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Transport by Turbidity Currents, Shoaling Solitary Waves and Turbulent Jets

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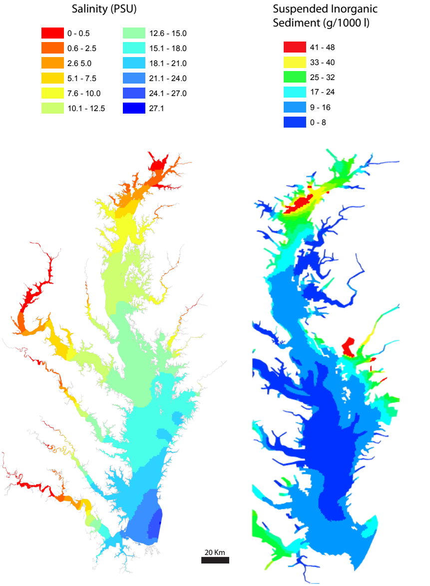
Settling of Fine Particles from River Plumes

Mississippi River Plume

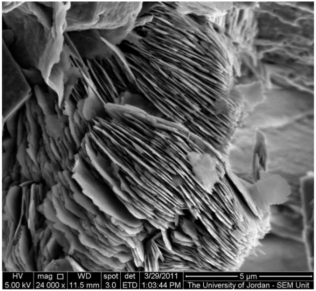
[NASA Earth Observatory]



[www.chesapeakebay.net and Cerco et al, Est. Coast. Shelf Sci. (2013)]

Clay Settling

- Clay is composed of tiny plates with sizes on the order of $1\ \mu$m.



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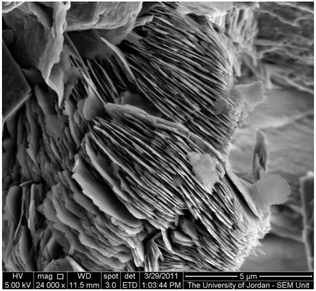

- Using Stokes' prediction based on particle size and density, estimate settling speed is on the order of

$$w_{\text{clay}} \simeq 10^{-4}\ \text{cm/s}$$

- So a particle would take 100,000 seconds (about a day) to fall 10 cm.
- With many particles in solution, the speed would be reduced and the time to fall even smaller.

Getting Up Close and Personal with Mud

This is why I am not a geologist . . .

Geologist in Paulliac

Geologist's student at Bay of Fundy

The Laboratory Experiment

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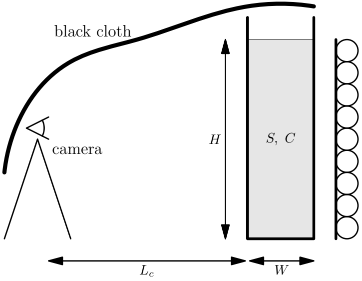
- Perform experiments in a rectangular tank.
  - fill tank with water
  - add clay and (sometimes) salt
  - stir briefly
  - observe patiently

Schematic of Laboratory Setup



Picture of Experiment in Progress

Settling of Kaolin Clay

- A 20 cm X 5 cm by 10 cm deep tank filled with a clay-water mixture. In some experiments, salt is added to the mixture.
- A camera looking through the tank width records settling:

Settling in Fresh Water

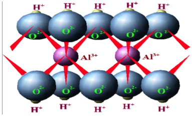
Salinity: 0 ppt; Clay: 30 ppt

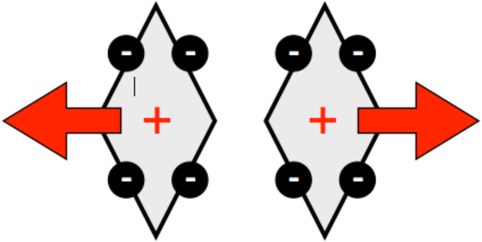
Settling in Salt Water

Salinity: 17 ppt; Clay: 30 ppt

Why Does Salt Enhance Settling?

- Clay particles have positive charge on flat surfaces
- Clay particles in fresh water naturally repel each other due to the positive charges





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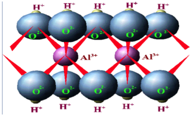
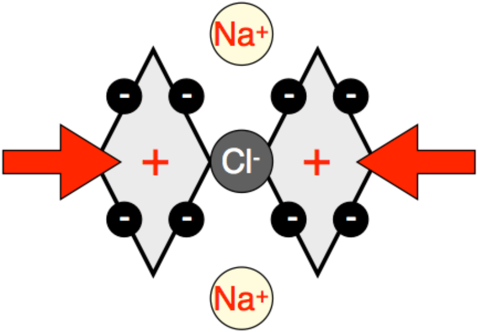
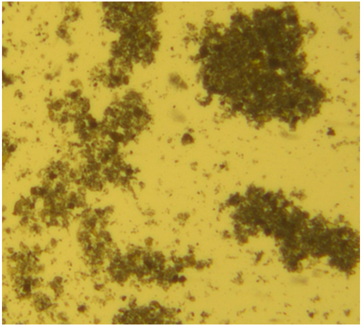


- Ions in salt water help neutralize the repulsion. Then negative charges at plate edges attract to the positive centres; they flocculate.

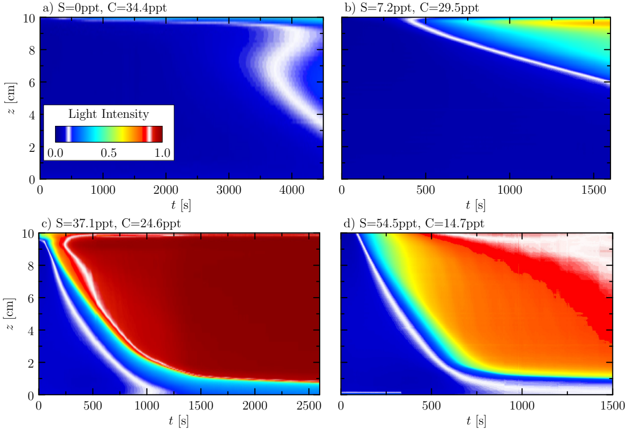




Time Series of Clay Settling

- We construct vertical time series by averaging across the field of view.
- The intensity of light is represented in false colour (cold colours - dark; warm colours - light).

Time Series from 4 Experiments



Measuring Settling Rate

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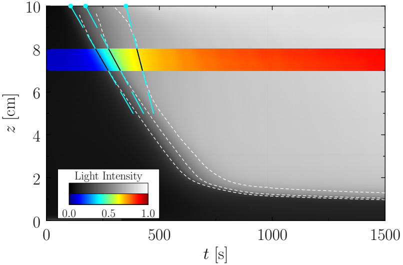
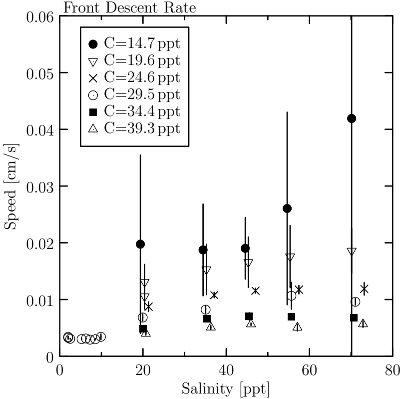
- We find that the settling speed varies weakly with salinity after a threshhold is reached: $S \gtrsim 10\,\text{ppt}$.
- The settling speed decreases with increasing clay concentration.

Measuring Settling Rate



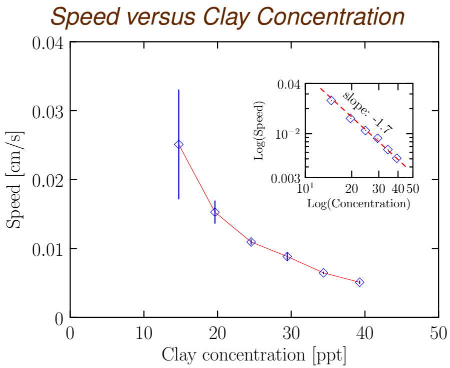
Speed versus Clay Concentration



Measuring Settling Rate

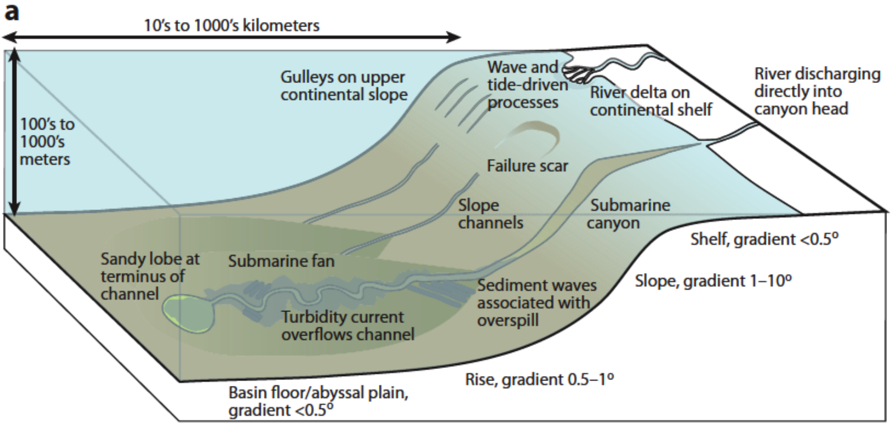
- Averaging the speeds for salinities between 15 and 60 ppt but with fixed clay concentration, we determine the mean descent speed w of clay in salt water with concentration C:

$$w \propto C^{-1.7}$$



Turbidity Currents in Stratified Ambients

- Turbidity currents result from the outflow of sediment-laden rivers or from submarine avalanches.

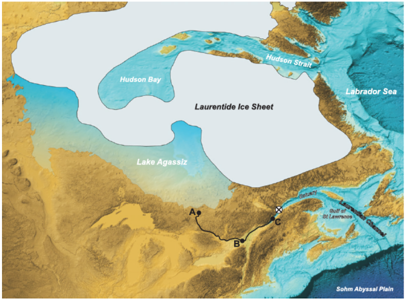


[Meiburg & Kneller, Ann. Rev. Fluid Mech. (2010)]

Hypopycnal and Hyperpycnal River Plumes

- A hyperpycnal river plume is so heavily laden with sediments that it descends as a turbidity current until sufficient sediments have rained out. The buoyant interstitial fluid then rises to surface.
- Perhaps the draining of Lake Agassiz through the Gulf of St Lawrence 10K years ago did not cap Atlantic Ocean with fresh water because sediments carried fresh water below surface and stratification kept it there.

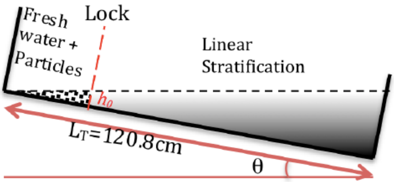
[NASA Image of Mississippi run-off, April 7, 2009]

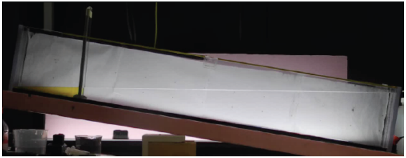


[Clark, Bush & Bush, J. Climate (2009)]

Turbidity Currents in Stratified Ambient Experiments

- Perform lock-release experiments of particle-driven flow down a constant slope in uniformly stratified fluid.
- Experiment parameters:
  - slope: $s = 0.077, 0.15$ ($\theta = 4.4°, 8.5°$)
  - stratification: $N = 0, 1.1, 1.9, 3.0\,\mathrm{s}^{-1}$
  - lock height: $H_\ell = 3, 4.5, 6$ cm
  - lock density: $\rho_\ell = 1.02 - 1.4$ g/cm^3.
  - particle diameters: $D_p = 1 - 38, 13 - 45, 38 - 53, 53 - 75\ \mu$m and none (Note: particles are glass spheres with typical concentrations $< 10\%$.)





Uniform Density Ambient

Slope: $s = 0.15$, *Lock Height:* $H_\ell = 3$ *cm*, $D_p = 1 - 38\,\mu$*m*, $\rho_a = 1.067$ *g/cm*^{3}

Hypopycnal: lock density $\rho_\ell = 1.055$ g/cm^3 $< \rho_a$

Hyperpycnal: lock density $\rho_\ell = 1.112$ g/cm^3 $\gg \rho_a$

Metapycnal: lock density $\rho_\ell = 1.095$ g/cm^3 $\gtrsim \rho_a$

Effect of Particle Concentration

Slope: $s = 0.15$, *Lock Height:* $H_\ell = 3$ *cm*, $N = 3$ *s*$^{-1}$

Saline/no particles, lock density $\rho_\ell = 1.08$ g/cm^3

Fresh/$D_p \simeq 28$ μm, lock density $\rho_\ell = 1.1$ g/cm^3

Fresh/$D_p \simeq 28$ μm, lock density $\rho_\ell = 1.4$ g/cm^3

Effect of Particle Size

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Slope: $s = 0.15$, *Lock Height:* $H_\ell = 6$ *cm*, $N = 3$ s^{-1}, $\rho_\ell = 1.1$ *g/cm*^{3}

$D_p \simeq 19$ μm

$D_p \simeq 45$ μm

$D_p \simeq 76$ μm

Along-Slope Front Position

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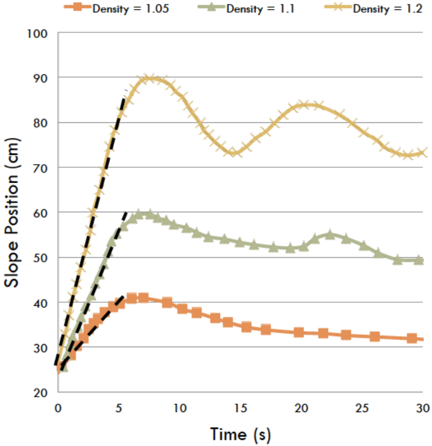
- From movies of each experiment extract a slice through each frame just above and parallel to the slope to construct an along-slope timeseries.

- From this can find along-slope position of descending front as a function of time.
- Generally find that the front advances at near constant speed then rapidly halts and reverses back upslope.



Turbidity Current Speed

- Models for gravity current speed along a flat bottom:
  - In a uniform ambient, $U = \text{Fr}\sqrt{g'H_\ell}$ with $\text{Fr} = 1/2$
  - In a stratified ambient, $U = \text{Fr}\, NH_\ell$ with $\text{Fr} = 1/4$

- Genererally expect

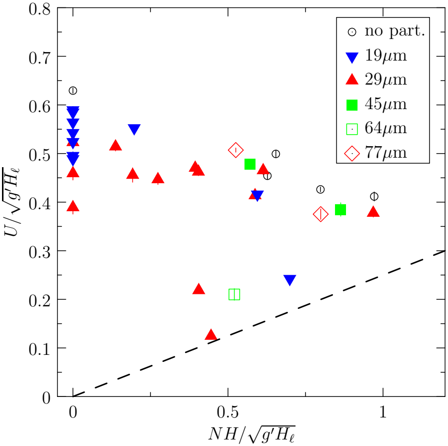
$$\frac{U}{\sqrt{g'H_\ell}} = f\left(\beta \equiv \frac{NH_\ell}{\sqrt{g'H_\ell}}\right)$$

with

$$f(\beta) \to \begin{cases} \frac{1}{2} & \beta \ll 1 \\ \frac{1}{4}\beta & \beta \gg 1 \end{cases}$$

- This prediction should change only moderately with small slopes.

[Britter & Linden, J. Fluid Mech (1980)]

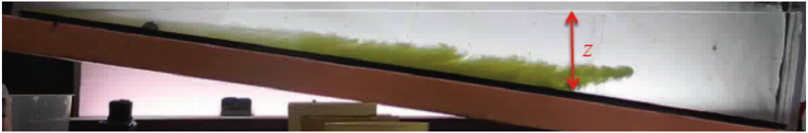


Locating the Separation Point

Lock pulled

Gravity current along slope at constant speed U

Intrudes into ambient at depth z



Locating the Separation Depth: Theory

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- Interstitial Fluid Density:
  - Assume constant entrainment velocity $U_e = \alpha U$ over current length $L \simeq Ut$. So $dV/dt = U_e L \;\Rightarrow\; V \sim V_0 + \alpha U^2 t^2/2$ is current volume/width.
  - Assume ambient density, ρ_a, varies little compared to current density, ρ. So $V_0 d\rho/dt \sim (\rho_a - \rho) dV/dt \;\Rightarrow\; \rho = \rho_a + (\rho_0 - \rho_a) e^{-V/V_0}$

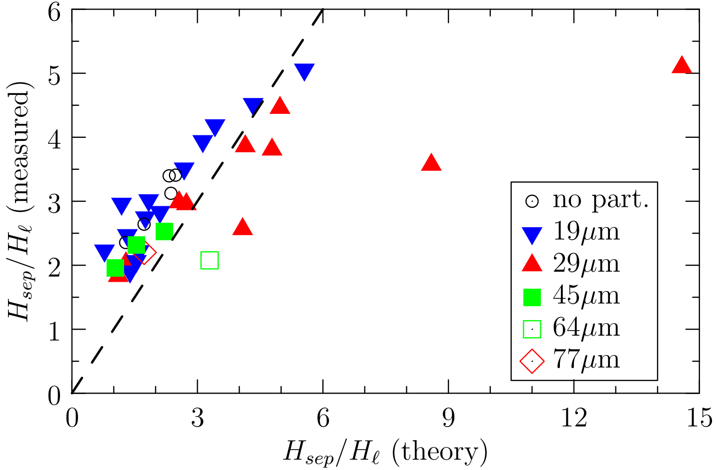
- Particle Concentration:
  - Assume particles rain out at settling velocity U_s over depth $h = V/L$ of current. So $dm_p/dt = -m_p U_s/h \;\Rightarrow\; m_p = m_{p0} \, (V/V_0)^{-\gamma}$ in which $\gamma \equiv U_s/U_e$.
  - Then particle concentration is $\phi \equiv m_p/(\rho_p V) = \phi_0 (V/V_0)^{-(\gamma+1)}$

- Separation Depth:
  - Current is neutrally buoyant when $\rho + \phi(\rho_p - \rho) = \rho_T + (\rho_B - \rho_T) L/L_T$.
  - Solve for separation time, hence separation depth, to give

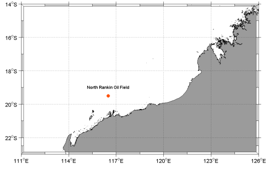
$$\frac{\mathrm{H_{sep}}}{H_\ell} = \beta^{-\frac{1}{\gamma+3/2}} \left(\frac{s}{\alpha}\right)^{\frac{\gamma+1}{2\gamma+3}}$$

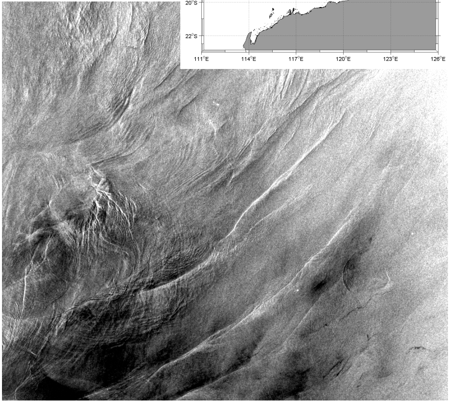
with $\alpha \equiv \frac{U_e}{U} \;\; (\simeq 0.1)$, $\beta \equiv \frac{N H_\ell}{\sqrt{g' H_\ell}} \;\; (\ll 1)$, $\gamma \equiv \frac{U_s}{U_e}$.

Measurements of Separation Depth



Internal Solitary Waves (and Offshore Oil)





[from "Atlas of Oceanic Internal Solitary Waves"
Global Ocean Assoc. (100km x 100km view)]

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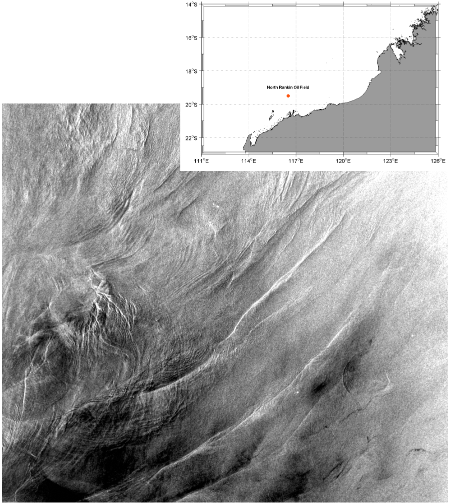

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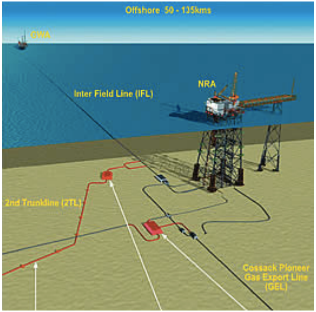


- Pipelines run along the ocean floor to the coast where oil is refined.
- Solitary wave breaking can resuspend sediments on which the pipes rest, rendering them unstable.

Motivation: Dongsha Atoll

- Internal solitary waves are generated by tidal flow over sills and the continental shelf.
- The waves shoal and break as they approach the coast.
- Breaking regions are sites of active biological activity.

Dongsha Atoll

Solitary Wave Scattering

[from National Parks of Taiwan website]

Internal Solitary Wave Generation and Shoaling

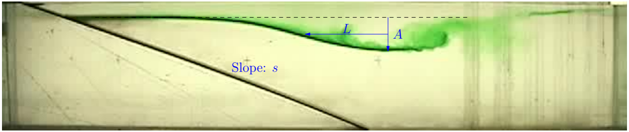
- A series of experiments were performed in which internal solitary waves, generated by lock-release, propagated toward a slope.

Internal Solitary Wave Generation and Shoaling

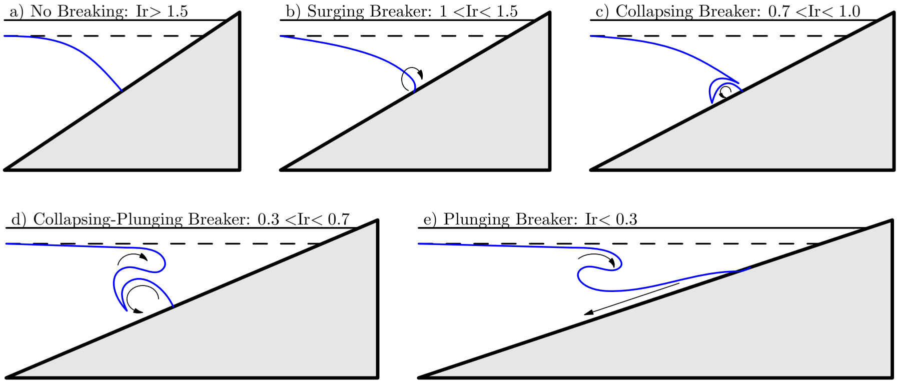
- A series of experiments were performed in which internal solitary waves, generated by lock-release, propagated toward a slope.

- How the waves shoal on a slope can be assessed by the Iribarren Number:

$$\text{Ir} = \frac{\text{topographic slope}}{\sqrt{\text{wave slope}}} = \frac{s}{\sqrt{A/L}}$$



Solitary Wave Breaking Regimes



Shoaling Solitary Waves

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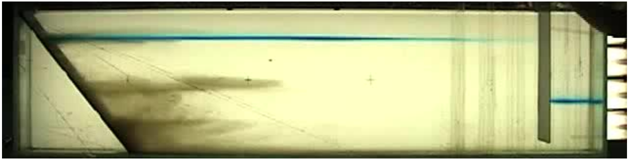
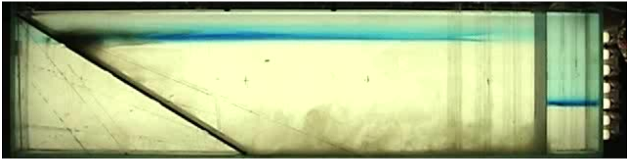
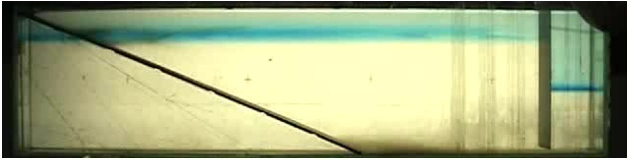
Reflecting (Non-breaking) Wave



Surging Breaker

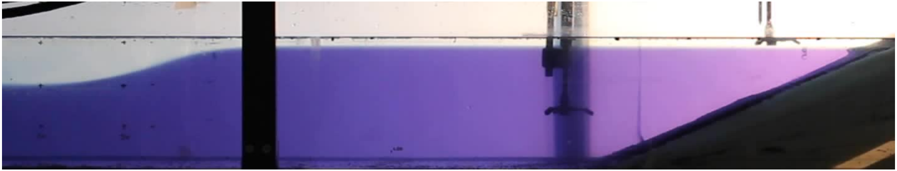


Collapsing Breaker

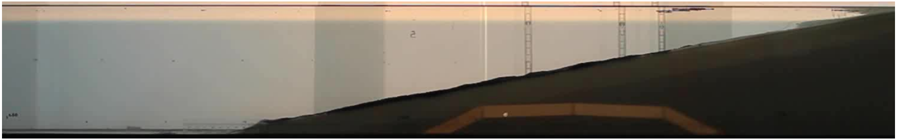


Shallow and Steep Slopes

Collapsing-plunging breaker: $Ir = 0.75$



Plunging breaker: $Ir = 0.36$



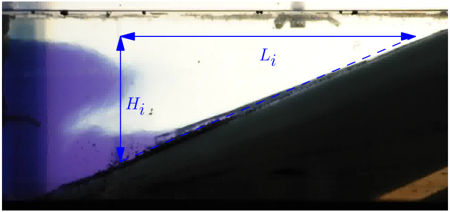
Solitary Wave Maximum Descent

- When solitary wave shoals, assume its area wave fills a triangle of height H_i and length $L_i = H_i/s$.
- Equate this area with the area, $A_{sw}(2L_{sw})$, of the incident internal solitary wave:

$$2A_{sw}L_{sw} = \frac{1}{2}H_iL_i = \frac{1}{2s}{H_i}^2$$

- So expect maximum deepening is

$$H_i \simeq \sqrt{4sA_{sw}L_{sw}}.$$



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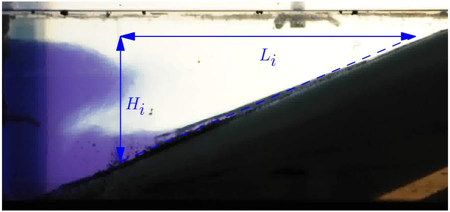
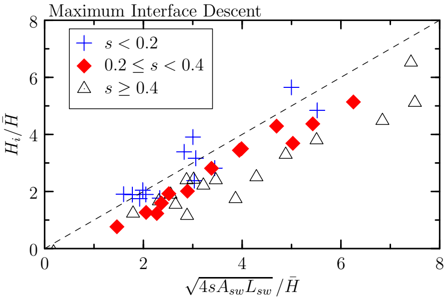
- So expect maximum deepening is

$$H_i \simeq \sqrt{4sA_{sw}L_{sw}}.$$

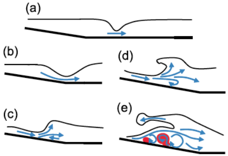
- This is consistent with experiments, though it differs qualitatively from empirical predictions of Boegman et al (2005) and Aghsaee et al (2010) who related H_i to total slope length.





Resuspension from Shoaling Solitary Waves

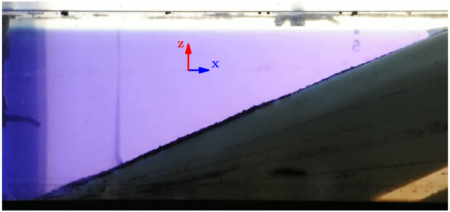
- When an internal wave encounters a slope, sediment is carried downslope in advance of the wave.
- Particles may resuspend where the trailing edge of the wave reaches the slope.

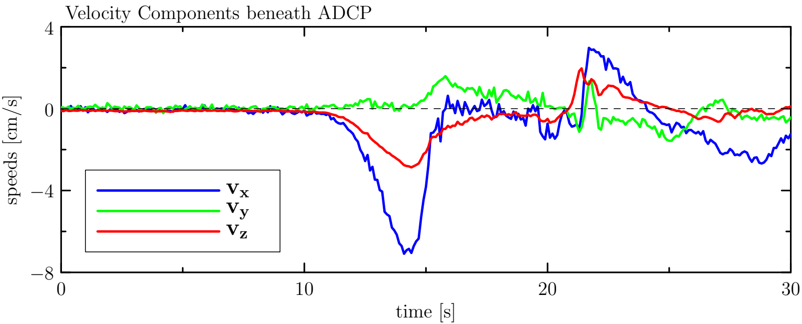


[Boegman & Ivey, JGR (2009)]

Measuring Flow on Slopes

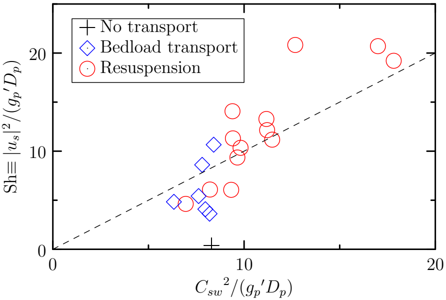
- Above the slope are two Acoustic Doppler Current Profilers (ADCPs).
- These measure the three components of velocity $0.5\,\text{cm}$ above the slope.





Sediment Transport and Resuspension

- From velocity components v_x and v_z, the ADCPs determine the along-slope speeds, u_s.
- The maximum downslope speed above the maximum descent scales approximately with the incoming solitary wave speed.



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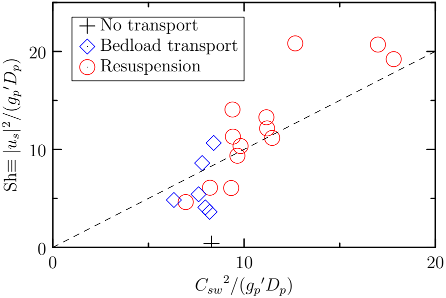


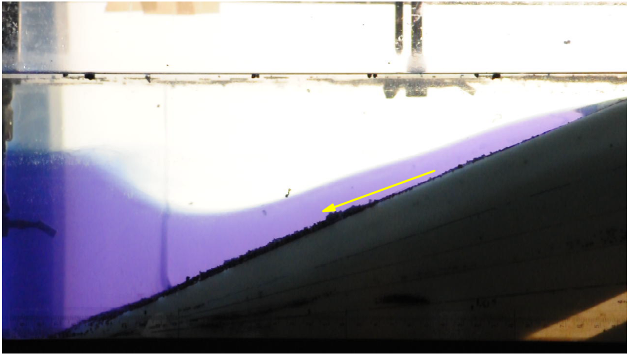
- Define the Shield's parameter to be the ratio of bottom stress to the buoyancy of the particles (with reduced gravity g_p' and diameter d_p):

$$\mathrm{Sh} \equiv \frac{{u_s}^2}{g_p' d_p}$$

- Find transport if $\mathrm{Sh} \gtrsim 1$ and resuspension if $\mathrm{Sh} \gtrsim 5$.

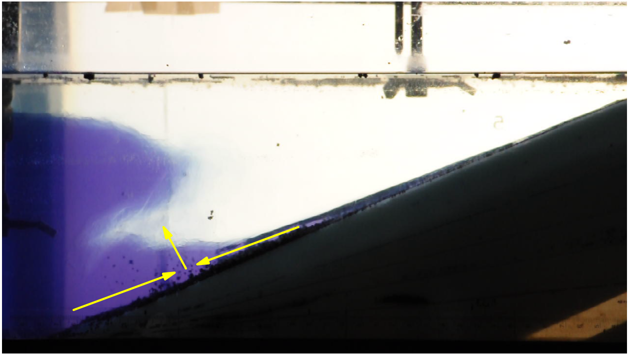
Limitations of the Shields Parameter

- The Shields parameter was developed to understand sediment resuspension by flowing rivers. It assumes steady flow and uniform density fluid.



Limitations of the Shields Parameter

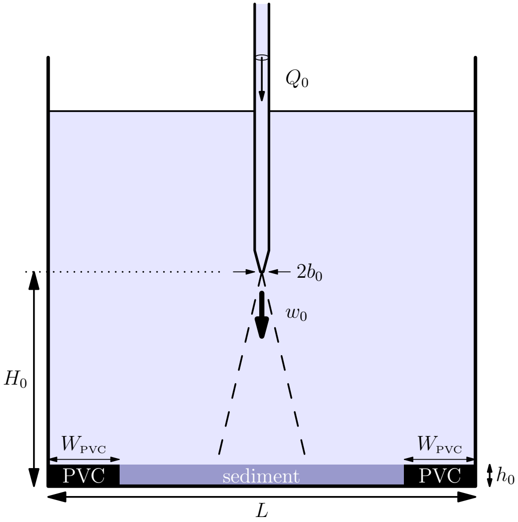
- The Shields parameter was developed to understand sediment resuspension by flowing rivers. It assumes steady flow and uniform density fluid.
- But resuspension occurs where the flow separates (where $\mathrm{Sh} = 0$).
  $\Rightarrow$ Need distributed, not localized, measurements to assess resuspension.



Particle Transport by Turbulent Jets

Turbulent Jet Experiment Setup

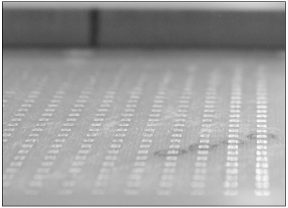
- Examine a turbulent jet of water impinging downward upon a uniform bed of spherical particles



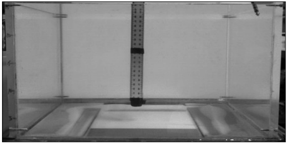
Measurement Methods

- Measure sediment depth in horizontal space and time using
  - a “depositometer” (an array of electrodes each measuring resistivity of current passing through overlying sediment)
  - light attenuation

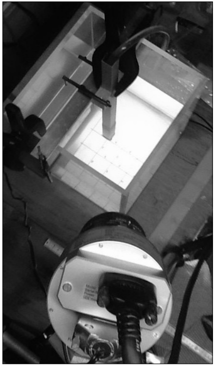
a) Depositometer Electrodes



b) Depositometer Set-up

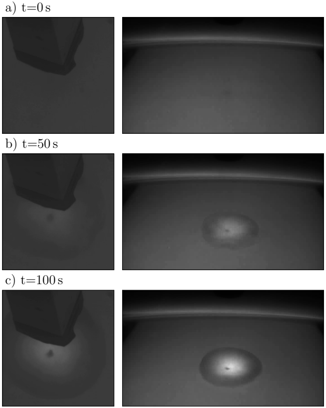


c) Attenuation Set-up



Movie and Snapshots

Jet Source Height: $H_j = 6.0$ *cm*, *Jet Source speed:* $w_{j0} = 39.7$ *cm/s*
Particle Diameter: $D_p = 90\,\mu$*m*, *Density:* $\rho_p = 2.5$ *g/cm*^{3}

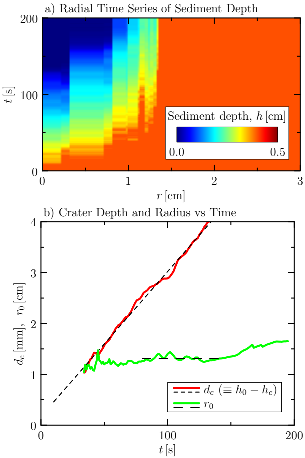


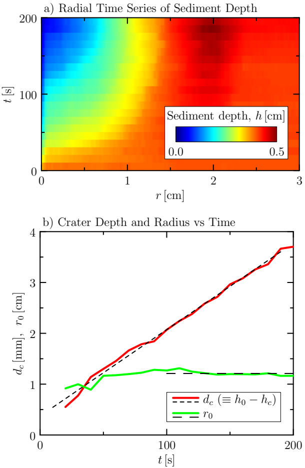
Jet Speed at bed: $w_j = 4.0$ cm/s, Setting Speed: $W_s = 0.66$ cm/s

Shields Number: Sh $= 2.4$, Rouse Number: Rs $= 0.41$

Crater Evolution

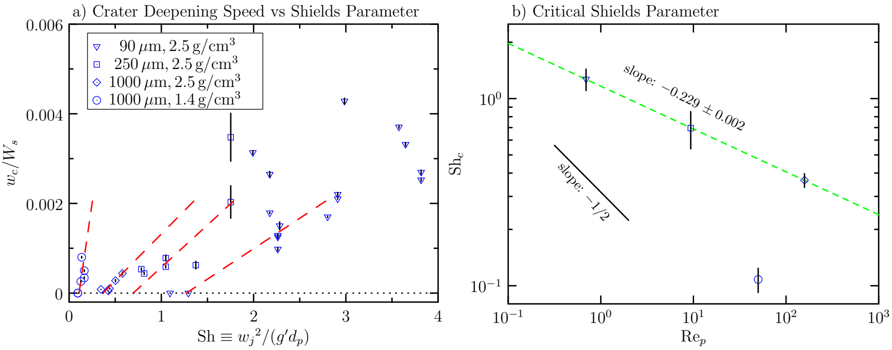
- Crater centre deepens at a near-constant speed while crater radius is approximately constant.





Crater Deepening: Shields Parameter

- Measure deepening speed at crater centre, w_c, relative to particle settling speed, W_s.
- Plot this versus the Shields parameter based upon the jet speed, w_j, and particle buoyancy.



Crater Deepening: Rouse Parameter

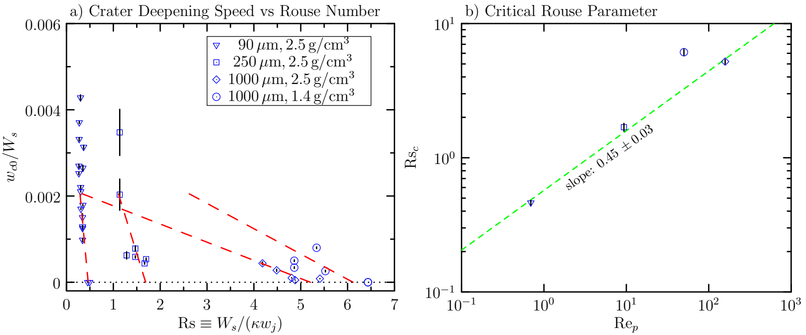
- Data seem to give better collapse when plotted against the Rouse parameter,

$$\text{Rs} \equiv \frac{W_s}{\kappa\, w_j}$$

with $\kappa = 0.41$ the von Kármán constant.

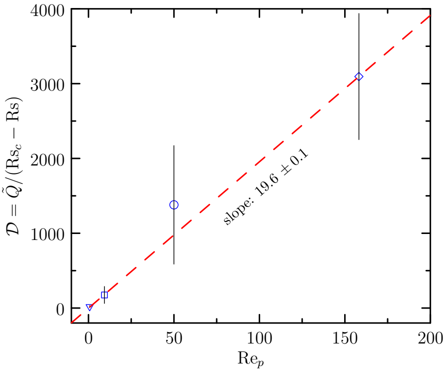
- For very small particles,

$$\text{Sh} \simeq 0.33 \frac{\text{Re}_p}{\text{Rs}^2} \quad \text{with} \quad \text{Re}_p \equiv \frac{W_s D_p}{\nu}$$



Sediment Volume Flux

- Sediment volume flux is $Q \propto {r_0}^2 w_c$, which is constant in time.
- By analogy with unidirectional turbulent flow, define non-dimensional volume flux to be $\tilde{Q} \equiv w_c/\sqrt{g' D_p}$.
- Find $\tilde{Q} \propto \mathrm{Re}_p\ (\mathrm{Rs}_c - \mathrm{Rs})$.



Discussion

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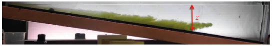
- Much of the theory for particle transport and sedimentation assumes a steady flow in a uniform ambient.


- Here we have examined some aspects of particle transport in the presence of a stagnation point where, on average, the Shields parameter is zero (no mean stress) and so particle transport might not be expected.

    - a turbidity current in a stratified ambient can separate from the slope and form finger-like intrusions.
    - a shoaling internal solitary wave can initiate an avalanche and resuspend particles at stagnation point.
    - a vertical jet forms a crater as a result of turbulent fluctuations about the mean stagnation point.