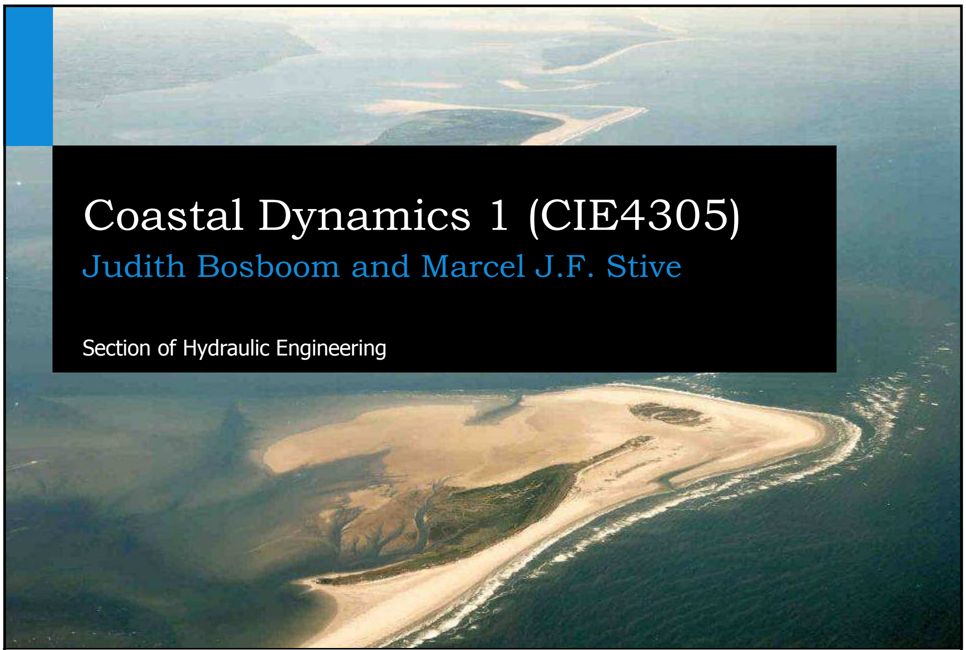


Coastal Dynamics 1 (CIE4305)

Judith Bosboom and Marcel J.F. Stive

Section of Hydraulic Engineering

6.

Sediment Transport

Series of waves during dune erosion tests

(Old & new) Delta flume:

- (Almost) prototype scale
- Regular and irregular waves (H_s up to 1.6m / 2.2m)
- Wave generator with reflection compensation
- Measuring frame fixed to mobile carriage

Coastal Dynamics 1

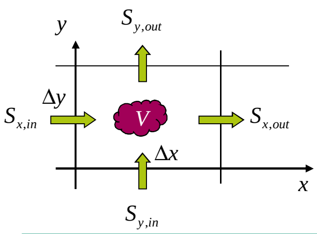
Contents

Sediment transport

Chapter 6 of lecture notes

6-A Introduction

Erosion and deposition are determined by sediment transport rates



$S_{x,y}$: Volume transport rates in $m^3/m/s$
V: Source term in $m^3/m^2/s$

Deposited volumes!

$$\Delta z_b \Delta x \Delta y = \underbrace{S_{x,in}\Delta y \Delta t - S_{x,out}\Delta y \Delta t + S_{y,in}\Delta x \Delta t - S_{y,out}\Delta x \Delta t}_{\text{Volumes transported in and out}} + V\Delta x \Delta y \Delta t$$

Change of sediment volume

Volumes transported in and out

Source or sink term (e.g. nourishment)

$$\frac{\partial z_b}{\partial t} + \frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y} = V$$

6-A Introduction

Transport definitions

$$\frac{\partial z_b}{\partial t}+\frac{\partial S_{ip,x}}{\partial x}+\frac{\partial S_{ip,y}}{\partial y}=0$$

$S_{ip,x,y}$ Deposited volume transport (transport including pores, in-situ) in m³/m/s

$$(1-p)\frac{\partial z_b}{\partial t}+\frac{\partial S_{ep,x}}{\partial x}+\frac{\partial S_{ep,y}}{\partial y}=0$$

$S_{ep,x,y}$ Volume transport of solid material in m³/m/s

$p \approx 0.4$ Porosity

$\rho_s \approx 2650 \text{ kg/m}^3$

$$I_m=(\rho_s-\rho)(1-p)S_{ip}$$

Immersed (under water) mass transport in kg/m/s

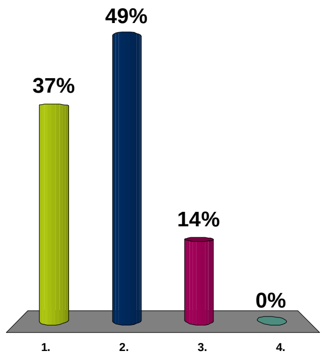
$$I=gI_m$$

Immersed (under water) weight transport in N/m/s

6-A Introduction

Using measured bathymetric changes and the sediment balance, sediment transport rates can be estimated?

1. True as long as there are no sinks or sources
2. ✓ Possibly true for a 1D problem
3. Never true
4. Abstain



$$\frac{\partial z_b}{\partial t}+\frac{\partial S_{ip,x}}{\partial x}+\frac{\partial S_{ip,y}}{\partial y}=V$$

Problem is under-determined.

But...1D situation of wave tunnel/flume => no 'alongshore' transport gradients and V=0

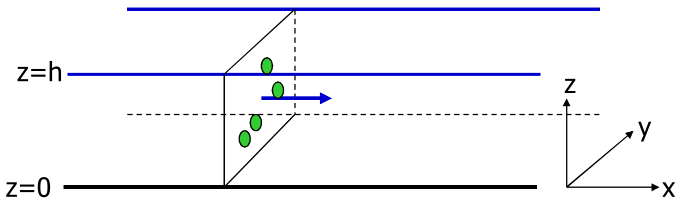
Also: assuming no losses in cross-shore direction, bulk longshore transport rates may be estimated from local accretion/erosion near structures

6-A Introduction

Sediment transport as the depth-integral of velocity times sediment concentration

$$S_x(t) = \int_{z=0}^{z=h} q(z,t)\,dz = \int_0^h c(z,t)\,u(z,t)\,dz$$

$$u = U + \tilde{u} \text{ and } c = C + \tilde{c} \Rightarrow \underbrace{\langle S_x \rangle}_{\text{time-averaged sediment transport rate}} = \underbrace{\int_0^h UC\,dz}_{\text{current-related part}} + \underbrace{\int_0^h \overline{\tilde{u}\tilde{c}}\,dz}_{\text{wave-related part}}$$



c: [kg/m^3]; [g/l]; [vol%]

q: $\left[\frac{\text{kg}}{\text{s.m}^2}\right]; \left[\frac{\text{m}^3}{\text{s.m}^2}\right]$

S: $\left[\frac{\text{kg}}{\text{s.m}}\right]; \left[\frac{\text{m}^3}{\text{s.m}}\right]$

Sediment transport

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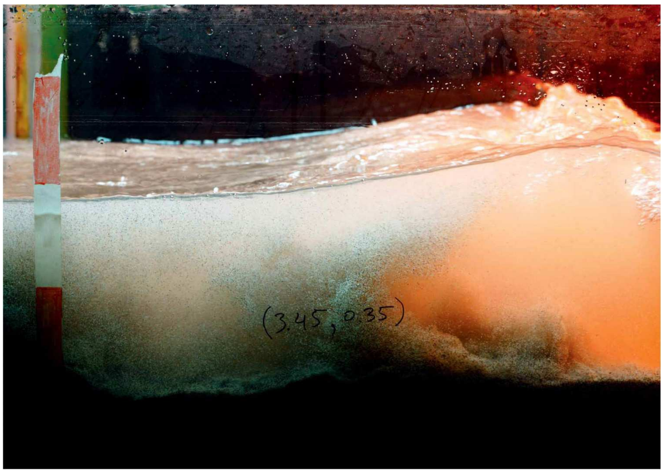
6-B Complexity in predictions

Albert Einstein advised his son against taking up sediment transport research…(too complicated)

Urban legend?!

6-B Complexity in predictions

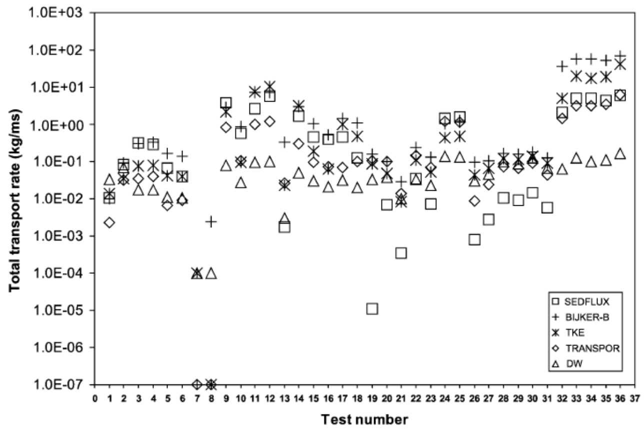
Detailled process research



PhD research by
Martijn Henriquez

6-B Complexity in predictions

Spread in predictions of various transport models

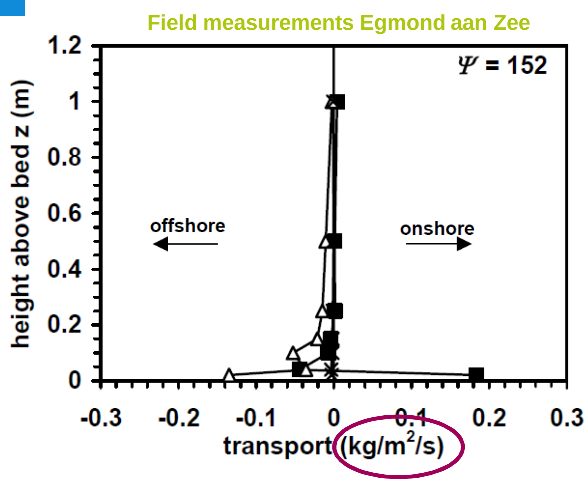


- Five models differing by factors of 5 to 10^4
- Typically, spread over a **factor of 100**
- Field sites with range of conditions

See Davies et al. (2002)

6-B Complexity in predictions

Field transport measurements

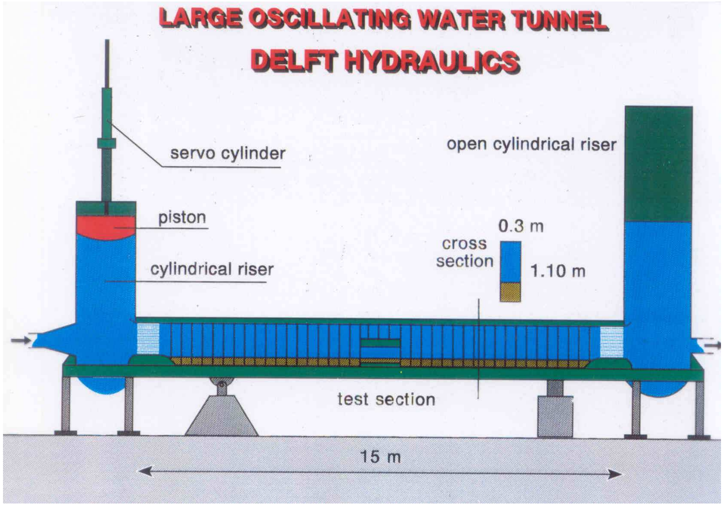


- Large near-bed gradients of concentration (and flow)
- Insufficient resolution near bed
- Wave-related transport direction reverses in vertical
- Opposite transport contributions due to waves and currents

From Grasmeijer

6-B Complexity in predictions

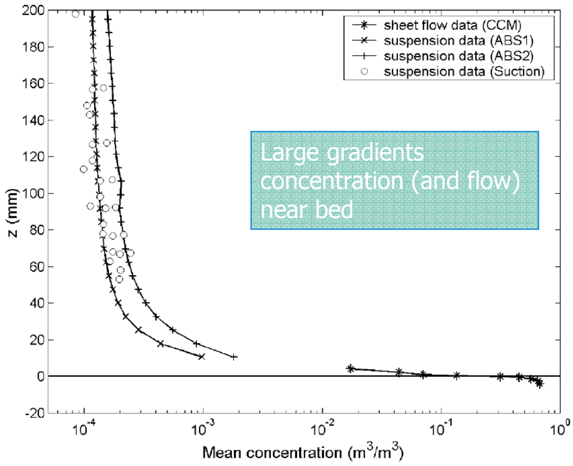
Full-scale facility simulating near-bed region



6-B Complexity in predictions

6-B Complexity in predictions

Detailed near-bed and total transport measurements in wave tunnel

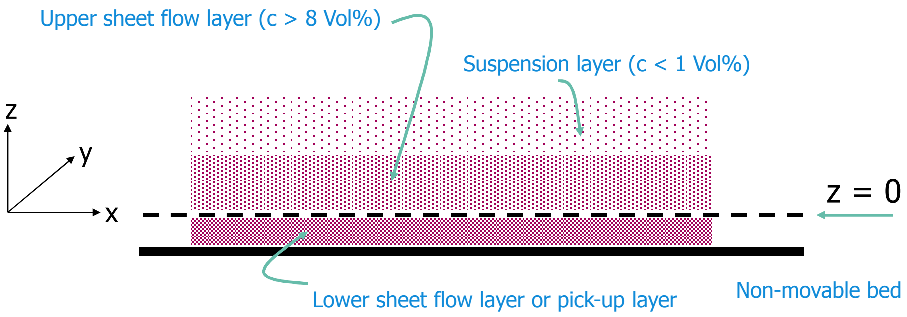


See Dohmen-Janssen & Hanes (2002)

https://www.youtube.com/watch?v=vpDHDAK53A8

6-B Complexity in predictions

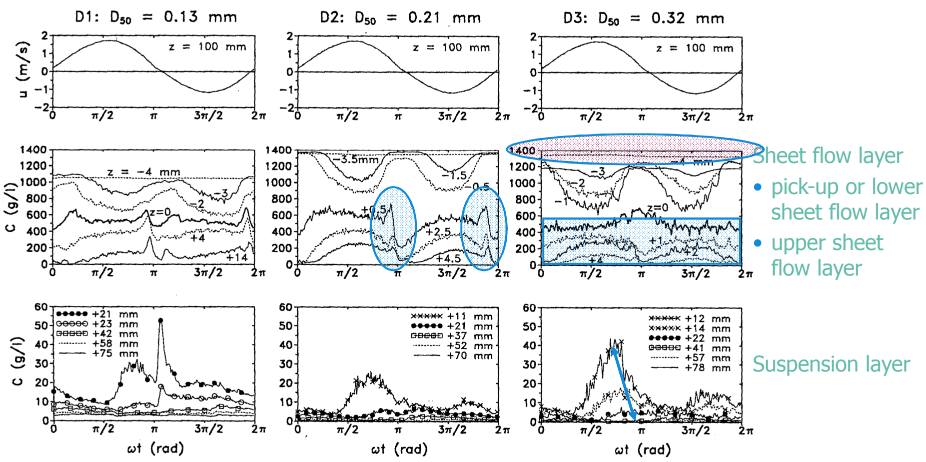
Detailed intra-wave resolution of velocity and concentration (1DV) from z = 0 upwards



https://www.youtube.com/watch?v=vpDHDAK53A8

6-B Complexity in predictions

Detailed near-bed and total transport measurements in wave tunnel



Dohmen-Janssen (1999)

5-D Wave skewness and asymmetry

Sediment transport due to wave skewness

- Wave skewness in shoaling waves
  - higher on-shore velocities at the crest
  - lower off-shore velocities at the trough
- Near-bed sediment concentration

For normal to coarse sediment. True for finer sediment?

$$c_s(t) \approx A\left|\tau_b(t)\right|$$

$$\tau_b(t) \approx \rho c_{f,w}\left|u_0(t)\right|u_0(t)$$

$$c_s(t) \approx B u_0{}^2$$

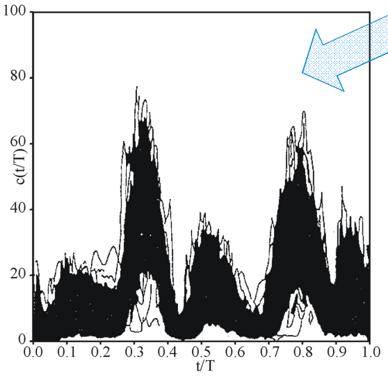
- Sediment transport $S(t) \approx u_0 c_s \approx B u_0^3$ $\qquad \langle S\rangle = B\langle u_0^3\rangle$

for a sine wave: $\langle S\rangle = 0$

for a positively skewed signal: $\langle S\rangle > 0$

6-B Complexity in predictions

Intra-wave sediment concentrations



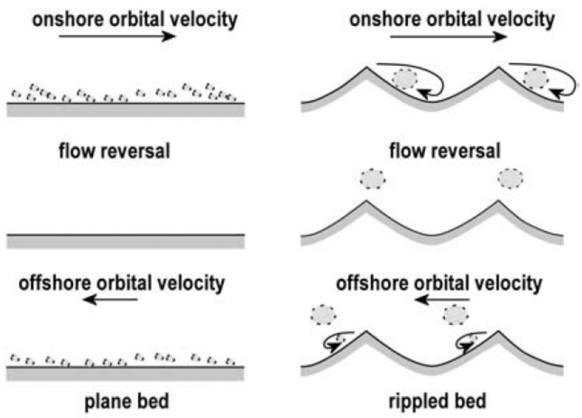
Many realizations!
Why are they so variable?

- Two peaks just after maximum onshore and offshore velocity (t/T=0.25 and 0.75)
- Two secondary peaks just after flow reversal
  - => associated with vortices developing over a rippled bed

6-B Complexity in predictions

Wave-related transport against wave propagation direction due to ripples

https://www.youtube.com/watch?v=zVPvyzkNAIc&feature=player_detailpage



6-B Complexity in predictions

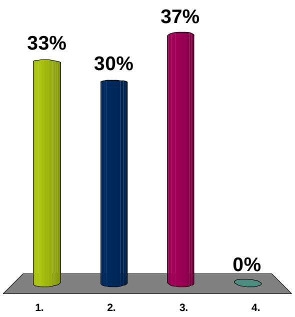
Contributing factors:

- Sediment suspension and transport respond non-linearly to the forcing
- Velocity field in the nearshore is oscillatory
- Vortex shedding due to the existence of bed forms
- Suspension ejection events at flow reversal
- Lagged response to forcing and phase differences in vertical
- Different transport contributions in opposite directions
- …

6-B Complexity in predictions

In a quasi-steady approach it is assumed that sediment transport reacts instantaneously (immediately) to a change in flow conditions. Such a direct response of the sediment can be expected for:

1. Fairly large orbital velocities
2. ✓ Relatively coarse sediment
3. Small enough wave periods
4. Abstain



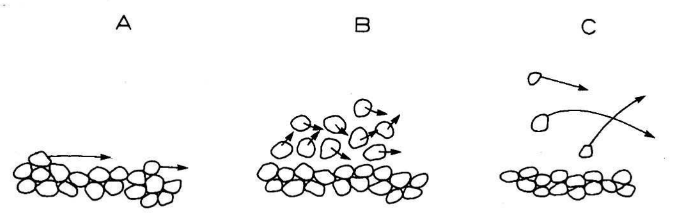
- Response time of sediment compared to oscillation period
- Large flow velocities and fine sediment increase response time
- Rouse number large => quasi-steady

Sediment transport

Chapter 6 of lecture notes

6-C Practical transport modelling

Transport modes: bed load and suspended load (and wash load)



Bed load (at small shear stresses)

Sheet flow (bed load at higher shear stresses)

Suspended load transport

Supported by intergranular forces

Supported by fluid turbulence

6-C Practical transport modelling

Bed load transport at low stresses: particles roll and slide (and jump)

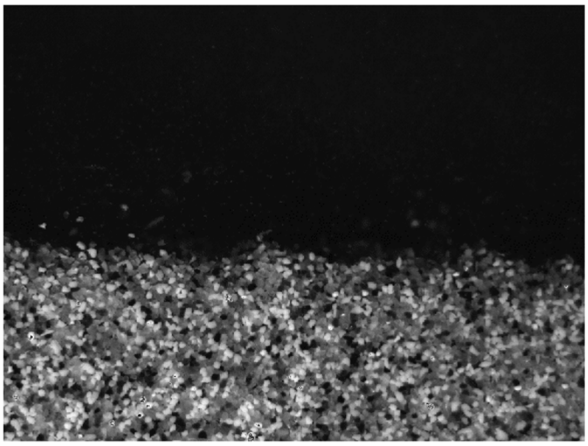
6-C Practical transport modelling

Intermittent sediment suspension above mobile bed

Sheet flow: entire bed (≈ 0.01 m) moves with oscillating motion

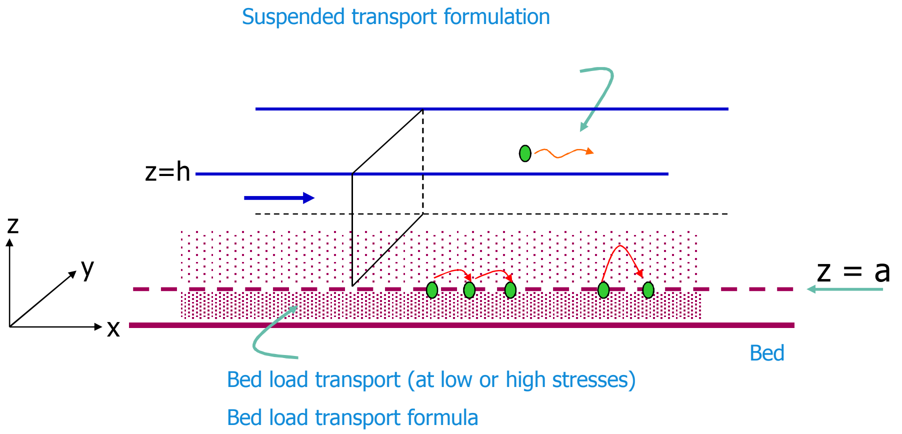
For high (orbital) velocities

PhD research by Martijn Henriquez



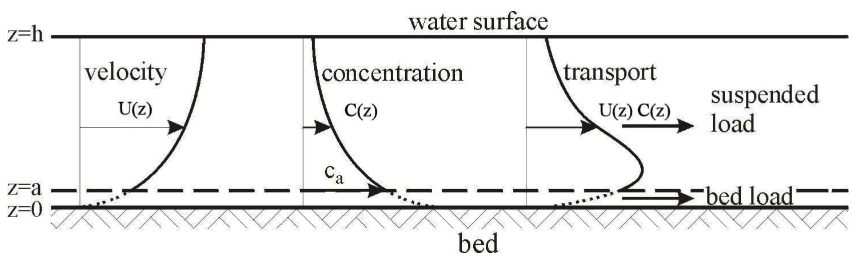
6-C Practical transport modelling

Practical transport modelling (as opposed to detailed intra-wave resolution of velocity and concentration)



6-C Practical transport modelling

Total load = quasi-steady bed load transport + current-related suspended sediment transport



Bed load transport responds instantaneously to time-varying (intra-wave) velocity or shear stress

Suspended sediment transport only current-related contribution (wave-related contribution neglected) => time-averaged velocity times concentration

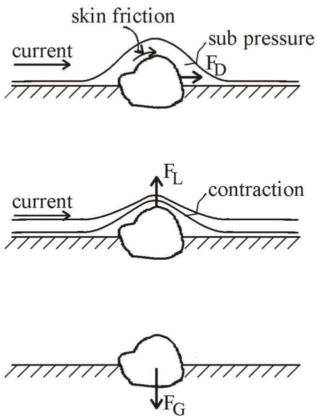
$$S_t = S_b + S_s$$

Sediment transport

Chapter 6 of lecture notes

6-D (Critical) bed shear stress

Forces on grains



Total driving force

$$F_{D,L} \propto \rho u^2 D^2$$

Resisting force

$$F_G \propto (\rho_s - \rho) g D^3$$

Horizontal, vertical or moment equilibrium

$$(\rho_s - \rho) g D^3 \propto \rho u_{cr}^2 D^2$$

Critical velocity

$$(\rho_s - \rho) g D \propto \tau_{b,cr} = \rho u_{*,cr}^2$$

Critical shear stress

Compare Appendix D: Iribarren and Hudson criterion for stone stability of rubble mound breakwater

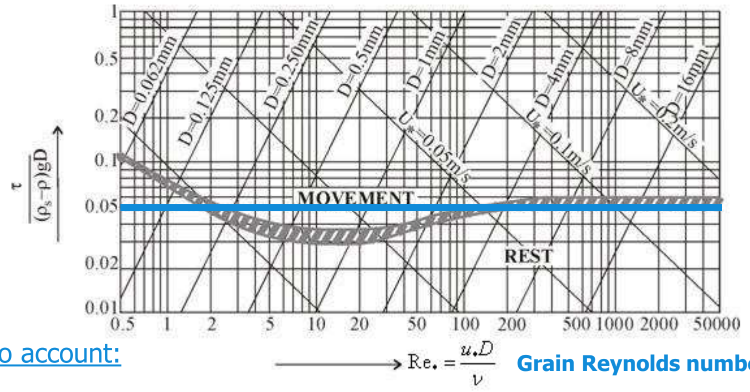
Critical Shields parameter

$$\boxed{\theta_{cr} = \frac{\tau_{b,cr}}{(\rho_s - \rho) g D} = \text{constant}}$$

6-D (Critical) bed shear stress

Shields curve for initiation of motion

$\theta_{cr} \approx 0.05$



Grain Reynolds number

Not taken into account:

- Gradation
- Ripples
- Oscillatory flow
- Slope effect
- Cohesive sediment

Sediment transport

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6-E Bed load transport

Quasi-steady approach to bed load transport

Assumption:

Instantaneous response to bed shear stress (or free-stream velocity) above a threshold or critical value (initiation of motion)

Dimensionless parameters:

Effective bed shear stress

Shields parameter (forcing on the grains) $\theta' = \dfrac{\tau_b'}{(\rho_s - \rho) g D_{50}}$

Critical Shields parameter (threshold of motion) θ_{cr}

Transport parameter $\Phi_b(t) = \dfrac{S_b(t)}{\sqrt{(s-1) g D_{50}^3}}$

$$\Phi_b(t) = f(\theta'(t), \theta_{cr})$$

Einstein!

6-E Bed load transport

Time-averaged bed load sediment transport

1 $\langle \Phi_b(t) \rangle = \langle f(\theta'(t), \theta_{cr}) \rangle$

- Based on water tunnel data
- Shields parameter using quadratic friction law
- Including a slope effect

For instance formulation of Ribberink:

$$\Phi_b(t) = \frac{S_b(t)}{\sqrt{(s-1) g D_{50}^3}} = 9.1 \frac{\beta_s}{(1-p)} \{|\theta'(t)| - \theta_{cr}\}^{1.8} \frac{\theta'(t)}{|\theta'(t)|}$$

2 $\langle \Phi_b(t) \rangle = f(\langle |\theta'(t)| \rangle, \theta_{cr})$

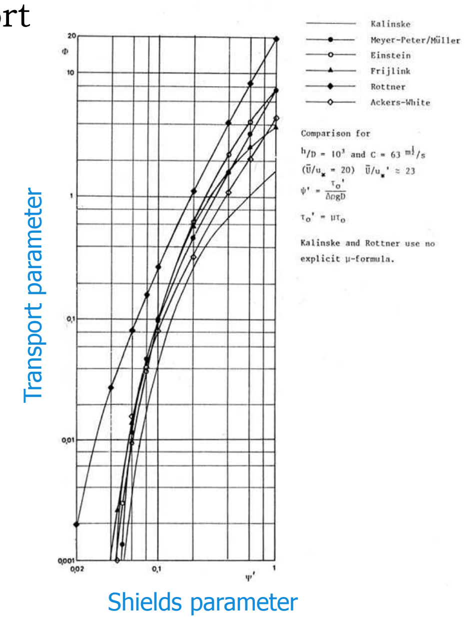
- e.g. using adapted river transport formulas

For instance Bijker formula:

$$S_b = B D_{50} \underbrace{\frac{U}{C} \sqrt{g}}_{\text{current only transports the sediment}} \underbrace{\exp\left[\frac{-0.27 (s-1) D_{50} \rho g}{\mu \langle |\tau_{cw}| \rangle} \right]}_{\text{sediment load mobilised by wave-current shear stress}}$$

6-E Bed load transport

Comparison of bed load formulas



6-E Bed load transport

Interpretation of (quasi-steady) bed load formulations

$$S(t) \propto sign(\tau_{cw})|\tau_{cw}|^m \Rightarrow$$

m=1.5-2

$$S(t) \propto sign(u)|u|^{2m}$$

$$S(t) \propto u|u|^{2m-1}$$

$$\text{with } n = 2m\text{: } S(t) \propto u|u|^{n-1}$$

Sediment load mobilised by waves and currents

Transporting velocity (mean and oscillatory)

m=1.5/n=3 $\Rightarrow$ $\langle S \rangle \propto \langle |u|^2 u \rangle$

Cf. bed load transport according to energetics approach

Sediment transport

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6-F Suspended load transport

Wave versus current-related suspended sediment transport

$$S_s(t) = \int_{z=a}^{h} c(z,t)\,u(z,t)\,dz$$

$$u = U + \tilde{u} \ \text{ and } \ c = C + \tilde{c}$$

Neglected in the following

$$\underbrace{\langle S_s \rangle}_{\text{time-averaged suspended sediment transport rate}} = \underbrace{\int_a^h UC\,dz}_{\text{current-related part}} + \underbrace{\int_a^h \overline{\tilde{u}\tilde{c}}\,dz}_{\text{wave-related part}}$$

Wave-induced:
- Undertow
- Longshore current
- LH streaming

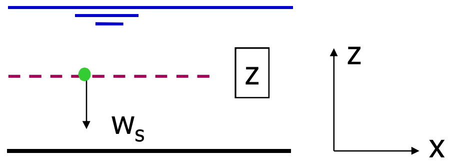
Transport by the oscillatory water motion:
- Short wave asymmetry
- Bound long waves

6-F Suspended load transport

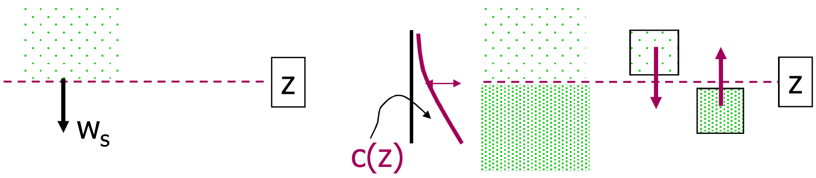
Sediment concentration via sediment mass balance

<u>Sediment concentration:</u>

- steady state
- no gradients in x/y-directions



Sediment concentration c(z) at level z above the bed



down: $w_s\, c(z)$	up: $\varepsilon_s(z)\, dc(z)/dz$

6-F Suspended load transport

Steady sediment mass balance

$$w_s C(z)\downarrow + \varepsilon_s(z)\frac{dC(z)}{dz}\uparrow = 0$$

$$C(z) = \underbrace{C(a)}_{\substack{\text{integration constant}\\ \text{(reference concentration)}}} \exp\left[-w_s \int_a^z \frac{dz}{\varepsilon_s(z)}\right]$$

Reference concentration:

- Function of bed shear stress
- Via empirical formulation

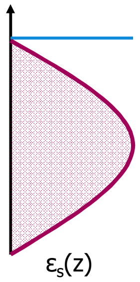
Diffusion or mixing coefficient:

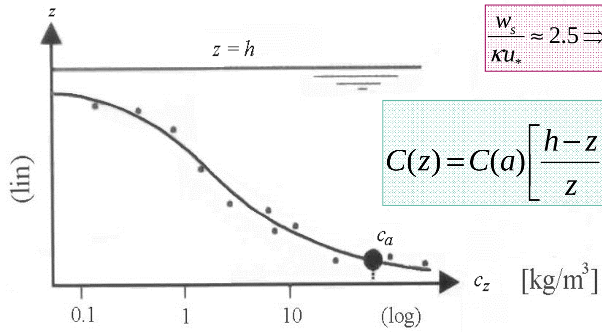
- Related to eddy viscosity of the fluid
- Effects of wave boundary layer, mean current, wave breaking)

6-F Suspended load transport

Time-averaged sediment concentration

Coarse/fine
Bed load/suspended load
Quasi-steady/time-lags





$$\frac{w_s}{\kappa u_*} \approx 2.5 \Rightarrow \frac{w_s}{u_*} \approx 1$$

$$C(z) = C(a)\left[\frac{h-z}{z}\cdot\frac{a}{h-a}\right]^{\frac{w_s}{\kappa u_*}}$$

$$\varepsilon_s(z) = \kappa u_* \frac{z}{h}(h-z)$$

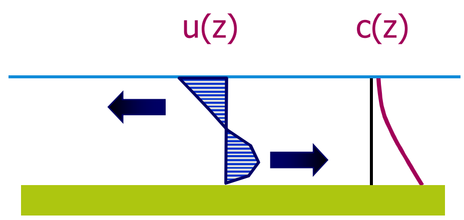
parabolic mixing (Rouse / Einstein):
- infinitely small c at water level; → 0
- infinite c at bed level; → ∞
- s-curve at log. paper

6-F Suspended load transport

What if depth-averaged current velocity is zero?

Combination of:

- Secondary current pattern (river bend, undertow profile)
- Uneven distribution of sediment over the water column



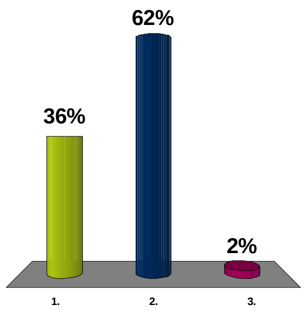
Transport direction?

Net current-related sediment transport may occur even for a zero depth-averaged velocity

6-F Suspended load transport

Which of the statements is correct? For small ratios of fall velocity over shear velocity (say smaller than 1), …

1. … a quasi-steady transport model is appropriate
2. … suspended sediment transport is the dominant mode of transport
3. Abstain



Exam questions 22 june 2010

The Rouse number is defined as $\frac{w_s}{\kappa u_*}$ (with w_s is the sediment fall velocity, $\kappa = 0.4$ is the von Karman constant and u_* is the shear velocity). Note that the shear velocity is related to the bed shear stress through $\tau_b = \rho u_* |u_*|$.

b. **[3]** Assume a large Rouse number (say larger than 2.5). What is the dominant transport mode in this case? Explain your answer.

c. **[3]** Discuss the validity of the above described quasi-steady approach for small and large Rouse numbers respectively.

Sediment transport

Chapter 6 of lecture notes

6-G Energetics approach

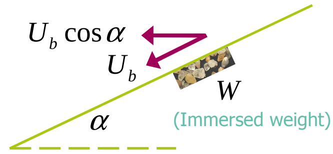
Sediment transport proportional to the rate of energy dissipation

- First developed by Bagnold (1963, 1966) for rivers
- Underlying idea:
  - Certain amount of 'work' is required to keep the bed load moving and the suspended load at a certain height above the bed;
  - Fluid acts as a machine expending energy (ability to do work) at a prescribed efficiency rate to offset the work done in transporting sediment
  - Power (work done per unit time) = efficiency factor x dissipated fluid power (rate of energy dissipation)

6-G Energetics approach
Down-slope bed load in uni-directional flow

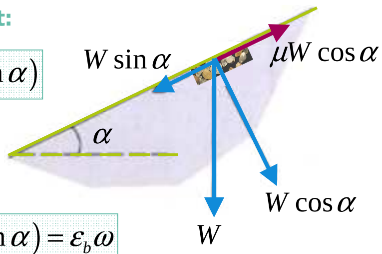
Immersed weight bed load transport:

$$I_b = W U_b \cos\alpha$$



Frictional resistance for downslope transport:

$$W\left(\mu\cos\alpha - \sin\alpha\right) = W\cos\alpha\left(\tan\varphi - \tan\alpha\right)$$



Work done per unit time (power):

$$W\cos\alpha\left(\tan\varphi - \tan\alpha\right)U_b = I_b\left(\tan\varphi - \tan\alpha\right) = \varepsilon_b\omega$$

dissipated fluid power / rate of energy dissipation

$$\Rightarrow \quad I_b = \varepsilon_b \frac{\omega}{\left(\tan\varphi - \tan\alpha\right)}$$

6-G Energetics approach
Time-varying bed load transport

Uni-directional flow along downsloping bed:

$$I_b = \varepsilon_b \frac{\omega}{\left(\tan\varphi - \tan\alpha\right)}$$

$\tan\alpha \to \tan\varphi$: avalanching or slumping

With dissipated fluid power due to bottom friction:

$$\omega = D_f = \tau_b u = \rho c_f |u| u^2$$

Bailard: more generalised

Bowen writes for cross-shore transport due to normally incident waves:

$$I_b(t) = \frac{\varepsilon_b \rho c_f u^3}{\left(\tan\varphi - u/|u| \tan\alpha\right)} \qquad I_s(t) = \frac{\varepsilon_s \rho c_f u^3 |u|}{\left(w_s - u\tan\alpha\right)}$$

u positive seaward

$\tan\alpha \to w_s/u$: autosuspension

6-G Energetics approach

Bailard's energetics formulation has components in direction of velocity and downslope

For slope aligned with velocity vector:

$$S(t) = \underbrace{C_1 u(t)\left|u(t)\right|^{n-1}}_{\text{quasi-steady response to time-varying flow}} + \underbrace{C_2 \left|u(t)\right|^{m} \tan\alpha}_{\text{response to downslope gravity force}}$$

- Bed load: n = m = 3
- Suspended load: n=4; m=5

Time-averaging:

$\langle S_b \rangle$ is proportional to $\langle u|u^2|\rangle$ *and* $\langle |u^3| \rangle$

$\langle S_s \rangle$ is proportional to $\langle u|u^3|\rangle$ *and* $\langle |u^5| \rangle$

Sediment transport

Chapter 6 of lecture notes

A. Introduction
B. Complexity in predictions
C. Practical transport modelling
D. (Critical) bed shear stress
E. Bed load transport
F. Suspended load transport
G. Energetics approach
H. Discussion

6-H Discussion

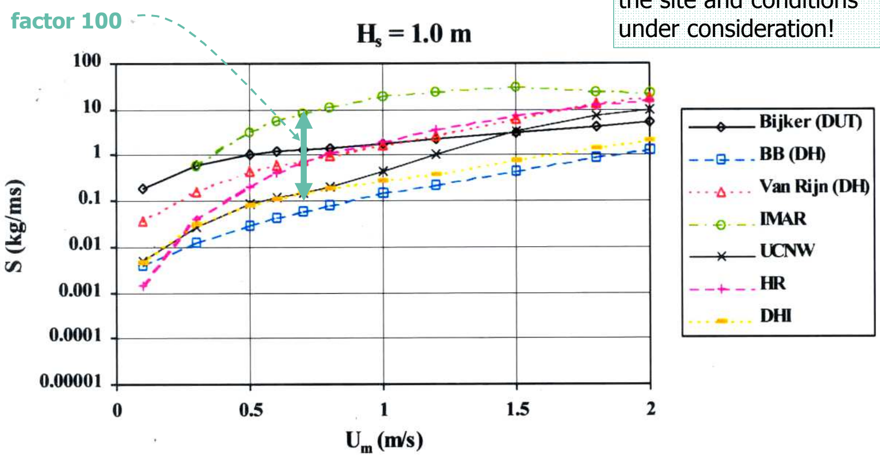
Present stage of research

- Quantitative transport descriptions still largely empirical
- Often large discrepancies with measurements and large differences between models (especially for rippled beds)
- More complex models not necessarily better than simpler models (e.g. energetics approach)
- Important part of coastal engineering practice: how to deal with uncertainties?

6-G Discussion

Considerable uncertainty if untuned models are used for absolute predictions for field conditions

Necessity of calibration for the site and conditions under consideration!



6-H Discussion

Dealing with uncertainty in morphodynamic computations

- Absolute predictions require calibration:
  - For the site and conditions under consideration
  - Prerequisite is correct qualitative behaviour
  - The more complex the model, the more calibration is required and the smaller the application range (data restrictions)
- What-if scenario's in morphodynamics modelling

6-H Discussion

Energetics approach at several places in lecture notes:

- Section 7.5:
  - Decomposition of cross-shore transport into components due to mean flow, short wave skewness and bound long waves
  - Equilibrium shoreface shapes by balancing onshore and offshore transport
- Section 8.2.3:
  - Bulk longshore transport by applying the energetics concept to the littoral zone
- Section 9.7.2:
  - Decomposition of tide-averaged sediment transport into contributions of residual currents, M2, M4 and M6 tidal constituents