Dredging Processes

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8. Hopper sedimentation
Hopper Sedimentation

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Sectie Offshore & Dredging Engineering

Delft University of Technology
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Settling velocity of sediments
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   Influence of the concentration
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Intro Hopper
Unloading TSHD

[Image of a ship in the water with a pipeline discharging material onto the shore.]

[Image of the same ship from a different angle showing its full structure.]

[3]

15 January 2013
Application of TSHD

Before 1980

- Maintenance Dredging
  - Deepening of harbours & entrance Channels
    - Maintenance due to siltation
    - Soft sediments (silt clay)
    - Not stationary (wires anchors), so less problems with shipping
Application of TSHD

- Capital Dredging (new projects)
  - Most Reclamation works
  - Less suitable:
    - Reclamation in combination with deepening
      - Short distance between dredging & reclamation.
    - Dredged material suitable for fill
    - Sediments in dredge area difficult for TSHD
Doha Airport
Qatar
(in progress)
TSHD Process Description

Sailing loaded
TSHD Process Discription

Discharge
TSHD Process Description

Sailing empty
TSHD Process Description

Excavation
Vertical transport
TSHD Process Description

Loading
Hopper sedimentation

Loading (overflow)
Overflow phase

Phase 1

Overflow level

Initial water level

Phase 2

Overflow level

Settled sediment

Phase 3

Settled sediment
Loading & Overflow system
Overflow system
Loading & Overflow system

- Loading system
  - Distribution of sediment
    - Influence on overflow losses
    - Influence on hopper load
    - Influence on trim of the hopper
- Overflow system
  - Adjustable in height
Overflow Losses

• Important to know:
  • Quantity of losses
  • Which part of the particle size distribution is lost

• Why:
  • Production
  • Sand Quality
  • Environment
Factors influencing overflow losses

• ?
Factors influencing overflow losses

- Sediment characteristics
  - Particle size distribution  \( \rightarrow \) Settling
  - Shape factor  \( \rightarrow \) velocity
- Equipment
  - Hopper dimensions (L,H,B)
  - Loading and overflow system
- Operational
  - Discharge
  - Concentration
  - Loading time
  - Loading procedure
  - Water temperature

Most important?
Factors influencing overflow losses

- Sediment characteristics
  - Particle size distribution  }  Settling
  - Shape factor  }  velocity
- Equipment
  - Hopper dimensions (L,H,B)
  - Loading and overflow system
- Operational
  - Discharge
  - Concentration
  - Loading time
  - Loading procedure
  - Water temperature
General Properties

- Volume particles \( V_s \)
- Volume water \( V_w \)

Total Volume \( V_t = V_s + V_w \)

Volumetric Concentration \( C_v = \frac{V_s}{V_t} \)

Mixture density \( \rho_m = C_v \rho_s + (1-C_v) \rho_w \)
Discharge

mixture \( Q = A \bar{u} \)

solids \( Q_s = A_s \bar{u}_s = A c_v \bar{u}_s \)

\( Q_s = A \bar{u} c_{vd} \) \( C_{vd} = \) delivered concentration

\( c_{vd} = \frac{Q_s}{Q} = \frac{A \bar{u} c_{vd}}{A \bar{u}} = \frac{\bar{u}_s c_v}{\bar{u}} = \frac{\alpha_t \bar{u} c_v}{\bar{u}} = \alpha_t c_v \quad \alpha_t \leq 1 \)
Definition Overflow losses

\[ O_{V_{mom}} = \frac{\text{sandflux out}}{\text{sandflux in}} = \frac{\rho_s Q_{out} c_{out}}{\rho_s Q_{in} c_{in}} = \]

\[ O_{V_{mom}} = \frac{c_{out}}{c_{in}} \quad \text{if} \quad Q_{in} = Q_{out} \]

\[ O_{V_{cum}} = \frac{\text{cum sandflux out}}{\text{cum sandflux in}} = \frac{\int_0^t \rho_s Q_{out} c_{out} dt}{\int_0^t \rho_s Q_{in} c_{in} dt} \]
Settling velocity

- Derive a general equation for the settling (fall) velocity of a particle below the water surface
Settling Velocity

$$F_w = \frac{\pi}{4} D^2 C_D \frac{1}{2} \rho_w w_0^2$$

$$G = F_w$$

$$G = \frac{\pi}{6} D^3 g (\rho_s - \rho_w)$$

$$w_0 = \sqrt{\frac{4 (\rho_s - \rho_w) g D}{3 \rho_w C_D}}$$
\[ w_0 = \sqrt{\frac{4(\rho_s - \rho_w) g D \psi}{3 \rho_w C_D}} \]

\[ C_D = f \left( \frac{w_0 D}{v} \right) \quad \frac{w_0 D}{v} = Re_p \]

Shape factor

\[ \psi = \frac{V}{\frac{\pi}{6} D^3} \]
Drag Coefficient CD

\[ \text{Re}_p < 1 \quad \Rightarrow \quad C_d = \frac{24}{\text{Re}_p} \]

\[ 1 < \text{Re}_p < 2000 \quad \Rightarrow \quad C_d = \frac{24}{\text{Re}_p} + \frac{3}{\sqrt{\text{Re}_p}} + 0.34 \]

\[ \text{Re}_p > 2000 \quad \Rightarrow \quad C_d = 0.445 \]
$C_d$ as a function of $Re_p$

![Graph showing $C_d$ as a function of $Re_p$ with a transition from laminar to turbulent flow.](image-url)
Small particles: Stokes equation

\[ w_0 = \sqrt{\frac{4(\rho_s - \rho_w)gD\psi}{3\rho_wC_D}} \]

\[ w_0 = \frac{\psi\Delta gD^2}{18\nu} \quad \Delta = \frac{\rho_s - \rho_wC_D}{\rho_w} = \frac{24}{Re_p} = \frac{24\nu}{w_0D} \]
Coarse particles: Turbulent regime

\[ w_0 = \sqrt{\frac{4(\rho_s - \rho_w) gD\psi}{3\rho_w C_D}} \]

\[ w_0 = 1.8\sqrt{\Delta gD\psi} \quad \Delta = \frac{\rho_s - \rho_w}{\rho_w} \]

\[ C_D = 0.4 \]
Intermediate Regime

• Iteration of Cd

• Or use empirical equations

\[ w_0 = \frac{10\nu}{D} \left( \sqrt{1 + \frac{\Delta g D^3}{100\nu^2}} - 1 \right) \]
Particle Reynolds number

![Graph showing the relationship between particle diameter and particle Reynolds number for sand and gravel.](image-url)
Settling velocity influence temp

- $w_0$ [mm/s] for temp = 10
- Rel increase [%] for temp = 40 deg. Celc.

Graphs showing the relationship between grain diameter [micron] and settling velocity $w_0$ and relative increase [%].
Hopper sedimentation

- Section 2
Influence of the concentration

Return flow
Hindered settling

- Not one particle is settling:
  - Mutual influence
    - Return flow
    - Particle – particle interaction
- This effect is called hindered settling
- Settling velocity of single grain is reduced with a factor $f$

\[ w_s = w_0 \cdot f(c) \]
\[ f(c) = (1 - c)^n \]
Hindered settling function

\[ w_s = w_0 \cdot f(c) \]

\[ f(c) = (1 - c)^n \]

\[ n = f(Re_p) \]

- \( Re_p < 0.2 \) \quad n = 4.65
- \( 0.2 \leq Re_p \leq 1 \) \quad n = 4.35 \( Re_p \)^{-0.03}
- \( 1 \leq Re_p \leq 200 \) \quad n = 4.45 \( Re_p \)^{-0.1}
- \( Re_p > 200 \) \quad n = 2.39

Richardson & Zaki
Hindered settling exponent

- Rowe:

\[ n = \frac{4.7 + 0.41 Re_p^{0.75}}{1 + 0.175 Re_p^{0.75}} \]
Particle Reynolds number $Re_p [-]$

Exponent $n [-]$

Richardson & Zaki
Rowe
Influence concentration on settling velocity
• Settling velocity decreases with concentration

• And therefore loading velocity decreases also ????

• NO

• Settling flux = product of concentration and settling velocity is important
Settling flux = $W_s * C$

Optimal Loading Concentration ??
Sedimentation velocity

\[ T_{\text{load}} = \frac{H}{\bar{V}_{\text{sed}}} \]

Is vertical velocity of the settled bed
concentration

\[ C \]

\[ c_{bed} = 1 - n_0 \]

\[ W_s \]

\[ V_{sed} \]

Top of settled bed
• Volume of sediment moving along moving interface =
• Volume of sediment stored in bed

\[ c \left( w_s + v_{sed} \right) = (1 - n_0) v_{sed} \]

\[ v_{sed} = \frac{cw_s}{1 - n_0 - c} = \frac{c(1-c)^n}{w_0 \left(1 - n_0 - c \right)} \]

Or:
\[ \frac{v_{sed}}{w_0} = \frac{c(1-c)^n}{1 - n_0 - c} \]
\[ \frac{v_{sed}}{w_0} = \frac{c(1-c)^n}{1-n_0 - c} \]

Small concentration:

\[ \frac{v_{sed}}{w_0} = \frac{1}{1-n_0} c \]
Schematic Process Overview

\[ c_{in} \quad Q_{in} \quad c_{out} \quad Q_{out} \]

\[ v_{sed} = f\left(w_0, c, u_b, \ldots\right) \]
Sedimentation Velocity

- Vertical velocity of interface between settled sand and mixture above
- So far only sedimentation without flow near the bed
- In general:

$$v_{sed} = \frac{S - E}{\rho_s (1 - n_0 - c)}$$

$$S = \rho_s c w_s$$

$$E = f(u, D, c, ...?)$$

- $S$ : Sedimentation Flux  $E$ : Erosion Flux
- $c$ : Near bed concentration
- $n_0$ : Porosity
• Overflow loss correlates good with S*

• Relation cannot be applied in general
  • Based on lab tests (influence erosion?)
  • Influence PSD
Modelling the settling in a hopper

- Camp based models
- 2DV model
Camp based models

- ‘Ideal’ settling basin
- Originates from clarifiers
- First published by Camp (1946)

- Extended and applied for dredging by Vlasblom & Miedema
Ideal settling basin
Particles with settling velocity $w_s$ starting between bc will settle

This is $r_g = \frac{\vec{bc}}{ac}$ from the total number of particles
\[
\frac{bc}{L} = \frac{w_s}{u} \quad \frac{ac}{L} = \frac{H}{L} = \frac{v_0}{u} \quad \Rightarrow \quad r_g = \frac{bc}{ac} = \frac{w_s}{v_0}
\]

\[
v_0 = u \frac{H}{L} \quad u = \frac{Q}{BH} \quad \Rightarrow \quad v_0 = \frac{Q}{BL}
\]
Influence Particle Size Distribution

\[ dr_g = \frac{w_s(p)}{v_0} \, dp \]

\[ r_r = 1 - p_0 + \frac{1}{v_0} \int_0^{p_0} w_s \, dp \]
Influence of turbulence

• The particle trajectories in the previous slides were straight lines. Only possible in laminar flow
• Reynolds number with \( u = 0.1 \text{ m/s}\) \( H = 10 \text{ m} \):

\[
Re = \frac{uH}{\nu} = \frac{0.1 \cdot 10}{10^{-6}} = 10^6
\]

-> Turbulent flow!
Including turbulence

• Continuity equation: Advection – diffusion equation
• Control volume
• Rate of change of sediment inside volume = equal to the fluxes through the boundaries
• Fluxes through the boundaries are resulfion from:
• Advection: particles are carried with the flow
• Diffusion: mixing through the effect of turbulent eddies

\[
\frac{\partial c}{\partial t} + \frac{\partial (uc)}{\partial x} + \frac{\partial (vc)}{\partial y} = \frac{\partial}{\partial x} \left( e_x \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( e_y \frac{\partial c}{\partial y} \right)
\]
Only horizontal Advection:

\[ uC \]

\[ uC + \frac{\partial}{\partial x} (uC) \Delta x \]

\[ \frac{\partial c}{\partial t} \Delta x \Delta y = uC \Delta y - \Delta y \left( uC + \frac{\partial}{\partial x} (uC) \Delta x \right) \]

\[ \frac{\partial c}{\partial t} + \frac{\partial}{\partial x} (uC) = 0 \]
Only horizontal diffusion:

If a difference in concentration is present over the boundary, sediment will be transported.

Transport through left wall: \(-\varepsilon \frac{\partial c}{\partial x} \Delta y\)

Difference: \(\frac{\partial}{\partial x} \left( \varepsilon \frac{\partial c}{\partial x} \right) \Delta y \Delta x\)

\[
\frac{\partial c}{\partial t} \Delta x \Delta y = \frac{\partial}{\partial x} \left( \varepsilon \frac{\partial c}{\partial x} \right) \Delta y \Delta x
\]

\[
\frac{\partial c}{\partial t} = \frac{\partial}{\partial x} \left( \varepsilon \frac{\partial c}{\partial x} \right)
\]
Horizontal advection + diffusion:

\[
\frac{\partial c}{\partial t} + \frac{\partial}{\partial x}(uc) = \frac{\partial}{\partial x}\left(\varepsilon \frac{\partial c}{\partial x}\right)
\]

Horizontal and vertical advection + diffusion:

\[
\frac{\partial c}{\partial t} + \frac{\partial}{\partial x}(uc) + \frac{\partial}{\partial y}(vc) = \frac{\partial}{\partial x}\left(\varepsilon_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon_y \frac{\partial c}{\partial y}\right)
\]

u and v are particle velocities
General equation:

\[
\frac{\partial c}{\partial t} + \frac{\partial}{\partial x} \left( \mathcal{U} \frac{\partial c}{\partial x} \right) + w_s \frac{\partial c}{\partial y} = \frac{\partial^2 c}{\partial x^2} \frac{\partial c}{\partial x} + \frac{\partial}{\partial y} \left( \varepsilon_y \frac{\partial c}{\partial y} \right)
\]

Approximations

Horizontal diffusion is small compared with horizontal advection

Stationary flow

Vertical velocity is equal to \( w_s \) and not a function of \( c \)

Horizontal particle velocity = flow velocity and uniform

Diffusion is constant

Analytical solution by separation of variables
The image contains a diagram with a mathematical equation and associated text. The equation is:

\[ U \frac{\partial c}{\partial x} + w_s \frac{\partial c}{\partial y} = \varepsilon \frac{\partial^2 c}{\partial x^2} \]

The diagram shows a flow field with the variables \( c \), \( H \), and \( y \). The input is labeled as \( UHc_{in} \) and the output as \( U \int_0^H c \, dy \).

The text in the image states:

**In:** \( UHc_{in} \)  \hspace{1cm}  **Out:** \( U \int_0^H c \, dy \)

Additionally, there is a calculation for \( r_r \):

\[ r_r = \frac{U \left( Hc_{in} - \int_0^H c \, dy \right)}{UHc_{in}} \]
\[ \Gamma = \varepsilon \]

\[ \Gamma = 0.075 Hu_* \]

\[ u_* = \sqrt{\frac{\tau}{\rho}} = \sqrt{\frac{f}{8}} U \]

\[ \frac{w_s H}{2\Gamma} = \frac{1}{0.15\sqrt{f / 8}} \frac{w_s}{U} \]
Influence horizontal flow velocity

- Advection (transport from inlet to outlet zone)
- Turbulence: “stirring up” of sediment
- Hindered sedimentation due to bed shear stress
  - Often called erosion or scour
- Review general sedimentation equation:

\[ v_{sed} = \frac{S - E}{\rho_s (1 - n_0 - c)} \quad S = \rho_s c w_s \quad E = f(u, D, c, ...?) \]

- E is sediment pick-up
How to determine sediment pick-up?

- Needed:
  - Velocity distribution in the hopper and especially near the bed
    - Often assumed as uniform or logarithmic
  - Relation between $E$, shear stress, particle size and concentration
    - Problem: Conditions in a hopper very different from normal encountered in nature (high concentration)
Uniform or logarithmic profile

\[ \overline{u} = \frac{Q}{BH} \]

Flow velocity increases with bed level (time)
For a certain critical flow velocity a particle with a diameter $D$ will not settle anymore in the bed due to bed shear stress.

\[ u_{cr} = \sqrt{\frac{8(1-n_0)\mu\Delta g D}{f}} \quad \rightarrow D_{cr} = \frac{f}{8(1-n_0)\mu\Delta g} u^2 \]
Influence Particle Size Distribution

From a $D_{cr}$ calculate a critical settling velocity $w_{s,cr}$

Particles with a smaller settling velocity will not settle:

Therefore the lower boundary for the integral is $p_s$

$$r_r = 1 - p_0 + \frac{1}{v_0} \int_{p_s}^{p_0} w_s dp$$
• In practice this method does not have large influence on results due to
  • Assumption uniform flow
  • Therefore Flow velocity < ucr
  • No influence apart from the very last loading stage (almost totally filled hopper)
Ideal settling basin
Coupling between concentration and velocity distribution
Modelhopper Top view
Discharge pipe
Due to difference in density, flow is concentrated near the bed. Flow velocity is higher compared with uniform distribution.
Measured flow velocity in hopper
Conclusion Camp model

• Shortcomings Camp approach:
  • Flowfield prescribed
    • In reality density currents
    • Influence bed shear stress on sedimentation
  • Inflow and outflow zone not modeled
    • Variation in location not possible
• But gives a good estimate for overflow loss for optimal loading situation
In the Camp model (with Turbulence) the sediment transport equations were solved using a prescribed velocity field. Separate equations have to be solved to determine the flow field:
- 2DV Reynolds Averaged Navier-Stokes
  - mixture model (no multi-phase flow)
- Hydrodynamic (non-hydrostatic)
- Coupling momentum - sediment transport equations
  - Buoyancy (density currents)
- k-eps turbulence modelling
2 DV model (continued)

- Moving bed
  - Erosion - Sedimentation boundary condition
- Moving Water surface
  - filling of hopper, variation overflow level
- influence PSD by n fractions mutually coupled
- Loading and Discharge location
  - variation of position and quantity (in time)
  - Inlet conditions (velocity, turbulence intensity)
Reynolds Averaging:

- Reynolds stresses are assumed to be analog to viscous stresses, for instance

\[ \rho u' w' = -\rho v_e \frac{\partial u}{\partial z} \]

‘eddy viscosity’

\[ v_e = c\mu \frac{k^2}{\varepsilon} \]
Overview 2DV Model

Cons. Volume + Momentum

2D RANS
\[
\frac{D(\rho_m \vec{u})}{Dt} = \ldots
\]
\[
\nabla \cdot \vec{u} = 0
\]

Turbulence Model
\[
\frac{Dk}{Dt} = \ldots
\]
\[
\frac{D\epsilon}{Dt} = \ldots
\]
\[
\mu_t = c_u \rho \frac{k^2}{\epsilon}
\]

Sediment Transport
\[
\frac{D(c_i)}{Dt} = \epsilon_i \nabla^2 c_i
\]

\[
\frac{D(c_i)}{Dt} = \epsilon_i \nabla^2 c_i
\]

\[
\frac{D(c_i)}{Dt} = \epsilon_i \nabla^2 c_i
\]
Computed hor. Velocity in hopper
Computed Concentration in the hopper
Modelling the hopper sedimentation process

- Very simple ‘model’:

- If $s_{\text{sed}}$ is the mass settling in the bed and $s_{\text{in}}$ the mass of sediment loaded in the hopper one could expect that:

- $OV = f\left(\frac{s_{\text{in}}}{s_{\text{sed}}}\right)$
• Inflow mass:
  \[ s_{in} = \rho_s Q c_{in} \]

• Settling flux:
  \[ s_{sed} = \rho_s (1-n_0) v_{sed} BL \]

• BL = width * Length of hopper

• With:
  \[ v_{sed} = \frac{S - E}{\rho_s (1-n_0-c)} \]
  \[ S = \rho_s c w_s \]

• Ratio
  \[ \frac{s_{in}}{s_{sed}} = \frac{1-n_0-c}{1-n_0} \cdot \frac{c_{in}}{c w_s - E / \rho_s} \cdot \frac{Q}{BL} \]
• In case E=0 (no erosion)

\[ S^* = \frac{s_{in}}{s_{sed}} = \frac{c_{in}}{c} \cdot \frac{1 - n_0 - c}{1 - n_0} \cdot \frac{Q}{w_s BL} \]

\[ H^* = \frac{Q}{w_s BL} \]

• \( S^* \) is a product of a function \( f(c) \) and the dimensionless overflow rate \( H^* \)
$V_0 = \frac{Q}{(B \cdot L)}$

Ratio between vertical velocity and settling velocity:

$$H^* = \frac{v_0}{w_s} = \frac{Q}{B L w_s}$$
Cum OV versus H* en S* (Lab tests)
• Hopper (HAM 318 old):
  • L = 79.2  B = 22.5
  • Q = 14 m³/s

• PSD →
Example Camp no turbulence and no hindered settling

\[ L = 79.2 \text{ m} \]
\[ B = 22.5 \text{ m} \]
\[ Q = 14 \text{ m} \]
\[ v_0 = 7.856341 \text{ mm/s} \]

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\[ \text{total:} \quad 0.807493 \]
\[ Ov\_cum= 19\% \]
Camp no turbulence, including hindered settling

$L = 79.2 \text{ m}$
$B = 22.5 \text{ m}$
$Q = 14 \text{ m}$
$c_{in} = 0.17$ [-]
$v_0 = 7.856341 \text{ mm/s}$

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total: 0.731776

$Ov_{cum} = 27\%$
## Calculation of PSD in hopper

<table>
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<tr>
<th>p</th>
<th>p_cum</th>
<th>D</th>
<th>r_g</th>
<th>r_r</th>
<th>frac in hopp</th>
<th>frac in hopp cumulative</th>
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<td>3.311</td>
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<td>0.100</td>
<td>0.137</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Sum: 0.731776
PSD’s

PSD in
PSD settled
PSD in overflow

\[ p \] vs. \[ D \] [mm]

- \( p \) in [\(-\)]
- \( D \) in [mm]
Optimal loading time
HOPPERLOAD (m$^3$)

sailing

unloading

sailing

Cycle time

Overflow phase

m$^3$ unloaded

Loading

TIME
Cycle production

\[ P_{\text{cycle}} = \frac{m^3 \text{unloaded}}{\text{cycle time}} \quad \text{[} m^3 / s \text{]} \]

**Ham 318**

- Hopper load: 20,000 m³
- Sailing empty: 300 min
- Loading: 70 min
- Sailing loaded: 330 min
- Unloading: 15 min
- Turning etc.: 10 min

Total: 725 min

Cycle. Prod: 27.59 m³/min
\[
\tan(\alpha) = P_{\text{cycle}} = \frac{m^3 \text{ unloaded}}{\text{cycle time}} \quad \left[ m^3 / s \right]
\]
Long sailing distance

Short sailing distance
Questions?
Sources images

1. Trailing Suction Hopper Dredger, source: unknown.
2. Rotterdam, source: Van Oord.
3. HAM 318, source: Van Oord.
4. HAM 311, source: Van Oord.
5. Maasvlakte 2, source: Royal Haskoning.
7. Federation Island, Sochi, Russia. Source: Russkie Prostori.