Towards Better Prediction of Dredging Plumes:

Numerical and Physical Modelling of Near-field Dispersion

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Overview

Introduction

Different types of sediment spills

Objectives of the developments

Requirements for (operational) plume dispersion simulations

3D Near-field models: Physical and CFD

Development of parameterised near-field models

Implementation in 3D tidal flow models

Operational turbidity forecasting
The project

- Baekeland mandate with funding from
  - IWT (currently called VLAIO)
  - International Marine & Dredging Consultants
- PhD, with scientific support by:
  - Prof. T. De Mulder (Ghent University)
  - Prof. E. Toormann (KULeuven)
Introduction

**WHY ARE WE DREDGING?**

- Building new land
- Navigation channels
- Canals
- Port Construction
- Offshore construction
- … many more
Introduction

- Sediment spills: Environmental management
- Fate of turbidity plumes
- Large-scale dispersion simulations
- Source terms needed

→ Near-field behaviour?
Introduction

**PLUME MODELLING:**

- Simulations of plume dispersion through marine environment
  - Predict whether plumes move to environmentally sensitive areas (e.g. coral reefs, …)
  - Large-scale numerical models of tides and current
  - Source terms needed *(how much sediment goes in?)*

*Numerical Flow Model (far field)*

*Near field*
PLUME MODELLING: How?

- Far-field model: coarse grid, extent = 10’s-100’s of kilometers
- Near-field processes: scale difference prohibitive in far-field model
- Near-field model: fine grid, extent = 100’s of meters

Research topic = overflow plume models

3D CFD Model (Computational Fluid Dynamics)
Introduction

THE OVERFLOW:

- Trailing Suction Hopper Dredger (TSHD)
- Cost efficiency:
  - Transport from dredging site to disposal site
  - Reduce number of trips
  - Minimise transport of water
THE OVERFLOW

- Loading: sea bed material + water
- Water ends up in hopper
- Return back to sea: water + fine sediment + air bubbles
THE OVERFLOW PLUME

- Released water contains mud particles
- A plume can be formed behind the ship (at surface and/or below)
- Environment: avoid negative effects of turbidity
Environmental Scope of Dredging Projects

- Env. Quality Objectives (EQO) are translated to Trigger levels for measurable parameters (e.g., turbidity), with stepwise management actions if breached:
  - Trigger level 3: STOP dredging
  - Trigger level 2: Operational actions (reduced overflow, move dredging equipment, ...)
  - Trigger level 1: Investigate and increased monitoring
Introduction

Plume predictions ⇔ Environmental management

Sea current (from model)
Introduction

Plume predictions ↔ Environmental management

Sea current (from model)
Introduction

Plume predictions ↔ Environmental management

Sea current (from model)
Introduction

Plume predictions ↔ Environmental management

Sea current (from model)
Introduction

Plume predictions  ↔  Environmental management

**MAIN RESEARCH QUESTION:**
How much sediment to introduce in the far-field model and how is it distributed??
Introduction

Plume predictions  ↔  Environmental management

**TODAY:**

* Assumptions with weak justification
* ‘Best guess’ sediment distribution
Introduction

Plume predictions ↔ Environmental management

SOLUTION:
Develop a new near-field model to simulate detailed flow near ship!
Different types of sediment spills

**Types of sediment spills** taken into account

- Draghead (TSHD)
- Propeller wash (TSHD, self-propelled barges with DP)
- Cutterhead (CSD)
- Bucket loss (Backhoe, Grab dredge)
- Reclamation area runoff
- Open-water placement
- Placement using spreader pontoon
Different types of sediment spills

For each active spill type, determine:

- Spill rate (kg/s)
- Vertical distribution in the water column

Optimal methodology:

Near-field models → Parameterisations → Far-field model
Objectives - long-term vision at IMDC

General

• Increase accuracy of scenario predictions (tender phase + operational)
• Decrease probability of project shutdown due to turbidity threshold violations

Specific

1. Improve near-field models for overflow plumes (CFD)
2. Develop fast but accurate parameterisations for overflow plumes
3. Flexible framework for Pro-Active Adaptive Management of spills
4. Develop simulation tools for other types of spills
Objectives (PhD)

General

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Specific

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Requirements for plume dispersion simulations

- **Far-field model:**
  1. Regional model
  2. Local flow model

- **Near-field models**
  - for dispersion of specific type of spills:

- Spill parameterisations (based on near-field models)
- Soil model project site
- Dredge equipment characteristics
- Planning of foreseen dredging activities
Requirements for plume dispersion simulations

• **Far-field model:**
  1. Regional model
  2. Local flow model

• **Near-field models** for dispersion of specific type of spills:
  • Overflow (with/without green valve)
  • Sidecasting
  • Containment bund runoff
  • Propeller wash

• Spill parameterisations (near-field models)
• Soil model project site
• Equipment characteristics
• Planning of foreseen dredging activities
Requirements for plume dispersion simulations

1. Regional models at **continental shelf** scale:
   - Large-scale tidal propagation models (in-house IMDC, 1000’s of km, in 2D)
   - Very efficient (1 month tidal flow simulation in ~ 1h on 16 CPU’s)

<table>
<thead>
<tr>
<th>iCSM</th>
<th>Tethys model</th>
<th>iSAM model</th>
</tr>
</thead>
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Persian Gulf
Gulf of Oman
Gulf of Aden
Red Sea
Indian Ocean
Tethys model
Requirements for plume dispersion simulations

Continental shelf models available at IMDC
Requirements for plume dispersion simulations

2. Local models at estuary/coast/port scale:

- Local flow models (10-100 km, usually in 3D)
- At present: usually unstructured grids, focussed on area of interest
- Detailed calibration of tides and flow velocity
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Near-field model overflow plumes

Research Hypothesis
Overview Model development

Lab EXPERIMENTS

Lab-scale MODEL

Real-scale MODEL

Real-scale MEASUREMENT
Overview Model development

Lab EXPERIMENTS

Lab-scale MODEL

Real-scale MODEL

Real-scale MEASUREMENT
Overview Model development

Lab-scale MODEL

Lab experiments

Real-scale MEASUREMENT
Overview Model development

Model matches Experiment?

Lab EXPERIMENTS
Lab-scale MODEL
Real-scale MODEL
Real-scale MEASUREMENT
Overview Model development

Next step: validate upscaling to real-life scale
Overview Model development

- Lab EXPERIMENTS
- Lab-scale MODEL
- Real-scale MODEL

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Overview Model development

Lab EXPERIMENTS
Lab-scale MODEL
Real-scale MODEL
Real-scale MEASUREMENT
Overview Model development

Model matches Field Measurements?
Overview Model development

Applications:
- *Simplified Model
- *Influence factors
- *Ship Design
Experiments

- Lab EXPERIMENTS
- Lab-scale MODEL
- Real-scale MODEL
- Real-scale MEASUREMENT
Goal of the experiments:

- Insights in sediment plume behaviour
- Produce data set to compare with model results
- Preliminary estimate of influence factors:
  - Air bubbles
  - Ship hull
• 34 different plumes at scale 1/50
• Flume: length = 15m, width = 0.8 m, depth = 0.6 m
• $W_0 = 4 \text{–} 30 \text{ cm/s}; C_0 = 5 \text{–} 50 \text{ g/l}; D = 3.4 \text{–} 6.5 \text{ cm}$
• Sediment: kaolin, $d_{50}=4 \mu$m
• Dynamically scaled:
  • Densimetric Froude number $F_\Delta$
  • velocity ratio $\lambda$
Experiments

Lab experiments
Lab-scale model
Real-scale model
Real-scale measurement
Results

Lab EXPERIMENTS

Lab-scale MODEL

Real-scale MODEL

Real-scale MEASUREMENT

LAB-SCALE MODEL

REAL-SCALE MODEL

MEASUREMENT

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Results

1. Plume trajectory

2. Profiles of:
   - Sed. concentration

3. Influence factors
   - Air bubbles
   - Ship hull

\[
Ri = F_{\Delta}^{-2} = \frac{g D \Delta \rho / \rho_w}{W_0^2}
\]
Overview Model development

Lab EXPERIMENTS

Lab-scale MODEL

Real-scale MODEL

Real-scale MEASUREMENT
Lab-scale Model

- Navier-Stokes eq’s for the water-sediment mixture
- Large-Eddy Simulation (LES)
- Open boundaries:
  - water+sediment in pipe
  - clear water crossflow
- Numerical
  - Finite Volumes
  - grid of ~2M cells
  - dt = 0.02 s
- Variables:
  - pressure
  - velocity components
  - sediment fraction
  - sub-grid scale turbulence variables

Water + sediment mixture (pipe)

Clear water flow (crossflow)
Results

- Impression of the sediment plume
Overview Model development

Model matches Experiment?

Lab experiments
Lab-scale model
Real-scale model
Real-scale measurement
Results

- Qualitatively:

Visually: Lab vs CFD

- Stable stratification
- Unstable stratification
Results

Quantitatively:

1. Trajectory: Laboratory vs CFD
   - Centerline
   - Upper/lower edge
   - Plume entrainment due to vessel hull

Results

Quantitatively:

2. SSC & Turbulence
   - RMS $u_i'$
   - RMS $c'$

\[ y^* = y/|\bar{z}| \]
\[ z^* = (z - \bar{z})/|\bar{z}| \]
Overview Model development

Model matches Experiment?  YES!
Overview Model development

Next step: validate upscaling to real-life size

Lab EXPERIMENTS → Lab-scale MODEL → Real-scale MODEL → Real-scale MEASUREMENT
Upscaling to **realistic scale**: CFD model with **lab geometry**
Upscaling LES model to prototype scale

1. Take CFD model lab scale
2. Scale grid to large scale (similarity laws buoyant jets)
3. CFD simulation
4. Validation, based on:
   • Trajectories in similarity coordinates must coincide with lab scale
   • TKE resolved > 80%, for LES completeness (Pope, 2004)
Overview Model development

Lab EXPERIMENTS
Lab-scale MODEL
Real-scale MODEL
Real-scale MEASUREMENT
Real-scale model

- 3D CFD
- 3 phases: water, sediment, air bubbles
- Resolves large turbulent motions (LES)
- Full-size TSHD
- Propellers included (actuator disk)
- Dynamic air bubble transport model:
  - Lagrangian,
  - Forces: Gravity, drag, virtual mass, grad(p)
  - Coalescence
Real-scale model

- CFD simulation result
Real-scale model

- CFD simulation result
Real-scale model

Deep water, light mixture

Deep water, heavy mixture

Shallow water

Air bubble concentration

! Validation needed

Monitoring campaigns
Overview Model development

- Lab EXPERIMENTS
- Lab-scale MODEL
- Real-scale MODEL
- Real-scale MEASUREMENT
Determination of sediment concentration:

- Sampling inside the overflow (to impose in model runs)

- Measurements and samples in the dredging plume
Overview Model development

Model matches Field Measurements?
Results Validation CFD

Validation Case 1:

- H=16m; D=2m; \( W_0 = 1.9 \text{ m/s}; \ U_\infty = 1.5 \text{ m/s}, \ C_0 = 55 \text{ g/l} \)
- Field measurements: Vertical profiles of SSC
- CFD model: CPU time = 25 hours at 32 CPU’s
Validation Case 1: Vertical profiles

- Measurement carried out at < 200 m for near-field validation
- Compared with time-averaged model results
Results Validation CFD (Site 2)

**Validation Case 2:**
- Data from second campaign
- $H=39\text{m} \quad D=1.1\text{m} \quad W_0=3.2\text{ m/s} \quad U_\infty=1.5\text{ m/s}, \quad C_0=10\text{ g/l}$

$\log(C/C_0)$

$\Diamond$: ADCP measurements of plume lower edge

→ In some cases: majority of sediments released to far-field plume
Overview Model development

Model matches Field Measurements? YES!

Lab EXPERIMENTS → Lab-scale MODEL → Real-scale MODEL → Real-scale MEASUREMENT

Model matches Field Measurements?
Overview Model development

Lab EXPERIMENTS
Lab-scale MODEL
Real-scale MODEL
Real-scale MEASUREMENT

Applications:
* Influence factors
* Ship Design
* Simplified Model
Influence factors on plume dispersion

- Influence factors on near-field dispersion
- Influence factors on green valve efficiency
  (Decrop et al, 2015, J. Environ. Eng. 141 (12))

Examples shown today

- Air bubbles
- Speed-through-water
- Overflow position
- Overflow extension
- Shape of the overflow shaft

Applications:
- Influence factors
- Ship Design
- Simplified Model
Influence of air bubbles

- Environmental valve: air bubbles -90% (Saremi, 2014)
- Perform simulations with/without air flow rate reduction
- But: efficiency of the valve is function of ambient conditions! (Decrop et al., 2015, J. Environ. Eng 141 (12))
Influence of sailing velocity

Relative velocity sea water - ship

- **2 knots**
- **6 knots**

\[ \log(C/C_0) \]

Applications:
- Influence factors
- Ship Design
- Simplified Model

\( \rightarrow \) sediment in surface plume \( x \times 10 \)
Overflow position

- Overflow at stern: plume mixed by propellers

- Overflow at aft: plume has more time to descend
Ship design: Overflow shaft extension

- Studied earlier by de Wit et al. (2015)
- C at surface reduced with factor up to 10
- Open question: feasibility

- Surface plume partially remains because of rising air bubbles
Ship design: rectangular overflow shaft

→ Potentially 50% reduction of surface plume sediment concentration
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Operational turbidity forecasting
Parameter model overflow plumes

Motivation
CFD model has **high CPU cost**, **not practical in some cases**

**Find a simple model** that is:
- Much faster
- Almost as accurate

**Parameter model**
= **combination of**
- Analytical plume solutions
- Parameter fits on data of +/- 100 CFD model runs

**A model with output:**
- In suitable form for input to far-field models
  → Vertical profile of sediment flux behind ship
Parameter model overflow plumes

- >100 CFD runs, with variation of:
  - Current velocity
  - Sailing speed
  - Sediment concentration
  - Overflow diameter, position
  - Air bubble concentration

  → For ‘Model Training’

- Model Validation: against extra dataset CFD results
  - 90% has $R^2 > 0.5$
  - Valid for standard cases, for specific cases still CFD needed

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- Different types of sediment spills
- Objectives of the developments
- Requirements for (operational) plume dispersion simulations
- 3D Near-field models: Physical and CFD
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- Implementation in 3D tidal flow models
- Operational turbidity forecasting
Implementation in far-field models

For overflow:
- Hopper model for sediment content in overflow discharge (Hjelmager et al., 2014)
- Fast parameter model for near-field overflow plume dispersion (< 1 sec.)
  - Programmed inside far-field modelling software → real-time evolution of overflow flux
  - Distribution of sediment sources depends on:
    - Current velocity and direction
    - Sailing speed
    - Sediment Concentration, % fines
    - Overflow diameter and position
Implementation in far-field models

**In tender/planning phase:**

- Include all other expected sediment spills on the site:
  - Reclamation runoff
  - Bucket loss
  - Draghead
  - ...

- Define evolution in time of equipment position, spill rate (kg/s), near-field distribution

- Implement time series of sediment sources in 3D far-field model

- Simulate different dredging works scenario cases

- Select work strategy with minimum turbidity impact at receptors
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Operational turbidity forecasting
Implementation in far-field models

Real-time plume forecasting

• In operational phase
• Simulate, Evaluate, Adapt

Pro-active Adaptive Management
Pro-active Adaptive Management (EcoPAM)

EVALUATE vs ENV. CRITERIA

SEDIMENT PLUME MODEL

ADAPT

FIELD OBSERVATIONS

DREDGING SCENARIO

DREDGE & MONITOR

SEDIMENT TRANSPORT

WIND

WAVES

HD

SED TRANSPORT

EVALUATE vs ENV. CRITERIA

FIELD OBSERVATIONS

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DREDGE & MONITOR

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SED TRANSPORT
Pro-active Adaptive Management (EcoPAM)

- Platform = Synapps (web-based, developed by IMDC)
- The system:
  - Runs on daily basis (forecast mode)
  - Can be used to assess environmental impact of modified dredging strategy (scenario mode)
Conclusions

- New generation of efficient far-field models
- Recent developments in CFD for near-field models
- More accurate plume dispersion simulations:
  - Reduces risk of inaccurate assessment in tender phase
  - Enhances real-time plume dispersion forecasting in operational phase
- Overall:
  - Reduced risk of turbidity threshold violations during operations
  - Impact of alternative dredging strategies can be predicted
Questions?

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