<td>Salinity</td>
<td>-</td>
</tr>
<tr>
<td>Exopolymers (EPS)/Mucopolysaccharides</td>
<td>-</td>
</tr>
<tr>
<td>Bioturbation</td>
<td>+</td>
</tr>
</tbody>
</table>

From Roberts et al. (1998)
Erodibility also can vary significantly in time and space. For example, consolidation causes $\tau_c$ to increase rapidly with depth into the bed and with time after deposition (Parchure and Mehta 1985).

Fig. 3. Three-zoned schematic description of bed shear strength profile for cohesive beds (After Parchure and Mehta 1985)

Fig. 4. Bed shear strength profiles after 1 day and 8 days of consolidation (After Parchure and Mehta 1985)
Erodibility can change significantly in response to disturbance. Passage of a tropical storm, upper Chesapeake Bay, Sept 1992. Dredged sediment disposal site, 5 m depth.
Interactions between physical and biological disturbance of the sea bed can lead to distinct layering or near homogeneity (x-radiographs courtesy of Linda Schaffner)

Increasing physical disturbance of sea bed

Physical disturbance overwhelms bioturbation at York River site

Bioturbation dominates fine sediment fabric at Chesapeake Bay site
Present state of the sediment bed can reflect a very dynamic interaction between rapidly repeated erosion and deposition.
Recent emphasis in field has been on development of new techniques for site-specific, *in-situ* erosion testing

- Laboratory tests on sediment samples from field used to be common, now less frequent
- *In situ* bottom landing devices
  - Annular and linear flumes
  - Small-scale erosion chambers
- Quasi *in situ* testing of cores
  - Flumes
  - Small scale erosion chambers
In situ annular and linear flumes

VIMS Sea Carousel – Jerome Maa (similar to Carl Amos’ device at SOC)

NIWA Linear Flume (Aberle et al. 2004)  
- Similar to Tom Ravens’ device in US
In situ small scale erosion chambers

10 cm diameter SedErode, successor to ISIS, Williamson and Ockenden (1996)

Cohesive Strength Meter, sold by Partrac Ltd, UK
Quasi *in situ* core testing

SedFlume, McNeil et al. (1996)

UMCES 10 cm diameter Microcosm
The UMCES Microcosm Core Erosion System

With thanks to Drs. Giselher Gust and Volker Mueller, TUHH
Huge scatter in reported erosion rates may be due to several factors:

- **Real differences in erodibility** – what we want to understand and predict

- **Differences in instrument calibration or performance** – what we need to know in order to compare different data sets

- **Differences in experimental design and data analysis** – what we need to resolve before we can compare instruments

From Gust and Morris (1989)
How do experimental design and data analysis procedures affect interpretation of erosion data? For illustration, consider data from an erosion device intercomparison experiment in Upper Chesapeake Bay, May 7, 2002.

Fig. 1-1. VIMS Sea Carousel Experiment Sites for the Middle Chesapeake Bay (M₁ and M₂) and Upper Bay Sites (U₁ and U₂).
We have known for years that a rapid increase of $\tau_c$ with depth into the bed results in a rapidly time varying erosion rate:

Example erosion test and derived critical stress profile from Parchure and Mehta (1985)
If erosion behavior is time dependent, then differences in the time history of stress application affect the results of erosion experiments.

• Most common to apply a sequence of constant stress steps, ranging from minutes to hours in duration.
• Sometimes gradually ramp up stress between stress steps (Maa et al. 1993).
• Others apply continuously increasing stress (Gust and Morris, 1989).
• Others apply short bursts of stress of increasing intensity (CSM of Tolhurst et al., 2000).
An unexpected time dependent erosion response leads to differences in interpretation or reporting of erosion rate data

- Many interpret erosion rate for each applied stress as the average over the time interval.
- If erosion rate is time dependent, then the average depends on the duration of the interval.
- Others interpret erosion rate as the average after the initial spike in response (Ravens and Gschwend 1999).
- Others report erosion rate as the initial spike (Maa et al. 1998).
- Others interpret erosion rate as an expected time varying response to changing erodibility during the interval (Sanford and Maa 2001).
- These differences in interpretation contribute to the orders of magnitude differences in erosion rates observed, even in controlled inter-comparison experiments (Tolhurst et al. 2000).

From Aberle et al. (2004)
Differences in interpretation of critical stress are also associated with time/depth dependence

- Many investigators focus on a single critical stress for erosion, the value at which initiation of motion occurs
  - Some define critical stress as that stress for which a significant increase in concentration is first observed
  - Others define critical stress as the zero intercept of an erosion rate vs stress regression
- Others define critical stress as a depth profile of stresses at which erosion stops
  - Much more common in older laboratory erosion tests, seldom reported for in situ measurements
- Others consider the concept of critical stress to be unimportant, or define it but do not use it in reporting erosion rate results
Sea Carousel v. Microcosm comparison using individual data analysis and interpretation techniques

\[ E = E_0 e^{-\lambda t} \quad E_0 \propto (\tau_b - \tau_c)^n \quad E = M(t)[\tau_b(t) - \tau_c(m)] \]

\[ E_0 \propto (\tau_b - \tau_c)^2 \text{ globally} \]

\[ E \propto (\tau_b - \tau_c) \text{ locally} \]
Time dependent erosion behavior is relatively straightforward to derive theoretically, especially for specific erosion formulations that yield analytical solutions:

**Time dependent linear – 2 parameters,**

\[ E'(z, t) = \beta(\tau_b(t) - \tau_c(z)) \]

Assume \( \beta = \text{constant}, \frac{d\tau_c}{dz} = \gamma z \)

for \( \frac{d\tau_b}{dt} = 0, \)

\[ E' = \beta(\tau_b - \tau_{c0})e^{-\beta\gamma t} \]

**Time dependent power law – 4 parameters, simple extension of Roberts et al. (1998)**

\[ E = A\tau_b(t)^n e^{-k\rho(z)} \]

assume \( \frac{d\rho_b}{dz} = \text{constant}, \)

then for \( n=2 \) and \( \frac{d\tau_b}{dt} = 0, \)

\[ E = \frac{E_0}{Bt + 1}, \text{ where } B = E_0 k \frac{d\rho_b}{dz} \]
Reanalysis of Sea Carousel data using the Microcosm approach reveals real similarities and differences.
Measurement Conclusions

• Ultimate goal is to predict fine sediment erosion behavior with a minimum of site-specific data
• Reliable data comparisons hindered by differences in instruments, experimental designs, and data interpretation/analysis
• Standardization of experimental design and data analysis protocols needed
  – Should be informed by appropriate choice of erosion model(s)
  – Accounting for time/depth changes in erodibility especially important – time dependent erosion response should be expected, not ignored
Measurement Conclusions, continued

• Experimentalists should archive and share erosion test time series, not just derived parameters
• Erosion experiments should be considered as spot measurements of a dynamically varying process
• Modelers should match formulations in sediment transport models to formulations used for data collection/analysis
Deposition

Exclusive Deposition - standard assumption for many cohesive transport models (e.g., ECOMSED cohesive module), supported by many lab studies

\[
D = w_s c_{ref} \left(1 - \frac{\tau_b}{\tau_c}\right) \quad \text{for} \quad \tau_b < \tau_c
\]

\[
D = 0 \quad \text{for} \quad \tau_b \geq \tau_c
\]

where \(w_s\) is the sediment fall velocity, \(c_{ref}\) is a reference suspended sediment concentration just above the bottom, \(\tau_b\) is the bottom shear stress and \(\tau_c\) is the critical stress for deposition.

Continuous Deposition - assumption of many other models (e.g., Harris and Wiberg 2000), in many cases agrees better with field studies (Sanford and Halka 1993)

\[
D = w_s c_{ref}
\]
Exclusive, unlimited sediment supply

Exclusive, limited sediment supply

Continuous, unlimited sediment supply

Time

\[ \tau_e \]

\[ \tau_d \]
From Sanford and Halka (1993)
Changeover
Modeling Cohesive Sediments: Erosion, Deposition, and Bed Processes
What are the main challenges for fine sediment transport research and application?

• Effective shear stress
• Sediment erosion/resuspension
• Shoreline erosion/protection
• Spatial heterogeneity
• Flocculation and settling
• Sediment Deposition and Consolidation
• Biological effects
• Concentrated benthic suspensions
• Interactions with T/S stratification
• Large events
• Modeling
• Effective adoption of new technologies
• Disciplinary and geographical boundaries and biases
Bottom Sediment Erosion/Resuspension

- Resistance of the bed a function of cohesion, water content, grain size distribution and density. Often expressed as erodibility, parameterized by critical stress $\tau_c$ and erosion rate $E$.
- In general, erodibility is not predictable \textit{a priori} and at least some measurements are required (a sad state of affairs)
- Variety of methods to test erodibility exist, but no real standards for collection, interpretation, or use of the data
- Can measure, model erodibility profile at one point in time, but how does the bed evolve from that point or recover from disturbance?
  - Consolidation
  - Armoring
  - Bioturbation/bio-adhesion
- When to switch between fluid mud entrainment and cohesive bed erosion?
- Mass erosion – bed failure under high stresses, rather than particle by particle
Biological effects

- Particle stickiness, repackaging, biodeposition
- Bottom roughness of benthic communities
- Bioturbation – mixing of surface sediments changes surface texture, erodibility
- Macroscale structure/form drag - potential for feedbacks to sedimentation
  - Oyster beds and reefs, coral reefs
  - Seagrass beds
  - Marsh vegetation
Concentrated benthic suspensions

- Some major advances in recent years
  - AMASSEDS, STRATAFORM, COSINUS programs
  - Turbulence damping at lutoclines
  - Turbidity flows
- CBS are common where energy is high and sources are large, but just a slight decrease in energy can result in a change to normal sediment beds
  - Is this a state change? Why, and when is the switch thrown?
Spatial heterogeneity

• Changes in bottom sediment texture and strength can be abrupt, sometimes at smaller scale than model cells
  – Why? Is this a state change, rather than gradual mixing? Can we model it?
  – Recent work of van Ledden et al. provides a framework for interpretation/modeling

• New measurements are fantastic, but how do we utilize the information to improve understanding and prediction?
Modeling

• How to best incorporate all of the above into workable models?
  – 1-D process models are important, especially for development, but 3-D long term, large scale models are critically needed
  – Detailed knowledge of processes must be parameterized, but retain essential features
• Best models are as simple as possible, but no simpler…
• The NOPP Community Sediment Transport project – a major opportunity
• What can be adopted from previous work, and what needs new development?
Selected cohesive sediment erosion formulations

I
\[ r_e = \frac{\partial m}{\partial t} = E_0 \exp \left[ P_e \left( \tau_0 - \tau_{ce(z)} \right)^{0.5} \right] \]
Gularte et al. (1980), others

II
\[ E = M \left( \frac{\tau_b}{\tau_c} - 1 \right)^n \quad \text{for } \tau_b > \tau_c \]
\[ E = 0 \quad \text{for } \tau_b \leq \tau_c \]
Lick (1982), many others

III
\[ E = A \tau_b(t)^n e^{-k\rho(z)} \]
Roberts et al. (1998), Lick et al. (2006)

IV
\[ E = M \left( \frac{\tau_b}{\tau_c} - 1 \right) \quad \text{for } \tau_b > \tau_c \]
\[ E = 0 \quad \text{for } \tau_b \leq \tau_c \]
McLean (1985), many others

V
\[ E'(z, t) = \beta(\tau_b(t) - \tau_c(z)) \]
Sanford and Maa (2001)
Consolidation effects on erosion

• Expressions I, III, and V explicitly allow for a consolidation effect
• Lick and co-workers have modified II to allow for a consolidation effect according to

\[ M = \frac{a_0}{T_d^m \times 3600 \text{sec}} \]

• Keen and Furukawa (2006) also modified II to allow for a consolidation effect (as well as bioturbation) using multiplicative factors parameterized based on observations
• However, few sediment transport models include both time-dependent consolidation AND consolidation effects on erosion (time-dependent, supply-limited erosion)
Time dependent erosion behavior is straightforward to derive for specific erosion formulations:

Start with \( E = M(m)[\tau_b(t) - \tau_c(m)] \), take \( \frac{d}{dt} \), and set \( \alpha = \frac{d\tau_c}{dm} \)

get \( \frac{dE}{dt} + \alpha ME = M \frac{d\tau_b}{dt} \)

if \( \tau_b = At \), then \( \frac{d\tau_b}{dt} = A \) and

\[
E = \frac{A}{\alpha} \left( 1 - e^{-\alpha Mt} \right) + M \left( \tau_{b0} - \tau_{c0} \right) e^{-\alpha Mt}
\]

set \( \lambda = \alpha M \), average over time step \( \Delta t \) and set \( b = \frac{1 - e^{-\lambda \Delta t}}{\lambda \Delta t} \)

then \( \bar{E} = \frac{A}{\alpha} \left( 1 - b \right) + bM \left( \tau_{b0} - \tau_{c0} \right) \)

Time dependent behavior is important when \( b < 1 \), i.e., when the time scale of sediment depletion is short relative to the time step of the model (\( \lambda \Delta t > 1 \)).
What would an ideal cohesive bed/erosion/deposition model include?

• Physically correct consolidation model (based on modified Gibson equations and including both phases of consolidation) including sand-mud mixtures, erosion/deposition, discontinuities

• General representation of erosion behavior
  – Including arbitrary sand-mud mixtures
  – Including dependence on consolidation state
  – Time- and depth-dependent erosion behavior (limited sediment supply as a function of applied stress)
  – Parameterization of changes in erosion behavior between fluid mud entrainment, surface erosion, and mass erosion

• Parameterizations for bioturbation and bio-adhesion (both erosion behavior and bed evolution)

• Deposition formulation that allows for multiple particle classes, floc behavior, and high erodibility of recent deposits

• Compatibility with non-cohesive model components
Selected Existing Cohesive Sediment Transport Models

- **SEDZLJ** (Jones and Lick 2001)
  - includes sediment mixtures with empirical cohesive erosion parameterizations, but limited bed dynamics
  - Now being incorporated into ECOMSED (Hydroqual) with Sanford’s consolidation mechanism for deposited sediments
- **DELFT3D**
  - Proprietary code, but containing much of the high quality work done at TU Delft (Winterwerp, Kranenberg, van Kesteren, and their students and post-docs)
  - Rumored to become open source soon
- **SEDTRANS05** (Neumeier et al. 2007)
  - Latest incarnation includes Gularte type cohesive erosion with a limited empirical approach to equilibrium consolidation capability
- **EFDC** (Hamrick, Tetratech)
  - Includes sophisticated, but complex algorithms to handle mixed sediments and consolidation (I think), but not easily accessible
- **OTHERS** (MORPHOS, WES CH3DSED, OSU CH3DSed(?), …?)
- **ROMS-SED** – Warner et al. in press, under development
Sediment Bed Model Development in ROMSSED based on Sanford (in press)

- Use a layered bed model with continuous profiles of $\tau_c$, layer-averaged erosion constant $M$ and sand fraction $f_s$
- Use sediment bed mass $m$ as independent variable instead of depth (better for consolidation)
- 2-component mixture of sand and mud
  - Separate erosion parameters for sand and mud (interaction effects not yet incorporated)
  - Erosion rates proportional to fractions at interface
- Mud erosion follows Sanford and Maa (2001)
- Sand erosion follows Harris and Wiberg (2001)
- Assume constant $\tau_{c,sand}$
- Assume that $\tau_{c,mud}$ approaches an equilibrium profile at a first order rate $\gamma$
- Allow for sediment mixing (bioturbation, bedload transport)
- Assume that newly deposited mud particles carry with them a very low $\tau_{c,mud}$, which lowers the critical stress of the sediment surface layer
- Interface moves down/up through bed layers during erosion/deposition
- Only mix mass between layers when a threshold is exceeded (minimizes numerical dispersion)
- Model evolution of $\tau_{c,mud}$ and $f_s$ as a function of $m$ and time
How well does an exponential approach to equilibrium approximate consolidation? Comparison to data of Toormann and Berlamont (1993)

Original data and full consolidation model by T&B (1993)  
T&B (1993) data, exponential approach to equilibrium approximation
Example: Erosion, deposition, and consolidation of a pure mud and a sand-mud mixture

- Bed consists of 25 layers 0.05 kg m\(^{-2}\) thick
- Critical stress profile initiated with average of Baltimore Harbor profiles from Sanford and Maa (2001), also assumed to be equilibrium profile
- Assume \(M = \beta \rho_s \phi_s\) where \(\beta = 11.75\) m d\(^{-1}\) Pa\(^{-1}\) from SM2001
- Spring-Neap cycle of tidal shear stress, max varies between 0.15-0.30 Pa
- A 1.25-day event starting at day 21.25 increases the max stress 2.5X
- Very low sediment mixing of 0.01 cm\(^2\) yr\(^{-1}\)
- \(w_{sm} = 86.4\) m d\(^{-1}\), \(h = 2\) m
- Consolidation rate = 3.0 d\(^{-1}\), swelling rate = 0.03 d\(^{-1}\)
- \(w_{ss} = 864\) m d\(^{-1}\), \(\tau_{csand} = 0.125\) Pa (fine sand)
All mud, very low sediment mixing
All mud, very low sediment mixing, 2 days during event and 1 tidal cycle 2 days after event
30/70 sand-mud, very low sediment mixing
30/70 sand-mud, sediment mixing 10 cm$^2$ yr$^{-1}$
Modeling Conclusions

• Layered bed model for critical stress profile in terms of bed mass simplifies formulation, avoids layer transfers during consolidation.
  – Z-dependent model also possible
• Specification of equilibrium conditions based on observed erosion behavior promising, but may need tweaking.
• “Consolidation” formulation predicts reasonable behavior with little computational effort, but needs more validation
• Mud-sand mixture and diffusive mixing schemes lead to realistic complex bed structures and directly affect resuspension
Modeling Conclusions, continued

• Need to incorporate sand-mud interaction effects on erodibility

• Need to simplify code, translate into Fortran for inclusion in ROMSSED (in progress)
Changeover
Estuarine Turbidity Maxima with particular attention to the upper Chesapeake Bay
Well-documented turbidity maxima are found all over the world

- Chesapeake Bay
- Hudson
- St. Lawrence
- Columbia
- San Francisco Bay
- Chikugo
- Ems
- Gironde
- Weser
- Tamar
- ACE Basin
- Seine
- Scheldt
- Jiaojiang
- Etc., etc.
Observations about particle trapping in ETMs

• Particle trapping in ETMs occurs by asymmetrical tidal transport of a pool of resuspendible particles with a limited range of settling velocities

• Fine sediments in estuarine environments almost always exist in aggregated (flocculated) form. Aggregation and disaggregation can be active processes, depending on concentration, stickiness, and small scale shear.

• Settling velocities of fine sediments trapped in ETMs are determined by the aggregate properties (size and specific density), not the individual particle properties
Infilling of the Old Susquehanna Channel

[Graph showing depth in meters along the Old Susquehanna Channel with markers for Modern Bay Depth and Old Susquehanna Channel Depth.]
Upper Bay Bathymetry from a 3D charting program
Continuous, natural infilling of shipping channels requires continuous maintenance dredging.
Chesapeake ETM has been studied from physical and biological perspectives in four recent programs, 3 supported by NSF

- Seasonal, short term studies during 5 of the last 7 years (3-9 days cruises in spring, summer, and fall)
  - 1996 – very wet
  - 1998 – wetter than normal
  - 1999 – drought
  - 2001 – dryer than normal
  - 2002 – extreme drought
  - 2007 – drought
  - 2008 - ?
Axial CTD Surveys and Moored Data

Conowingo Dam

Baltimore

BWI

CBOS
Physical Features of the ETM

TSS = Total Suspended Solids

Axial CTD Survey - May 2, 1996

Salinity, (PSU)

TSS, (mg/l)

Distance from Head of Bay [km]
Zooplankton in the ETM, May 1996

Distance From Top of Bay (km)
Striped Bass

Spring 1996 TIES Program

White Perch
*Morone americana*

Striped Bass
*Morone saxatilis*

White Perch Larvae

Striped Bass Larvae

No. m⁻³

0

500

70

0
Conceptual diagram of ETM sediment and zooplankton trapping at the limit of salt.
Annual Susquehanna River flows and suspended sediment loadings to the upper Bay, 1991-1999

Monthly river flows and sediment loads to upper Bay during 1996, compared to the average during the 1990s
Previous conclusion (Sanford et al. 2001): Particle trapping in CB ETM highly dependent on settling speeds of flocculated fine sediments, which vary seasonally.

February 1996 flood

October 1996 flood
Near Bed Salinity Gradient v 1 PSU

- **1996**
  - Data points for 1 PSU and dS/dx locations, with a 1:1 line.

- **2001**
  - Data points for 1 PSU and dS/dx locations, with a 1:1 line.

- **2002**
  - Data points for 1 PSU and dS/dx locations, with a 1:1 line.

- **All Data**
  - Combined data points for 1 PSU and dS/dx locations, with a 1:1 line.
Critical Stress and Erosion Rate Constant

![Graph showing the relationship between critical stress and eroded mass. The equation is given as y = -0.0014 + 1.5688x^{1.6070} with R^2 = 0.78.]

![Graph showing the relationship between erosion rate constant and eroded mass.]
Spatial and Temporal Variation

![Graph showing erodible mass over time for Tolchester, Grove Pt., and TSL from May '01 to Oct '02.](image)
Eroded Mass vs $w_s$ and Loading
Particle size and settling velocity measurements

Modified Valeport bottom withdrawal settling tube – with water jacket and reflective insulation

Video In-situ Settling Tube Apparatus (VISTA) mounted on profiling rig with LISST, ADV, CTD; water pumped through tube, valves closed, particle settling videotaped

Laser In-Situ Scattering and Transmission (LISST) – particle size in 32 bins between 2-500 microns, plus forward transmission
## Disaggregated Sediment Sizes: high-volume filtering 1 mab

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sampling Duration (h)</th>
<th>Total Mass (g)</th>
<th>d25 (microns)</th>
<th>d50 (microns)</th>
<th>d75 (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May Flood (25 cm s⁻¹)</td>
<td>2.5</td>
<td>7.05</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>May Ebb (45 cm s⁻¹)</td>
<td>6</td>
<td>35.78</td>
<td>&lt;1</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>July Flood (75 cm s⁻¹)</td>
<td>2.5</td>
<td>28.32</td>
<td>&lt;2</td>
<td>3</td>
<td>16</td>
</tr>
<tr>
<td>July Ebb (40 cm s⁻¹)</td>
<td>9</td>
<td>13.37</td>
<td>&lt;2</td>
<td>&lt;2</td>
<td>2</td>
</tr>
</tbody>
</table>
Video clip from May 2002 VISTA sample (approx 1 cm across)
May 11, 2002 Strong Ebb Survey: LISST Data
October 11, 2002 Weak Flood Survey

1. **TSS (mg/l)**
   - Depth (m)
   - River Km

   - Depth (m)
   - River Km

3. **D50 (microns)**
   - Depth (m)
   - River Km

4. **Vol. Conc. <66.5 um (ul/l)**
   - Depth (m)
   - River Km

5. **Vol. Conc. >66.5 um (ul/l)**
   - Depth (m)
   - River Km

6. **Bulk Density (g/cm^3)**
   - Depth (m)
   - River Km
Tidal Cycle Anchor Station October 10, 2002: Flood - Ebb

Shear (s-1) and current (cm s-1)

Total Volume (ul l-1) and TSS (mg l-1)

D50 (microns) and Salinity (psu)
VISTA: Floc Settling Speed v. Floc Size, 10/10/2002

Surface

\[ y = 5.3443x^{1.0495} \]
\[ R^2 = 0.4548 \]

Middle

\[ y = 26.597x^{1.1912} \]
\[ R^2 = 0.4544 \]

Bottom

\[ y = 1.908x^{0.8331} \]
\[ R^2 = 0.4744 \]

Owen tube

\[ y = 147.15x^{1.3923} \]
\[ R^2 = 0.6077 \]
## VISTA Results:

<table>
<thead>
<tr>
<th>depth [m]</th>
<th>$w_{s,ave}$ [mm·s⁻¹]</th>
<th>$d_{ave}$ [μm]</th>
<th>$\rho_{bulk}$ [g·cm⁻³]</th>
<th>D3 [-]</th>
<th>$d_r$ [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.66*</td>
<td>170**</td>
<td>1.05</td>
<td>2.05</td>
<td>3.85</td>
</tr>
<tr>
<td>7</td>
<td>1.41*</td>
<td>243</td>
<td>1.05</td>
<td>2.19</td>
<td>3.15</td>
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<tr>
<td>9.5</td>
<td>2.26*</td>
<td>294</td>
<td>1.06</td>
<td>1.83</td>
<td>16.07</td>
</tr>
<tr>
<td>all</td>
<td>1.54</td>
<td>243</td>
<td>1.06</td>
<td>2.39</td>
<td>0.79</td>
</tr>
</tbody>
</table>
Valeport Settling Tube Results:

1996 (♦), 2001 (■), 2002 (▲)
Conceptual Model of Particle Dynamics in Chesapeake Bay ETM:
Preliminary Conclusions

• Particle size usually smaller near surface, but evidence of large, watery flocs in pycnocline sometimes
  – d50 50-100 microns near surface, 100-200 microns near bottom
  – Only weak relationships to turbulent shear

• Some very slowly settling particles always present, settling particles appear to be resuspended and deposited tidally with a broad range of settling speeds (ws50 0.4-8 mm/s)
  – No relationship between ws50 and concentration apparent
ETM (essentially) session at ERF 2007 (Houde and Sanford)