# Innovative simulation tools for turbidity management

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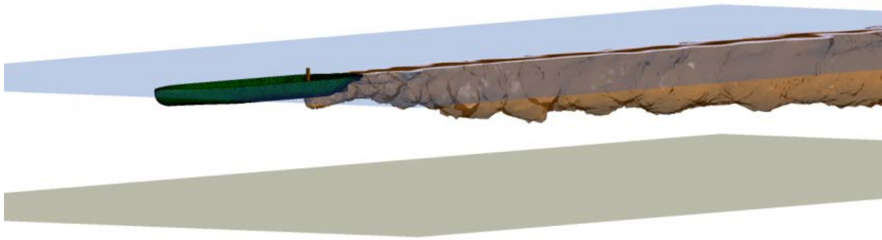
International Marine & Dredging Consultants



# Overview

Introduction

Objectives of the developments

Different types of sediment spills

Requirements for (operational) plume dispersion simulations

CFD near-field models

Development of parameterised near-field models

Implementation in 3D tidal flow models

Operational turbidity forecasting



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# Introduction

- Environmental management
- Fate of turbidity plumes
- Large-scale dispersion simulations
- Source terms needed
- Only visible at water surface

→ Near-field behaviour below surface?

→ 3D, near-field plume simulations


# Objectives

Objectives of recent developments in plume dispersion modelling

## General

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

## Specific

- Improve near-field models for overflow plumes (CFD)
- Develop fast but accurate parameterisations for overflow spills
- Develop simulation tools for all other spills
- Improve reliability of operational turbidity forecasting
- Flexible framework for Pro-Active Adaptive Management of spills



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# Objectives

Objectives of recent developments in plume dispersion modelling

- 
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## Specific

- **Improve near-field models for overflow plumes (CFD)**
- **Develop fast but accurate parameterisations for overflow spills**
- 
- **Improve reliability of operational turbidity forecasting**
- 

# Different types of sediment spills

**Types of sediment spills** taken into account

- Overflow (TSHD, barges)
- 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

# Overview





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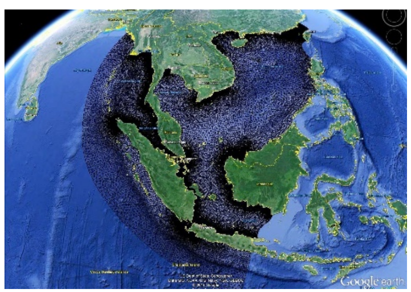
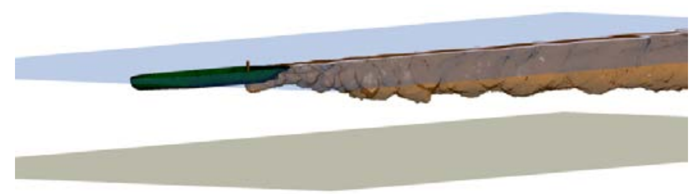
# Requirements for plume dispersion simulations

- **Far-field model**:
  - Regional model or satellite-based altimetry (TPXO)
  - 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** (based on near-field models)
- **Soil model project site**
- **Equipment characteristics**
- **Planning of foreseen dredging activities**

# Requirements for plume dispersion simulations

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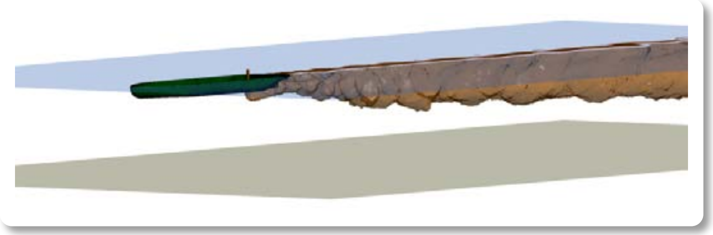

- **Spill parameterisations** (near-field models)
- **Soil model project site**
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# Requirements for plume dispersion simulations

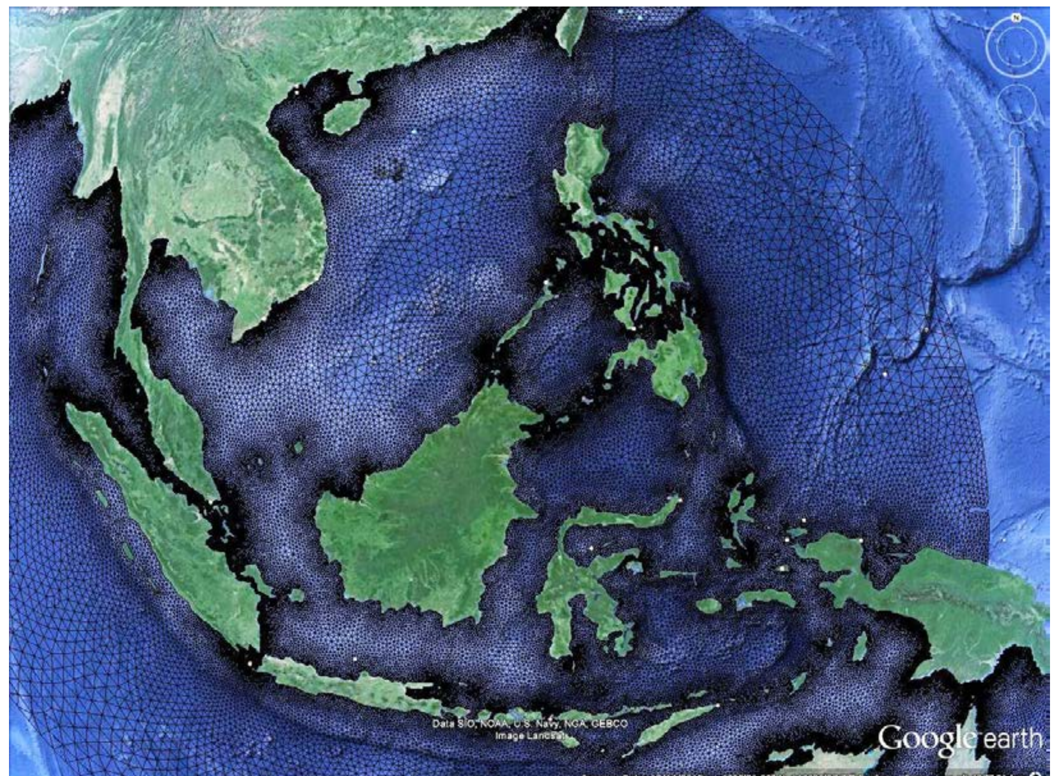
**Far-field (tidal) models at continental shelf scale**:

- → Large-scale tidal propagation models (in-house IMDC, 1000's of km, in 2D)
- → Very efficient due to unstructured grids (1 month in +/- 1h CPU time)

**iCSM**

**Tethys model**

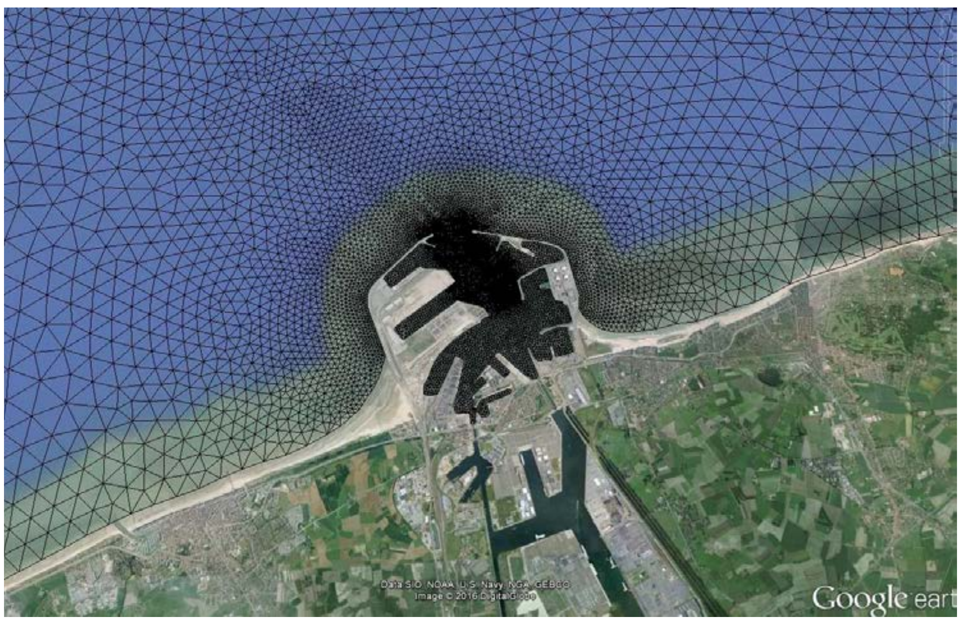

**iSAM model**

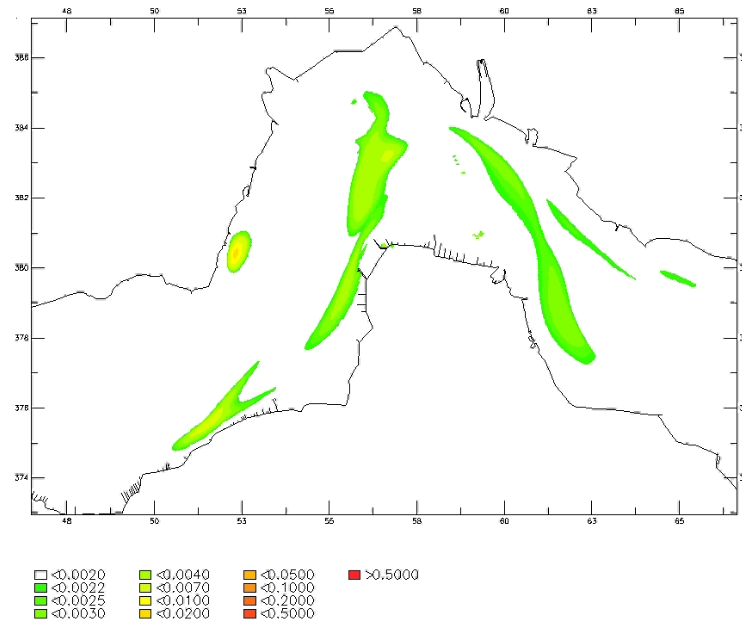


# Requirements for plume dispersion simulations

**Far-field models at local 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





# Requirements for plume dispersion simulations

- **Far-field model**:
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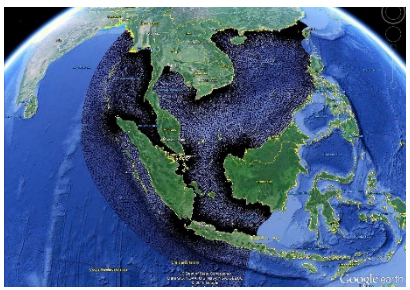
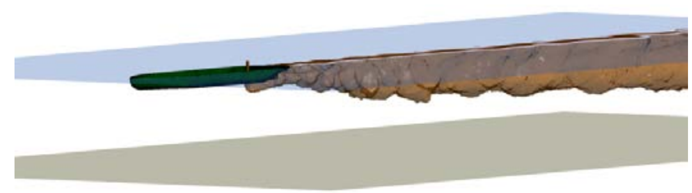


- **Near-field models (CFD):** of specific type of spills:
  - Overflow (with/without green valve)
  - Sidecasting
  - Containment bund runoff
  - Propeller wash

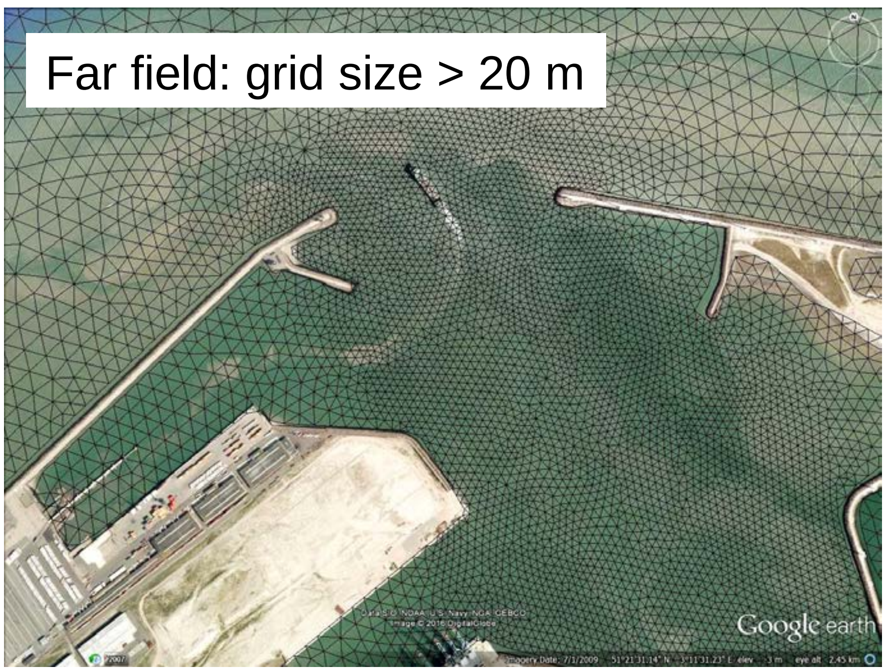


- **Spill parameterisations** (near-field models)
- **Soil model project site**
- **Equipment characteristics**
- **Planning of foreseen dredging activities**

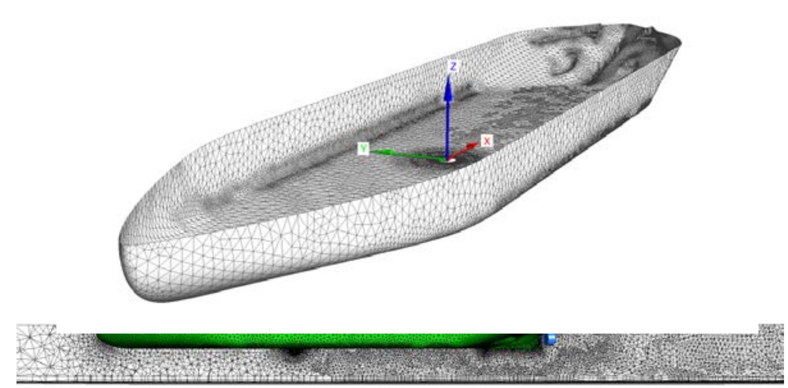
# Requirements for plume dispersion simulations

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

- Physics in large-scale models not suitable (e.g. hydrostatic assumption, etc.)
- Grid discretisation in large-scale models not detailed enough
  (for CPU time reasons)




Near field: grid size > 0.1 m





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# Requirements for plume dispersion simulations

**Near-field models for dispersion of**:

- Overflow (with/without green valve)
- Sidecasting
- Containment bund runoff
- Propeller wash

**Spill as percentage of production for:**

- Draghead loss (TSHD)
- Cutterhead loss (CSD)
- Bucket loss (Backhoe, Grab dredge)
- Open-water placement
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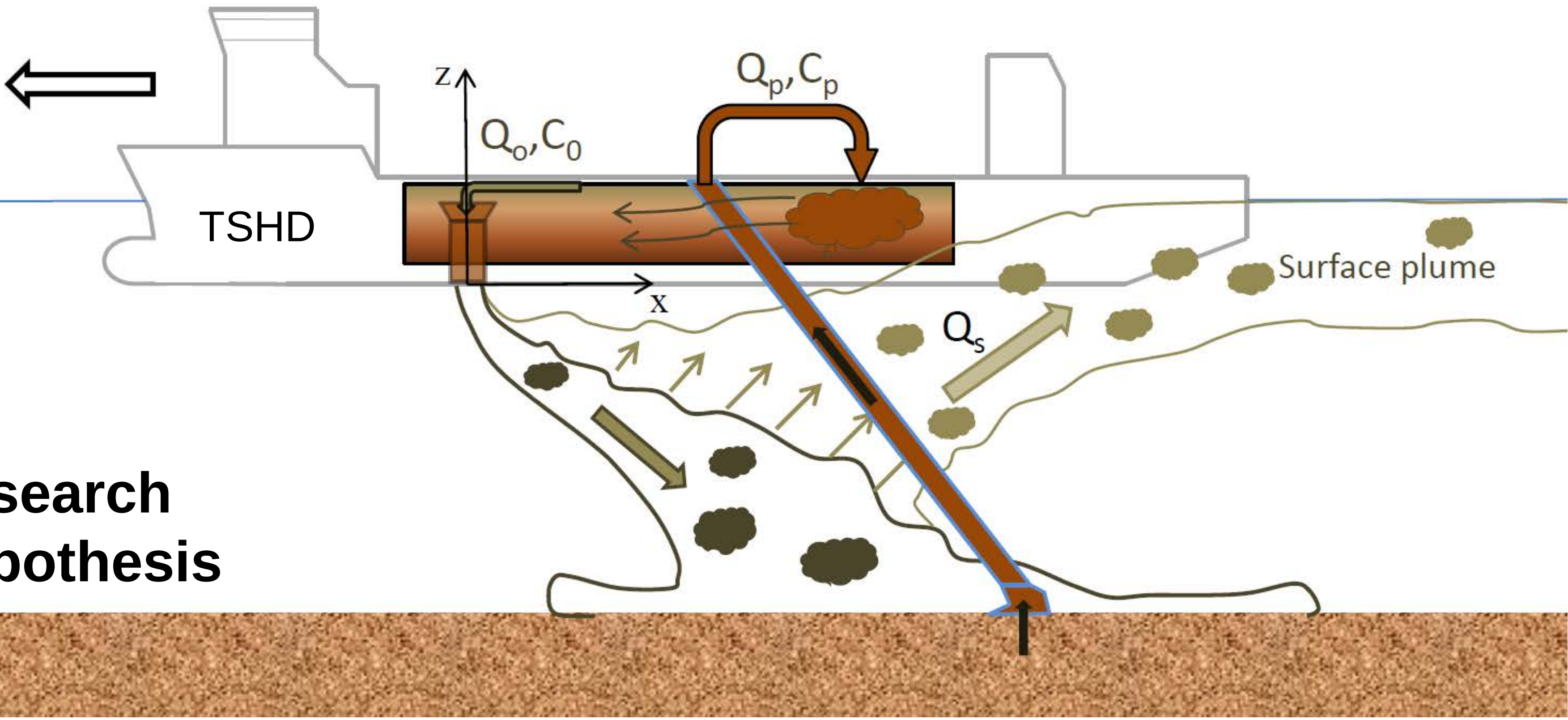
# Near-field model overflow plumes

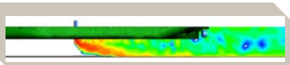



**Research Hypothesis**

# Overview Model development

**Lab**
**EXPERIMENTS**

**Lab-scale**
**MODEL**



**Real-scale**
**MODEL**

**Real-scale**
**MEASUREMENT**



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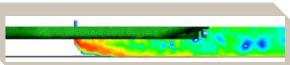
# Overview Model development

**Lab**
**EXPERIMENTS**

**scale**
**ODEL**



**Real-scale**
**MODEL**

**Real-scale**
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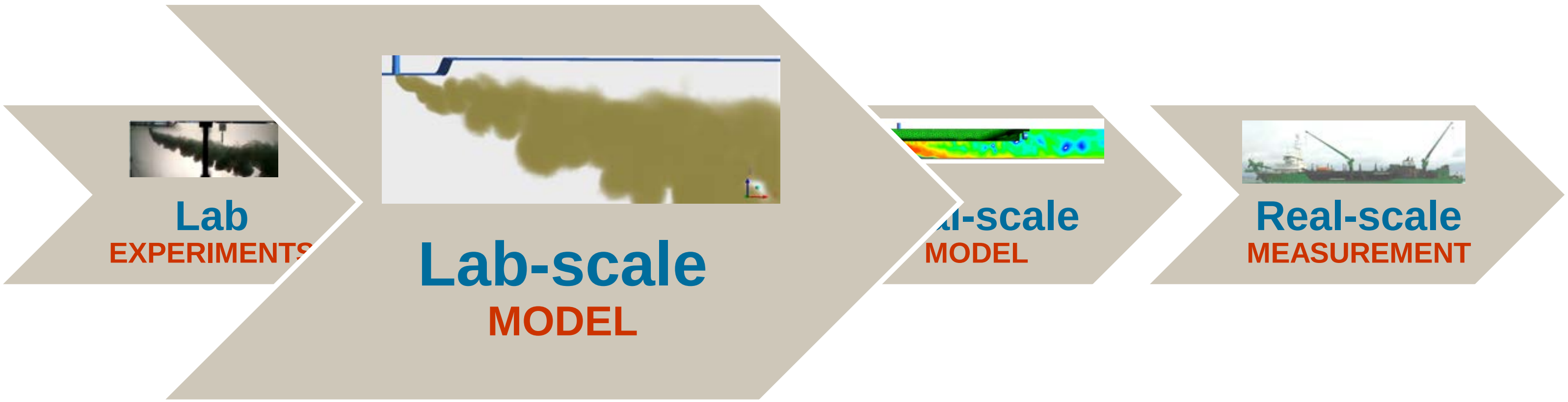
# Overview Model development



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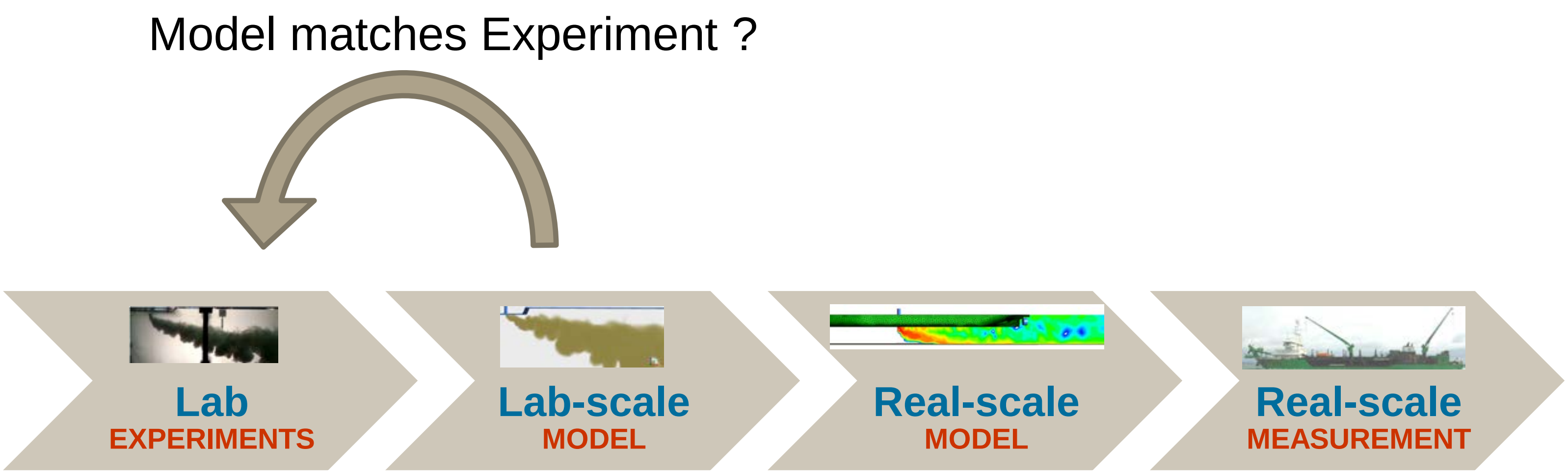




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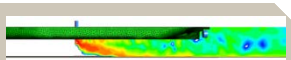
# Overview Model development

Next step: validate upscaling to real-life scale

**Lab**
**EXPERIMENTS**

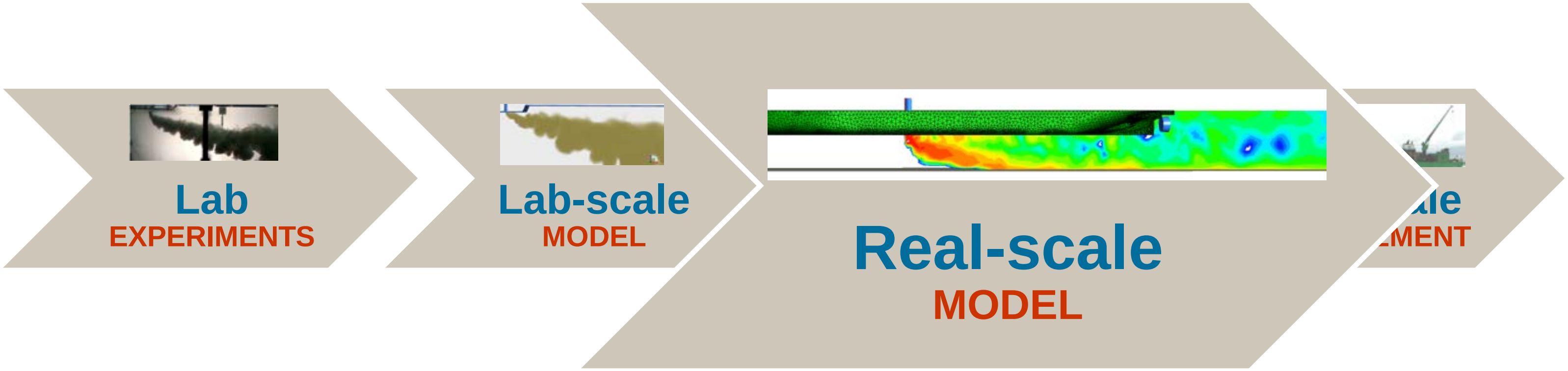
**Lab-scale**
**MODEL**



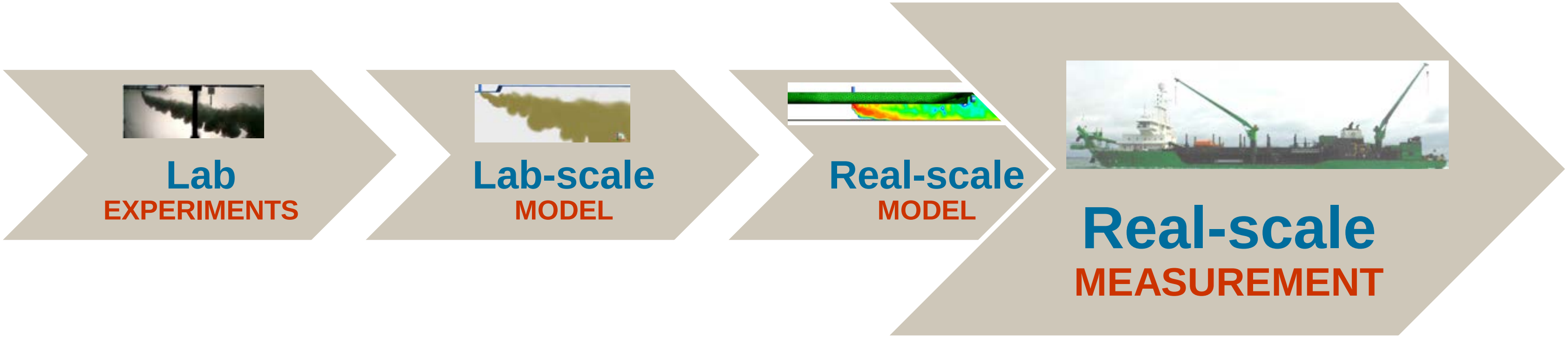
**Real-scale**
**MODEL**

**Real-scale**
**MEASUREMENT**

# Overview Model development

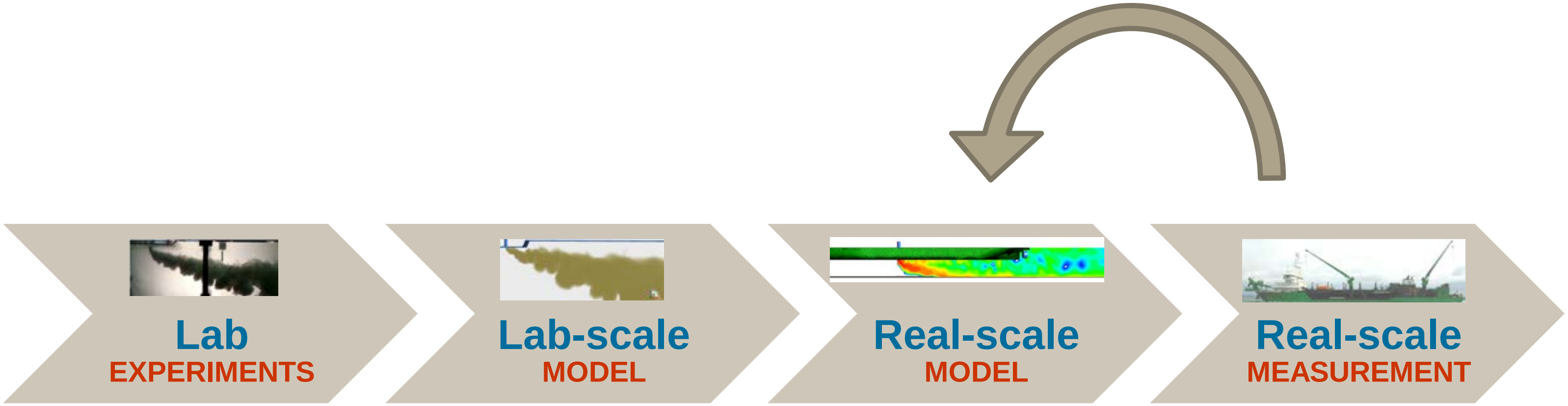


# Overview Model development



# Overview Model development

Model matches Field Measurements ?



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# Overview Model development

**Lab**
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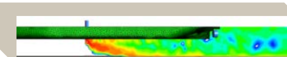


**Real-scale**
**MODEL**

**Real-scale**
**MEASUREMENT**

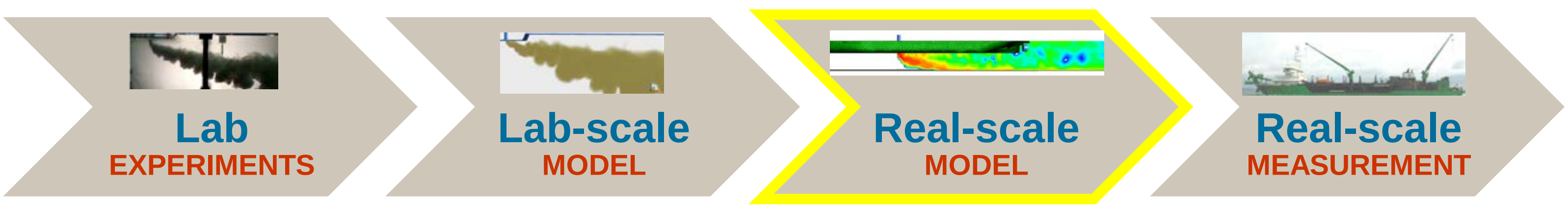
## Applications:

***Simplified Model**

***Influence factors**

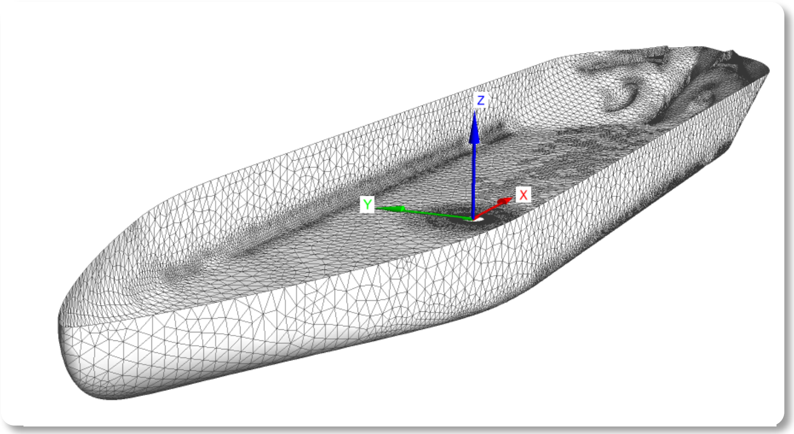
*** Ship Design**

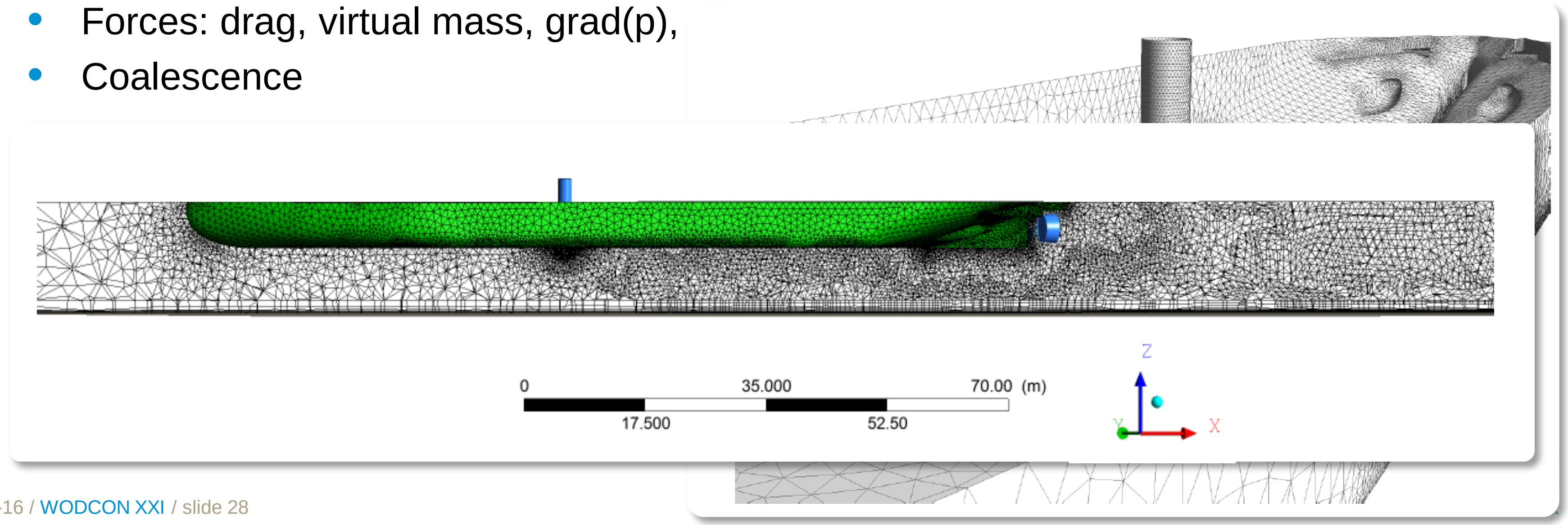
# Overview Model development



# 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: drag, virtual mass, grad(p),
  - Coalescence

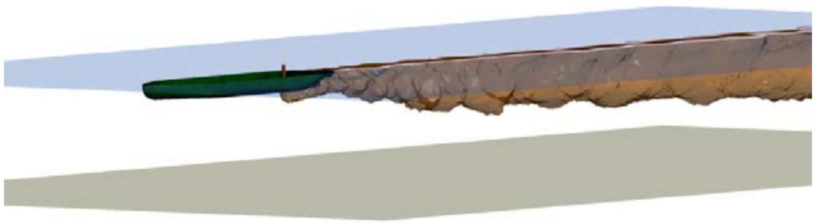


# Real-scale model

- CFD simulation result

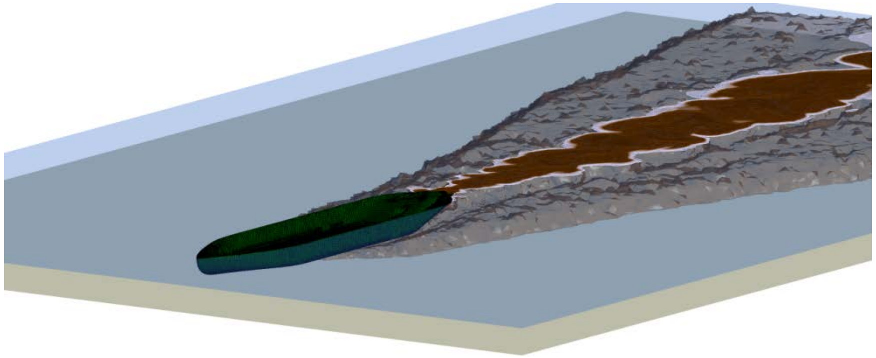
# Real-scale model



Deep water, light mixture

Deep water, heavy mixture

Shallow water

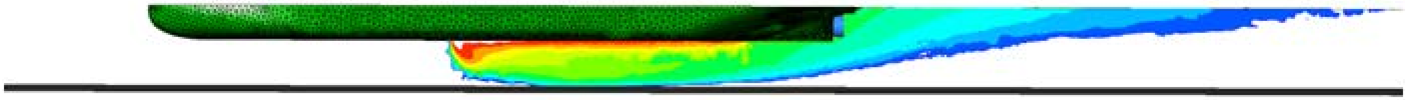


**! Validation needed**

↓

**Monitoring campaigns**

Air bubble concentration





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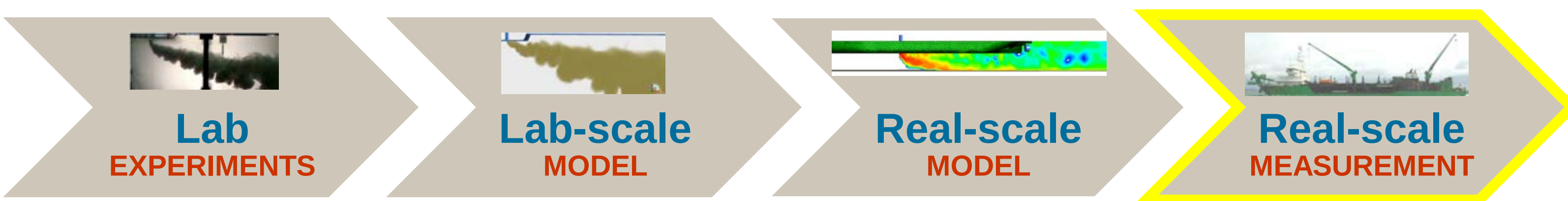
# Overview Model development



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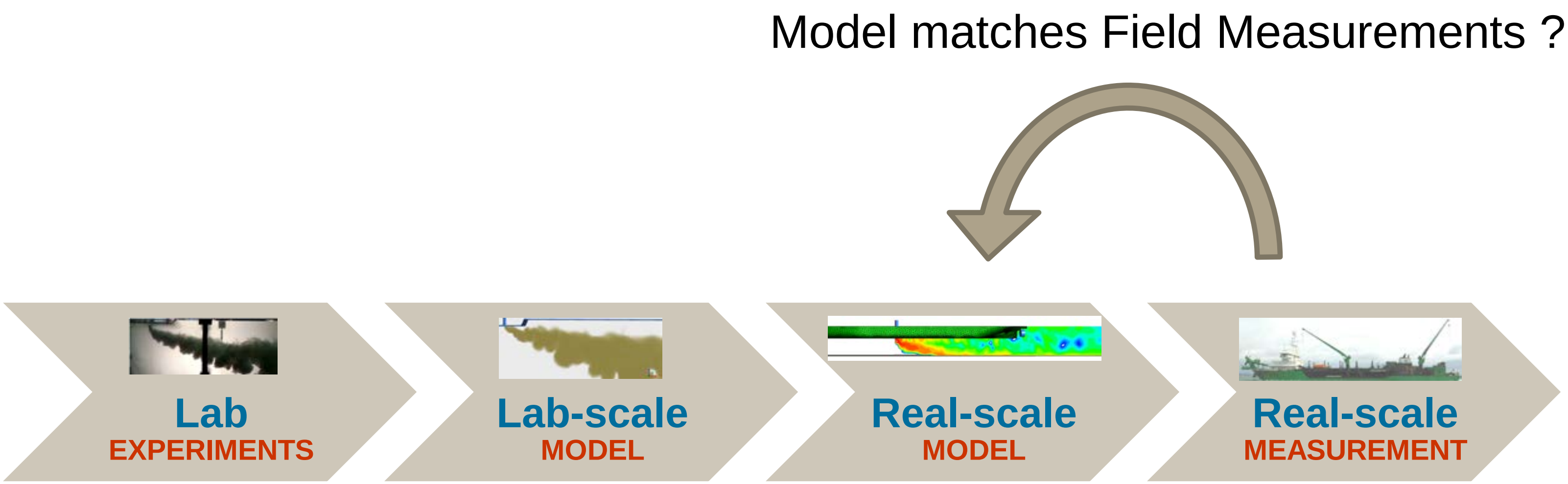
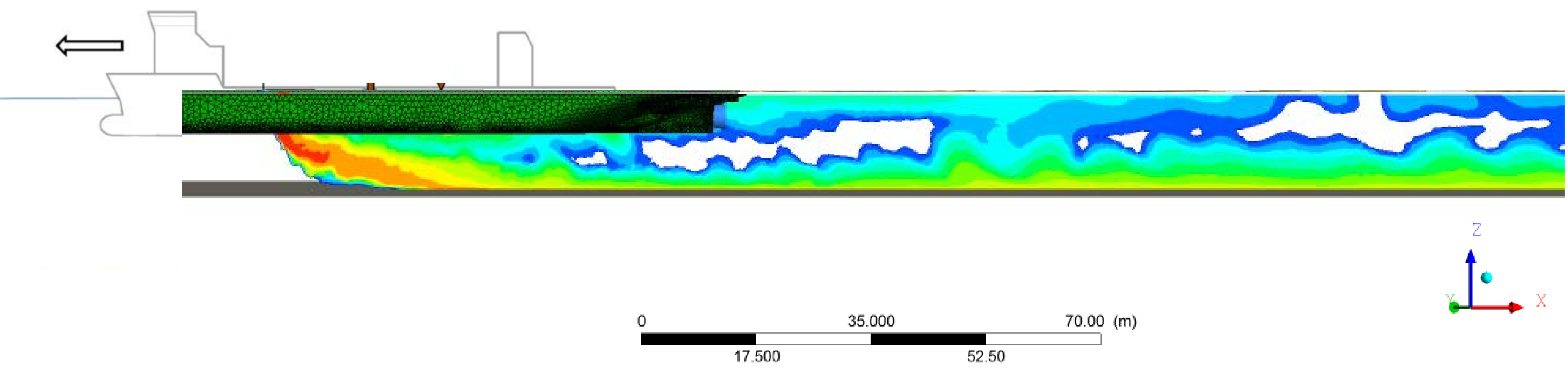


# Results Validation CFD

## Validation Case 1:

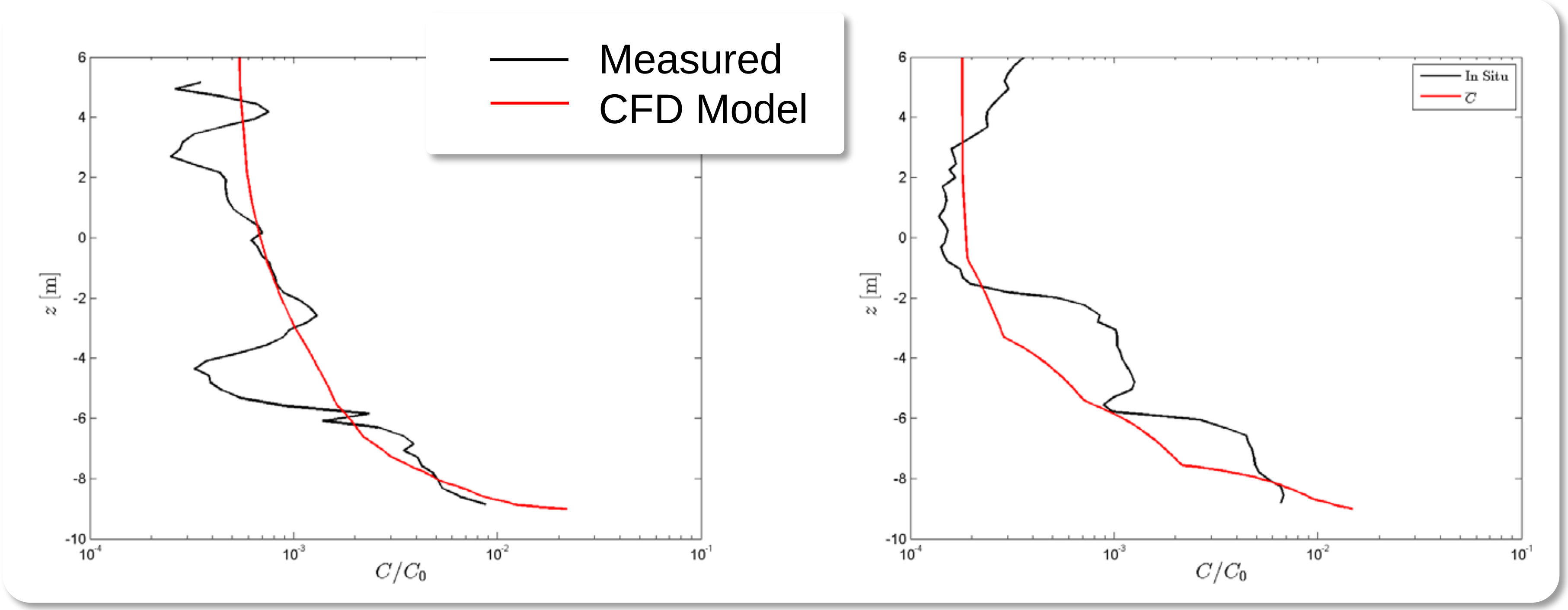
- H=16m ; D=2m; $W_0$=1.9 m/s; $U_\infty$=1.5 m/s, $C_0$=55 g/l
- Field measurements: SiltProfiler (vertical profiles of ssc)
- CFD model: CPU time = 25 hours at 32 CPU's



# Results Validation CFD

**Validation Case1: Vertical profiles**

- Measurement carried out at < 200 m for near-field validation
- Compared with time-averaged model results



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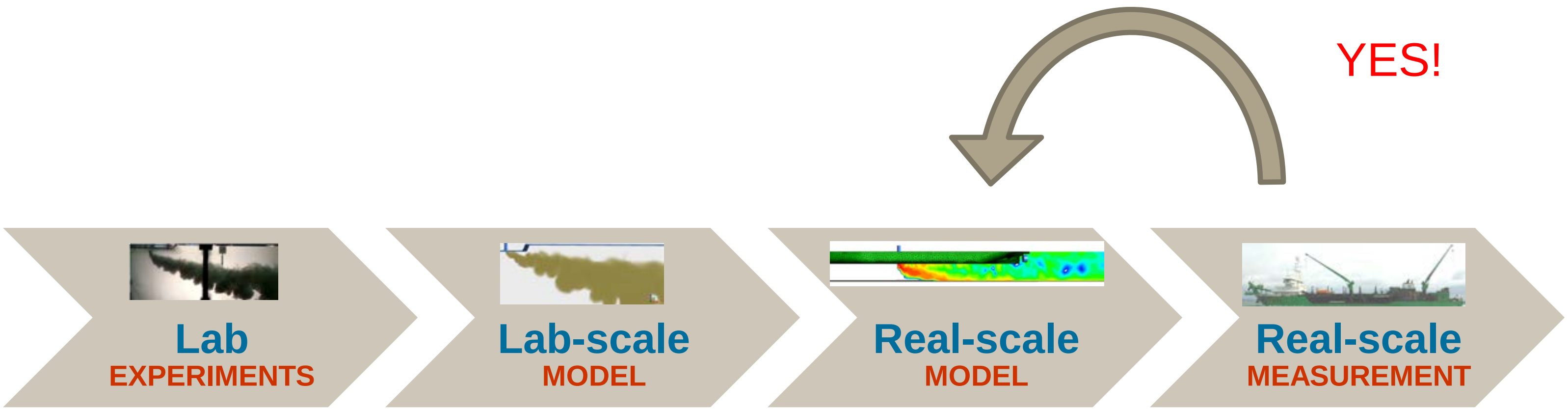
Model matches Field Measurements ?



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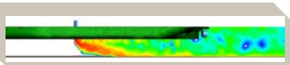

**Real-scale**
**MODEL**

**Real-scale**
**MEASUREMENT**

**Applications:**

*Influence factors

* Ship Design

*Simplified Model



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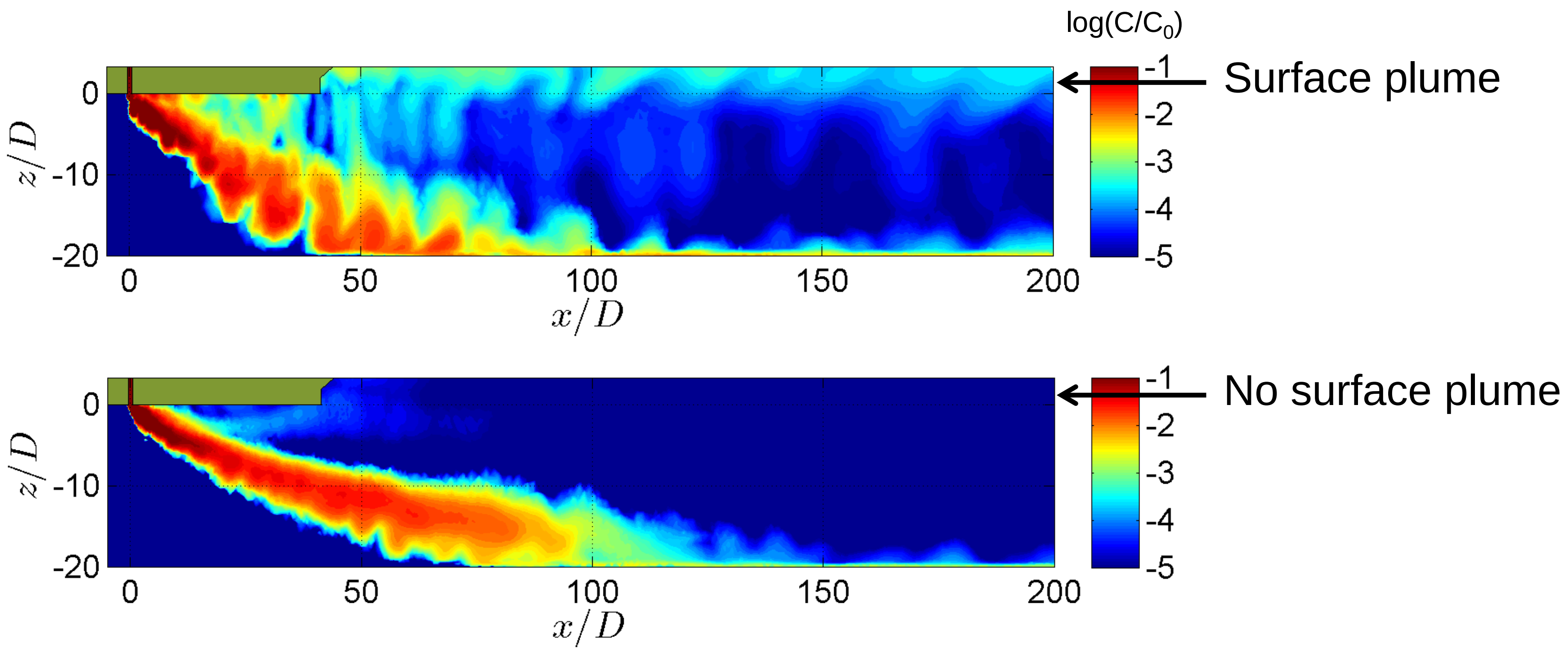
# Influence of air bubbles

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

- 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))



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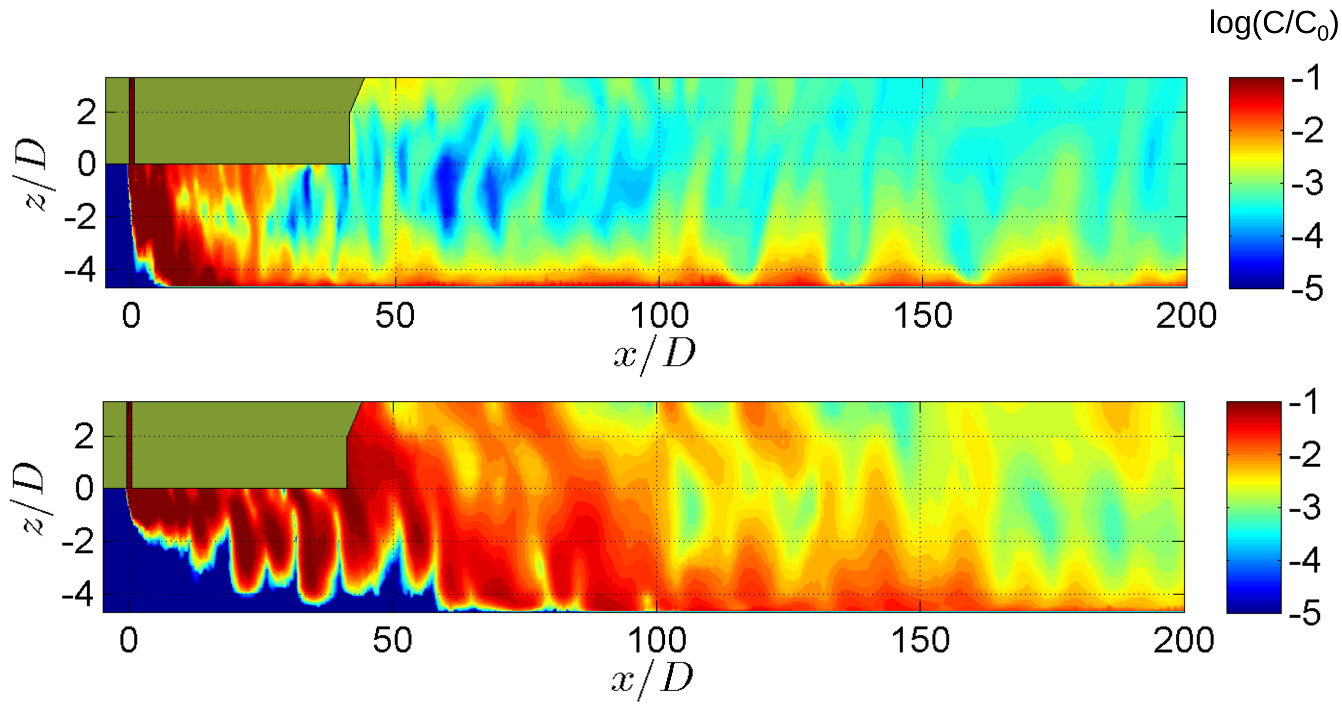
# Influence of sailing velocity

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

Relative velocity sea water - ship

2 knots

6 knots




→ **sediment in surface plume x 10**

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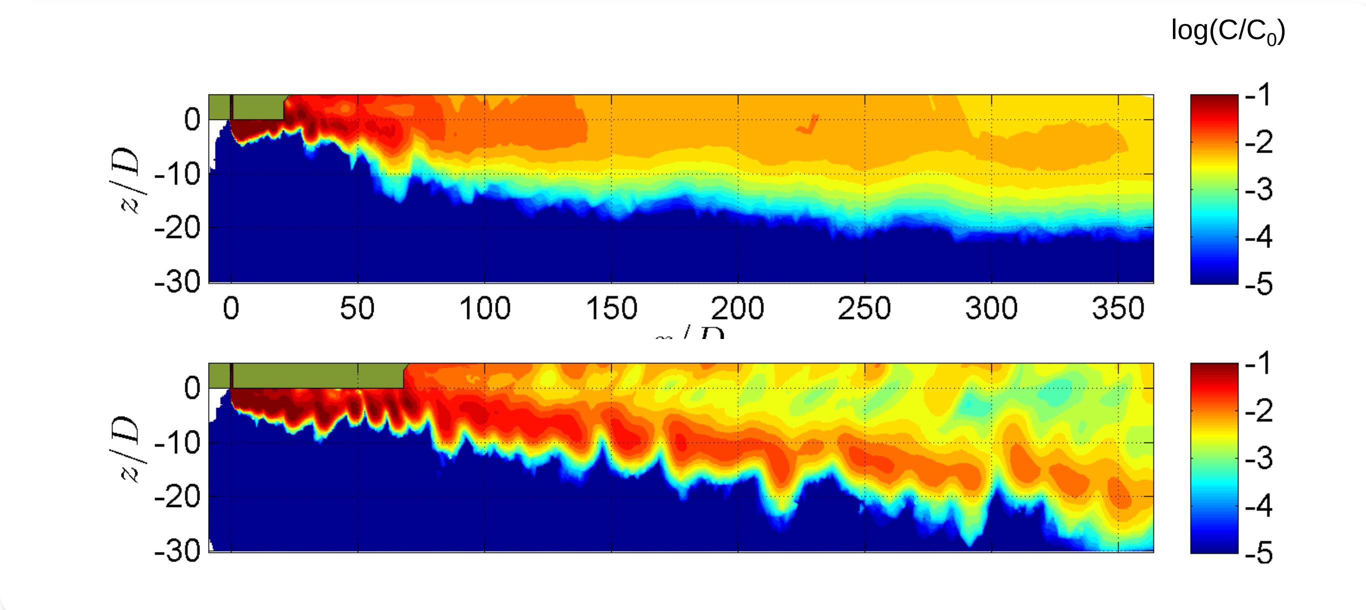
# Overflow position

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

- Overflow at stern: plume mixed by propellers
- Overflow at aft: plume has more time to descend



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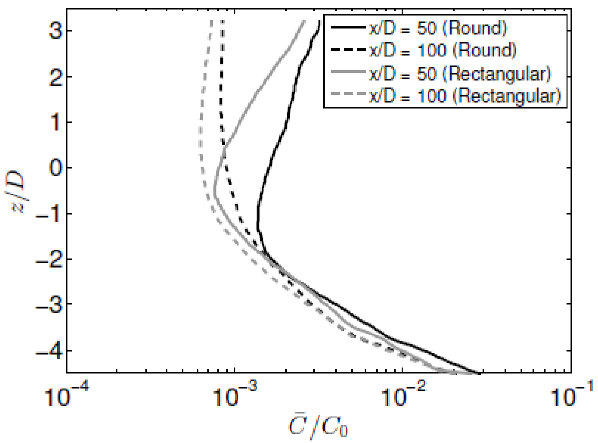
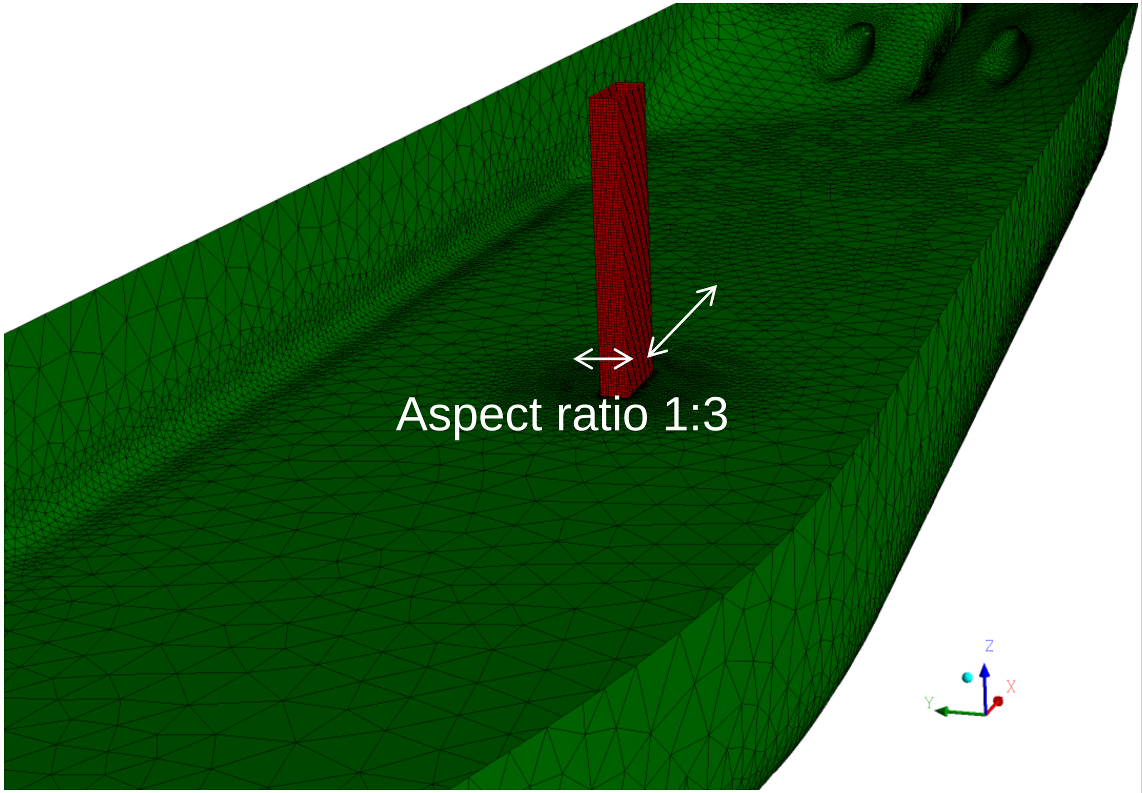
# Ship design: rectangular overflow shaft

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




→ **Potentially 50% reduction of surface plume sediment concentration**



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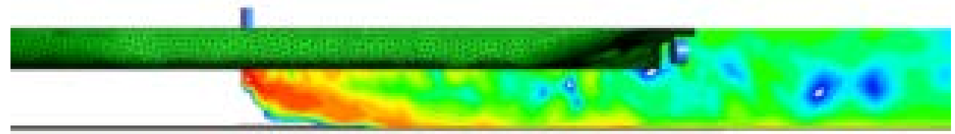
# Parameter model overflow plumes

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

## 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 far-field models input

→ Vertical profile of sediment flux behind ship

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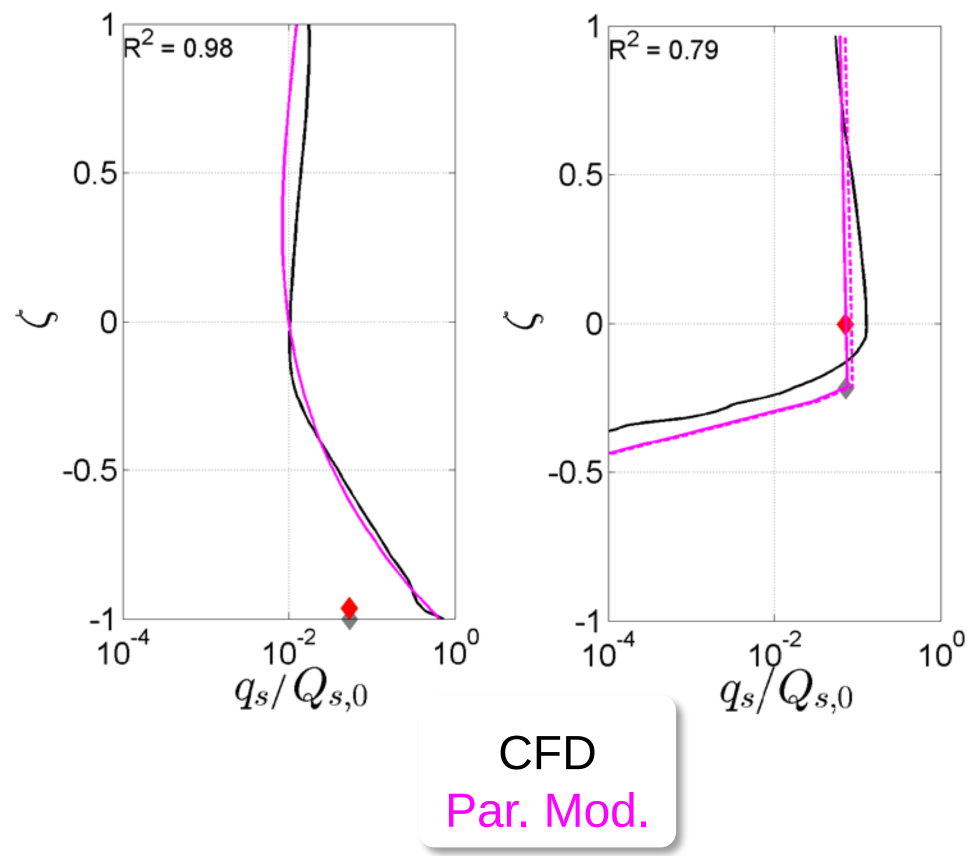
# Parameter model overflow plumes

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

- >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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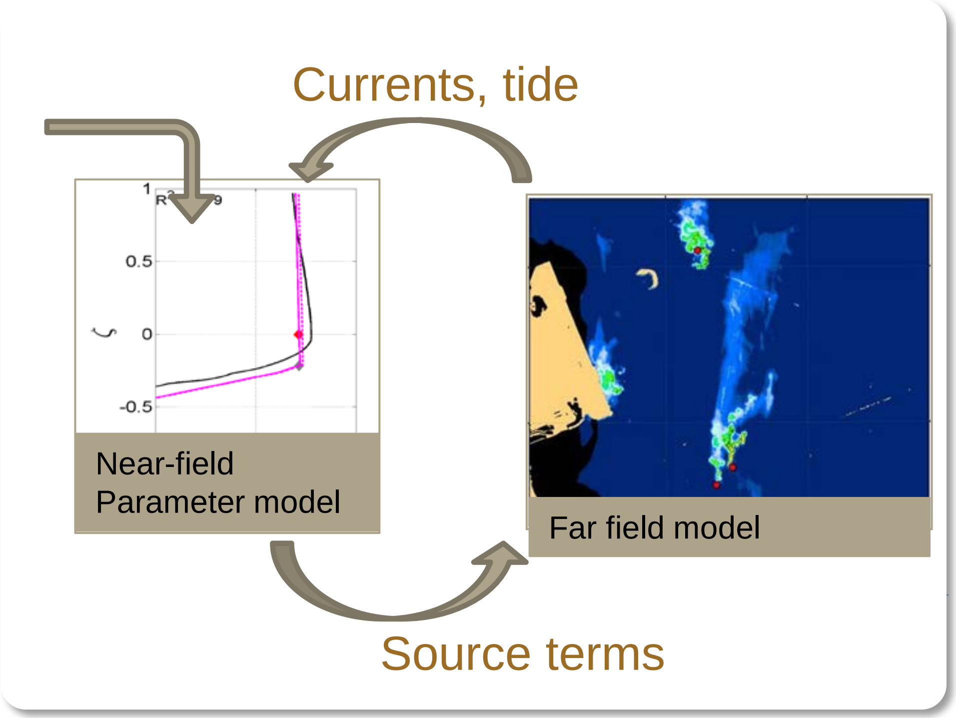
# Implementation in far-field models

**For overflow**:

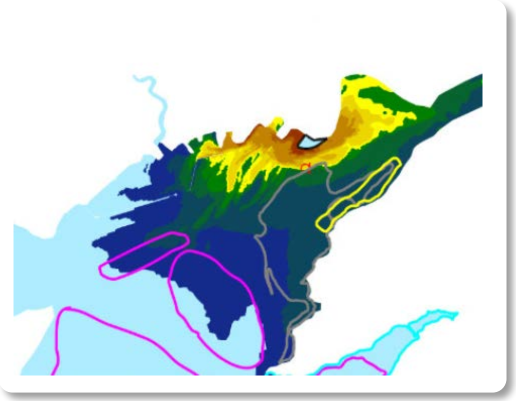
- Hopper model for sediment content in overflow discharge (Hjelmager et al., 2014)
- Fast parameter model for near-field overflow plume dispersion (< 1 sec.)
- Programmed inside far-field modelling software → real-time evolution of overflow flux
- Distribution of sediment sources is varying with:
  - 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**

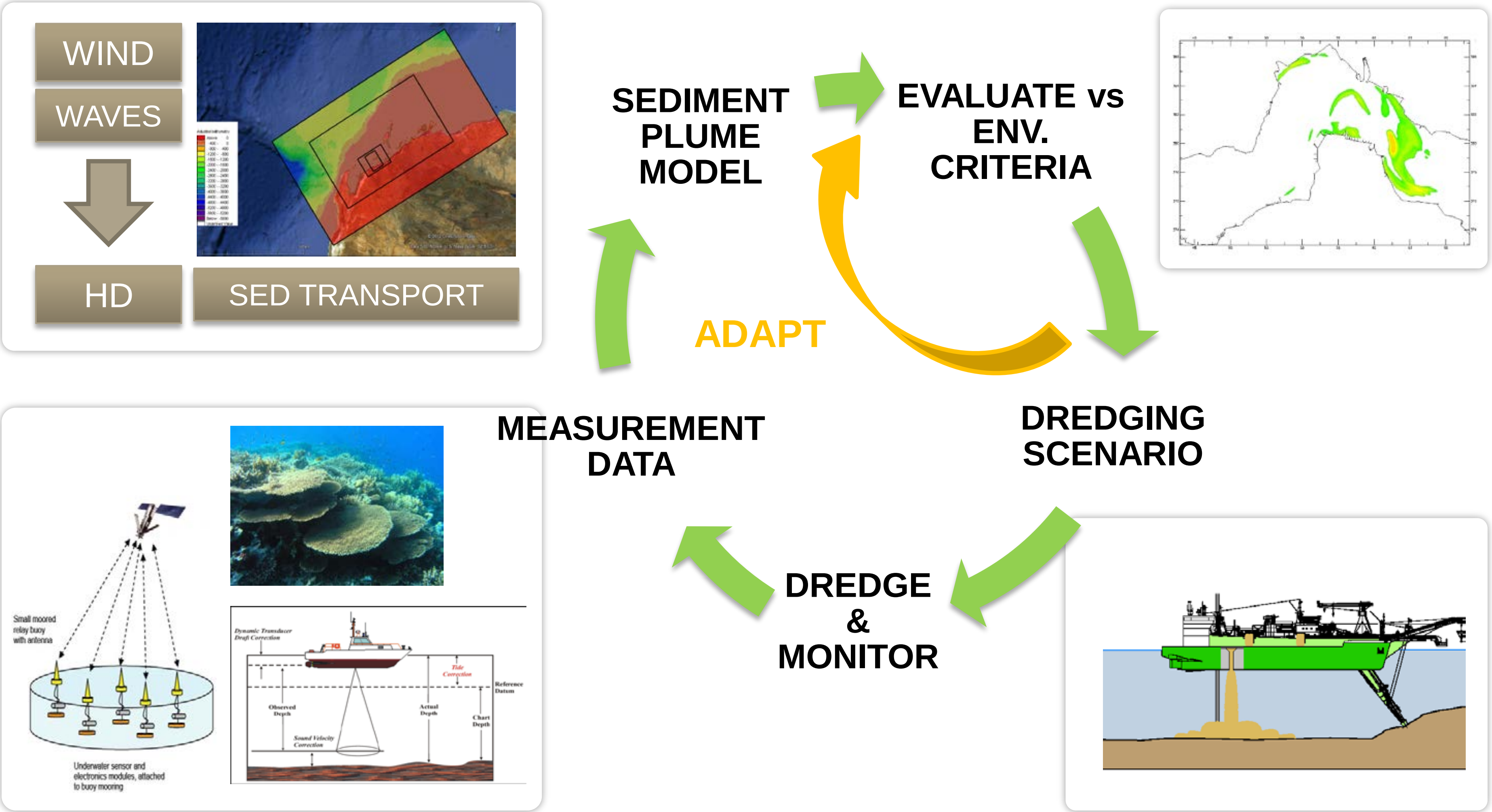
# Implementation in far-field models

## Real-time plume forecasting

- In operational phase
- Simulate, Evaluate, Adapt

→ **Pro-active Adaptive Management**

# Pro-active Adaptive Management (PAM)



# 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: Reducing risk of turbidity threshold violations



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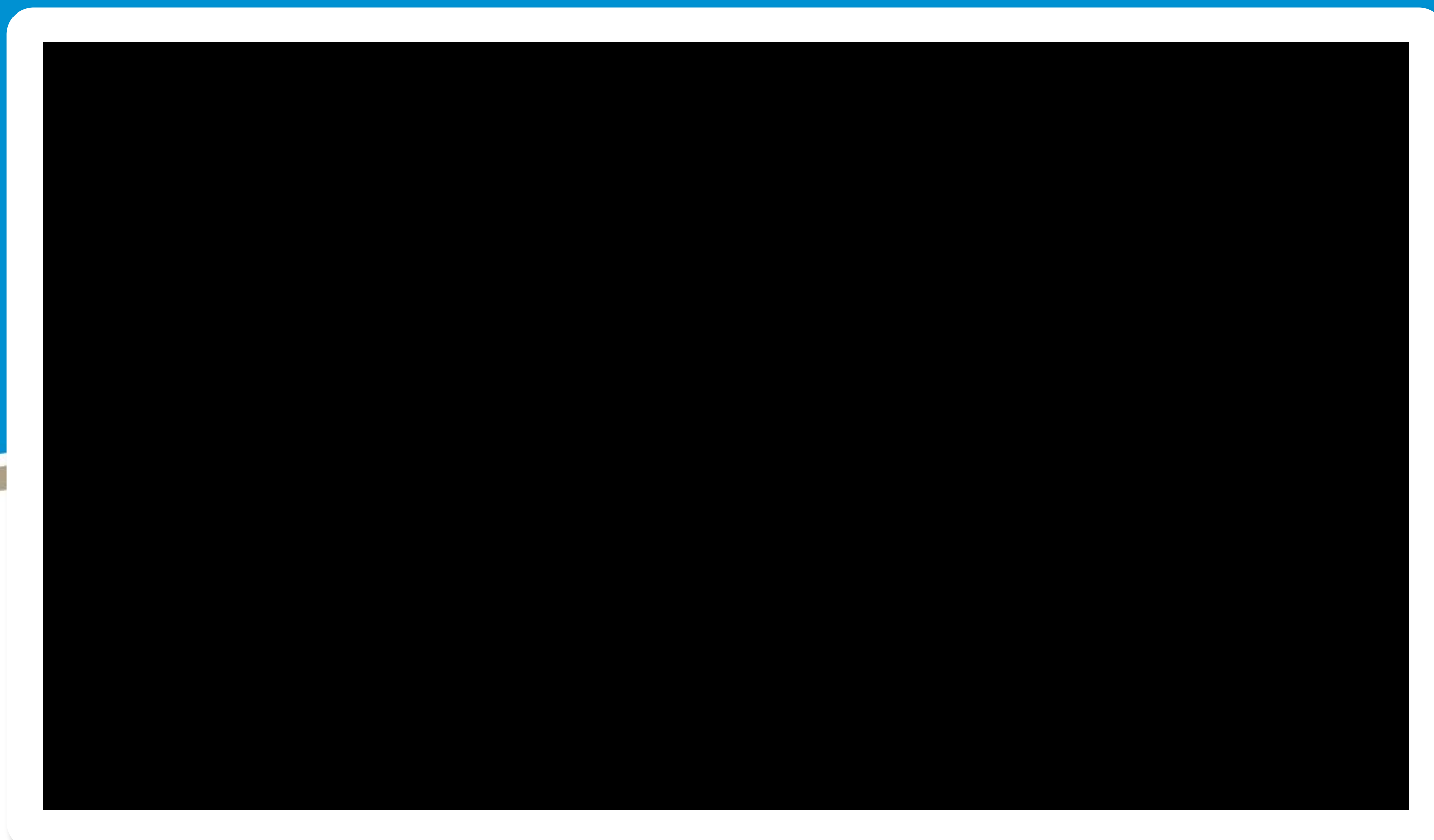
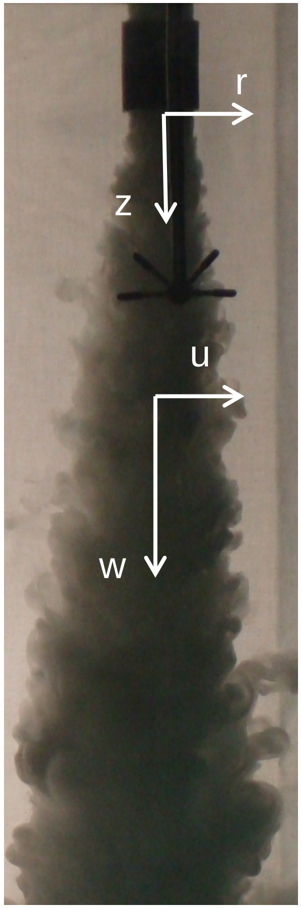
# Questions?



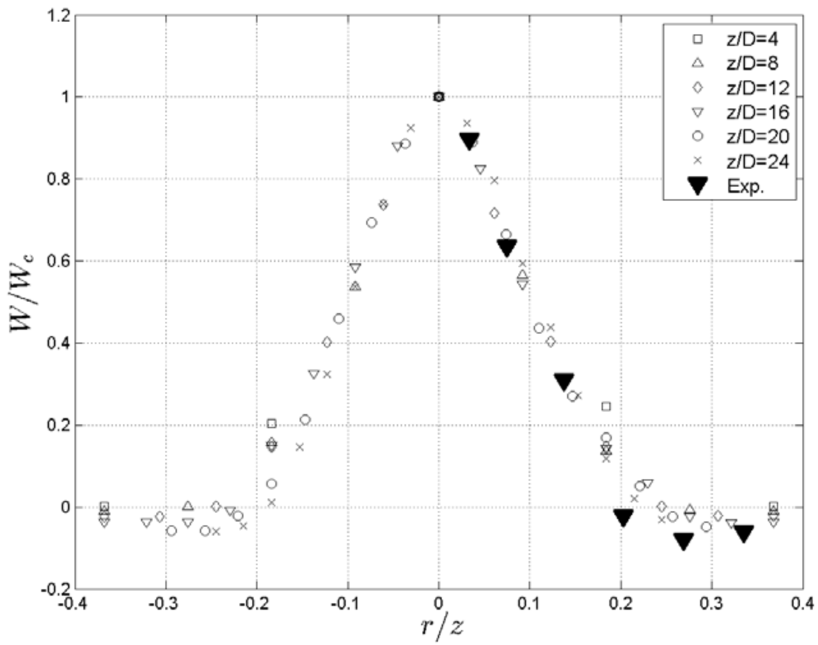
# Setup: Test case 'Vertical plume'

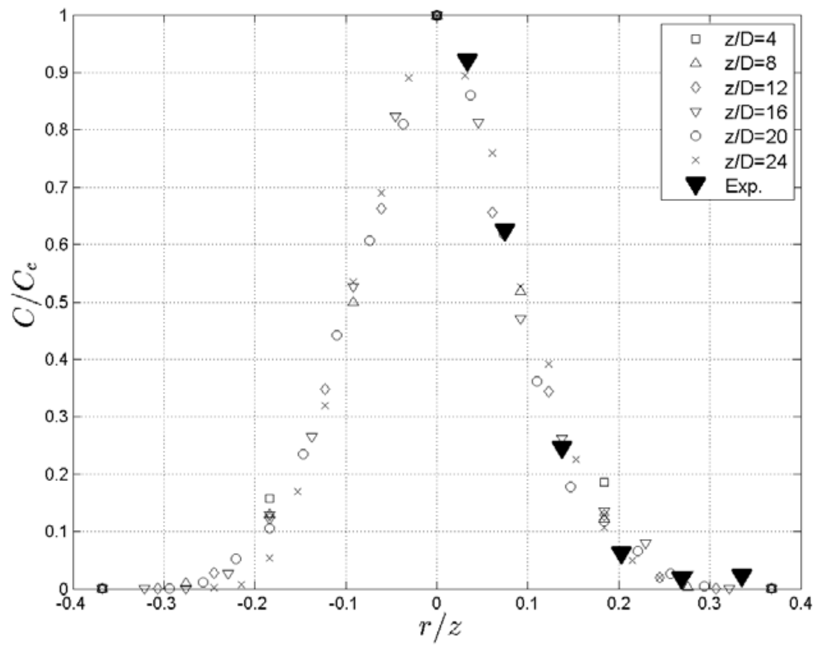
- Geometry:
  - Vertical plume as a first test case for the CFD model
- Mesh:
  - Unstructured tet mesh
  - 'Inflation layers' near walls (pipe)
- Mesh 'Adaptation':
  1. RANS simulation on relatively coarse mesh
  2. Refinement where gradients / SSC significant
  3. RANS on refined mesh
  4. LES



# Setup: Test case ‘Vertical plume’

- Results
  - Self-similarity for z/D > 8
  - Comparison with experiments
  - Good accuracy time-averaged W(r) and C(r)




Decrop, B. *et al.* (2015). New methods for ADV measurements of turbulent sediment fluxes – Application to a fine sediment plume. *Journal of Hydraulic Research 53* (3), p 317-331,



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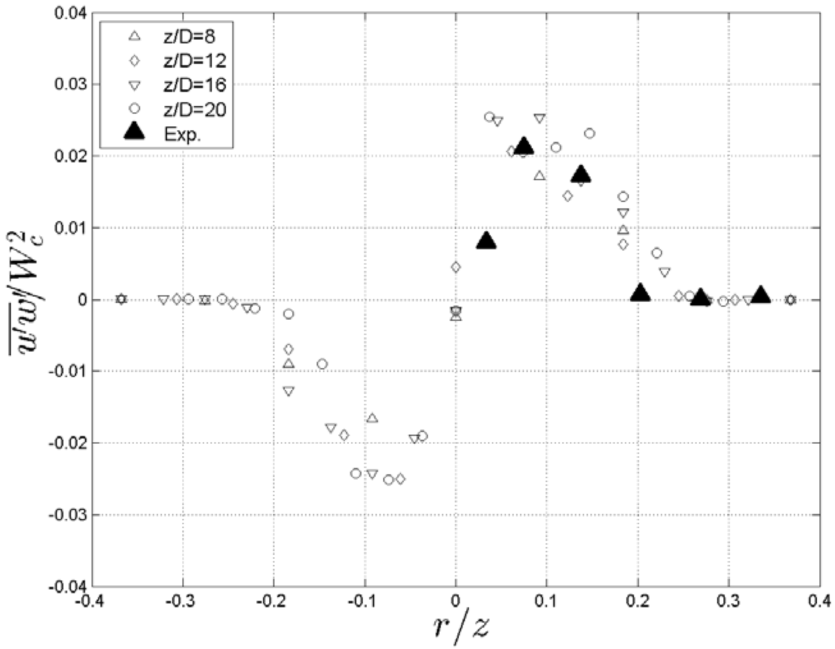
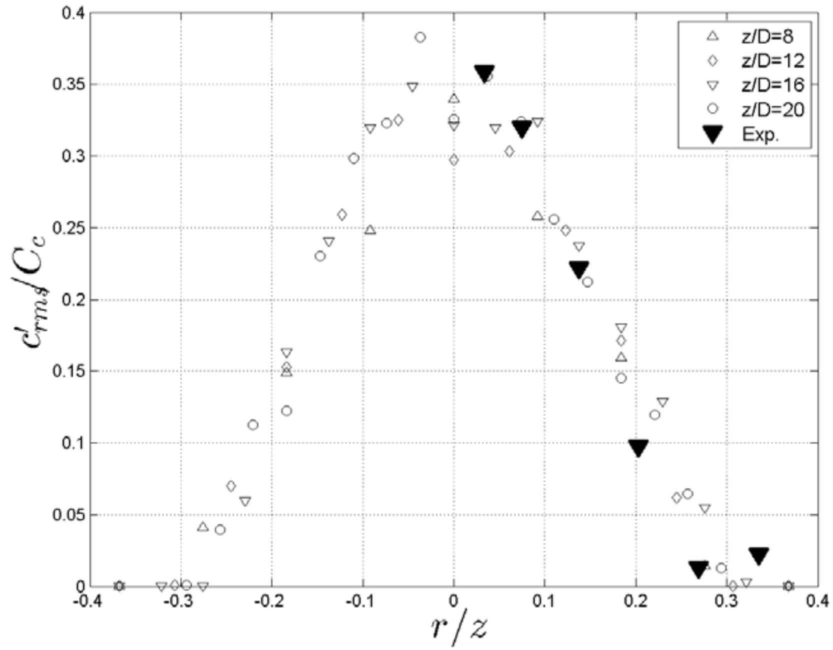
# Setup: Test case 'Vertical plume'

- Results
  - Reynolds stresses accurate: peak value, peak location
  - Turbulent fluctuations C: radial profile correct




Decrop, B. *et al.* (2015). New methods for ADV measurements of turbulent sediment fluxes – Application to a fine sediment plume. *Journal of Hydraulic Research 53* (3), p 317-331,

# Experiments



## 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



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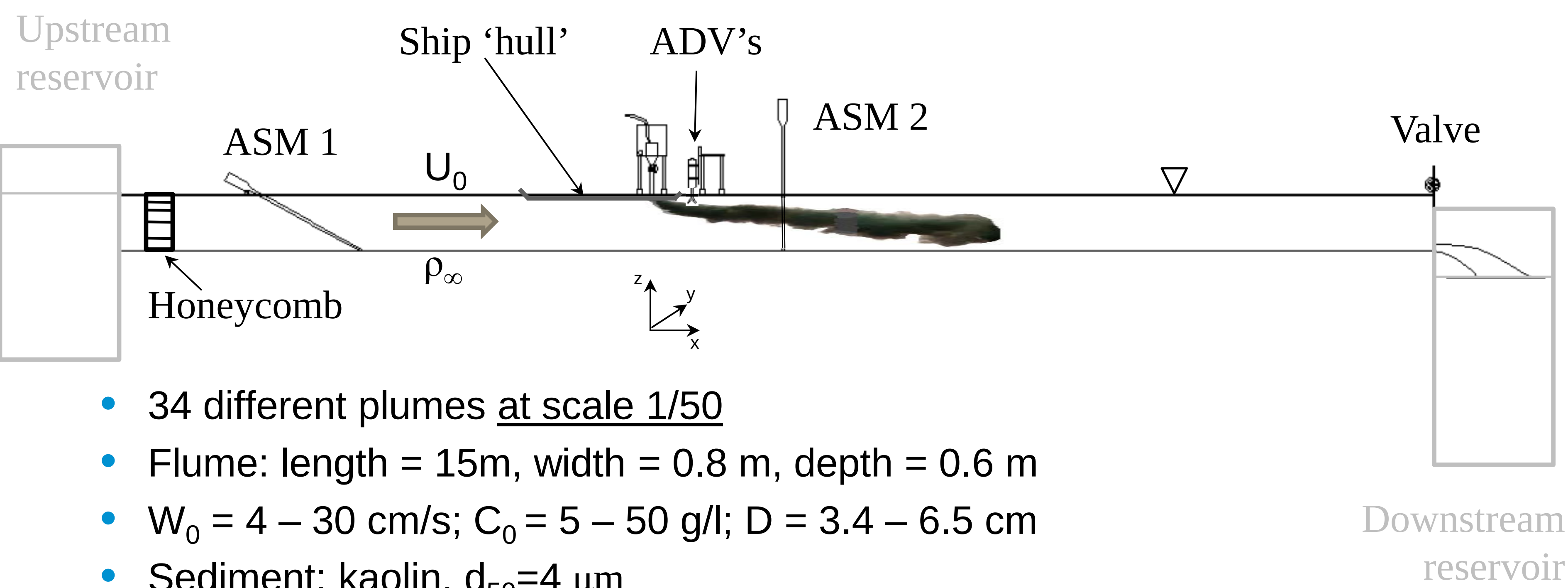
# Experiments



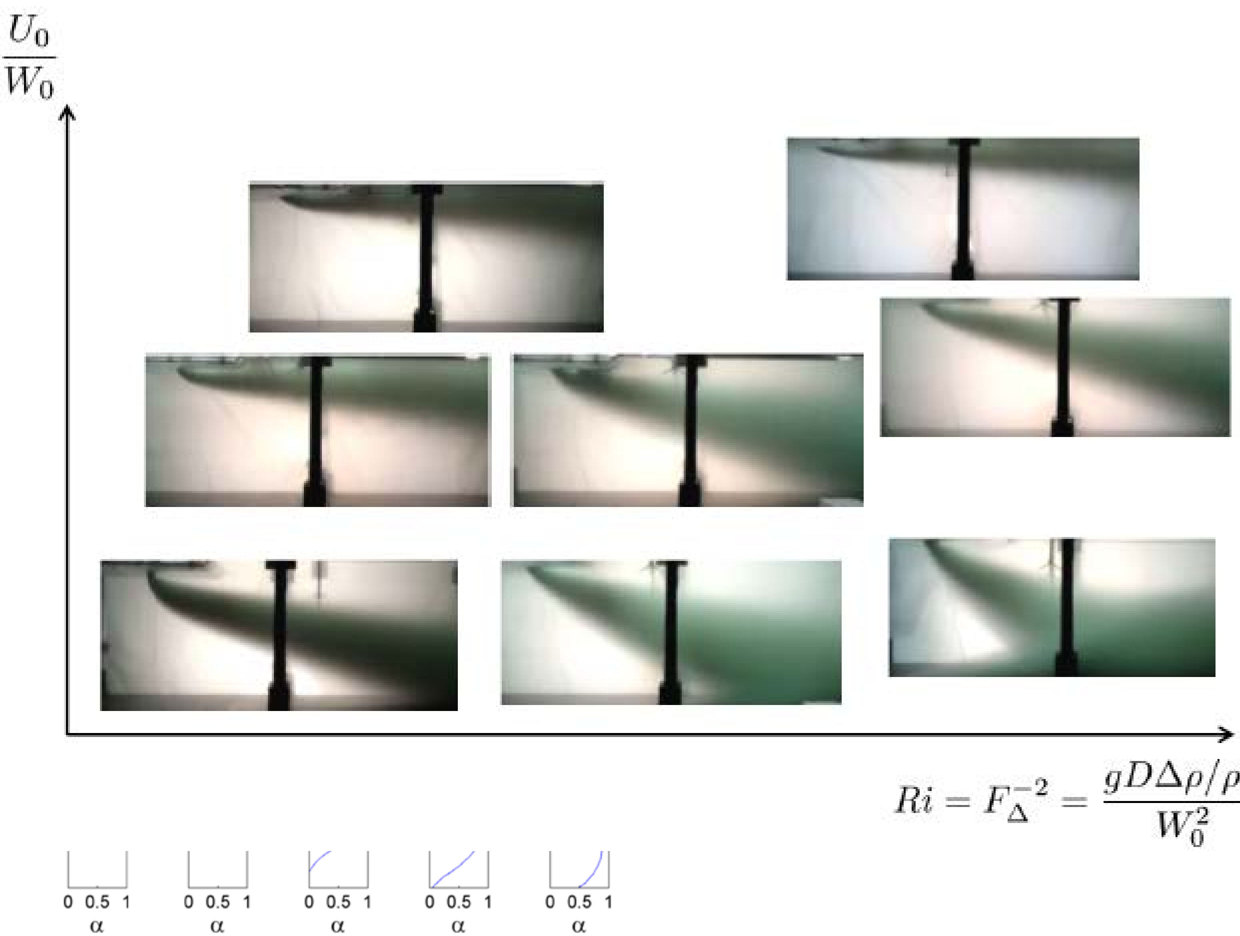



- 34 different plumes <u>at scale 1/50</u>
- Flume: length = 15m, width = 0.8 m, depth = 0.6 m
- $W_0$ = 4 – 30 cm/s; $C_0$ = 5 – 50 g/l; D = 3.4 – 6.5 cm
- Sediment: kaolin, $d_{50}$=4 μm
- Dynamically scaled:
  - Densimetric Froude number $F_\Delta$
  - velocity ratio λ

# Results

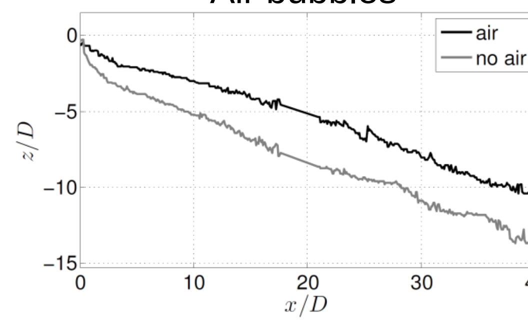


1. Plume trajectory
2. Profiles of:
   - Sed. concentration
3. Influence factors

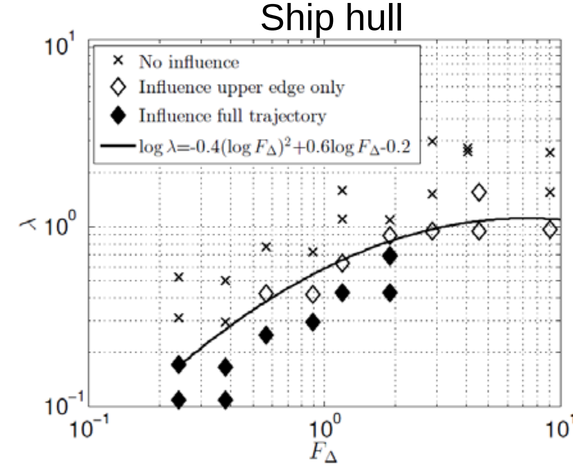



$$Ri = F_{\Delta}^{-2} = \frac{gD\Delta\rho/\rho_w}{W_0^2}$$

Air bubbles




Ship hull



# Lab-scale Model

- Navier-Stokes eq's for the mixture
- Models:
  - Multiphase: mixture model (with drift flux term, slip velocity, drag)
  - Turbulence: Large-Eddy Simulation (LES)
    - SGS model: Dynamic Smagorinsky

      → each (x,y,z,t): $\nu_t$, $D_t$ and $Sc_t$
- Phases mixture model:
  - Liquid phase: fresh water
  - Sediment: spherical, d=4 $\mu m$
    - Stokes number << 1
    - Volume concentration 0.2 to 4%
- Inflow boundary: spectral synthesizer (vortex mimicking)
- Water surface: rigid lid

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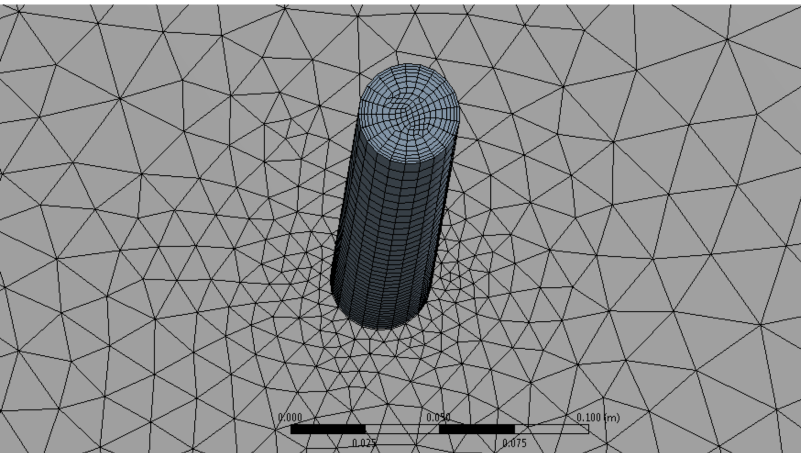
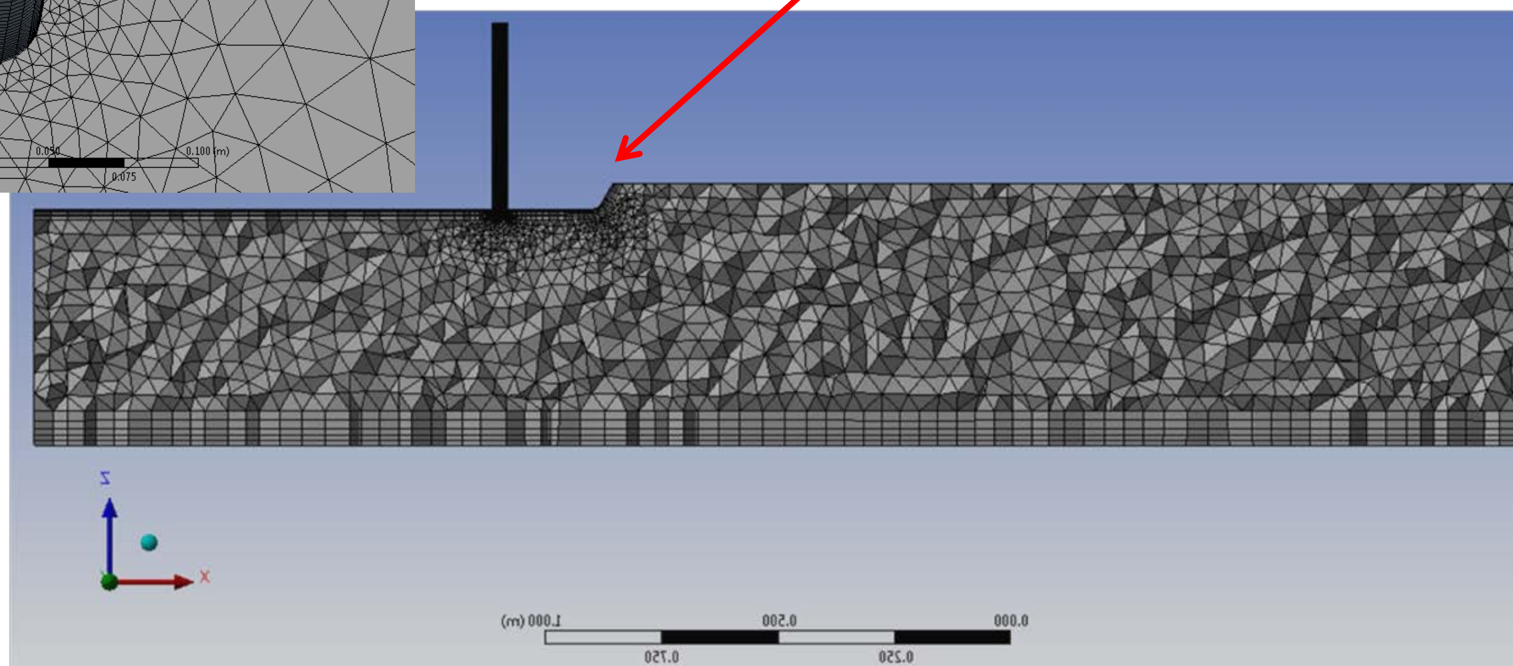
# Setup : Plume in crossflow

- Mesh, initial:

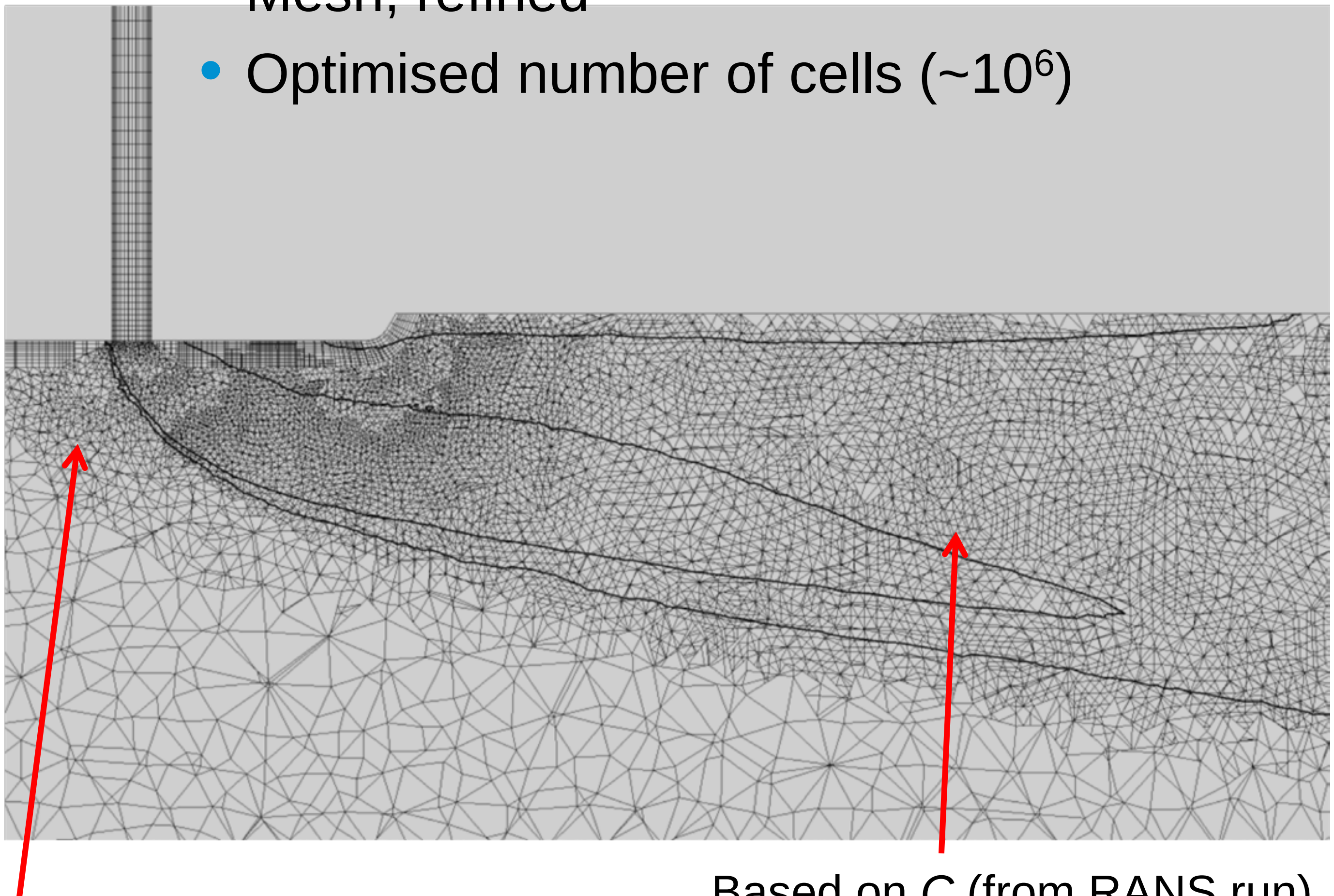



Schematised hull



# Setup : Plume in crossflow

- Mesh, refined
- Optimised number of cells (~$10^6$)



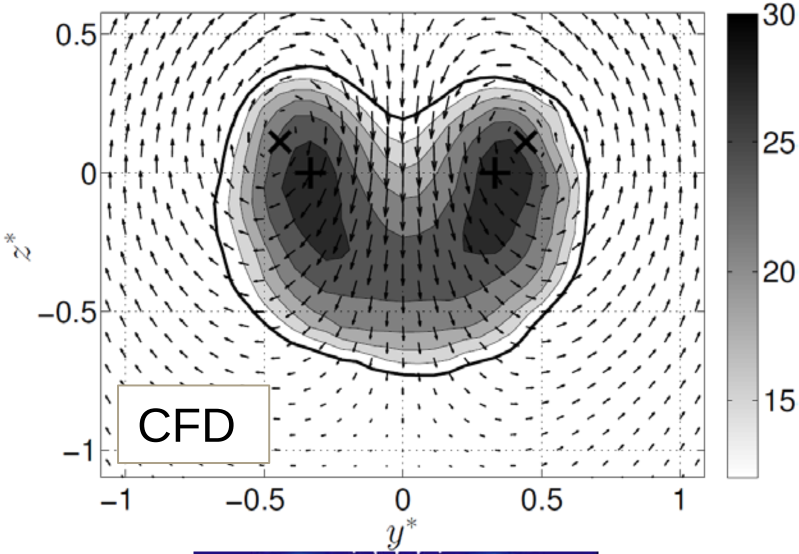
Based on *C* (from RANS run)

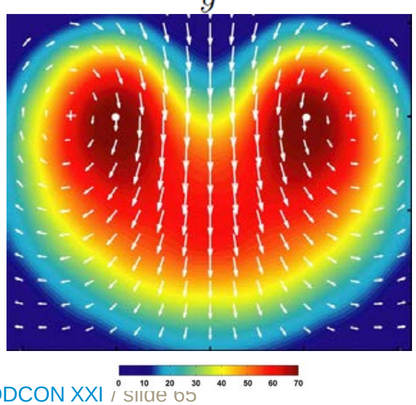
Based on strain rate

# Results

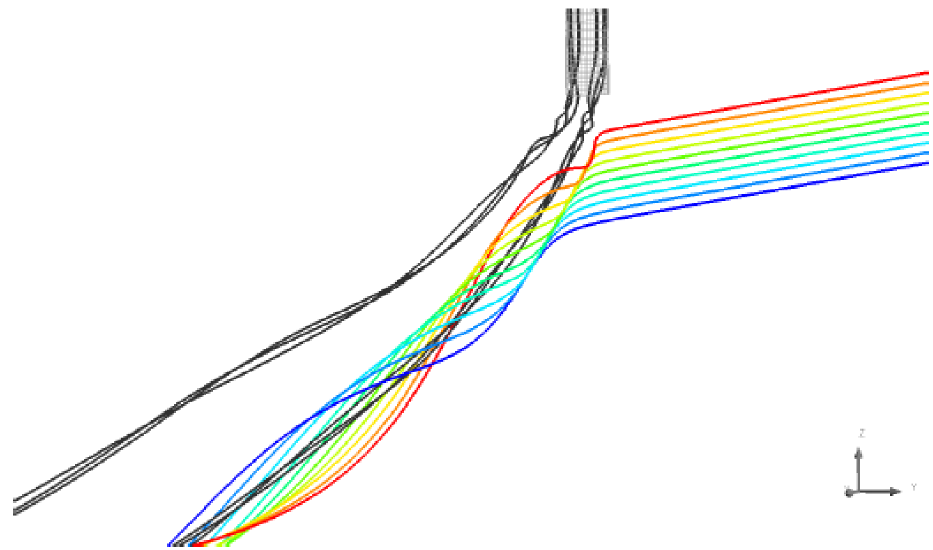
- Qualitatively : well-known turbulent structures are present:

2. Counter-rotating vortex pair + double C-peak



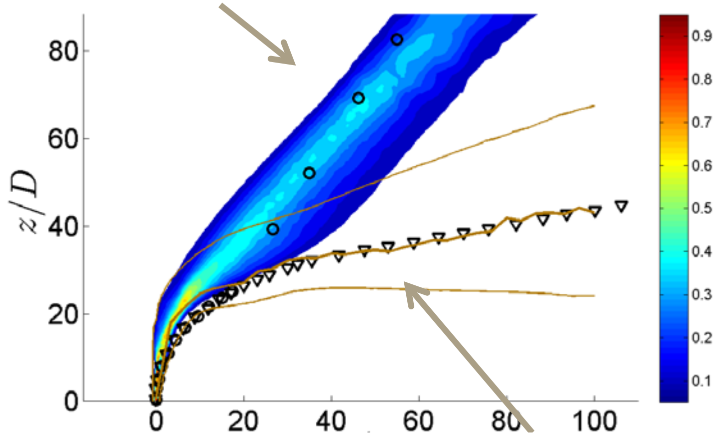

PIV/PLIF measurements, Diez *et al.* (2005)

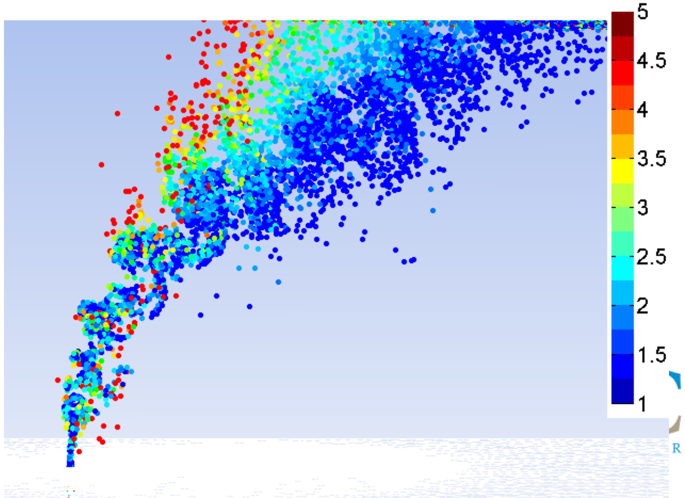


# Validation case : Bubble plume in crossflow

- Case of Zhang et al. (2013)
  - Upward bubbly jet (20 vol.% air)
  - Tracer in jet fluid
  - Centerline tracer plume
  - Centerline bubble plume
- LES model with three phases:
  - Water
  - Sediment (tracer)
  - Air bubbles:
    - Initial diameter: 1.7 mm
    - Collision model

      → Coalescence → bubble size distribution
  - Influence bubbles on sediment plume: ok
  - Separation bubble plume: ok

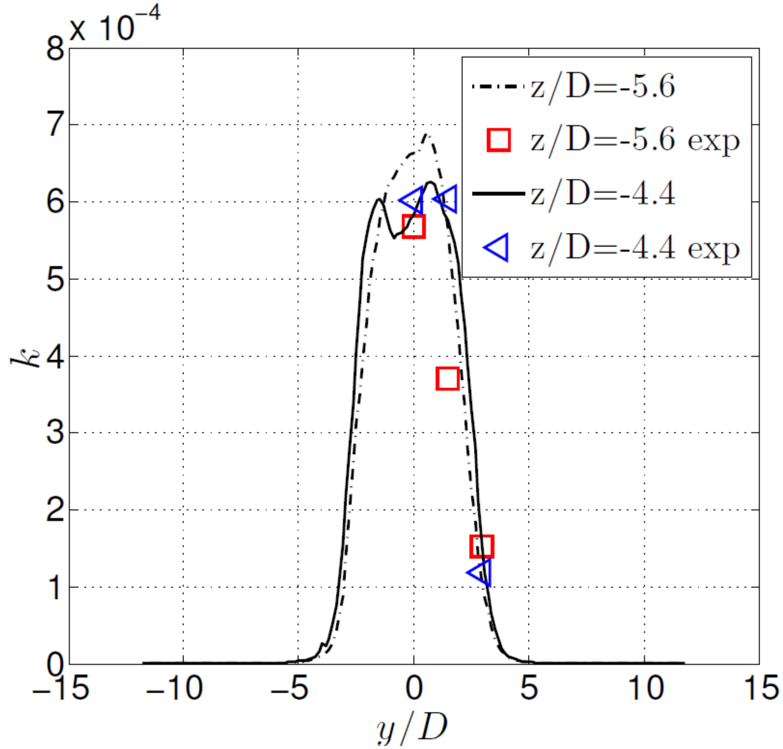


# Results

Quantitatively:

3. Turbulent Kinetic Energy *k*




Decrop, B. *et al.* (2015). Large-Eddy Simulations of turbidity plumes in crossflow. *European Journal of Mechanics - B/Fluids* (53), p68-84,



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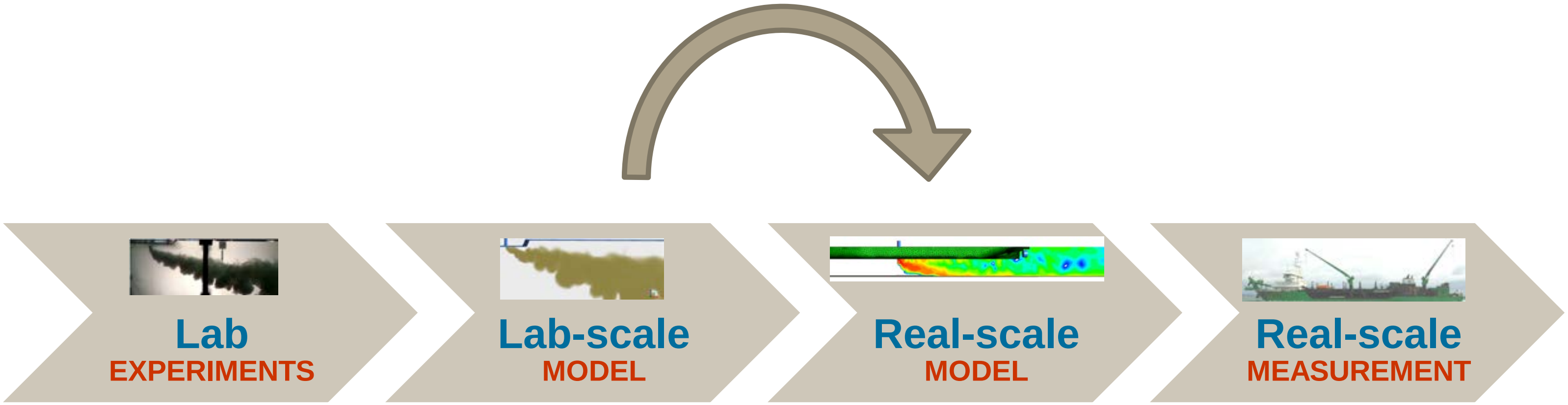
# Overview Model development

Next step: validate upscaling to real-life size



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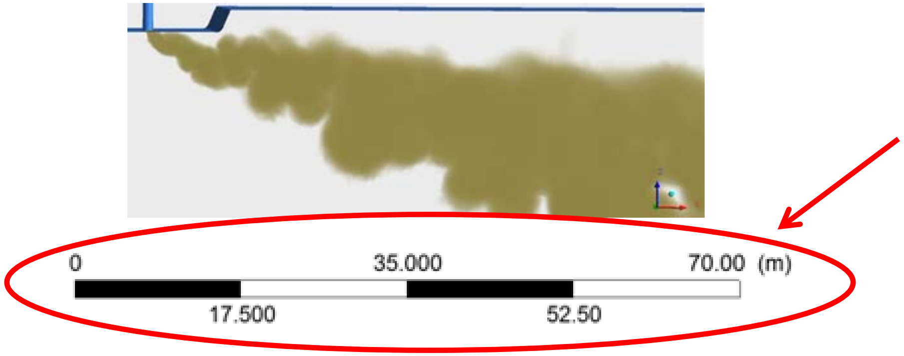
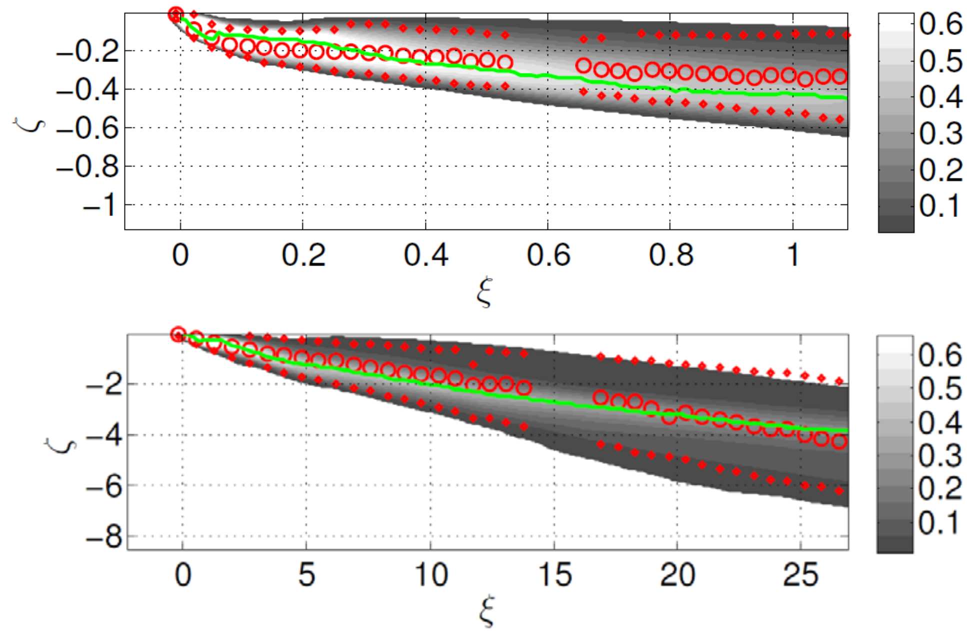
Upscaling to realistic scale:

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)




CFD (large scale, Re=1.9 $10^6$)

Physical model (small scale, Re=1.2 $10^4$)



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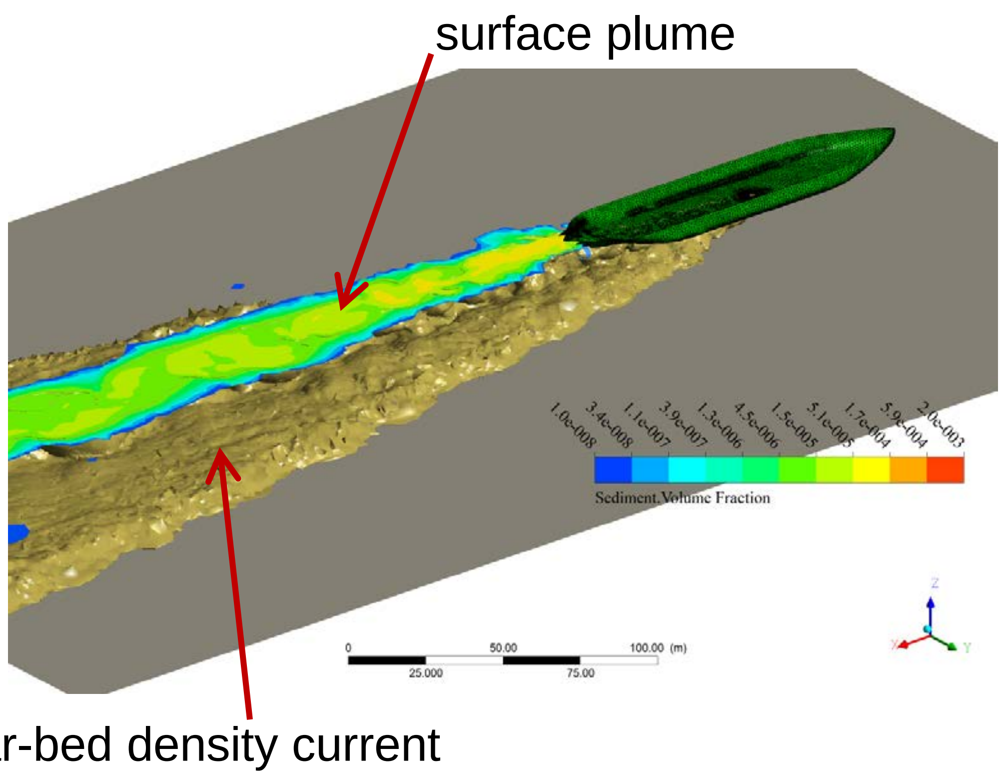
# Results Validation CFD

- Density current + Surface plume (air bubbles, propellers)
- 5% of sediments released to ‘far-field’ plume
- Hypothesis confirmed?



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# Measurements



Determination of sediment concentration:

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

- Measurements and samples in the dredging plume



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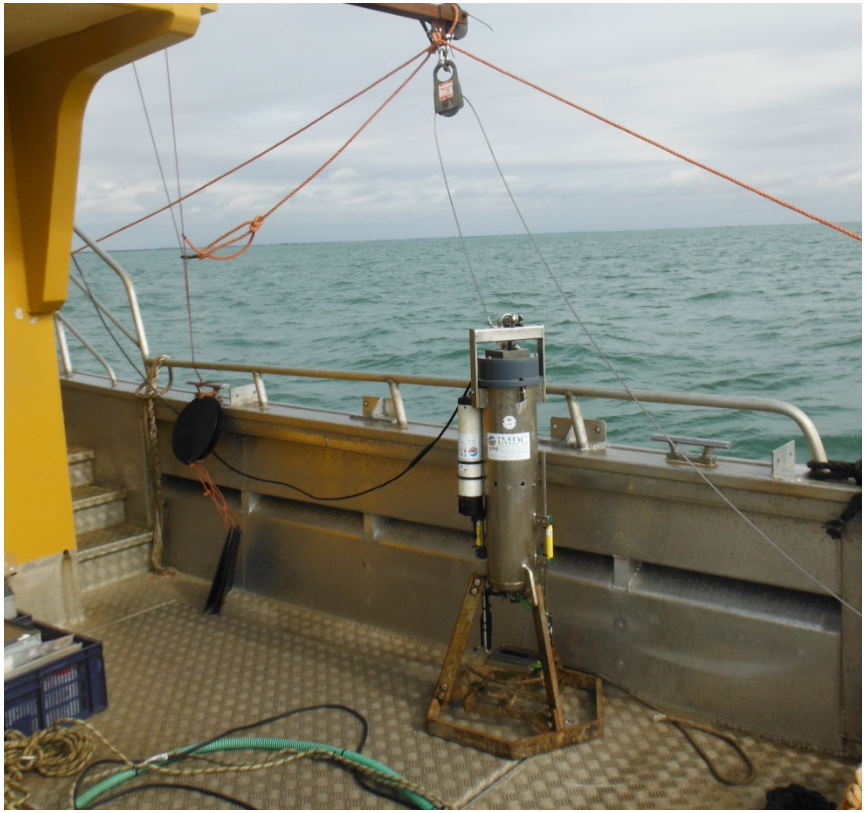
# Measurements

**SiltProfiler**:

- High-res. vertical profiler (free-fall,100 Hz)
- Wireless connection when above water (BlueTooth)
- CTD
- 3-step turbidity sensor (0 – 50,000 mg/l)
- Design avoids seabed disturbance

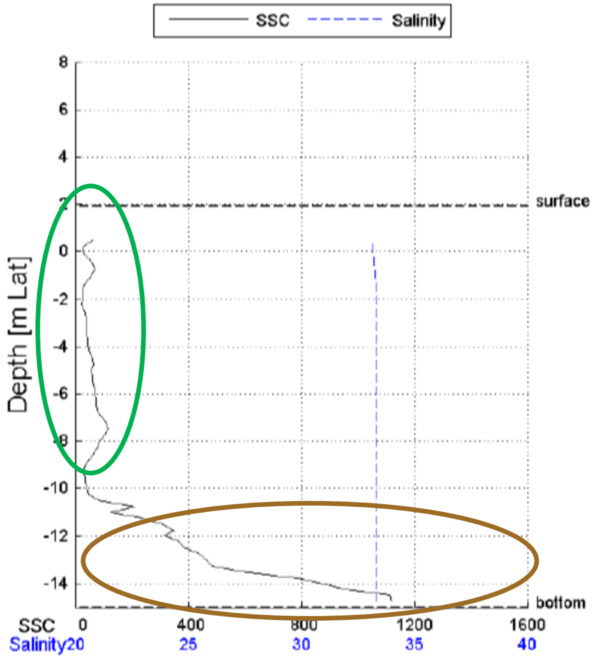


# Measurements

<u>SiltProfiler results</u>

→Consistent profile type:

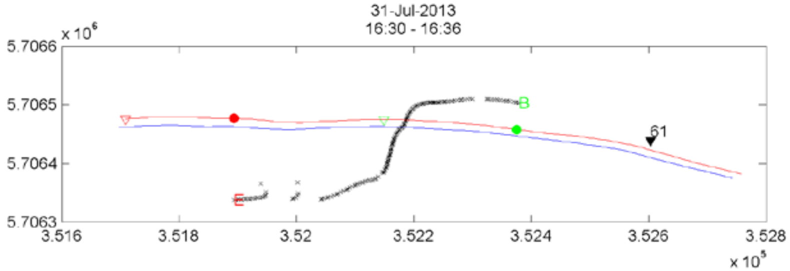
1. Diluted surface plume: 10-200 mg/l
2. Near-bed layer, 2-6m thick: 200-1500 mg/l



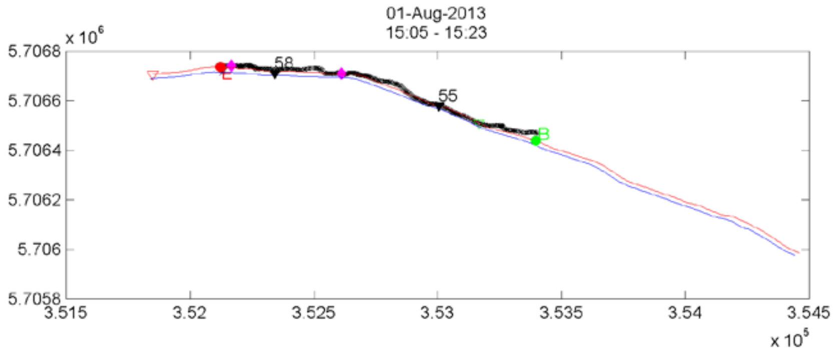
# Measurements

Transect sailing (near-field, 100-500m from stern)

Across the plume




Along the plume

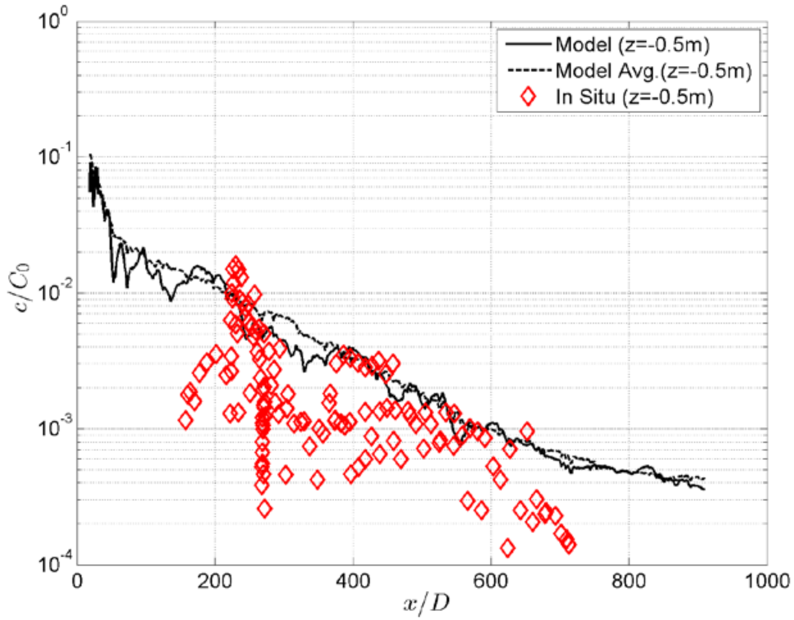


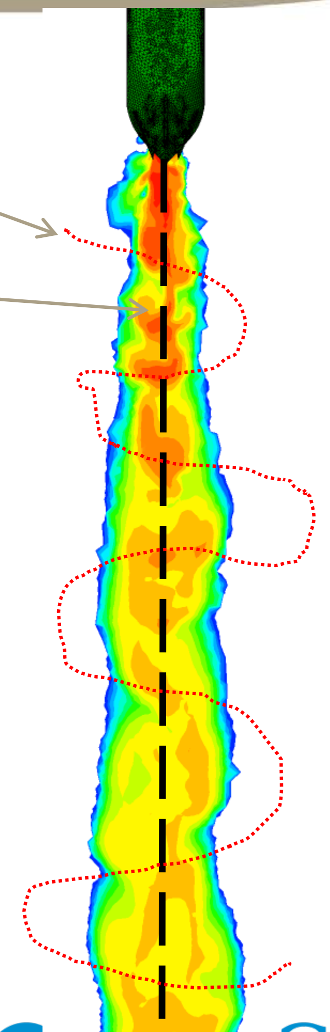
# Validation prototype scale CFD (Case 2)

Case 2: Surface plume (OBS measurements)

- In situ measurements: lumped, crossing the plume
- Model output: at centreline

→ $C_{max,insitu}$ should be = $C_{centreline,model}$

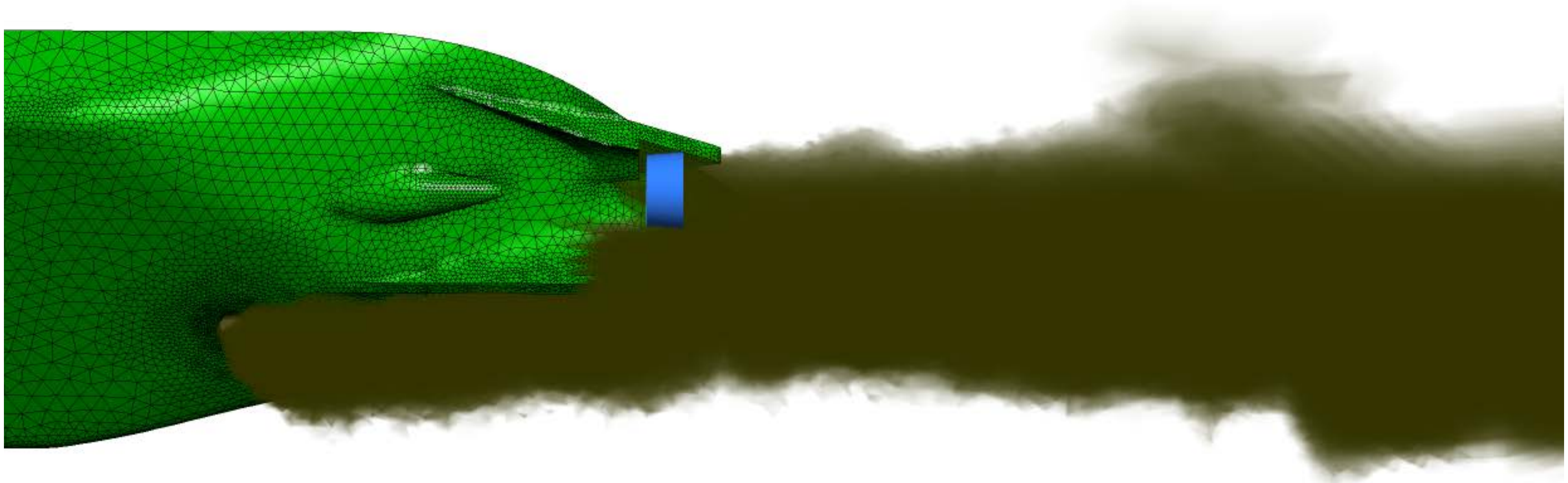


# Results Validation CFD (Site nr 2)

Validation Case 2:

- H=39m ; D=1.1m ; Overflow near stern

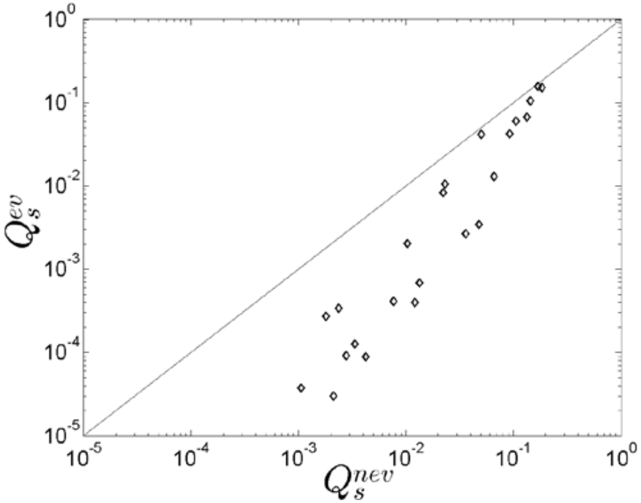


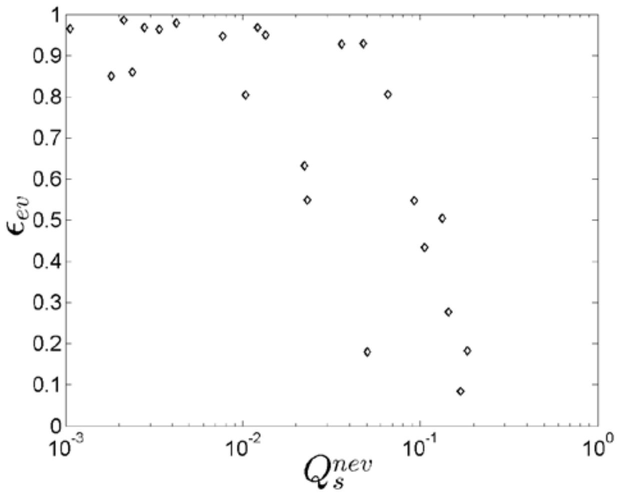
→ In contradiction to hypothesis: 100% of sediment released to far-field plume

# Environmental valve efficiency

- 2x 26 cases, with/without valve
- Valve efficiency = function of surface plume sediment flux with/without valve

$$\epsilon_{EV} = 1 - \frac{Q_s^{ev}}{Q_s^{nev}}$$



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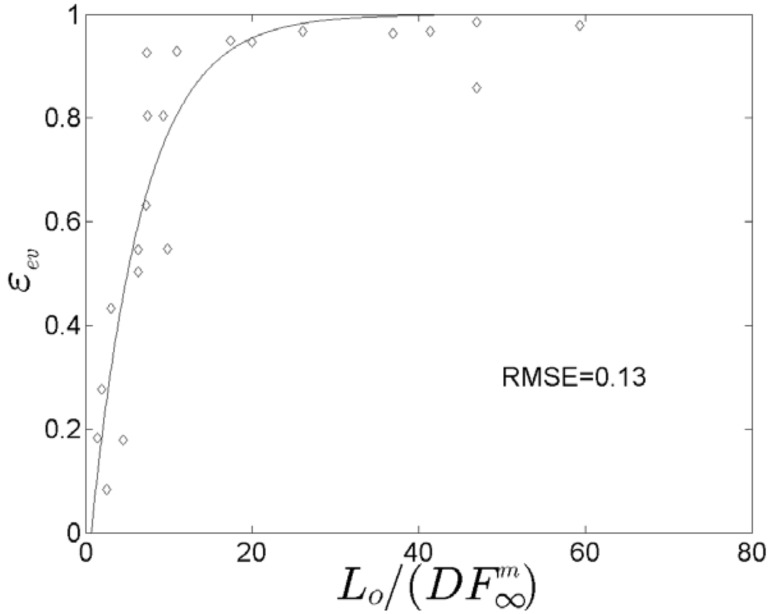
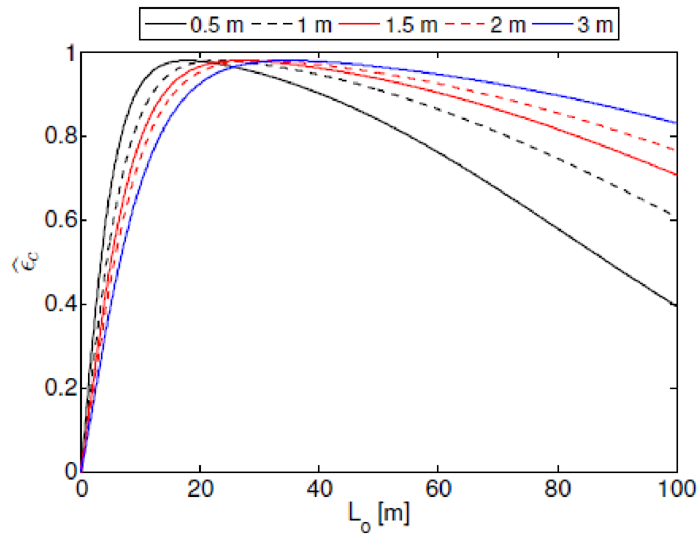
# Environmental valve efficiency

- Valve efficiency turns out to be related to a combination of length scales and a Froude number

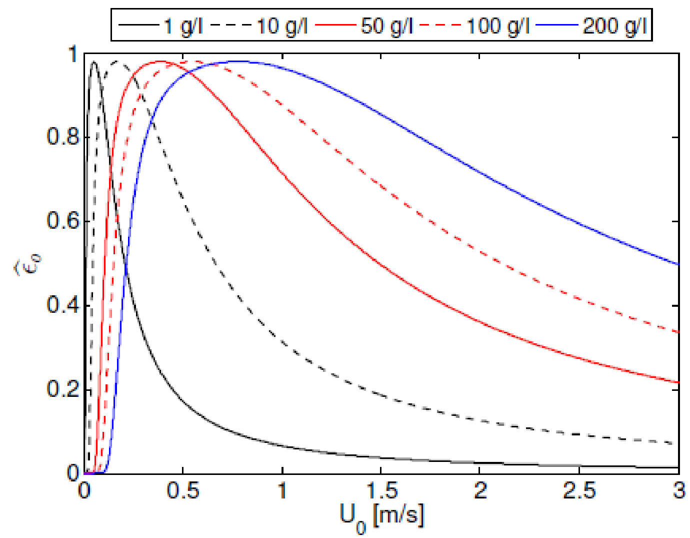


# Environmental valve efficiency

- Decomposition in constructional and operational efficiency
- Operation has more impact on efficiency than construction



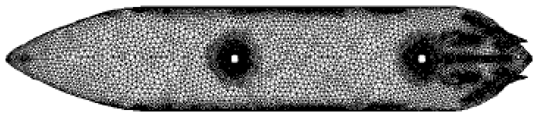

influence diameter and overflow position

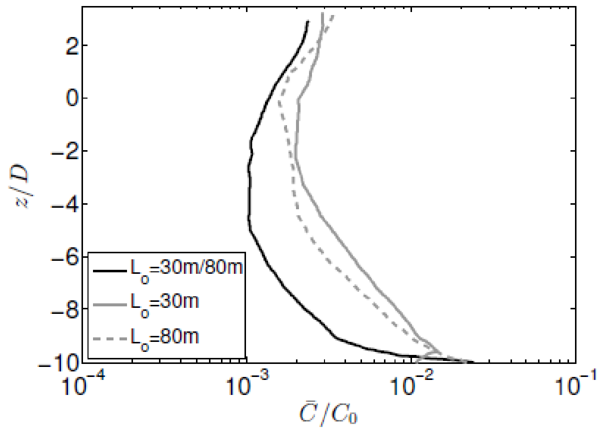



influence sailing speed and sediment concentration

# Influence on surface turbidity

- Number of overflows

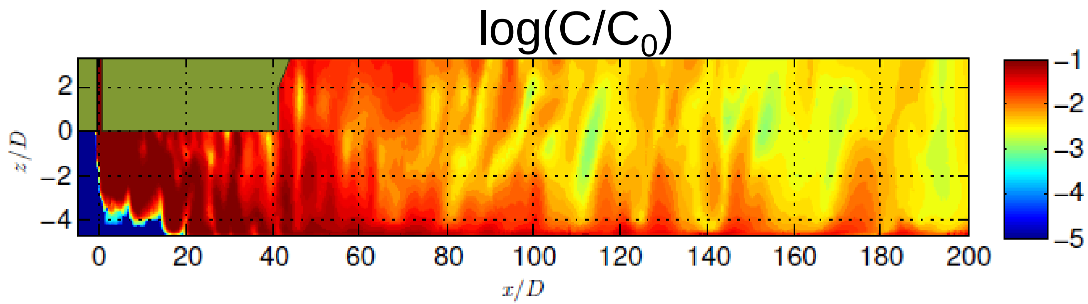




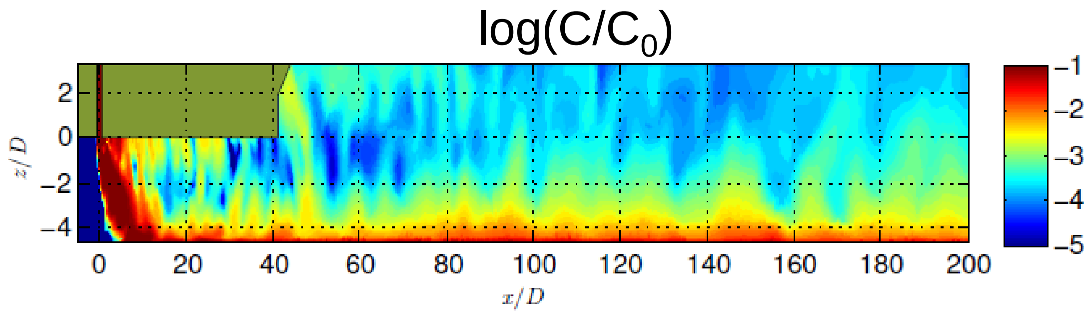
# Influence on surface turbidity

Applications:
*Simplified Model
* Ship Design

- Sediment load




$C_0$=10 g/l




$C_0$=150 g/l

→ sediment fraction in surface plume much larger for low $C_0$



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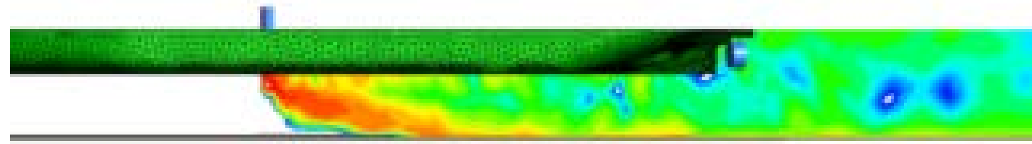
# Parameter model

Applications:
**_*Simplified Model_**
*Influence factors
* Ship Design

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



➢ Find a simple model that is:
1. Much faster
2. Almost as accurate

➢ A model with output:
✓ In suitable form for far-field models input
→ Vertical profile of sediment flux behind ship


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

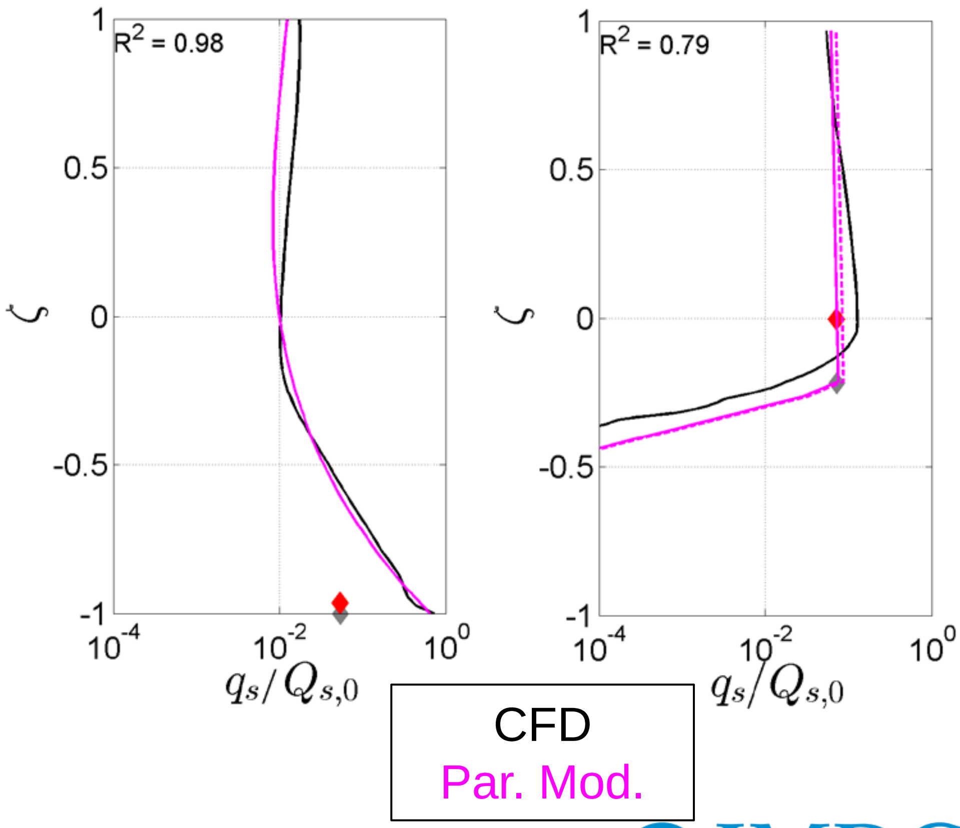
# Parameter model

Applications:
*Simplified Model
*Influence factors
* Ship Design

- O(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



# Overview Model development

## Applications:

*Simplified Model

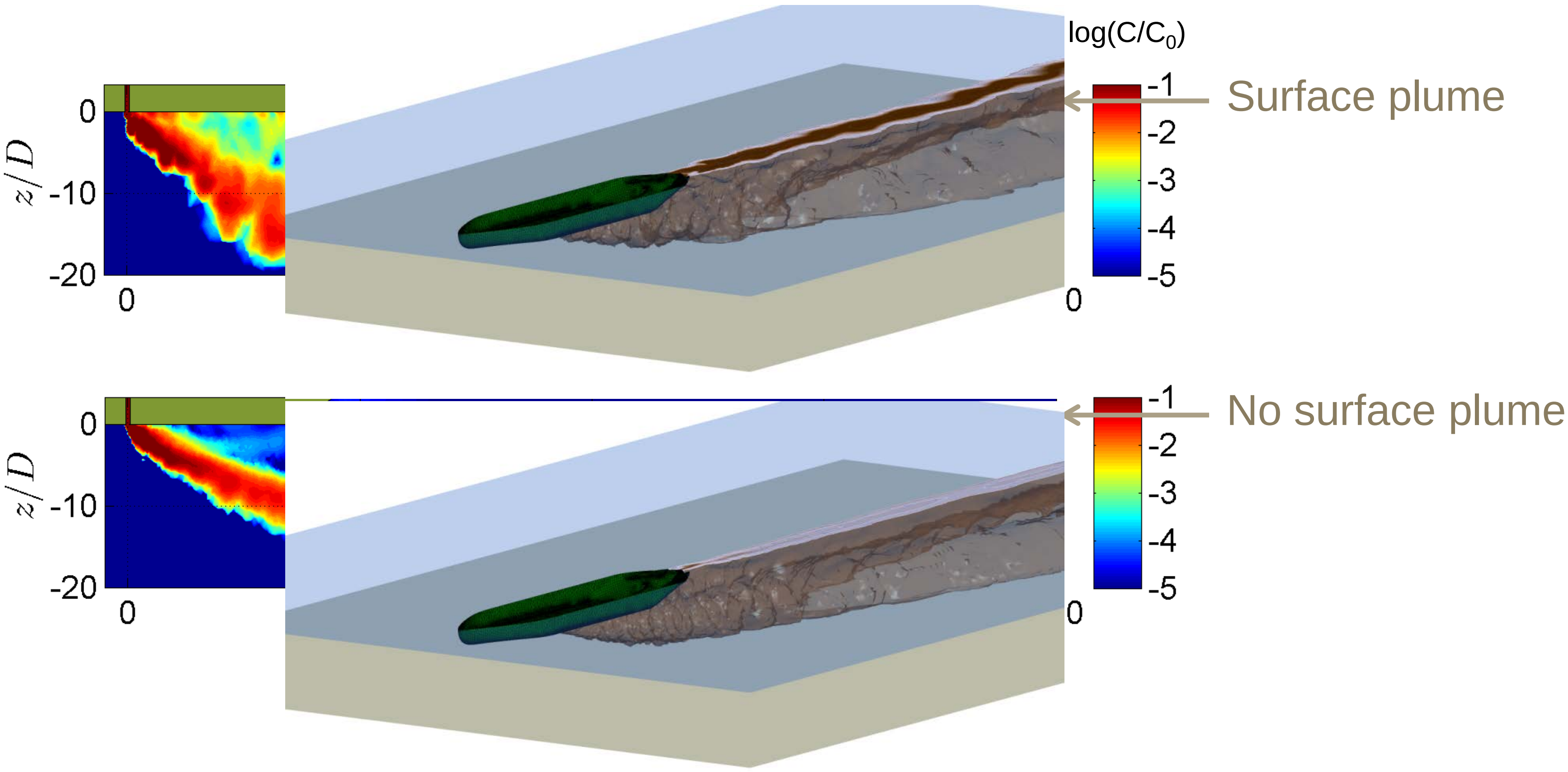
***Influence factors**

* Ship Design

# Influence of air bubbles

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

- Environmental valve: air bubbles -90% (Saremi, 2014)
- Perform simulations with/without air flow rate reduction



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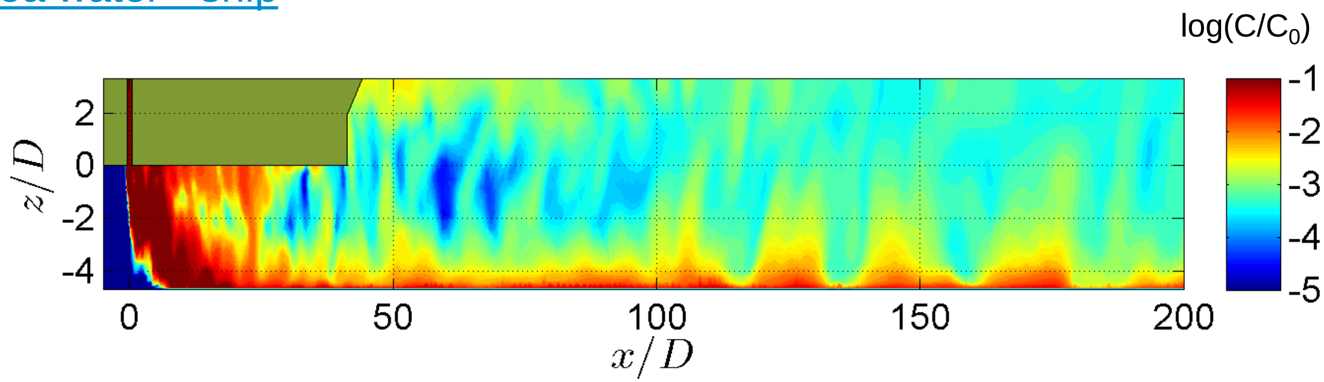
# Influence of velocity

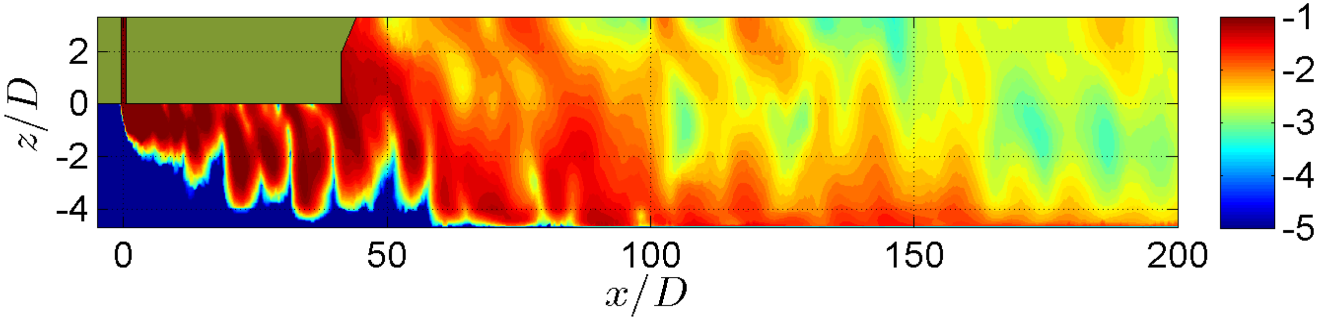
**Applications:**
*Simplified Model
***Influence factors**
* Ship Design

## Relative velocity sea water - ship

2 knots




6 knots




→ sediment in surface plume x 10



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# Overview Model development

## Applications:

*Simplified Model

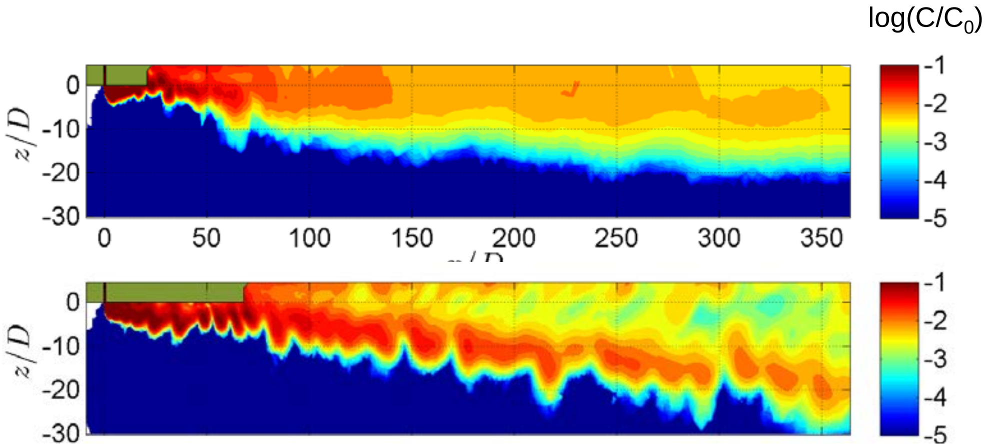
*Influence factors

*** Ship Design**

# Overflow position

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

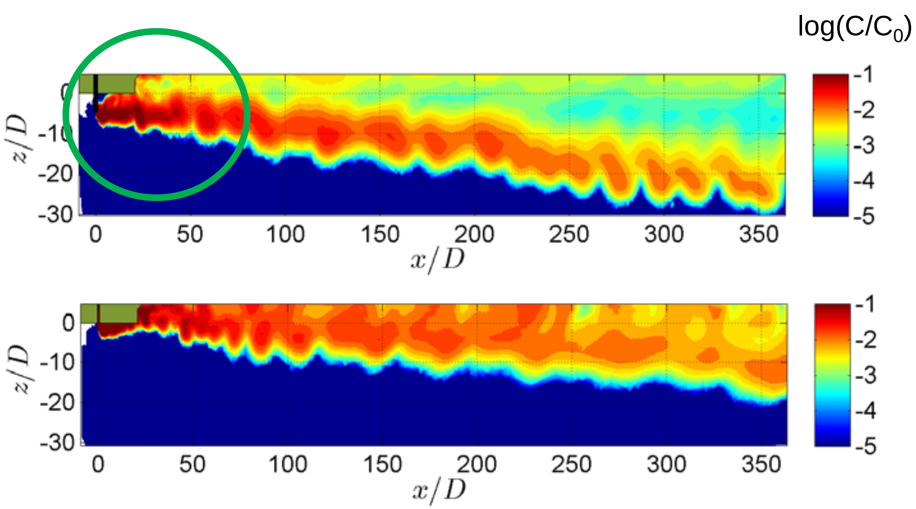
- Overflow at stern: plume mixed by propellers
- Overflow at aft: plume has more time to descend

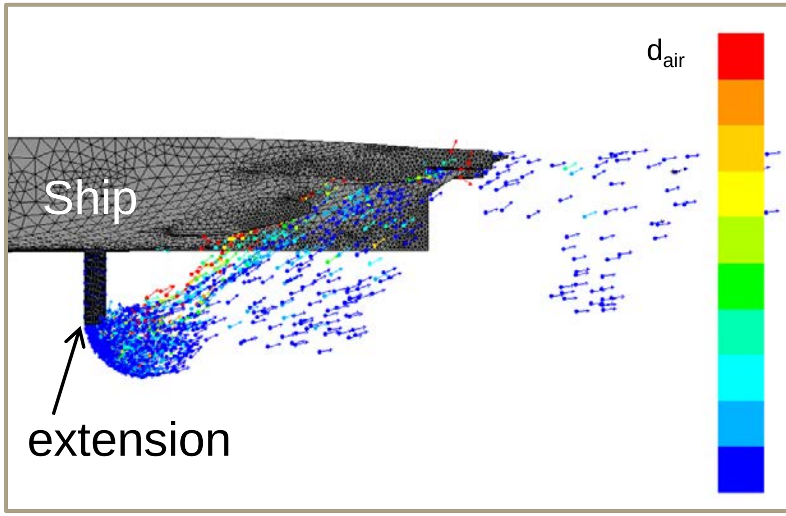


# Overflow shaft extension

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

- Studied earlier by de Wit *et al.* (2015)
- *C* at surface reduced with factor up to 10
- Still surface plume because of rising air bubbles



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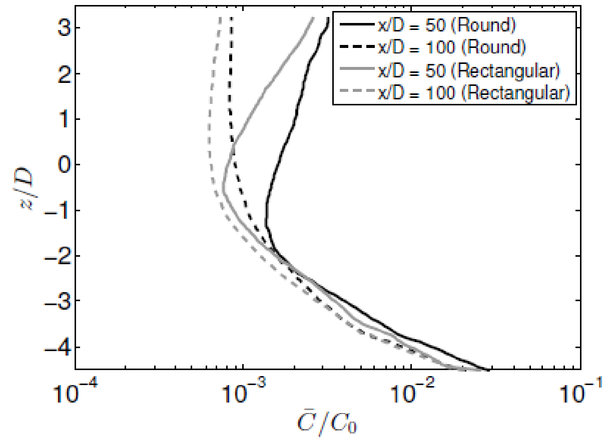
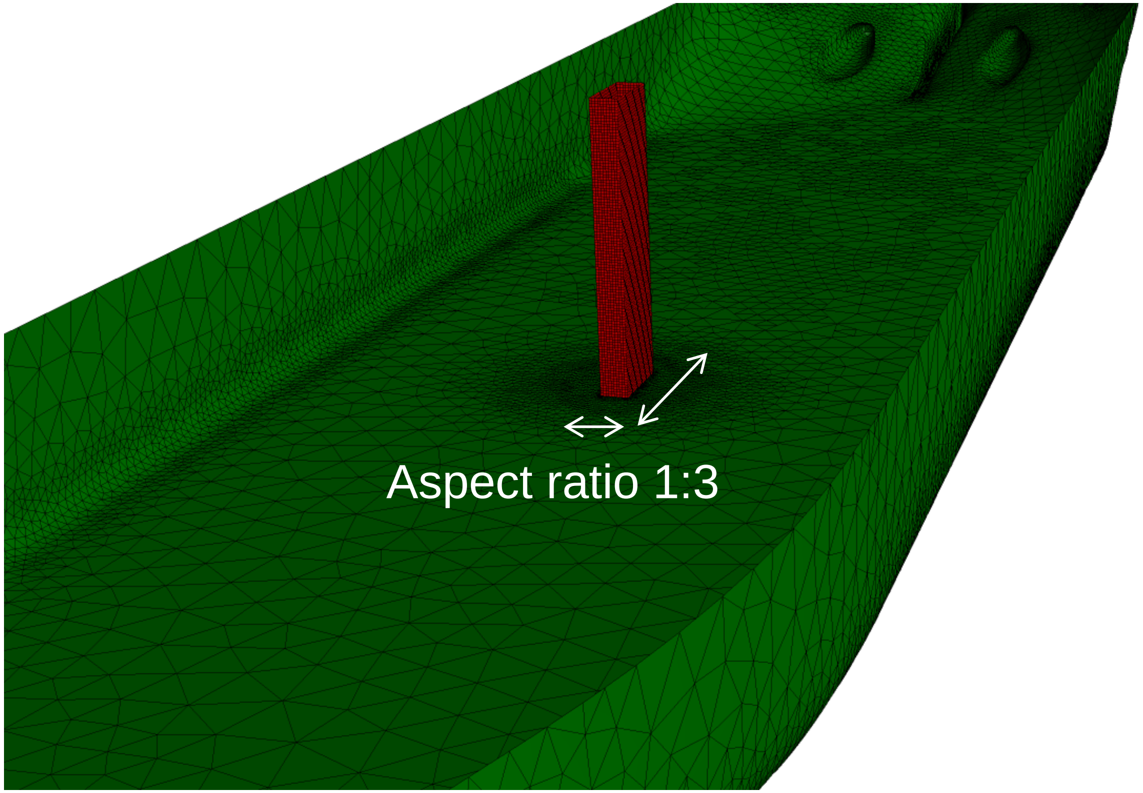
# Rectangular overflow shaft

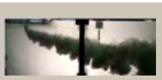
**Applications:**
*Simplified Model
*Influence factors
*** Ship Design**



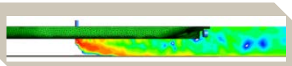

→ Potentially 50% reduction of sediment concentration

# Overview Model development



**Lab**
**EXPERIMENTS**

**Lab-scale**
**MODEL**



**Real-scale**
**MODEL**

**Real-scale**
**MEASUREMENT**

**Applications:**

*Simplified Model

*Influence factors

* Ship Design



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# Future research and applications

**<u>Overflow design (CFD model)</u>**

- Detailed study efficiency of:
  - Shaft extension
  - Rectangular overflow
- Influence of:
  - Lateral position overflow
  - Number of overflows
- Inclined overflow exit?
- Overflow via draghead jetting

**<u>Parameter model</u>**

- Real-time plume forecasting
- Tender-phase dredging strategy