Carsten Thorenz, with contributions by M. Zinkhahn,
M. Zaschke, M. Böhm, L. Mahl, R. Weichert, L. Kaminski,
F. Belzner, J. Pfrommer, G. Göbel

Fish & Ships: OpenFOAM in real world waterway engineering

BAW
Federal Waterways Engineering
and Research Institute

Göttingen, April 15th 2026

The BAW (Bundesanstalt für Wasserbau)

Federal Waterways Engineering and Research Insitute

- Research oriented public entity
- Consultancy for the ministry of transport
- Consultancy for waterway infrastructure projects

⇒ Roughly 300 weirs and 300 navigation locks at federal waterways

⇒ Continuous need for renovation and restauration

Navigation lock Zeltingen

Methods for investigation of hydraulics

- Physical scale models
- Laboratory and field measurements
- Numerical models
  - 2D shallow water equations for larger river areas (sediment transport and morphology changes)
  - 3D hydrostatic/nonhydrostatic for smaller river areas (sediment transport and morphology changes)
  - 3D CFD near ships and hydraulic structures

Historic physical modell of the Rio Negro

Areas of interest

Areas of interest

Hydro power plant
(Electricity)

Areas of interest

Hydro power plant
(Electricity)

Weir
(Water levels)

Areas of interest

Hydro power plant
(Electricity)

Weir
(Water levels)

Fish ladder
(Fish migration)

Areas of interest

Hydro power plant
(Electricity)

Weir
(Water levels)

Fish ladder
(Fish migration)

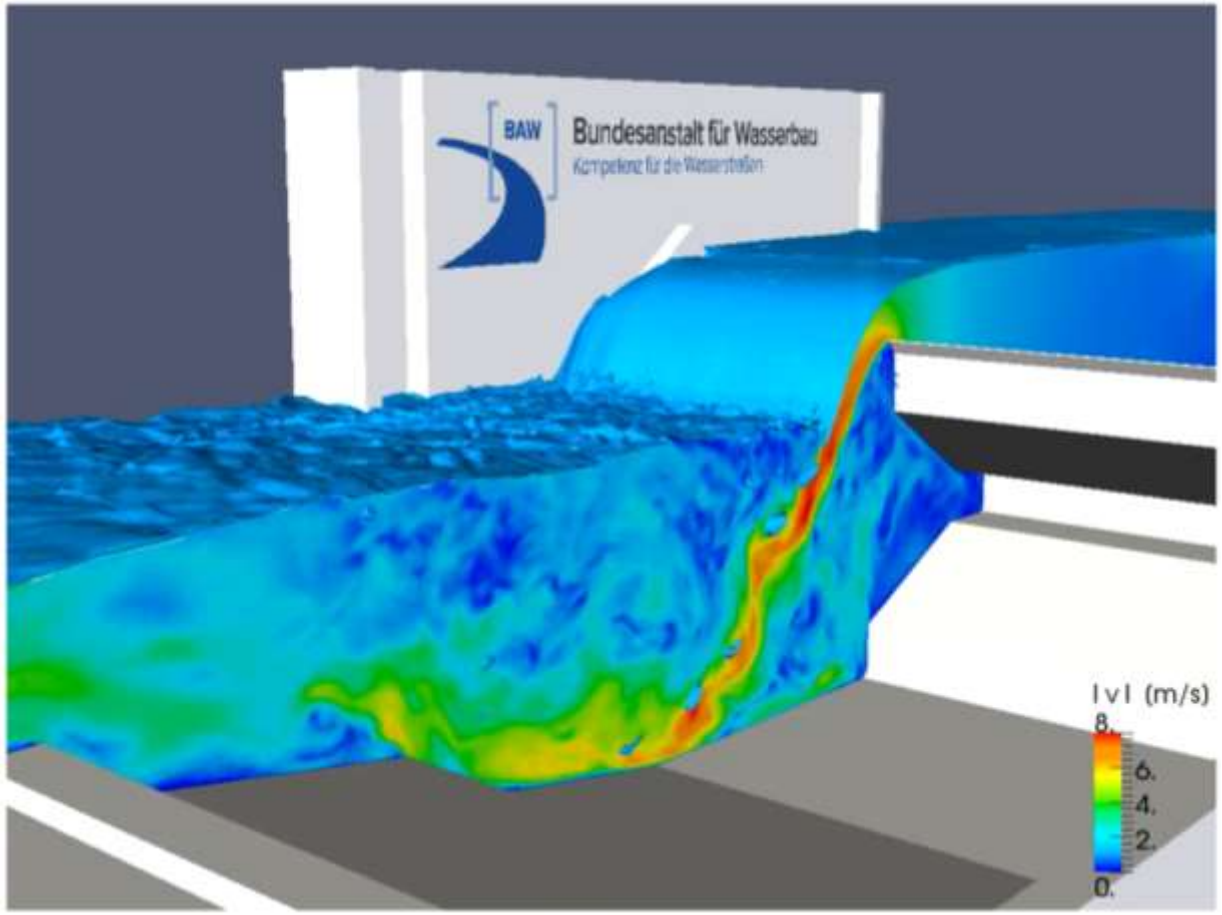
Navigation lock
(Ship traffic)

Engineering practice

OpenFOAM usage:

- Differing levels of expertise

- Quality controlled workflows:
  - Modelling “blueprints” provided
    (No “internet tutorials”!)
  - In-house boundary conditions



Engineering practice

OpenFOAM usage:

- Differing levels of expertise

- Quality controlled workflows:
  - Modelling “blueprints” provided

    (No “internet tutorials”!)
  - In-house boundary conditions
    - Flow rates
    - Water levels

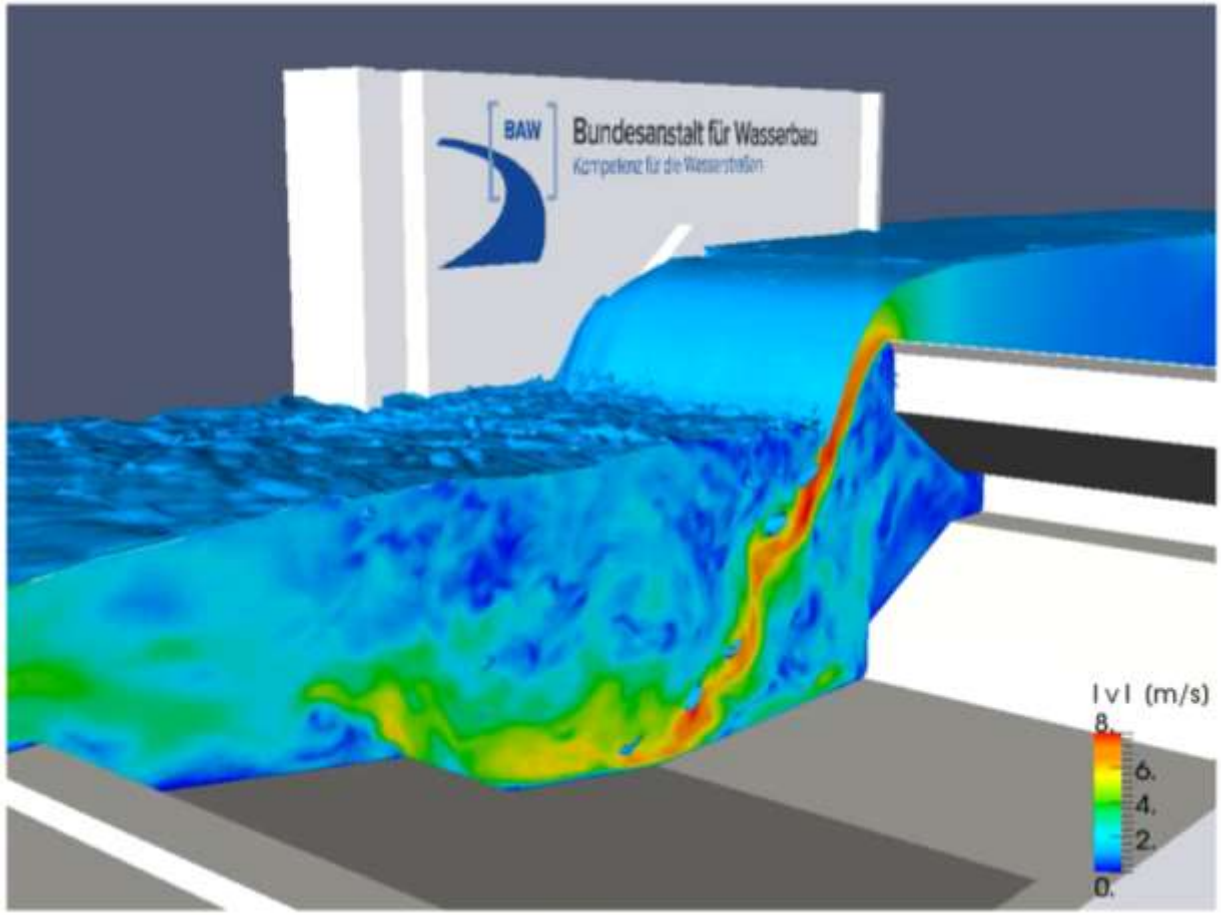
    Published as open-source with application examples

Project site at Github:

https://github.com/baw-de/HydBCsForOF

Typical hydraulic problems at weirs

- Energy dissipation
- Hydraulic loads
- Fluid structure interaction
- Hydro-abrasion
- Fish migration



Fish Migration: Motivation

- Some hundred barriers for upstream fish migration at federal waterways
  - ➢ Building fish ways
- How does the fish find the fish passage entrance?
  - ➢ Attraction flow is needed that gives fish a hydraulic information where the entrance is
- But how much auxiliary water for the attraction flow is needed?
  - As little as possible (loss for waterpower)

➢ OpenFOAM model to judge on the flow conditions

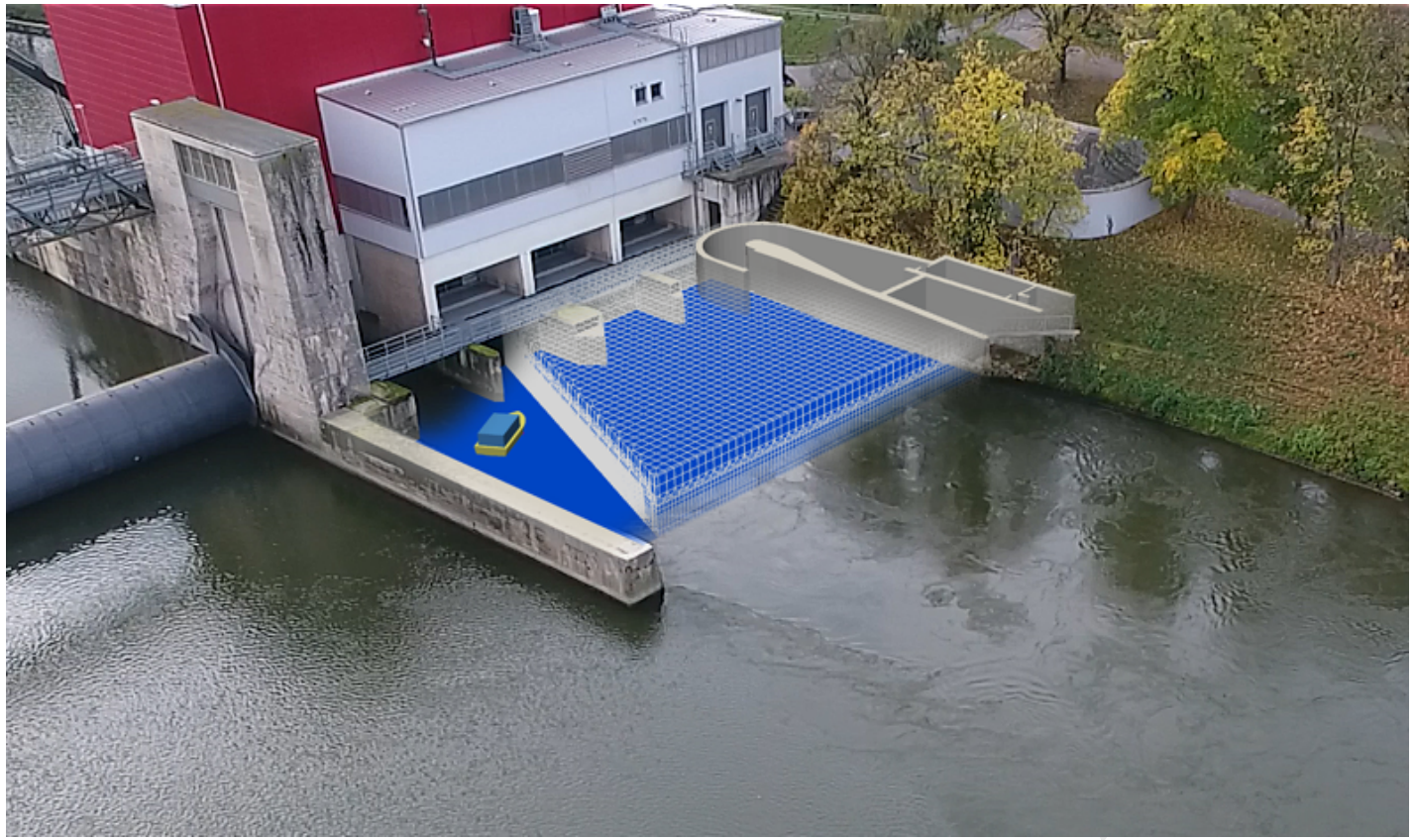
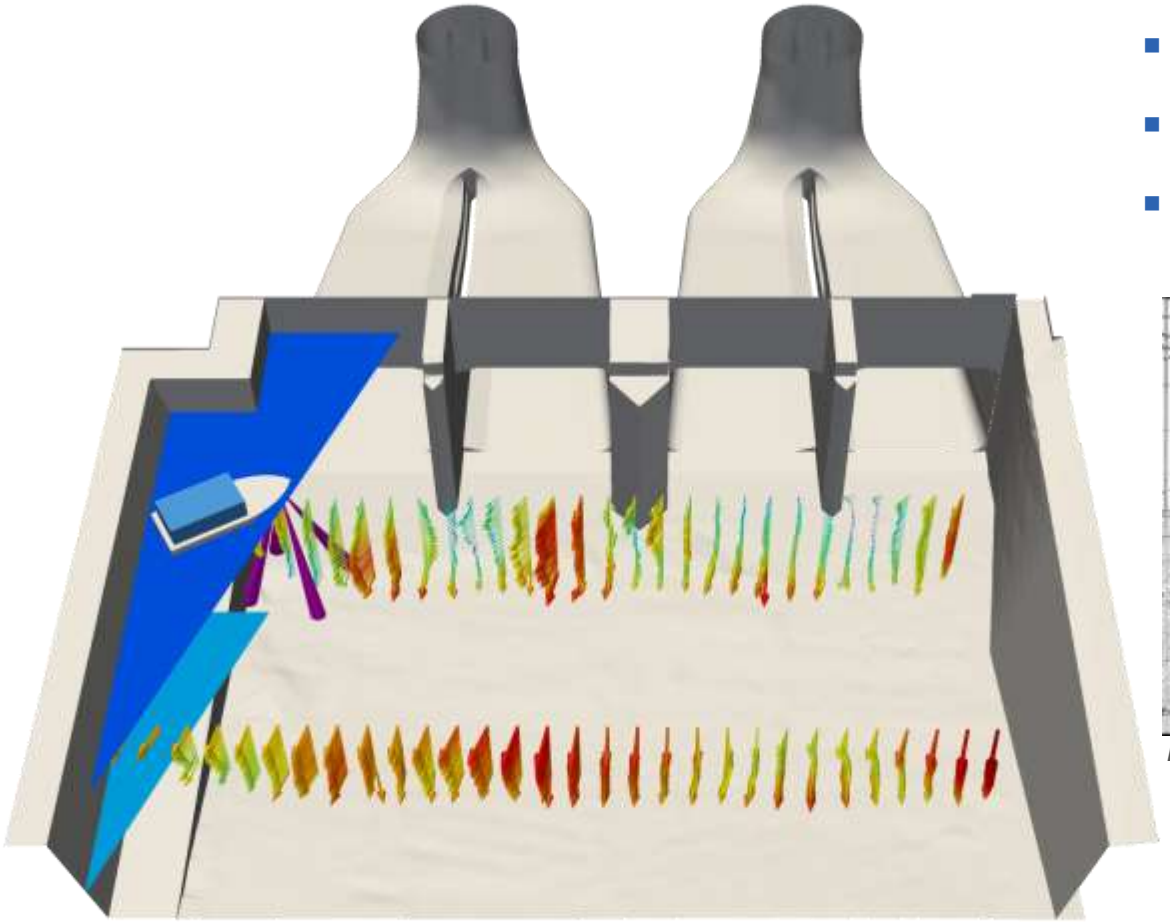


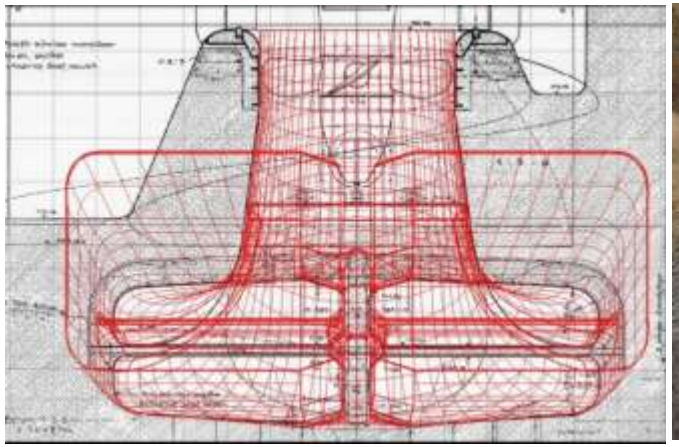
Figure source: BfG

Investigations at pilot site



Available data:

- 3D CAD geometry from old construction plans
- 3D laser scans
- ADCP velocity measurement

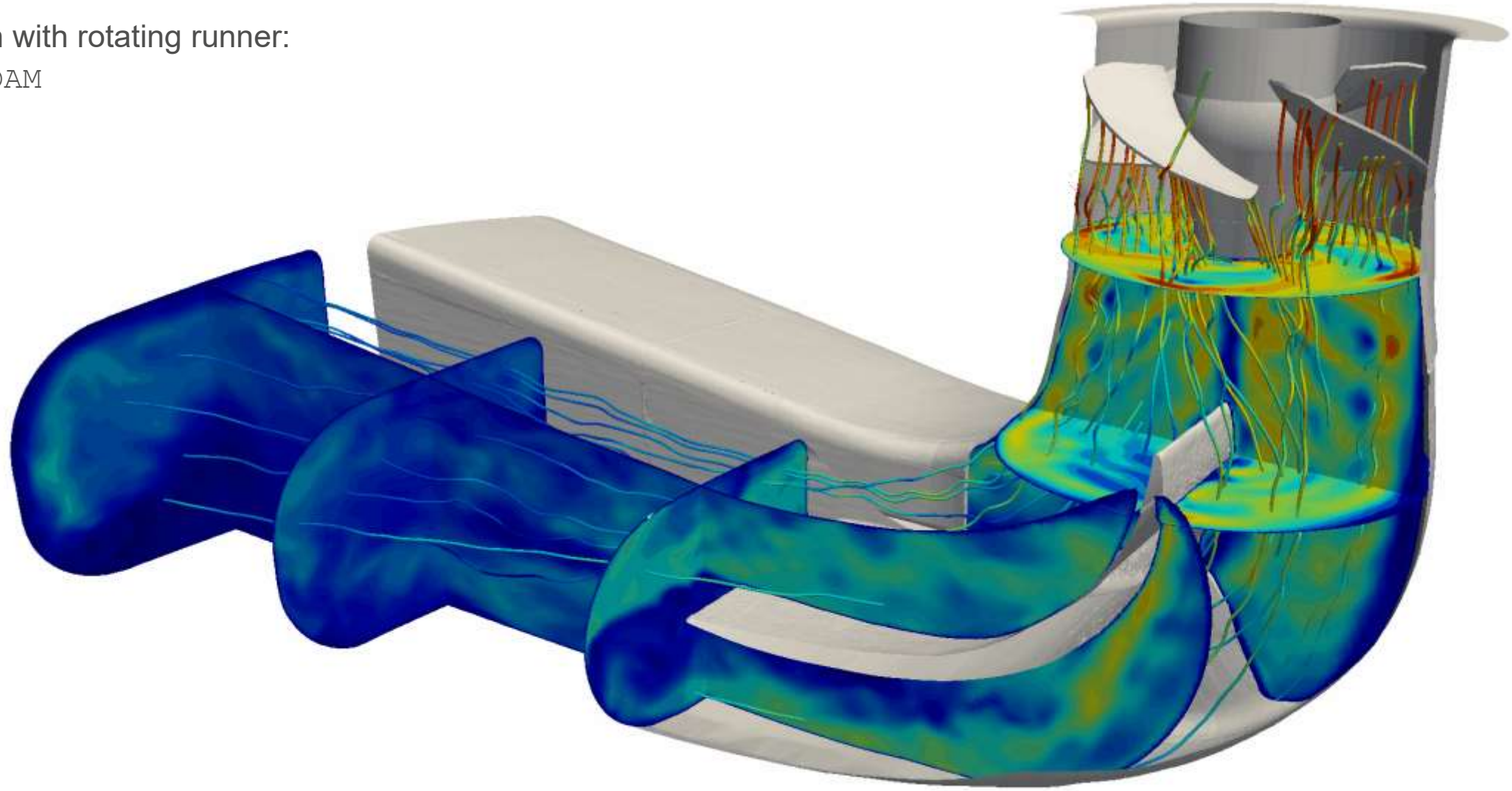


Draft tube Wallstadt (source: WNA Aschaffenburg)

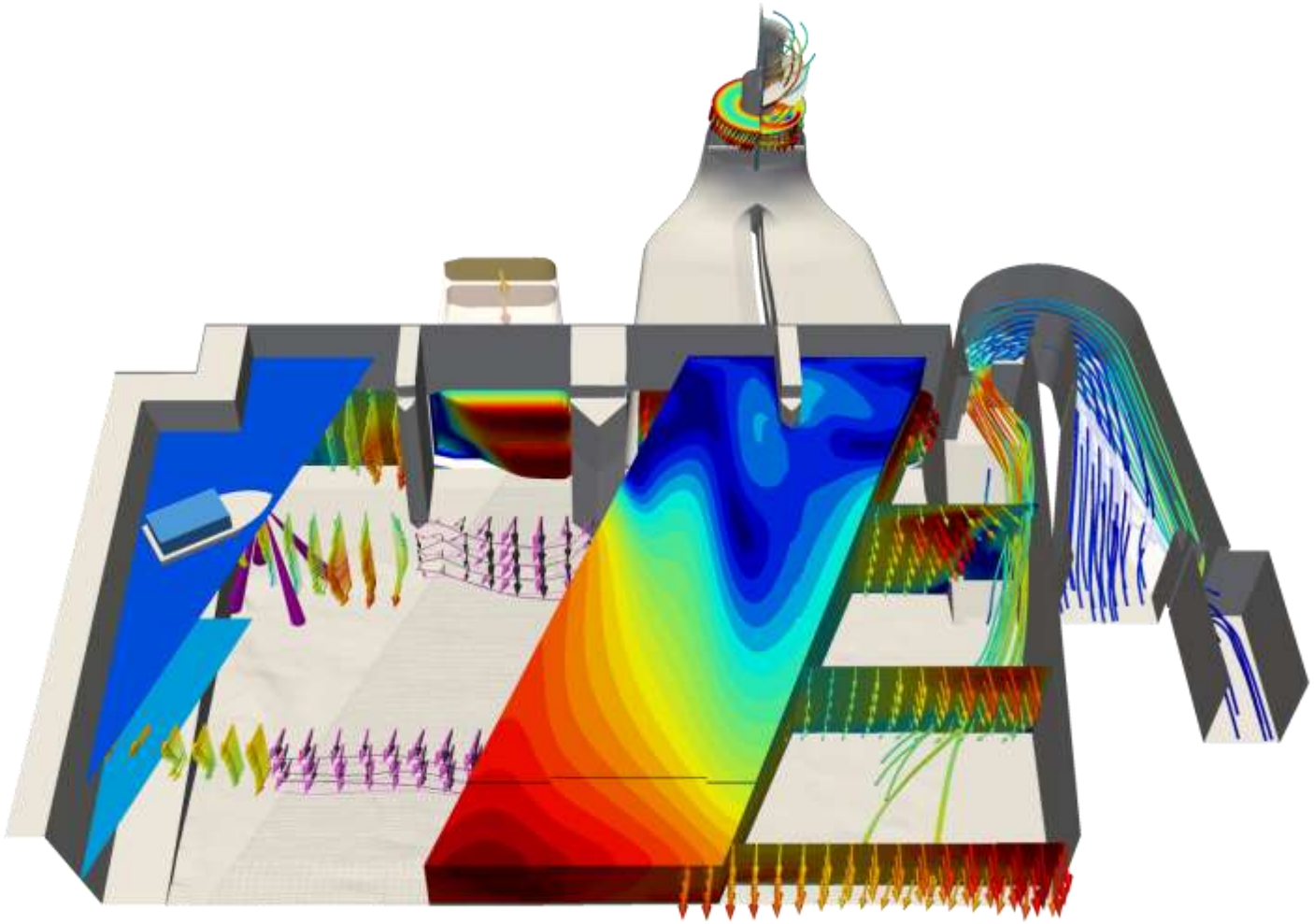
ADCP measurement (Source: Ingenierbüro Schmid)

Boundary conditions for velocity field at turbine: Resolved runner

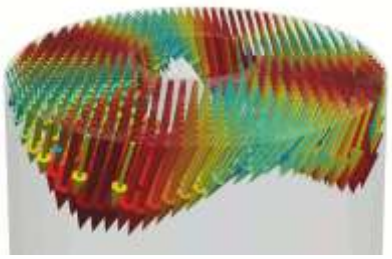
- Dynamic mesh with rotating runner:
  `pimpleDymFOAM`



Result with resolved turbine runner



- Good reproduction of flow field
- Required data (runner and guide vane geometry and their operation positions) rarely available
- Simulation costs too high
- Tests of simplified approaches yielded acceptable results, too

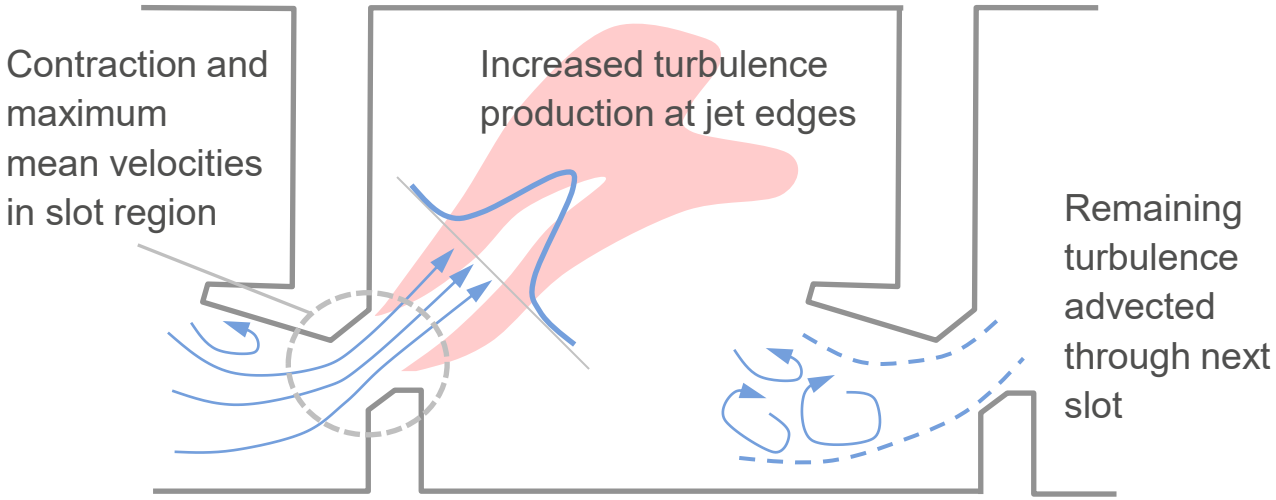


Flow investigation in vertical slot fish passes

Guidelines for dimensioning:

- Basin sizes
- Guide wall positioning
- Allowable flow velocities
- …

Turbulence conditions in the fish pass

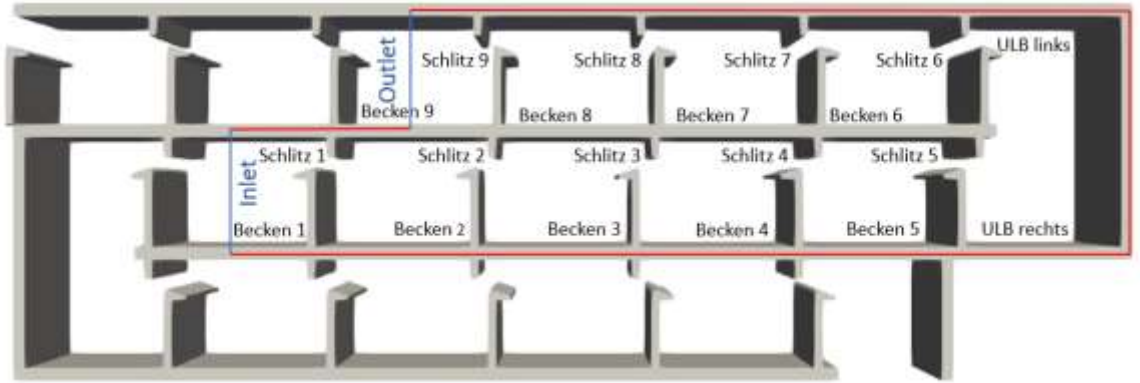


Vertical slot fishway (vsf) in Breisach (Rhine river, Germany)

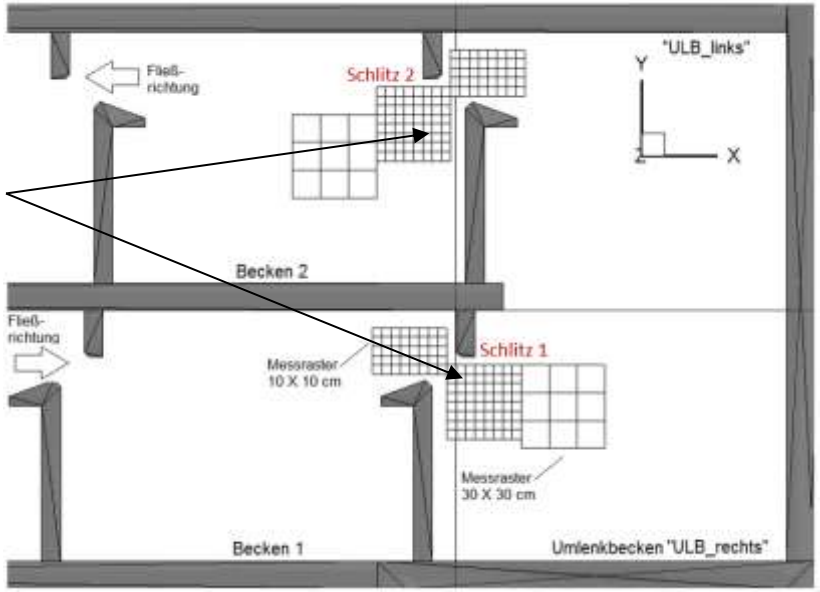
- Turbulence in slot region less intense than in active regions with high shear but:
  - Superposition of high mean velocities and additional turbulent motions might be critical for fish

Measurements campaign at the Koblenz fishway

Vertical slot fishway finalized in 2011 (Moselle river, Koblenz)

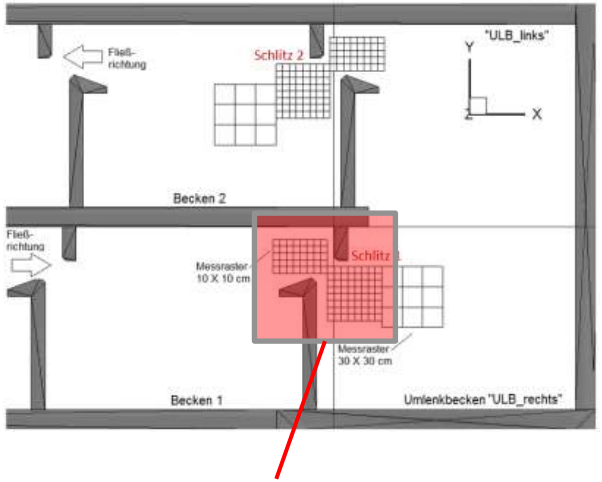


ADV probe positions at 1.1 m (level1) and 0.5 m (level2) above ground

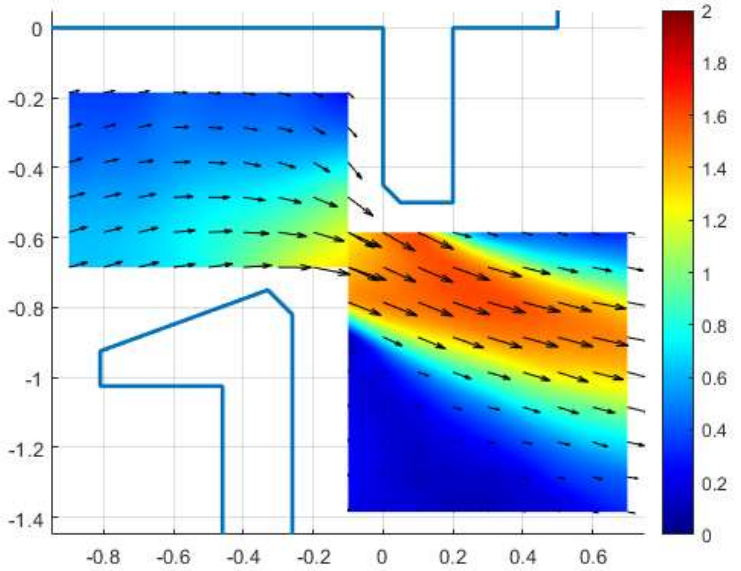


- Three-component timeseries @64Hz taken over 3 minutes at two levels (see right image), water height ≈1.5 m

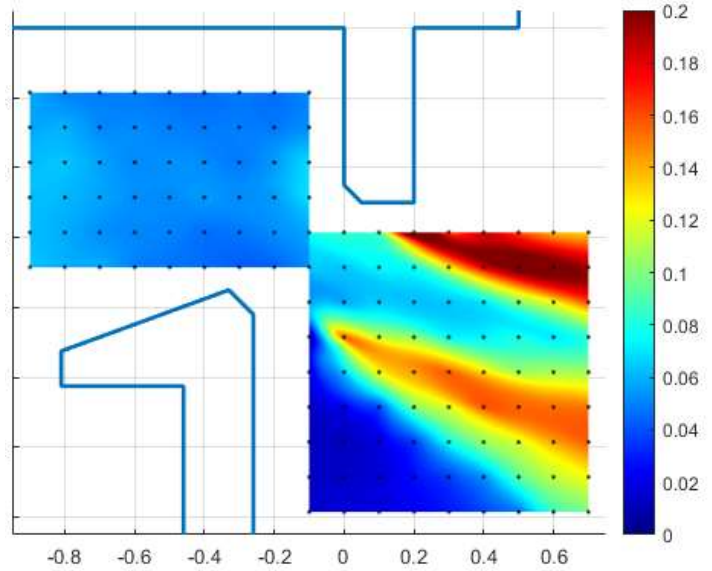
Evaluation of measured turbulence data



Region of interest

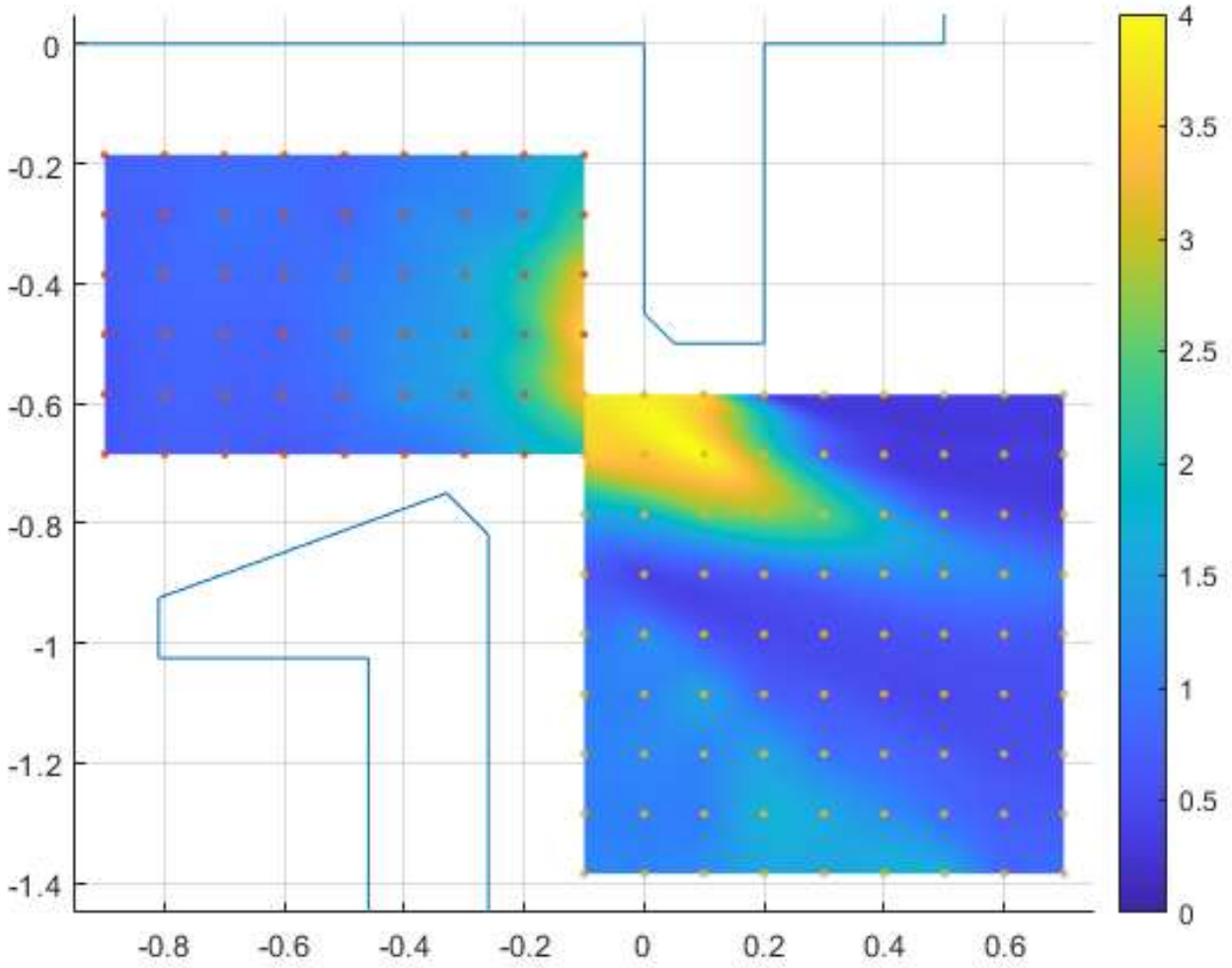


Absolute value of mean flow velocity [m/s]



Turbulent kinetic energy [m²/s²]

Turbulence anisotropy

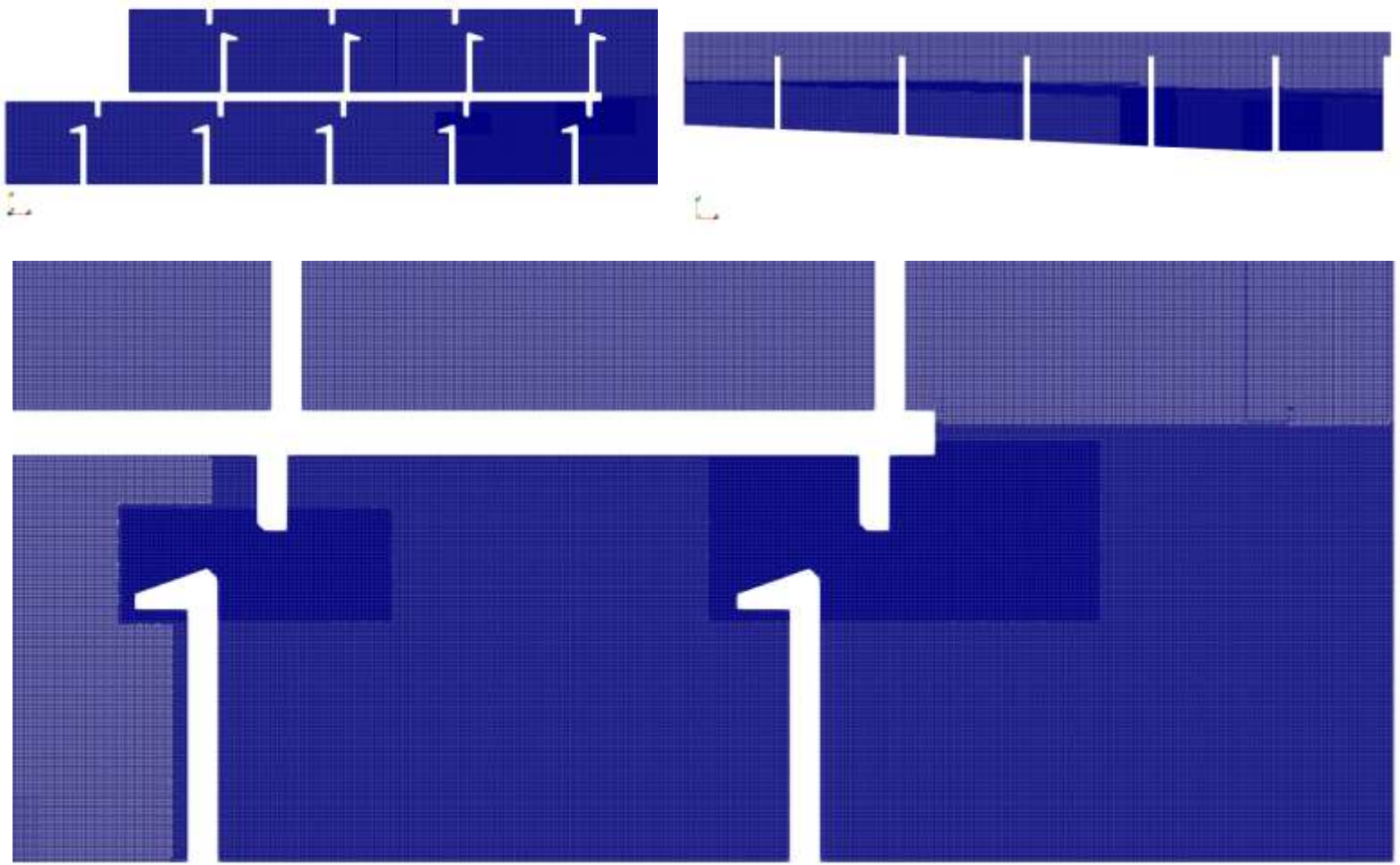


Anisotropy of turbulence

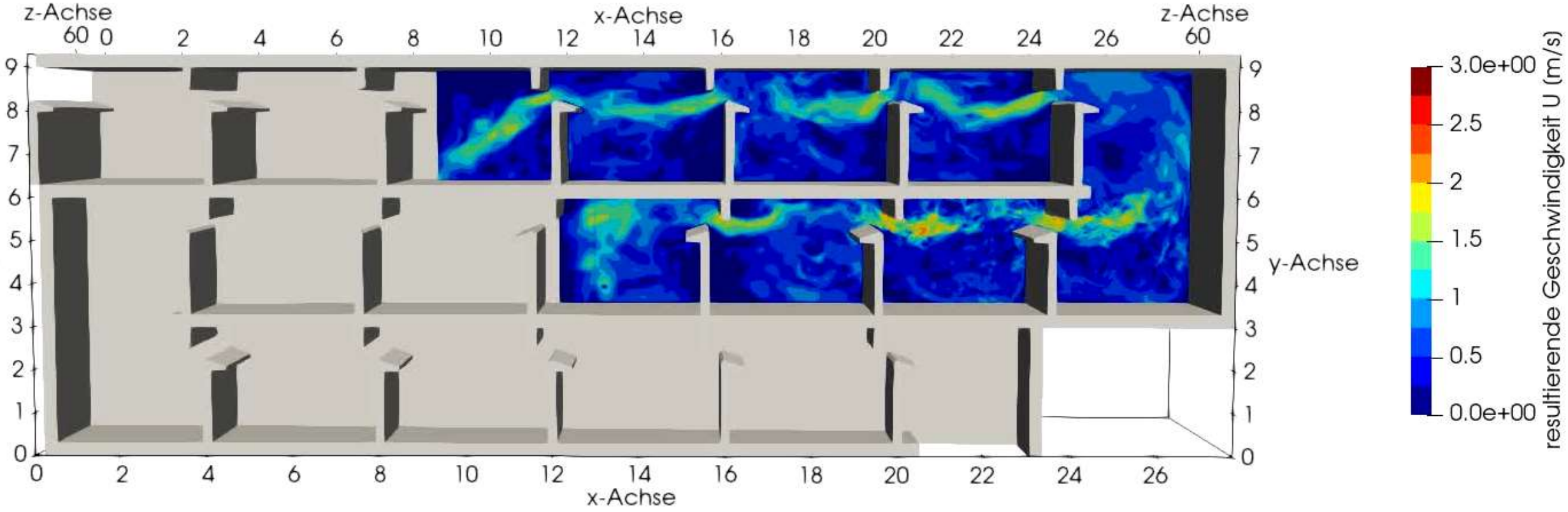
Simulation setup

Detached eddy simulation with interFOAM

- Mesh base size $\Delta = 40$ mm
- $\Delta_{min} \approx 5$ mm in slot zone
- Flow rate 0.9 m³/s
- DES-k-omega-SST model
- VOF (volume of fluid) method for two-phase physics
- Further simulations and evaluations currently underway

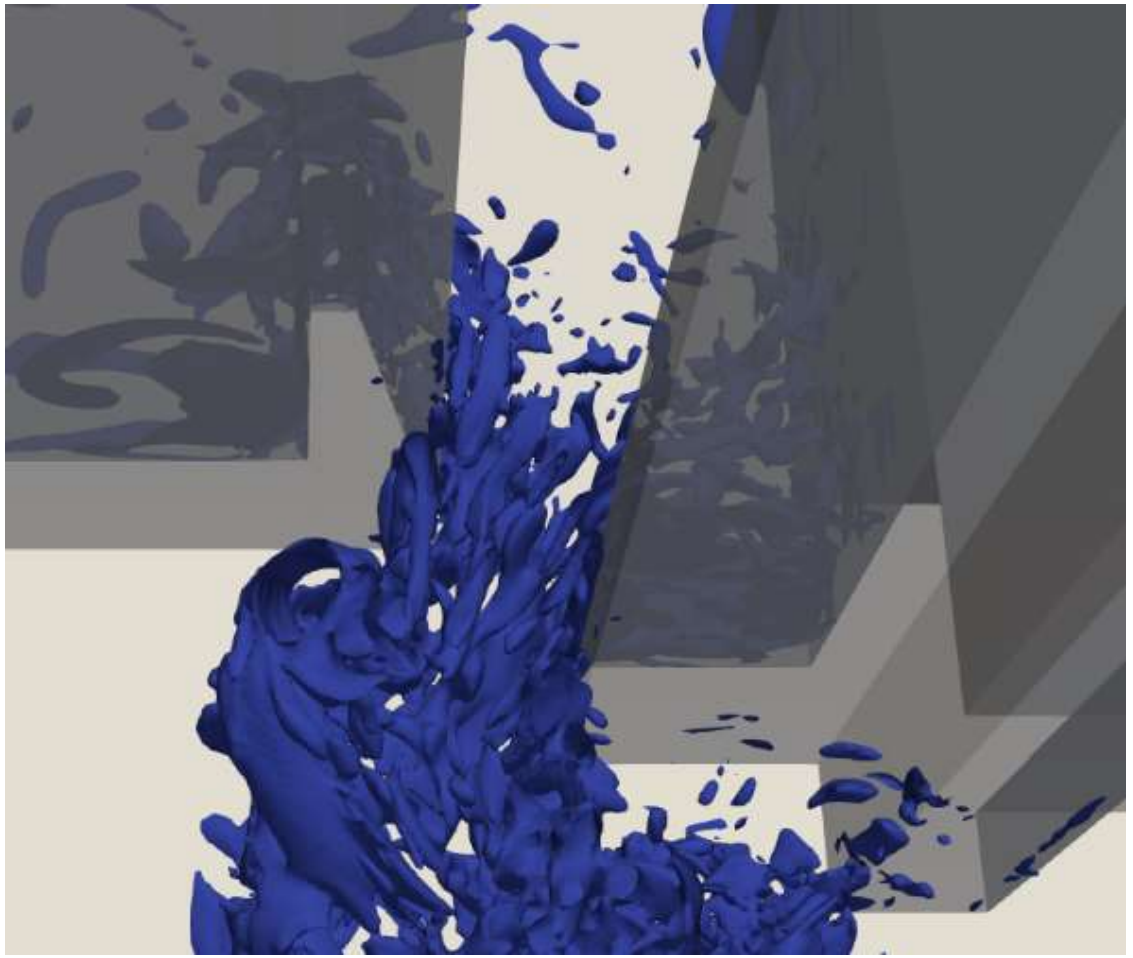


Simulation results: Plan view



Instantaneous absolute value of flow velocity

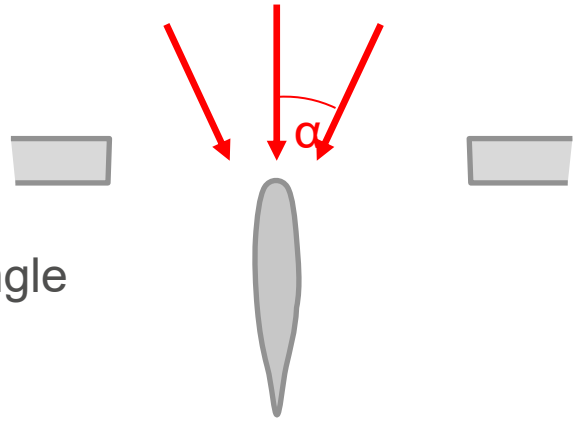
Simulation results: Details



Isosurfaces of Q criterion (Q = 50)
=> Pronounced vortex stretching

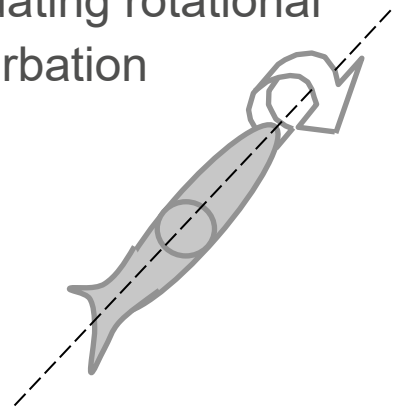
Impacts on upstream-migrating fish

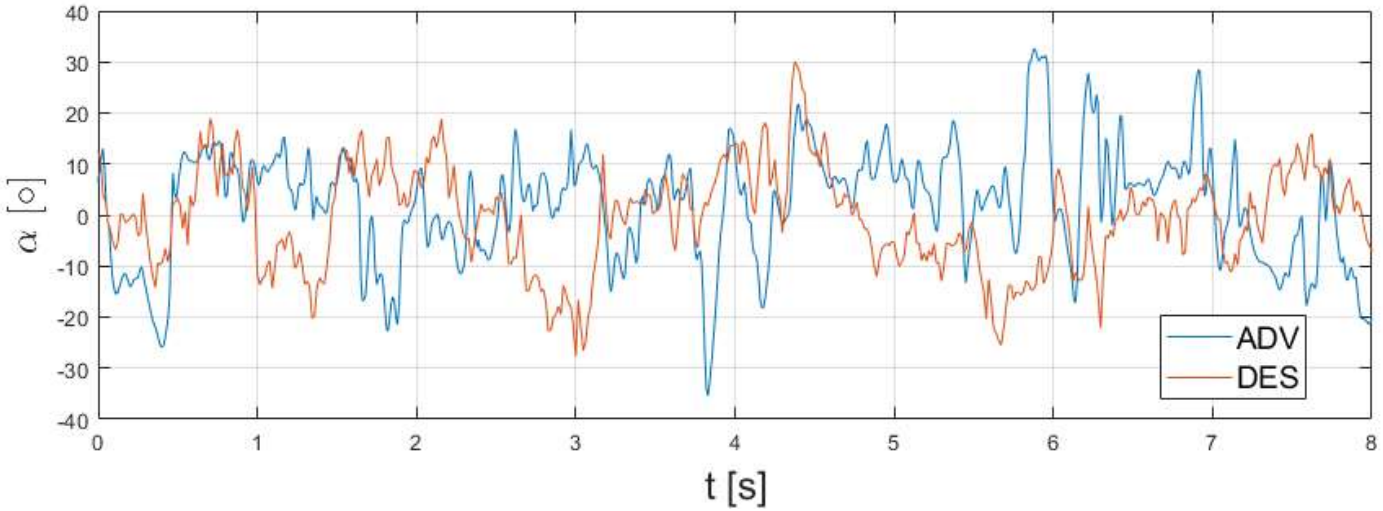
Possible turbulence-related stressors:



fluctuating angle of attack α

fluctuating rotational perturbation





Timeseries for angle of attack

Conclusion for fishes in the slot

Turbulence in the slot

- less intense than around the jet but with particular characteristics
- highly anisotropic with increased streamwise vorticity and high ratio between cross-stream and along-stream variances

Fish swimming through the slot

- possible impacts: roll perturbations, lateral deflections from swimming position
- superposition of turbulence-induced stressors and required high swimming speed (burst swimming)
- turbulence-induced impacts in the slot may be irrelevant for some species but become decisive for fish with lower swimming capacity or sensitivity to above perturbations

Further research

- observation of fish movements during slot passage (in real fishways) and classification of visible turbulence-generated impacts

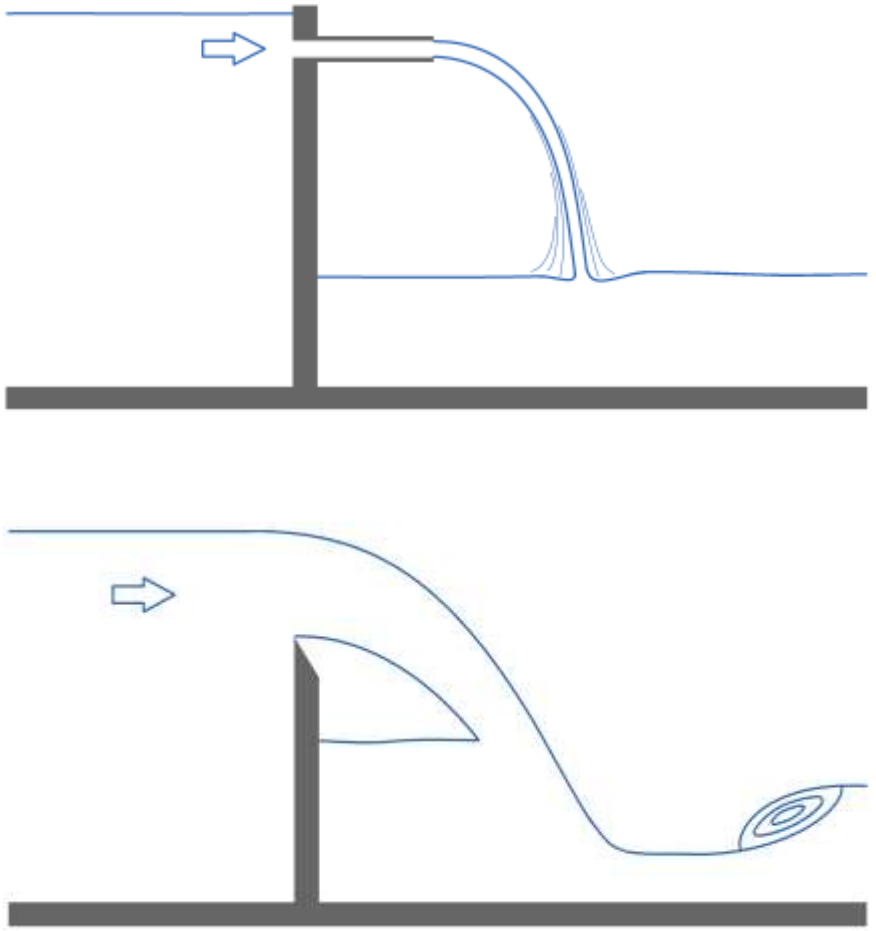
Downstream fish migration

Weir Geesthacht

Design guidelines

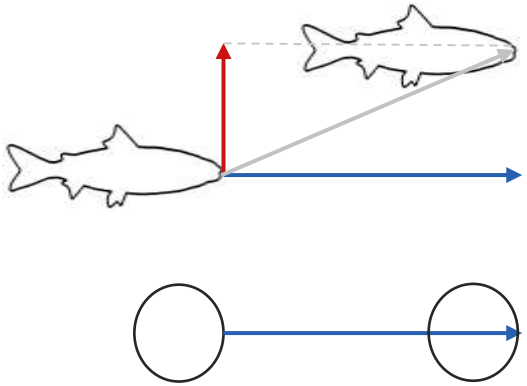
- German guidelines for fish transit over weirs are based on a paper on bypass tubes from 1998:
  - „Current design criteria require a plunge pool depth equal to a quarter of the differential head at a site, with a minimum depht of 0.9 m […].“
- No scientific background information (data, …) available
- Hydraulic situation at a weir can differ significantly from a bypass tube

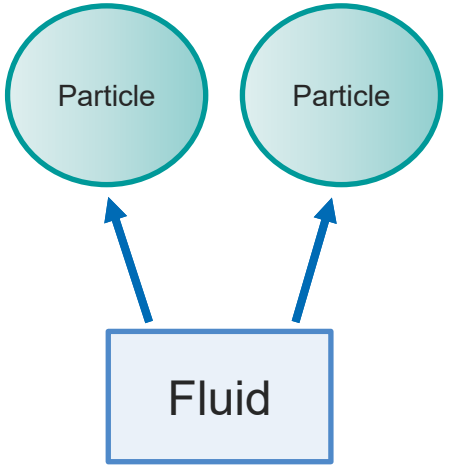
→ Numerical studies on possible impact on fish

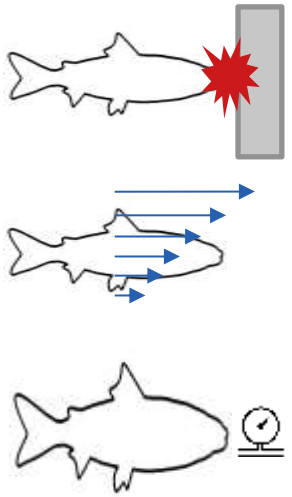


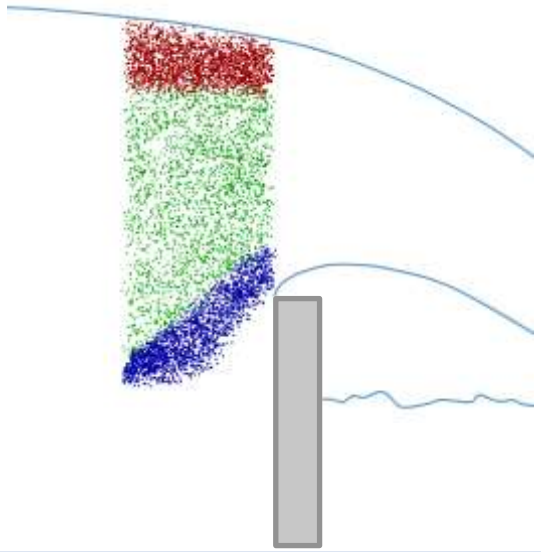
Numerical method

- Fish as passive Lagrangian particle
  - interFoam + kinematicCloud
  - One-way coupling
  - Evaluation of collisions, shear rate and pressure fluctuations

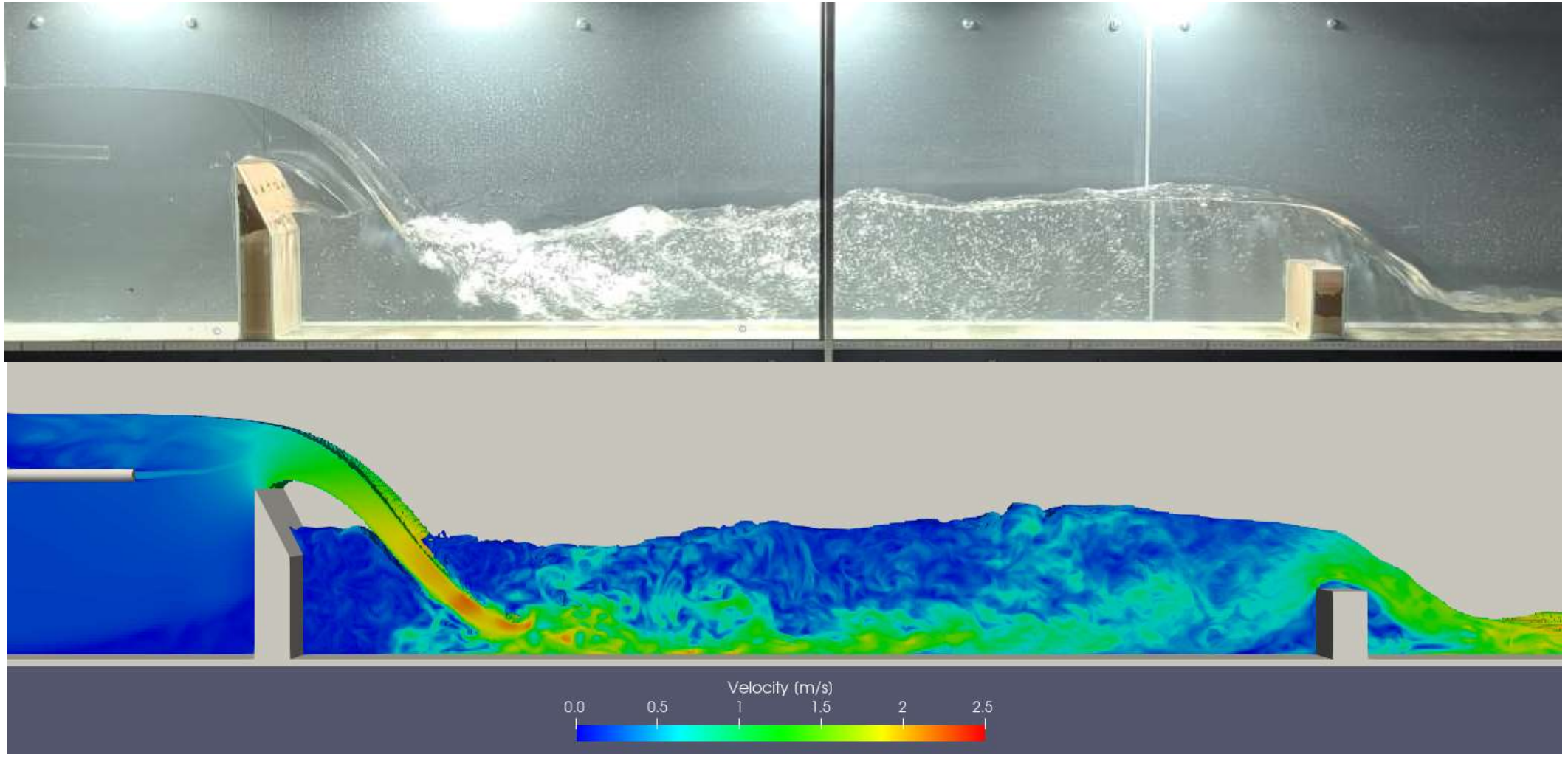




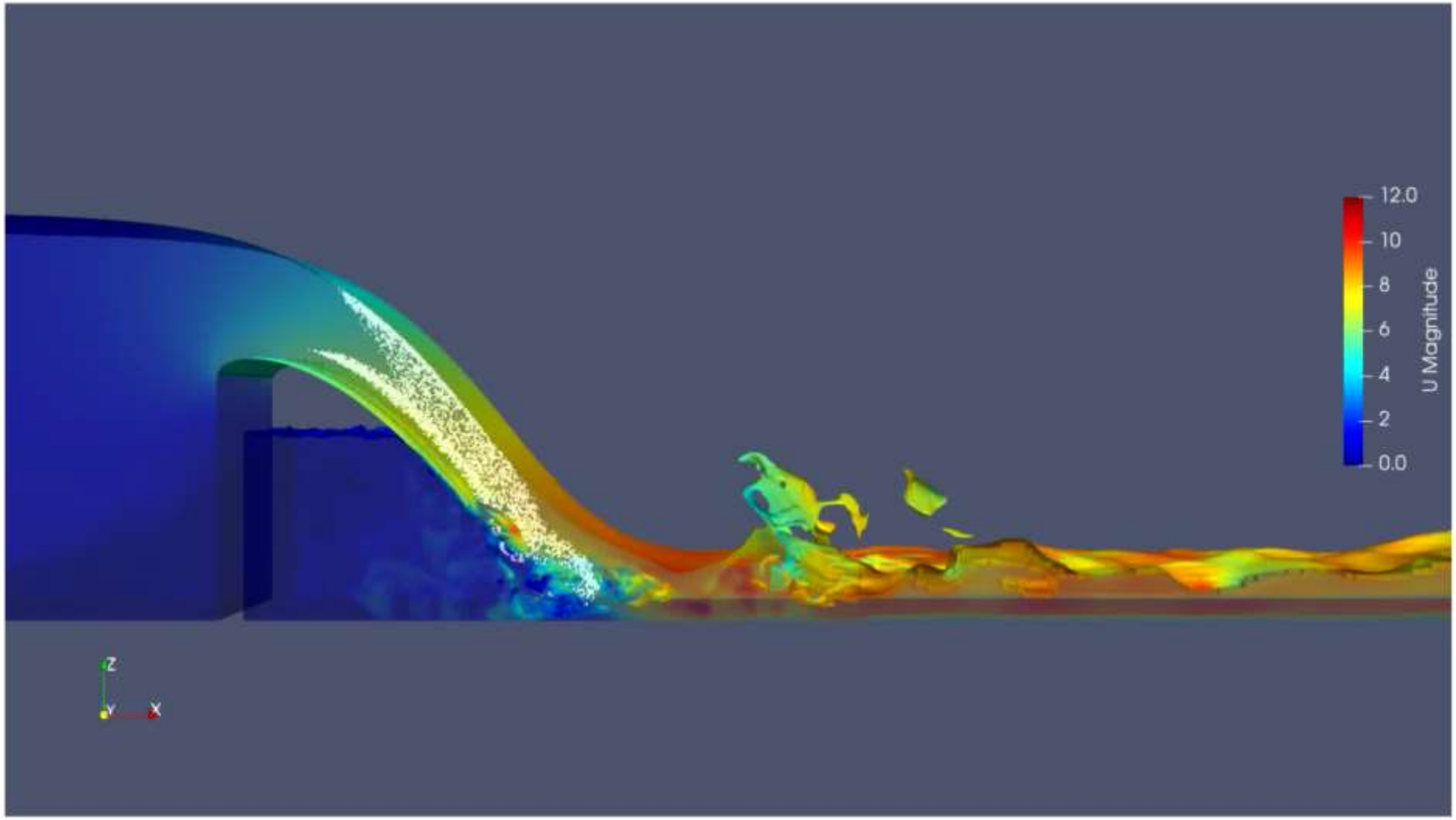




Physical model for validation

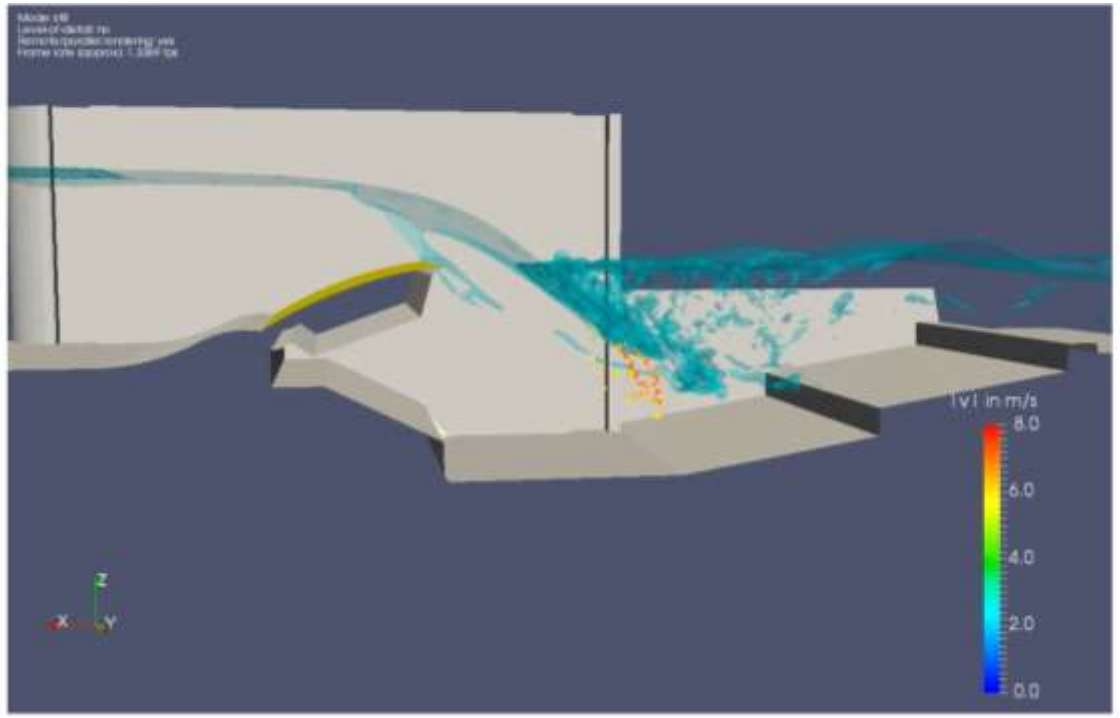


Numerical model results



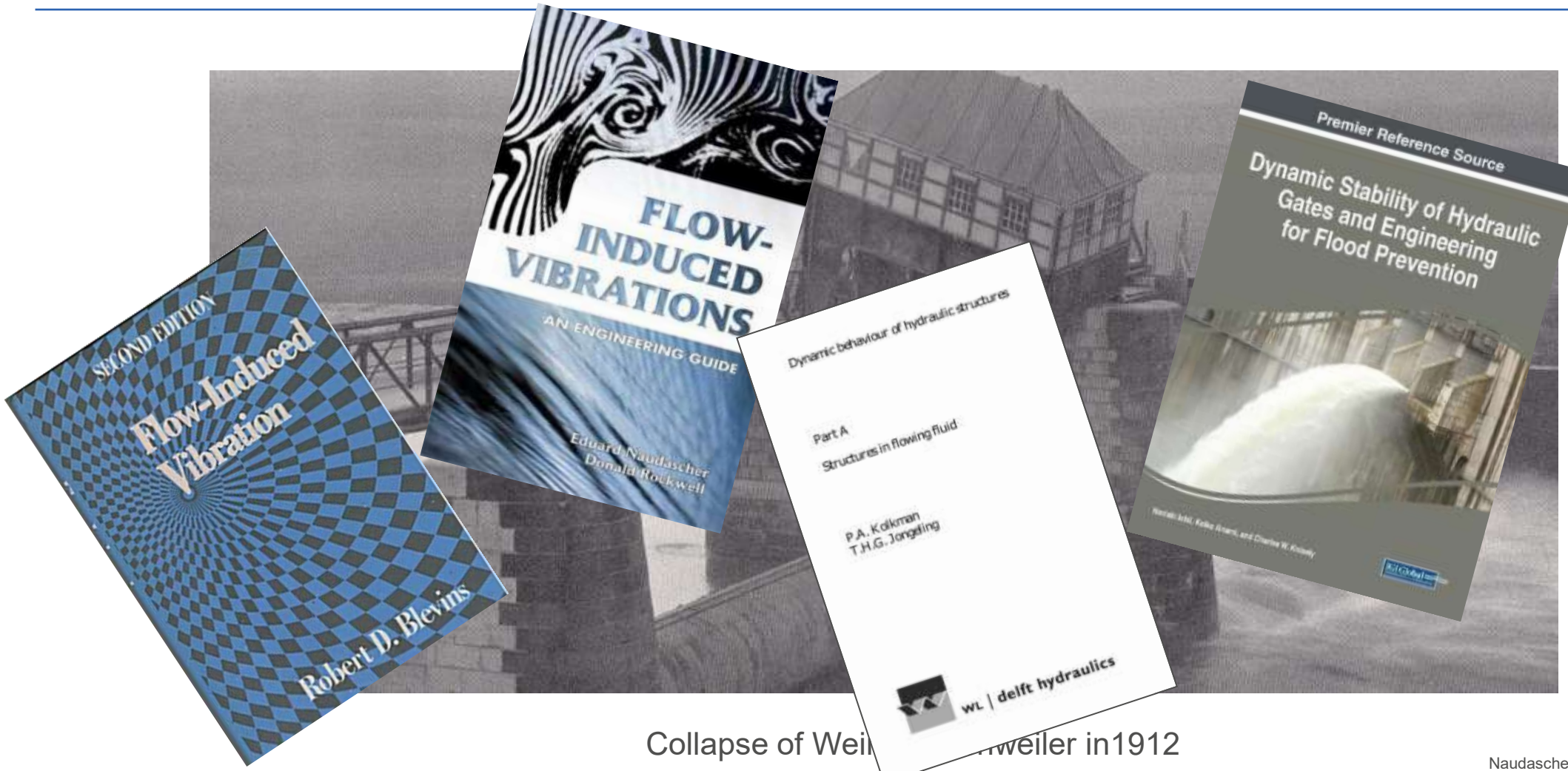
Current status for downstream fish migration evaluation

- Particle tracking helpful tool to evaluate collisions probability etc.
- Possible to predict impact probabilities for some standardized structures based a regression analysis
- Biological consequences scarcely studied and not very well understood
- Incorporation of active fish behaviour would be the next step



→ PhD Thesis is to be defended in July

Fluid-Structure-Interaction



Source: Maschinenfabrik Augsburg Nürnberg (1912)

Collapse of Weil ...weiler in1912

Blevins (1977),
Naudascher und Rockwell (1994),
Kolkman und Jongeling (2007),
Ishii et al. (2018).

Fluid-Structure-Interaction: Modern weir

- Segment gate with flap
- Height of the gate 4,5 m
- Water level difference ≈ 1 - 4 m
- Three gates, 34 m width each
- Mass of each gate ≈ 115 t

Video of surveillance camera

Numerical model

Mesh:

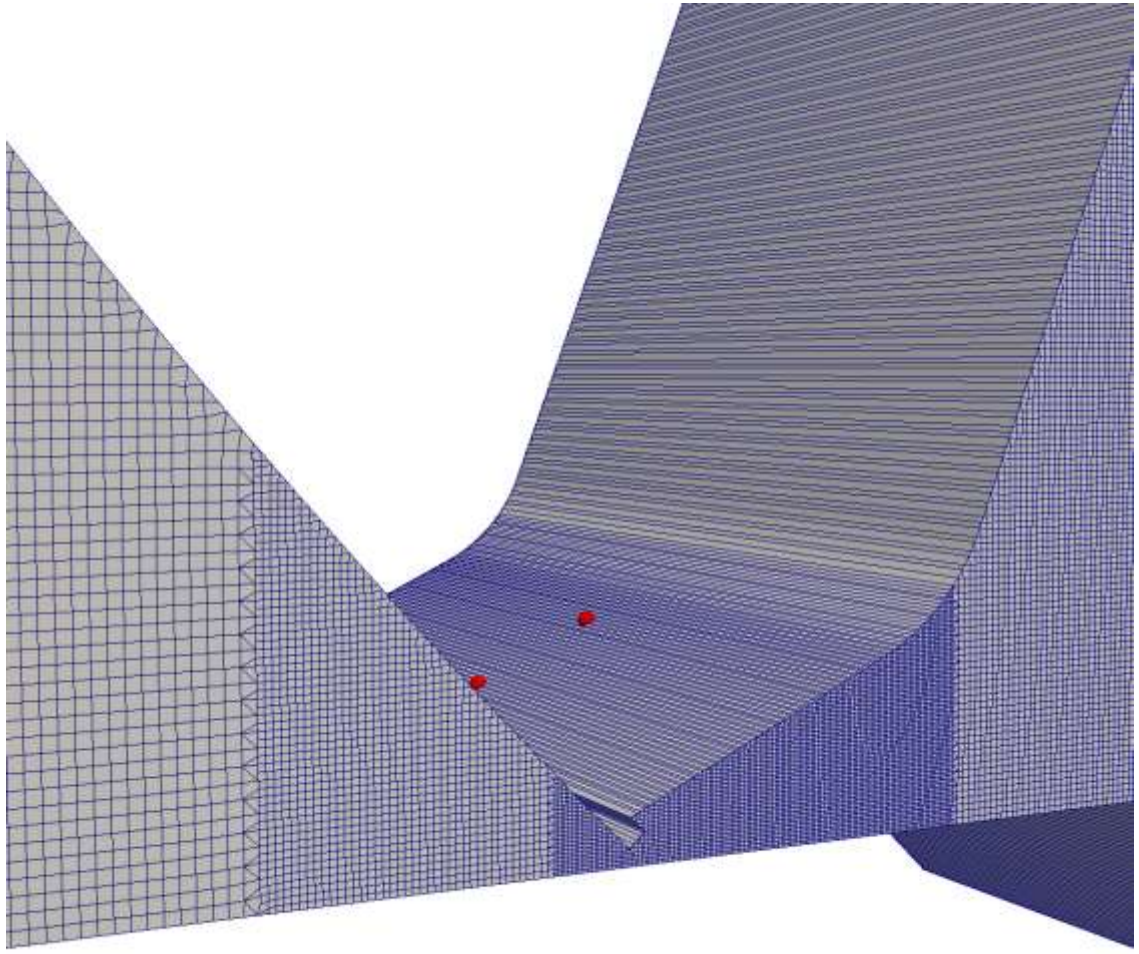
- 2D (1 m x 25 m)
- 320 000 Cells
- Cell sizes 10 cm to 0,3 cm

Numerics:

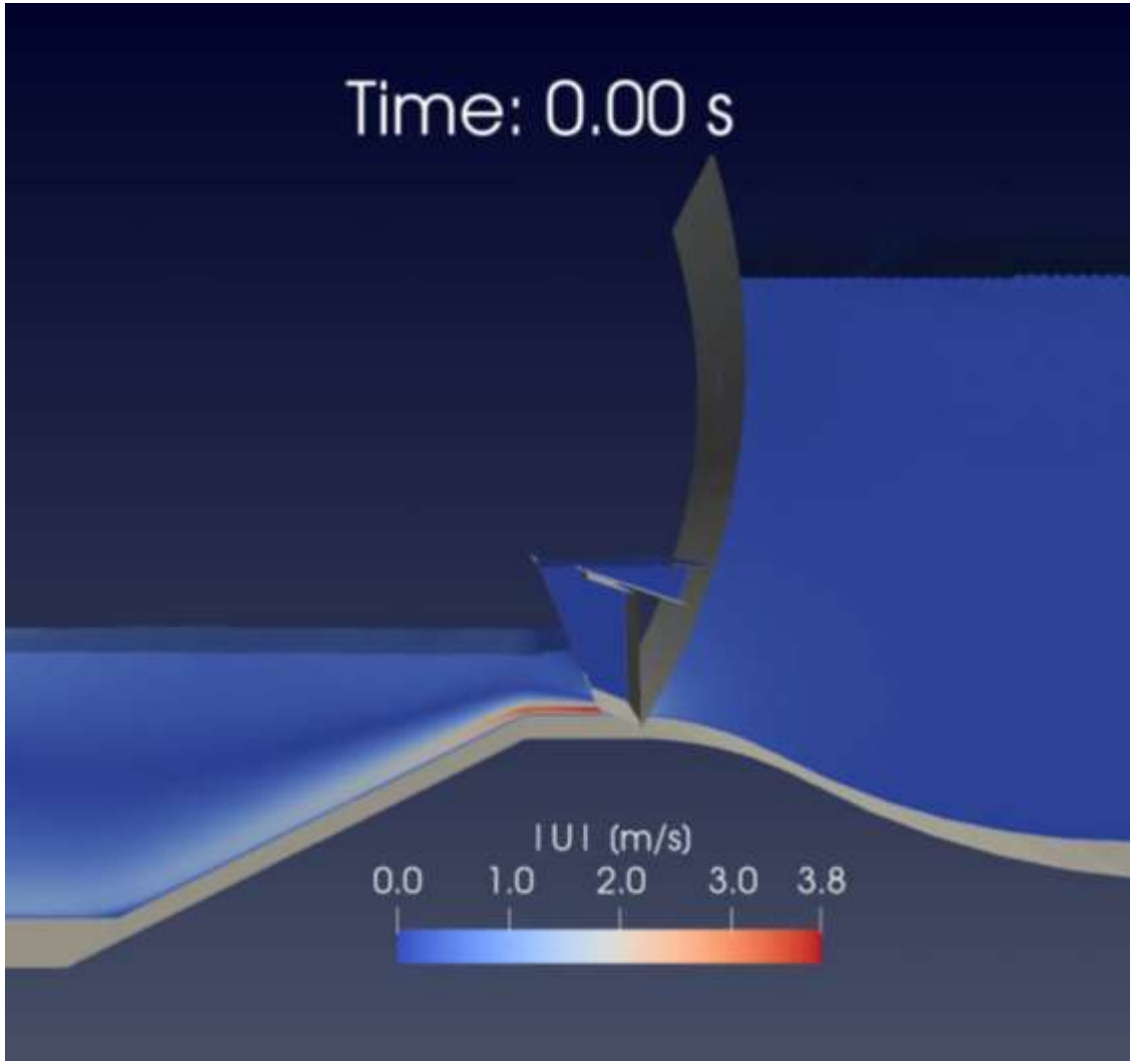
- OpenFOAM (interDyMFoam)
- Fixed water level boundary conditions
- Gate is a moving object: 1 DoF, prescribed
- k-ω-turbulence modell

Results:

- Pressures,
- Forces
- Movements

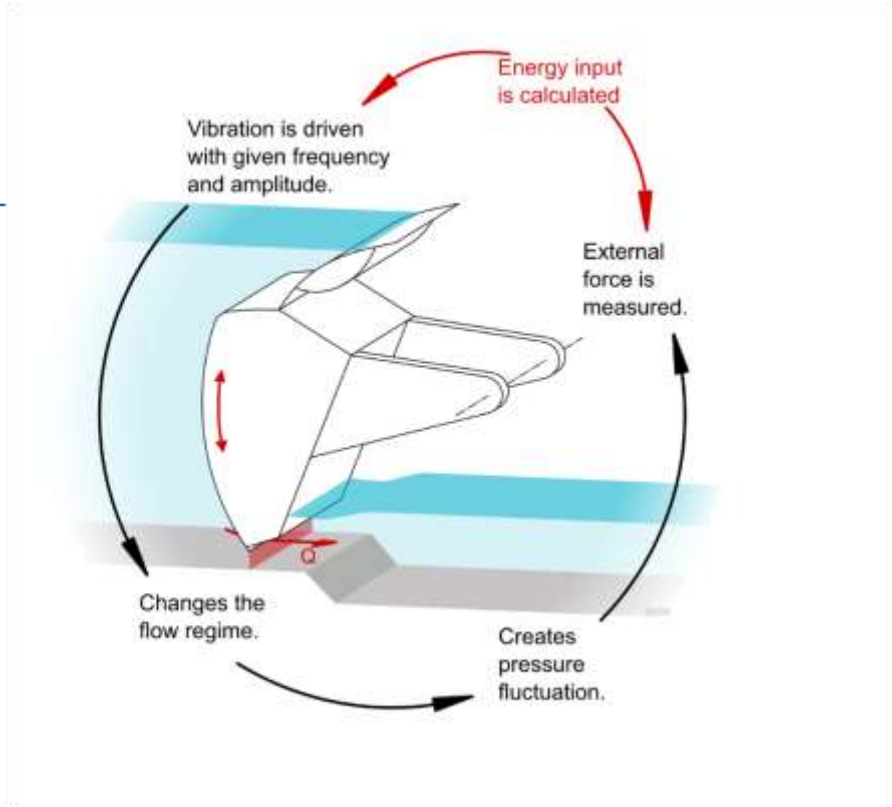


Analysis in physical and numerical model



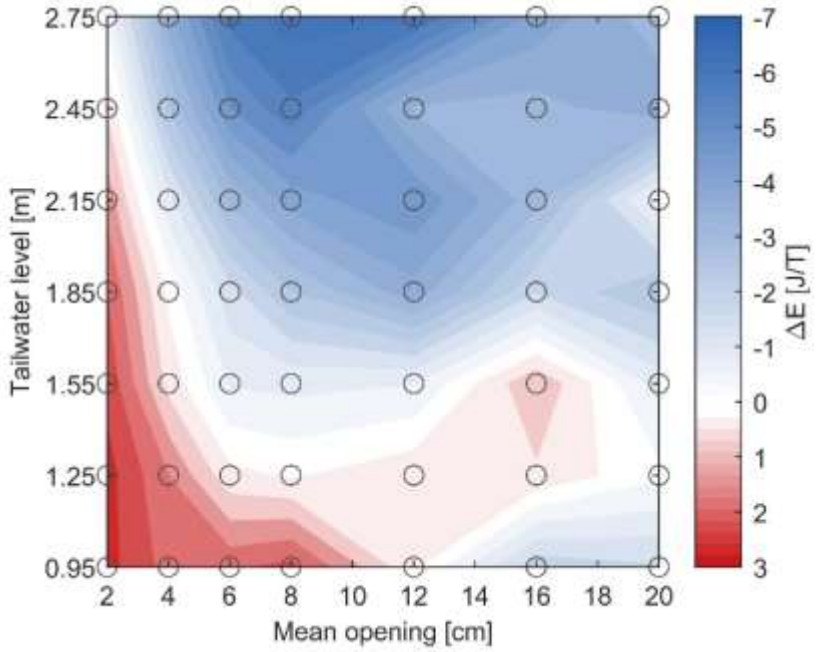
Conclusions from numerical model

- The simulation of the coupled process tends to be unstable due to:
  - Deformation of small cells
  - Large pressure gradients and transients



Conclusions from numerical model

- The simulation of the coupled process tends to be unstable due to:
  - Deformation of small cells
  - Large pressure gradients
  - High acceleration
- The free vibration is replaced with a forced vibration
- Phase of vibration and forces are compared by means of an energy consideration
  - If $\Delta E > 0$, the vibration is self-excited
  - If $\Delta E < 0$, the vibration is damped out



Heatmap of critical conditions

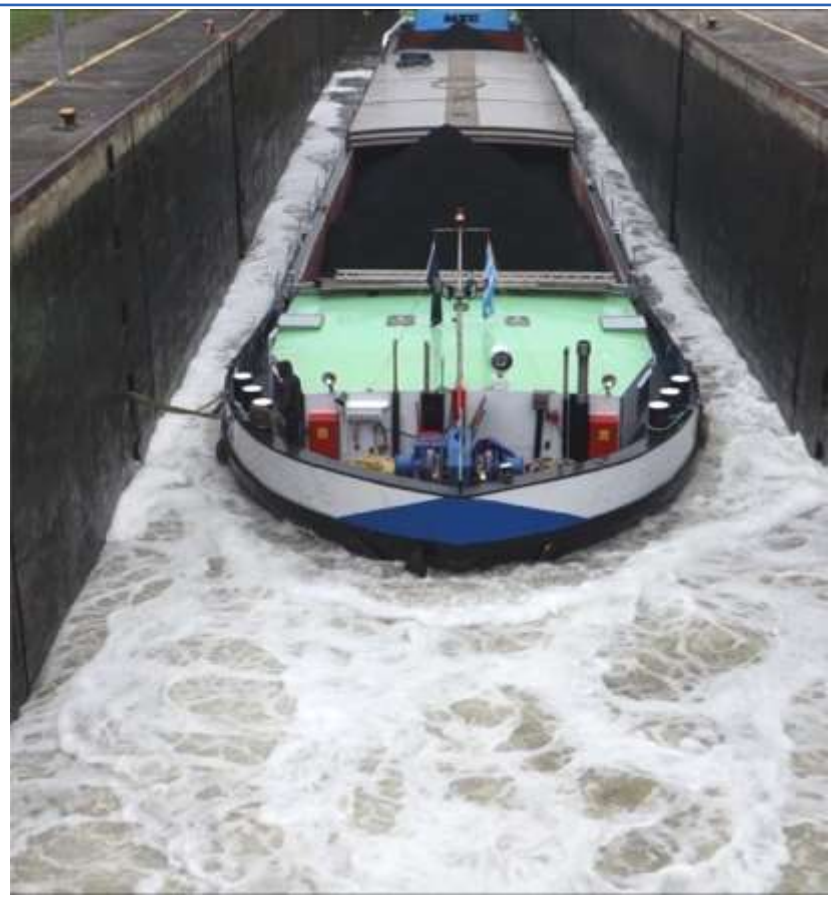
Air entrainment and air transport

- Hard to predict air entrainment intensity and transport behaviour

- Impact often unclear:

  - Very significant in navigation locks

  - Very significant in turbines



Example: Lock filling with air entrainment

Air entrainment and air transport

- Hard to predict air entrainment intensity and transport behaviour
- Impact often unclear:
  - Very significant in navigation locks
  - Very significant in turbines
  - Significance behind weirs ?

Example: Flowfield at the weir Geesthacht at river Elbe (Northern Germany)

interFoam: Volume-of-Fluid-Method

- **Two-phase** solver for Navier-Stokes equations

- **Advective transport** of a scalar entity „alpha“

  alpha = 1: Only water, no air

  alpha = 0: No water, only air

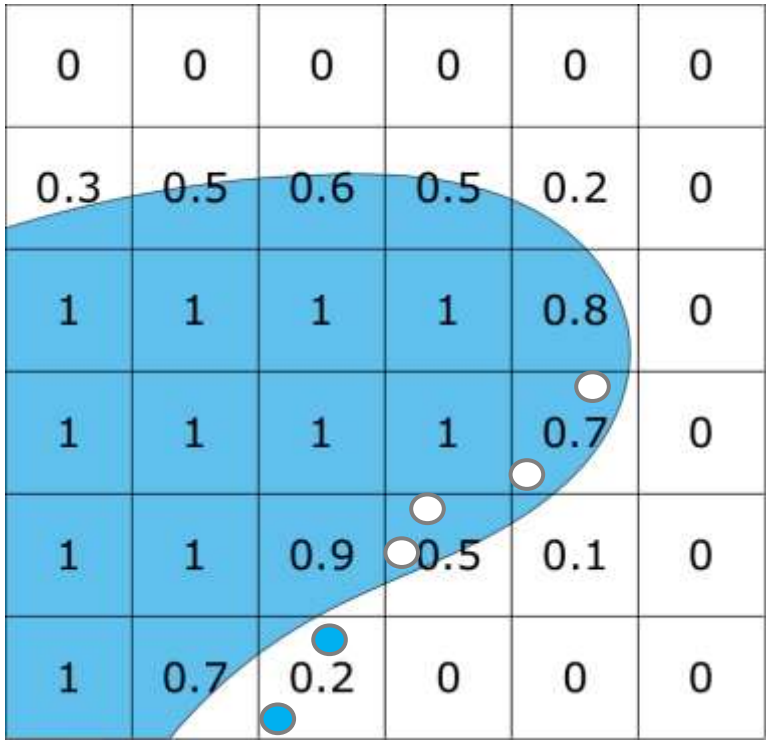
  0 < alpha < 1: Air-water mixture with undefined distribution

- Fluid properties within a computational cell in the grid:

  Volumetric weighting of fluid properties (density, viscosity)

- Only a **single set of** continuum and momentum **equations**

- Should only be used for **air-water-interfaces much larger than a cell**, because subgrid movement of air in water is not modelled!



(Wagner, 2020)

Classic VOF equation

- Basic VOF advection equation:

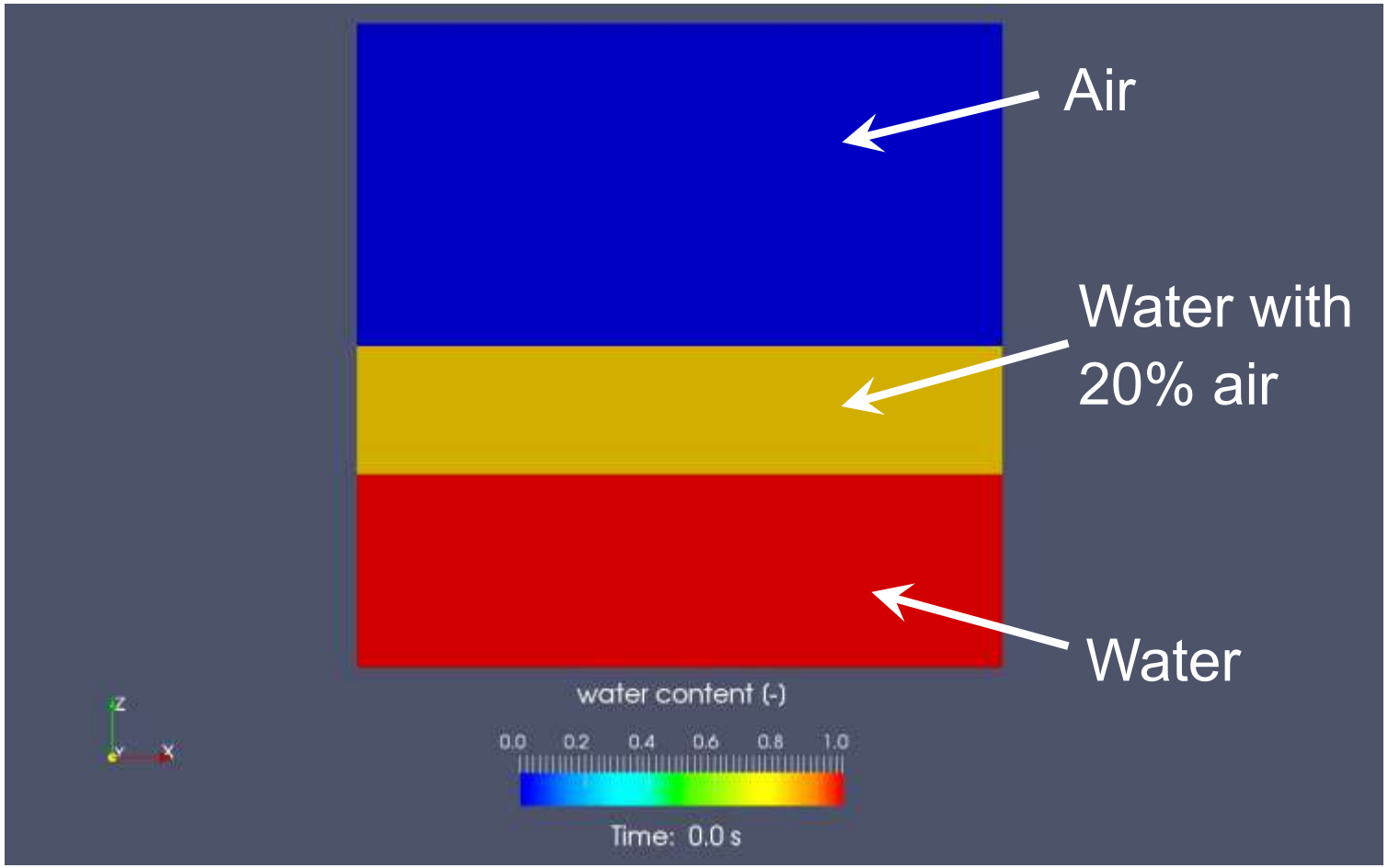
$$\frac{\partial \alpha}{\partial t} + \nabla(\alpha \cdot \mathbf{U}) = 0$$

- OpenFoam extension to sharpen the VOF air-water-interface:

$$\frac{\partial \alpha}{\partial t} + \nabla(\alpha \cdot \mathbf{U}) + \nabla(\alpha(1-\alpha)\mathbf{U}_\mathrm{r}) = 0$$

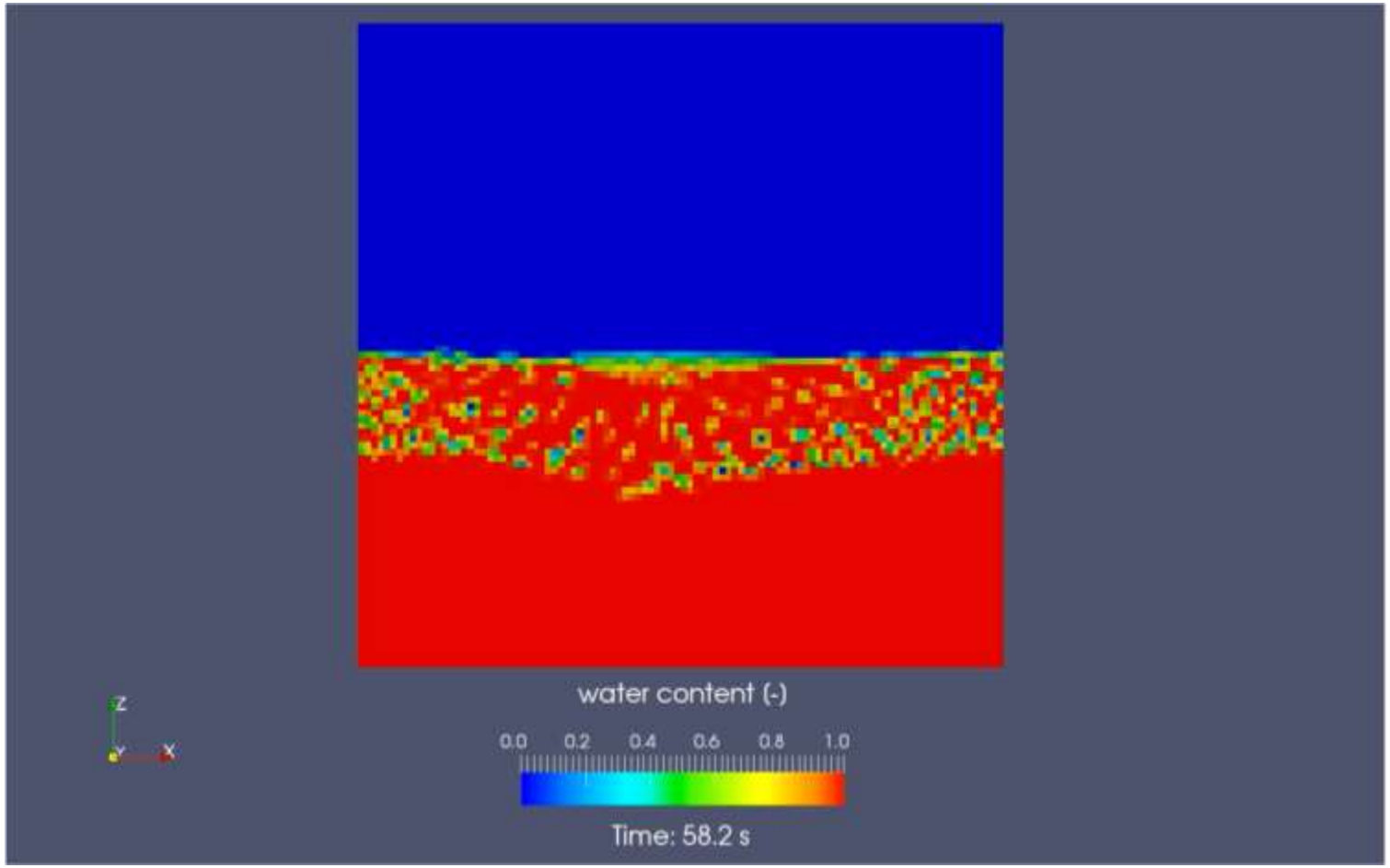
Numerical sharpening

Classic VOF equation



Example for numerical sharpening

Classic VOF equation



Example for numerical sharpening

Numerical concept for interFoam extension

Goal: A simple plug-and-play compatible enhancement for the VoF solver which enhances the physical correctness

Basic assumptions:

- Flow velocities >> relative bubble velocity

- Scale of the problem >> travel distance of a bubble to reach terminal bubble velocity

  ⇒ Instantaneous equilibrium of bubble resistance and bubble forces

- Momentum exchange „air⇒water“ negligible

  ⇒ Large scale impact of air on water flow sufficiently modeled by density reduction of the mixture

Extension of VOF equation

- OpenFoam VOF equation:

$$\frac{\partial \alpha}{\partial t} + \nabla(\alpha \cdot \mathbf{U}) + \nabla(\alpha(1-\alpha)\mathbf{U}_\mathrm{r}) = 0$$

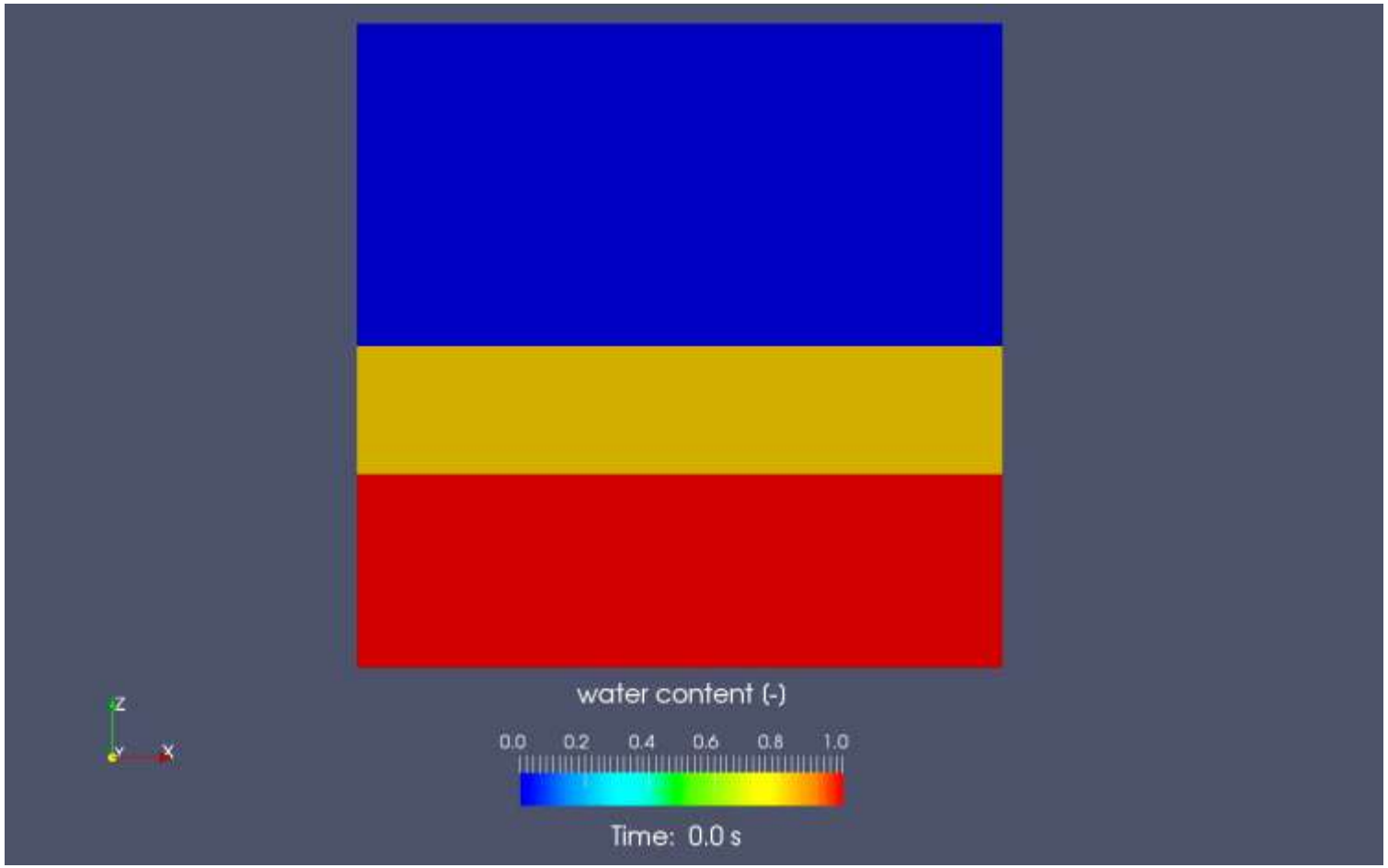
- Extensions to VOF advection equation:

$$\frac{\partial \alpha}{\partial t} + \nabla(\alpha \cdot \mathbf{U}) + \nabla(\alpha(1-\alpha)\mathbf{U}_\mathrm{r}) - \nabla\left(\frac{\nu}{S_c}\nabla(\alpha)\right) = 0$$

⇒ Subgrid-scale air bubble rise.
U_r with a physical meaning.

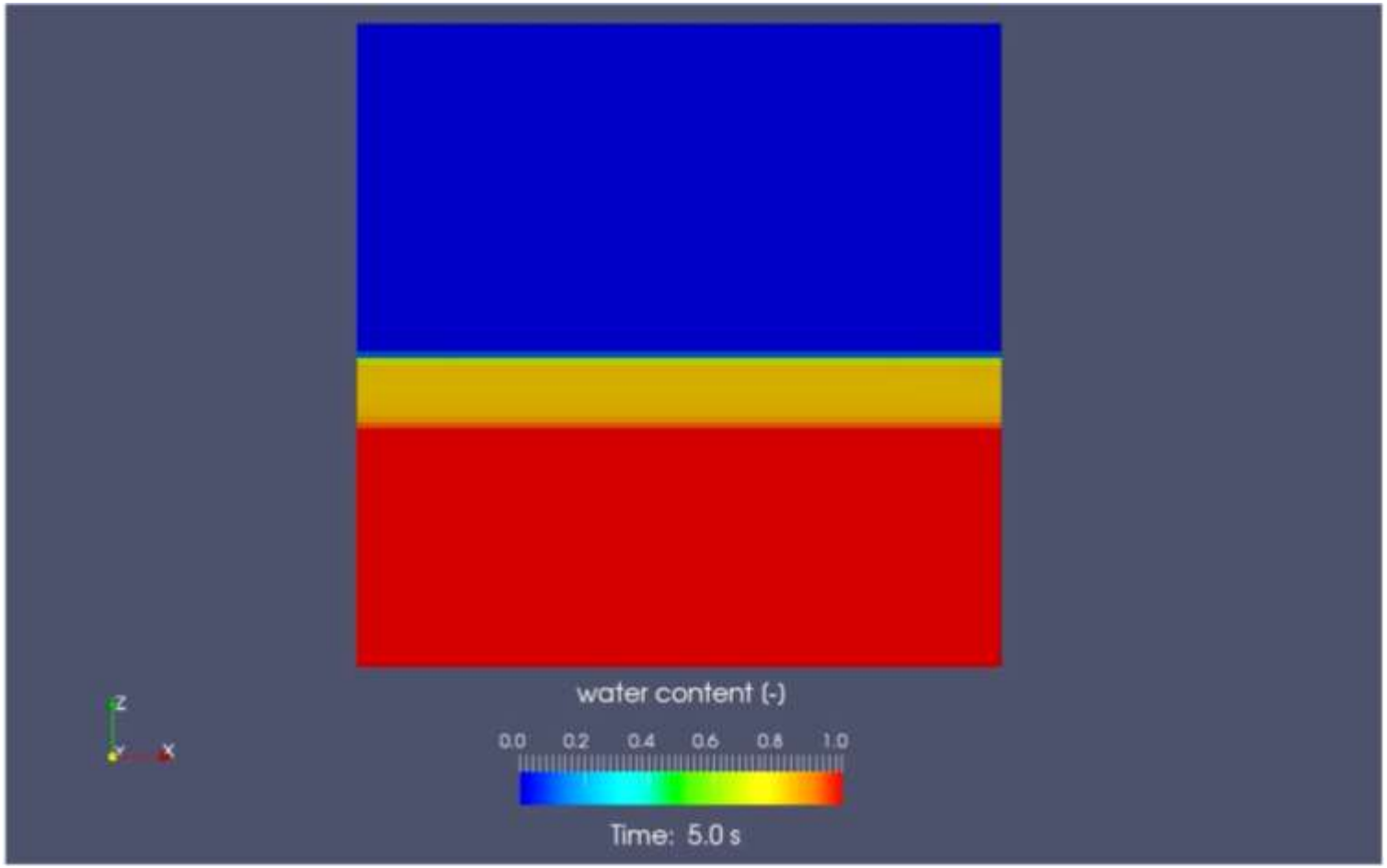
Air bubble diffusion due to turbulence

Extension of VOF equation



Example for physically based air bubble rise

Extension of VOF equation



Example for physically based air bubble rise

Extension of governing equation

- Subgrid-scale air bubble rise

  - *Air bubbles move in direction of negative pressure gradient (not simply upwards!)*
  - *Air bubble speed depends on magnitude of pressure gradient (bubbles don‘t rise in zero gravity!)*

- Subgrid-scale air bubble turbulent diffusion

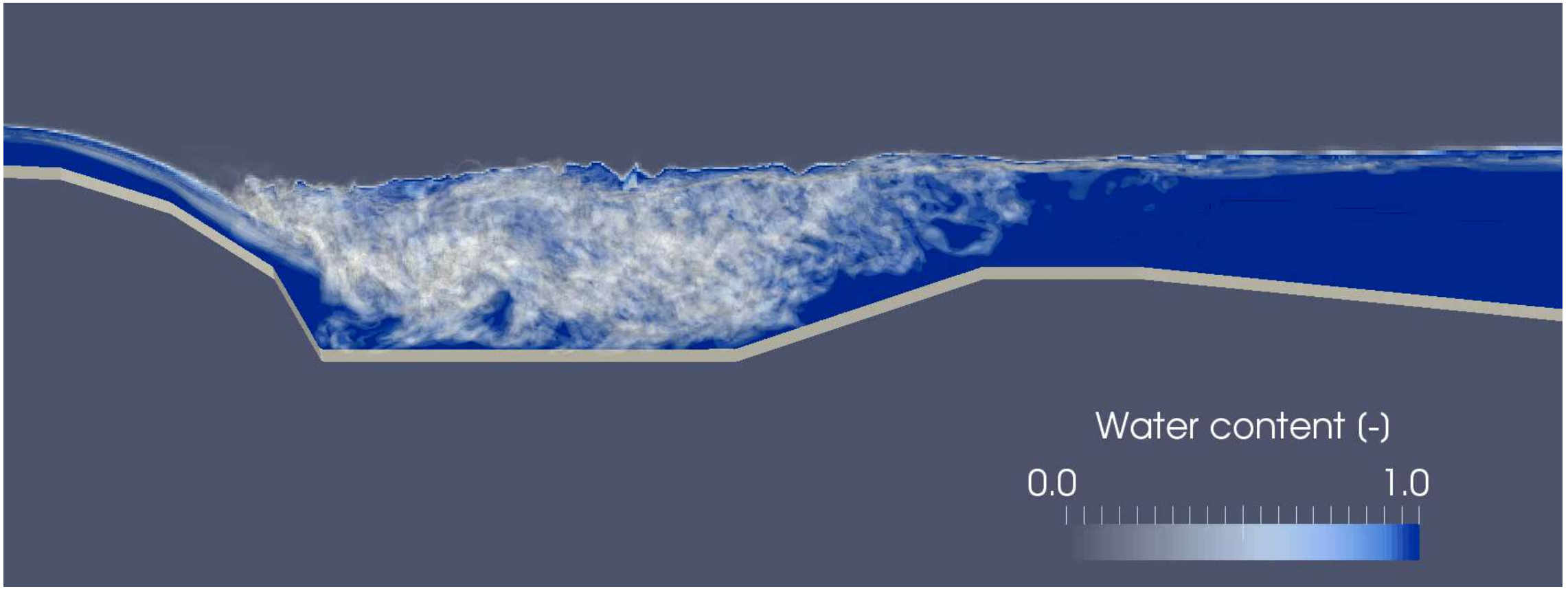
  - *Diffusion is estimated from turbulent viscosity scaled by turbulent Schmidt number*
  - *Impact of bubbles on turbulence model not yet implemented*

  ⇒ LES preferred in order to minimize errors from and onto turbulence modeling

Laboratory testcase

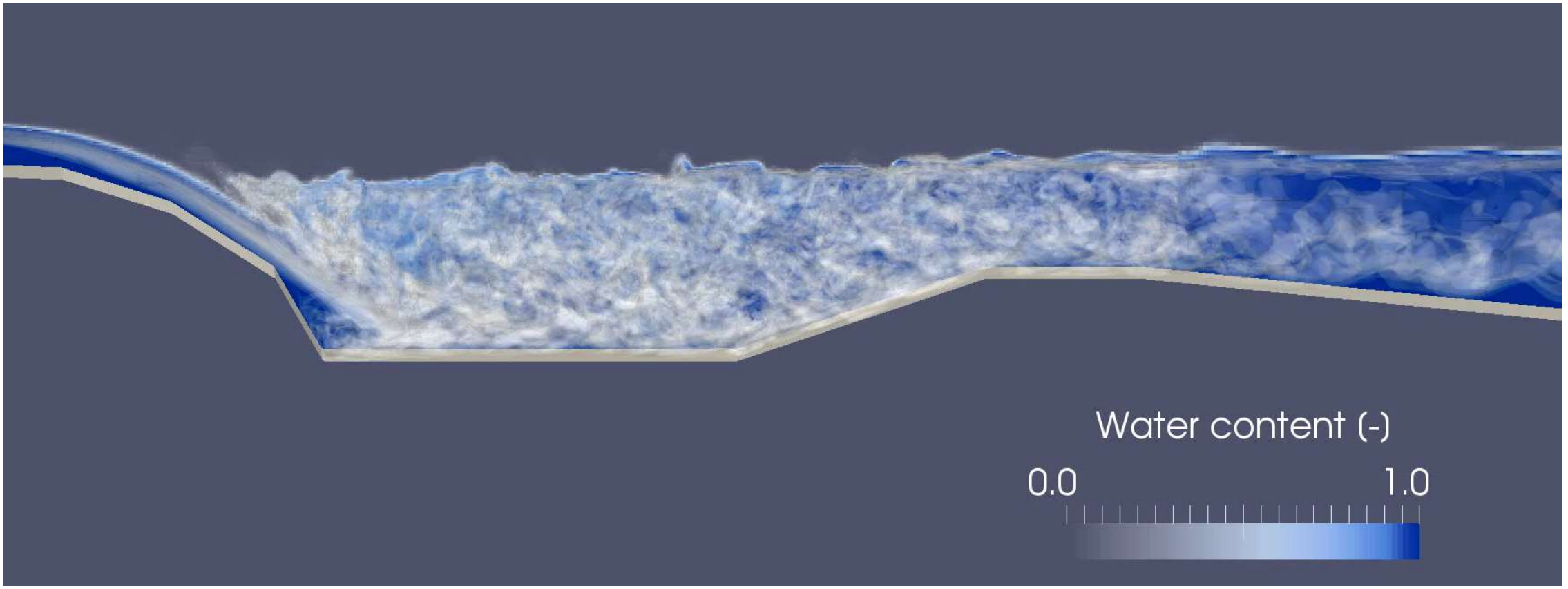
Physical model in scale 1:20 for stilling basin tests at weir Geesthacht: Variant with high weir back

Qualitative comparison in model scale



Numerical model results of VOF solver with air bubble extension in model scale

Qualitative comparison in prototype scale



Numerical model results of VOF solver with air bubble extension in prototype scale

Conclusions and future work

Conclusions

- Significant enhancement in air transport modeling over standard VOF solver for „bubbly“ flow situations

Ongoing and future work:

- Treatment of air entrainment into jets / nappe flow
- Validation by measurements in physical model with conductivity probes
- Evaluation of air movement impact on engineering questions (ship forces in locks, scouring behind weirs)

Future work:

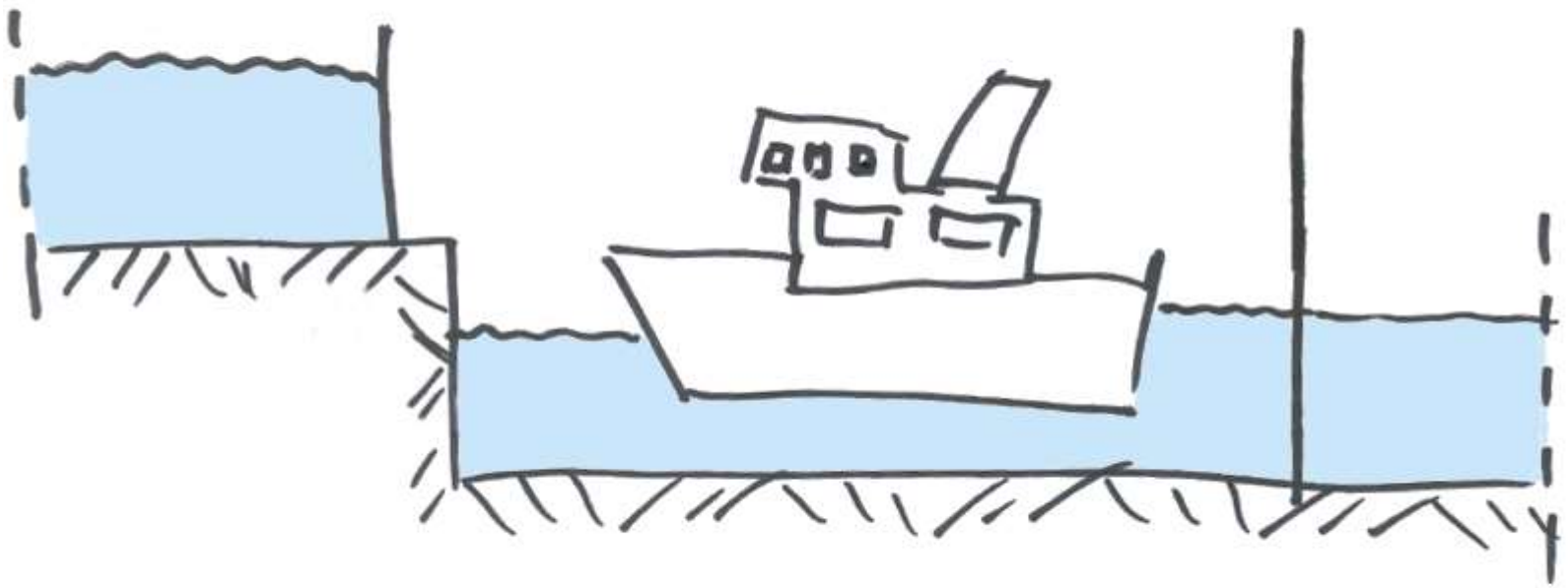
- Impact of strong strafification on turbulence models
  - Damping of turbulence
  - Anisotropic turbulent behaviour („Pancake turbulence“)

Ships in navigation locks

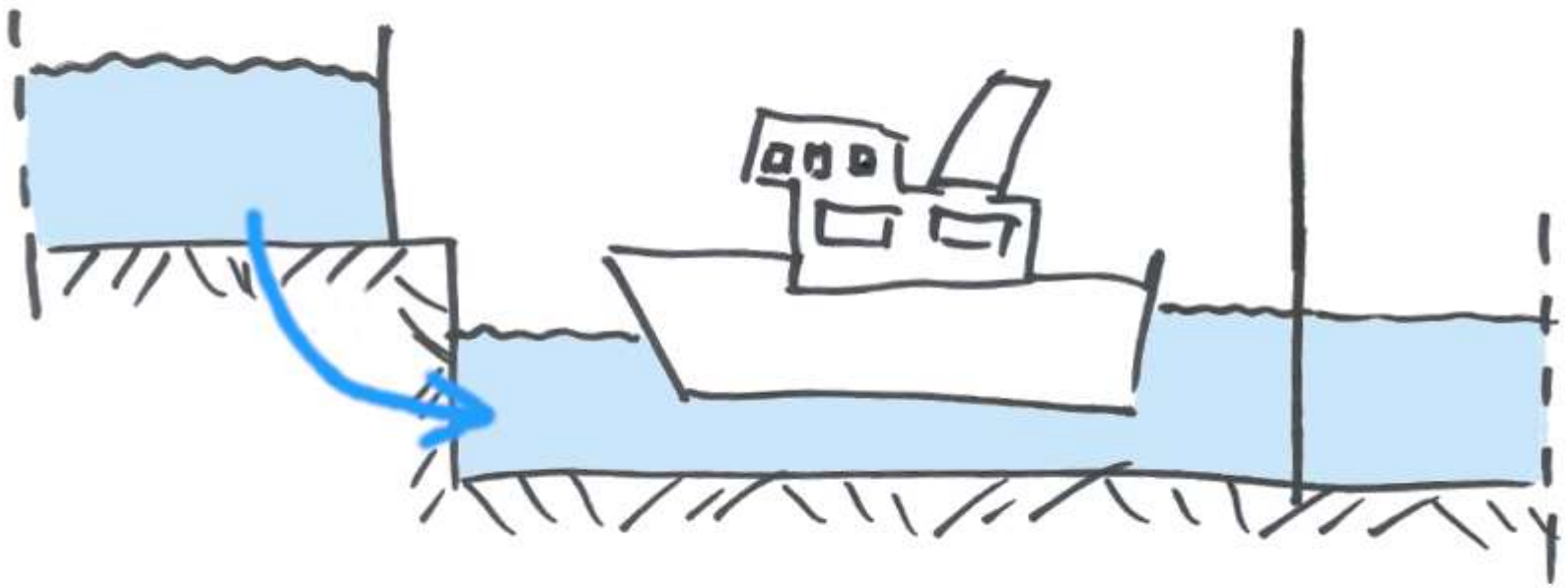
- Ships have a mass of thousands of tons
- Lifting or lowering by several meters
- Filling or emptying the lock chamber as fast as possible
- But it must still be safe!

Task for a large inland lock: Fill in 250000 bathtubs of water within minutes!

Safety for ships in navigation locks



Safety for ships in navigation locks



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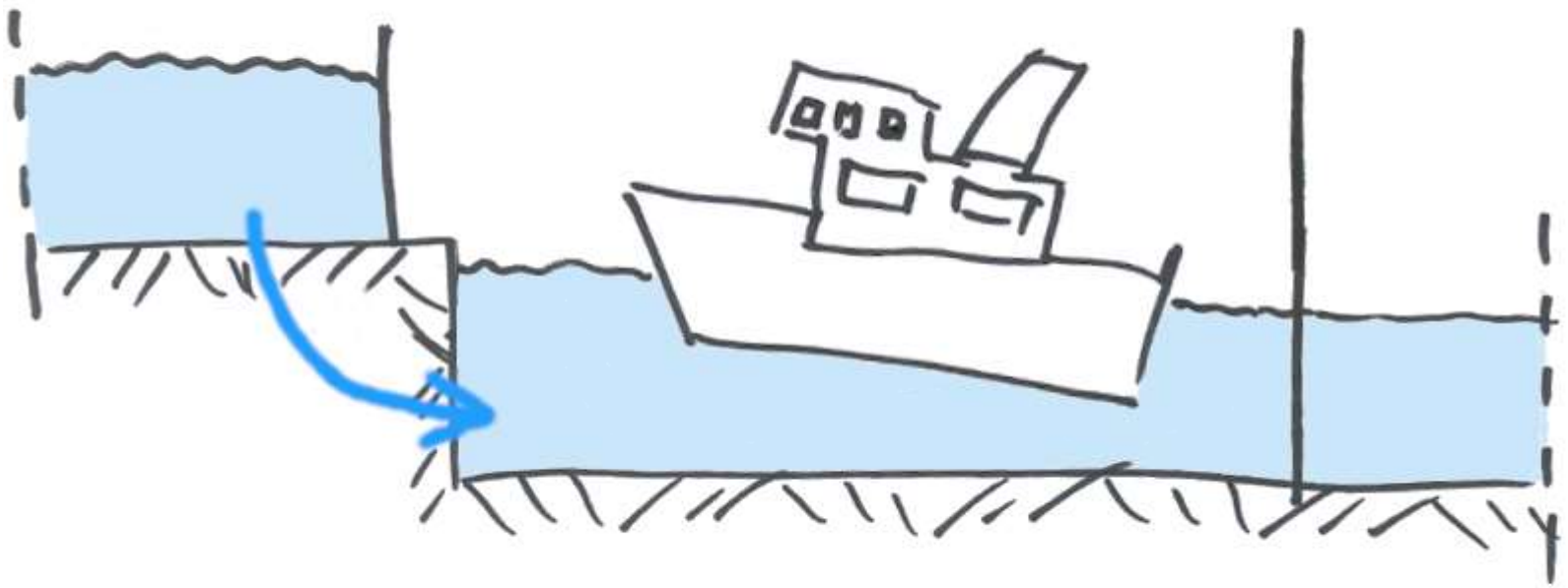

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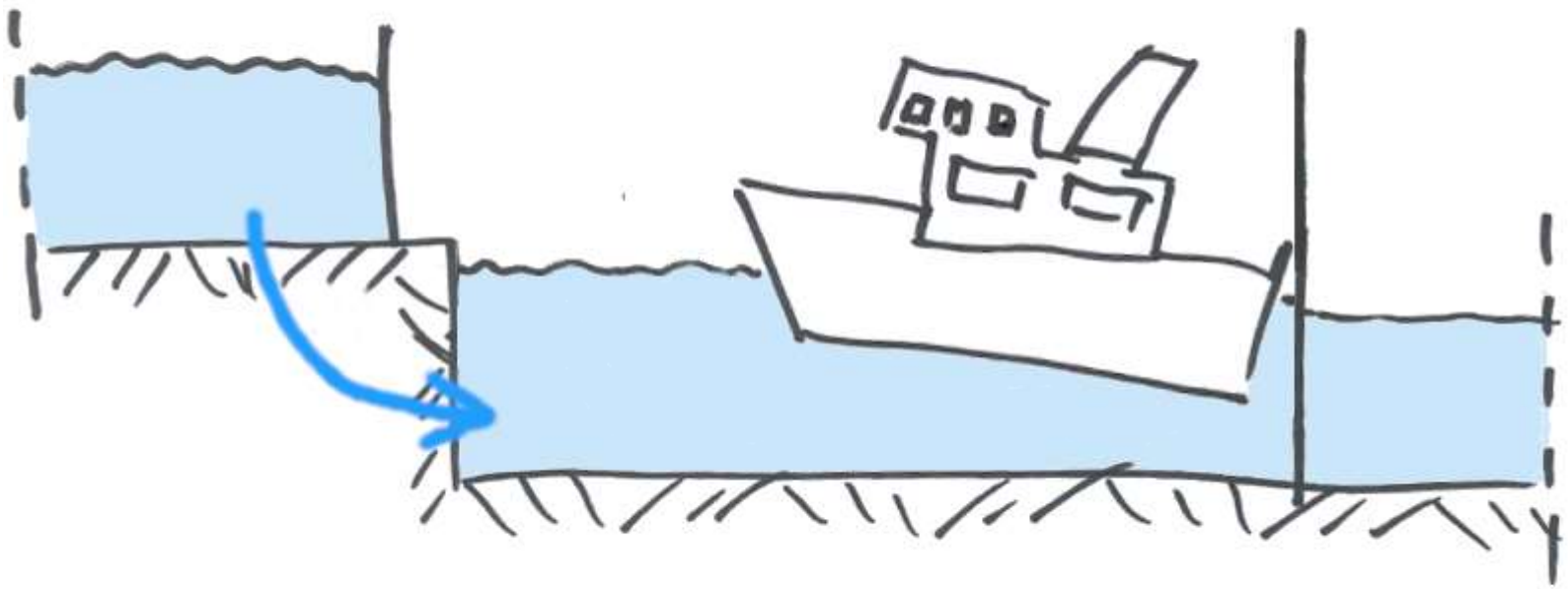

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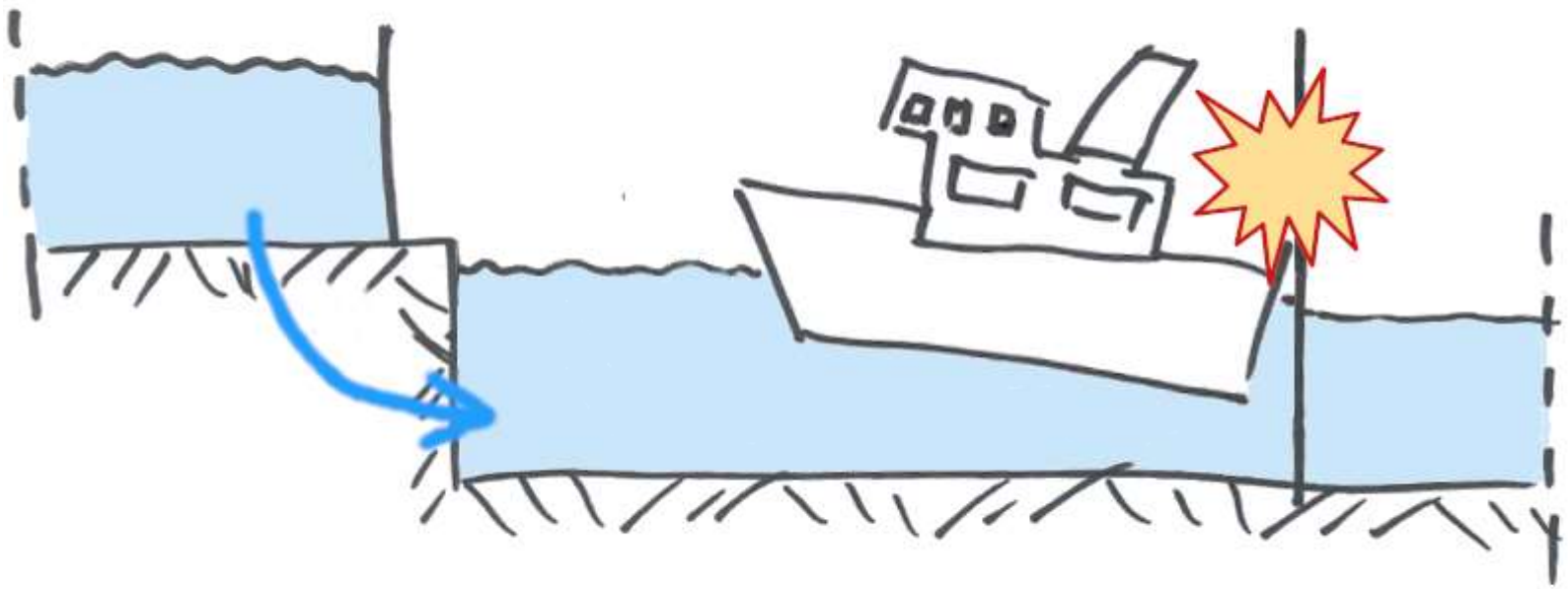
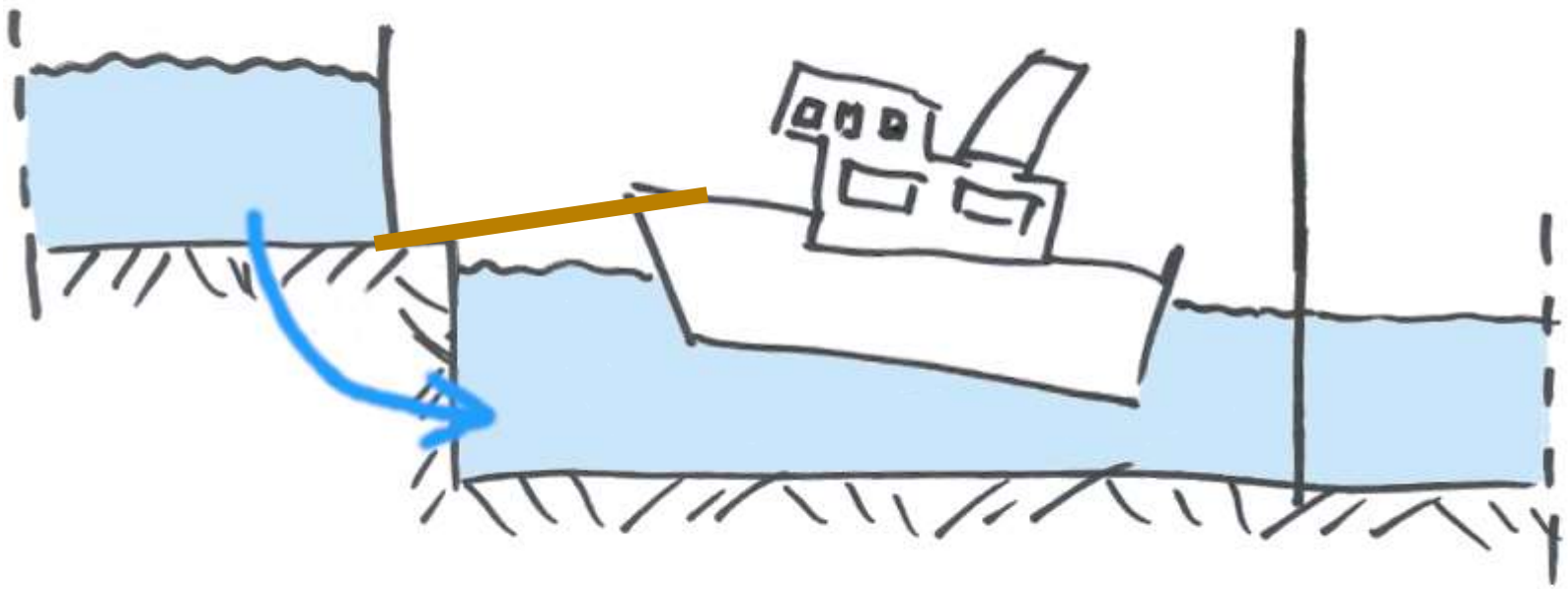


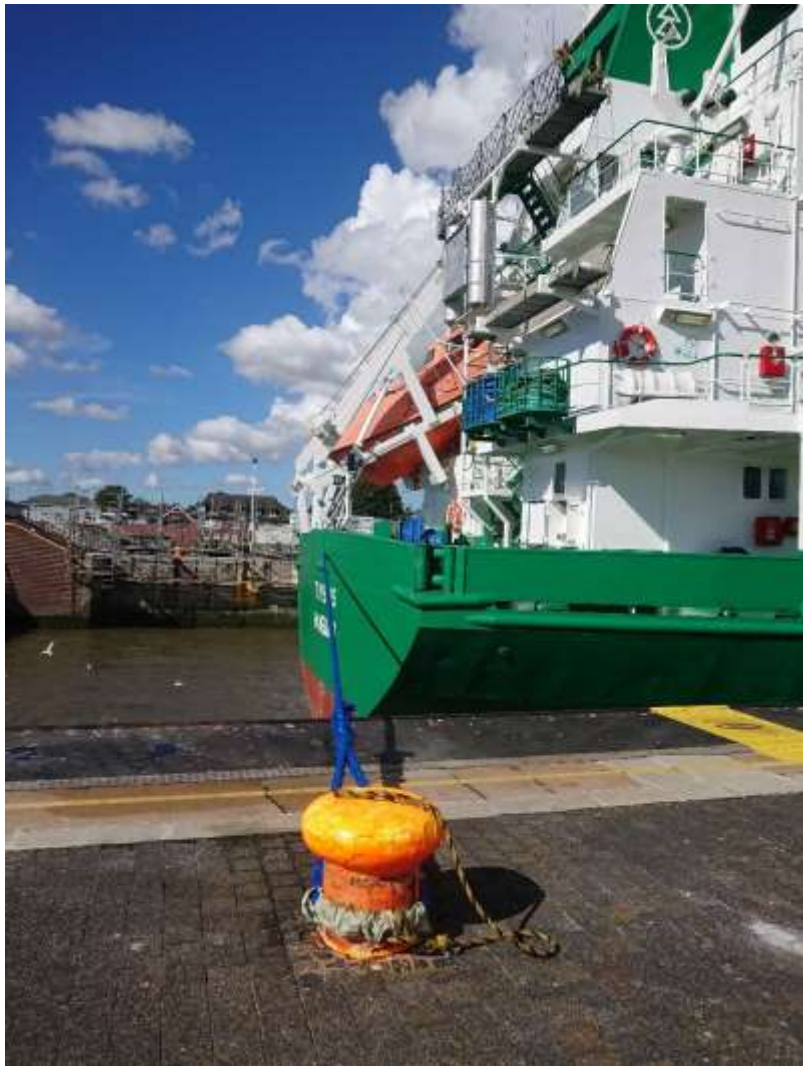
Safety for ships in navigation locks



Safety for ships in navigation locks

Safety for ships in navigation locks

Bildquelle: WSA Kiel



Safety for ships in navigation locks

Safety for ships in navigation locks

Bildquelle: WSA Kiel

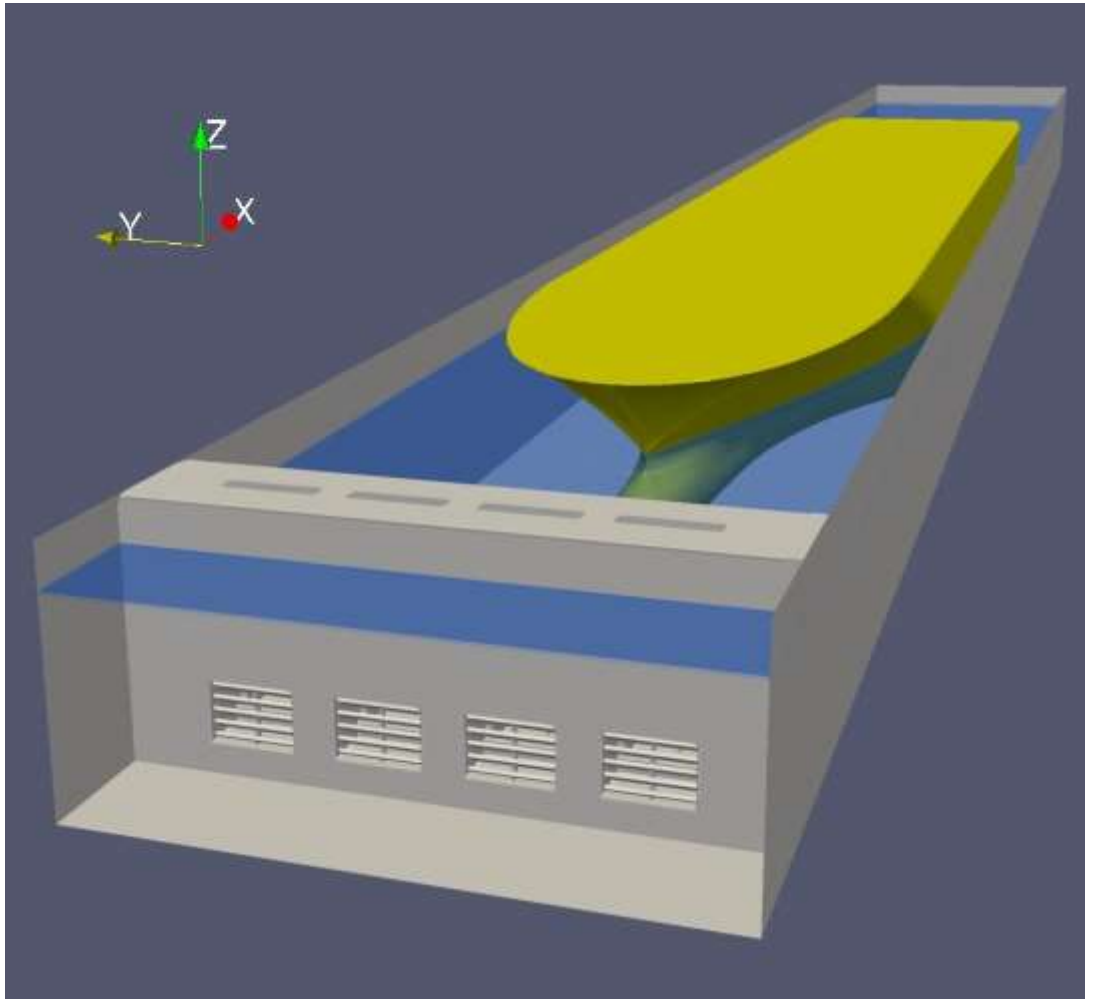
Numerical model to evaluate ship safety

Modelling approach:

- interFoam with moving mesh
- pointDisplacement BC:Six-degree-of-freedom for the ship
- Mesh deformation as Laplacian with variable coefficients
- Valves simplified as „poor man‘s immersed boundary“ (credits to Henrik Rusche)
- Additional physics:
  - Saltwater
  - Air

Results

- Flow dynamics
- Forces on the ship



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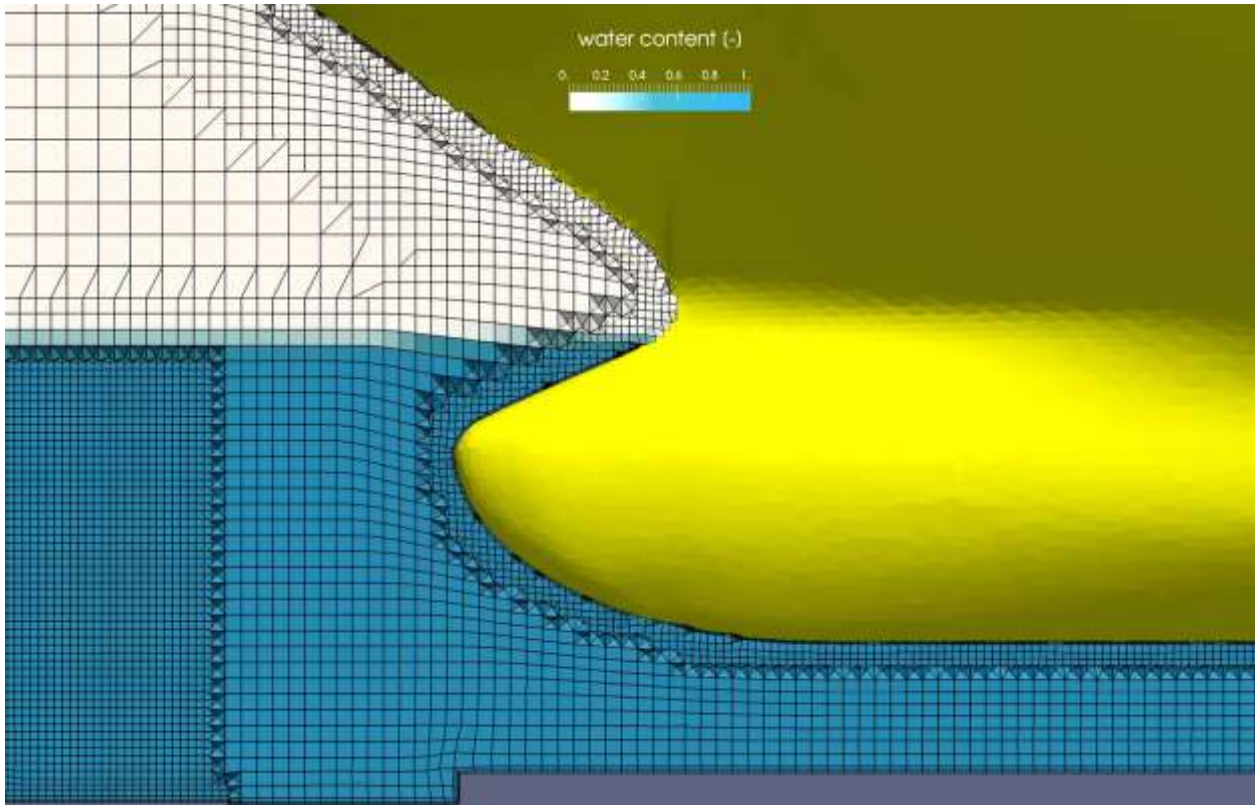


Results

- Flow dynamics
- Forces on the ship

The lock complex at Brunsbüttel

New lock between large and small old locks

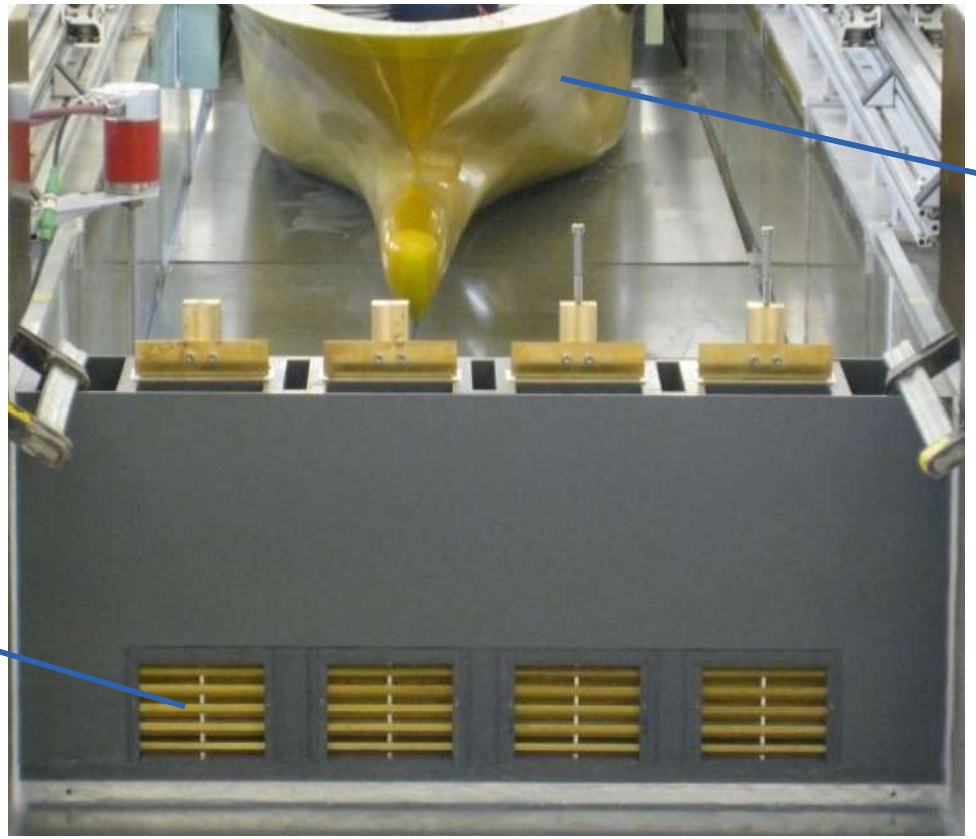
- 5th lock chamber at the lock complex at the western end of the canal
- Chamber dimensions 360 m x 45 m x ~14.5 m
- Currently under construction
- Through-the-gate filling system

Hydraulic tests for the new filling system

The hydraulic system had be validated:

- Numerical pre-studies and feasibility tests
- Physical model for detailed determination of ship forces , valve schedules etc. (Design ship of 40000 t, scale 1:47) with fresh water
- Numerical extrapolation to salt water, test cases with varying densities

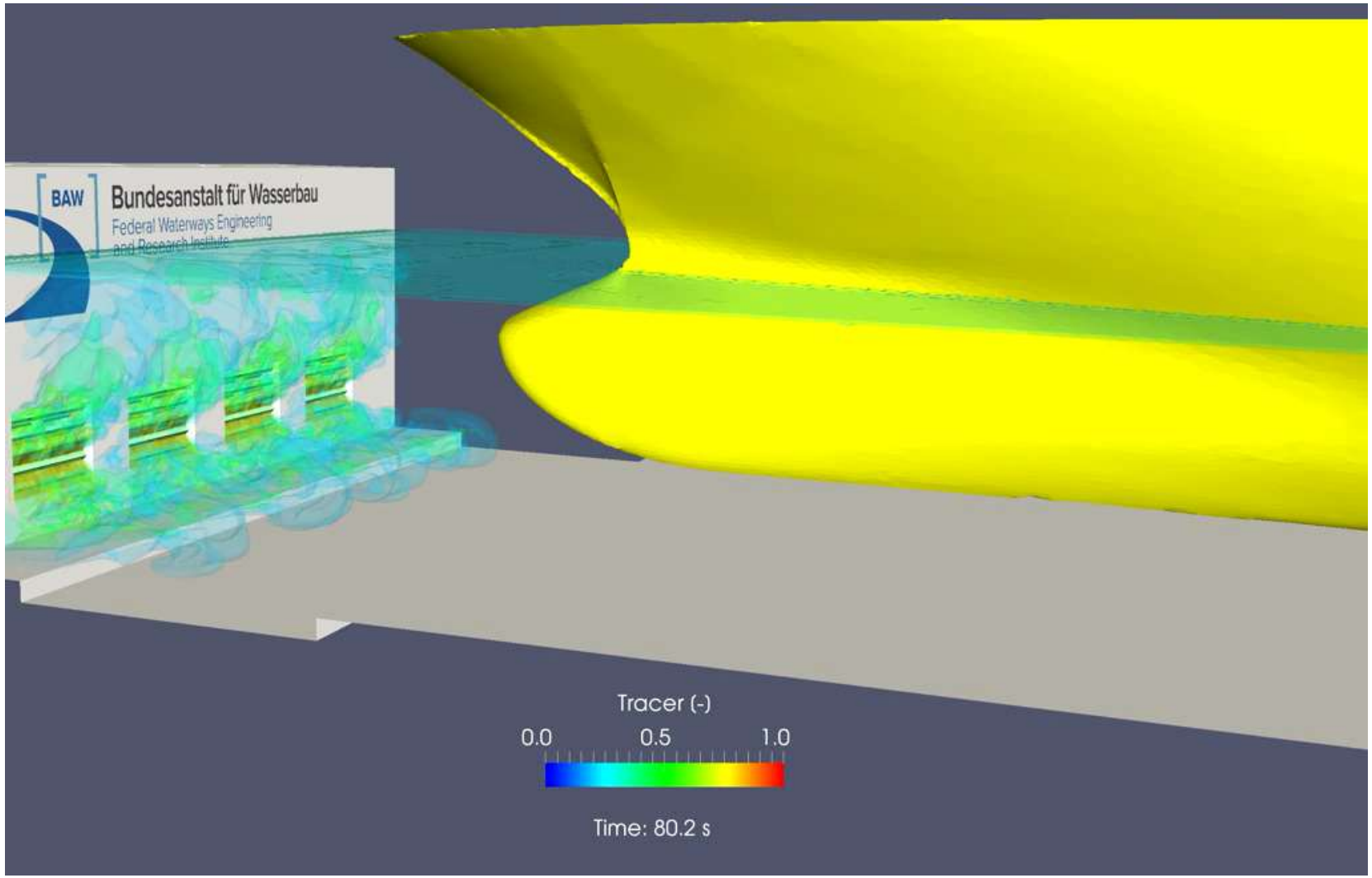
Physical model tests



Model of lock Brunsbüttel 1:47

Physical model tests

Numerical model results



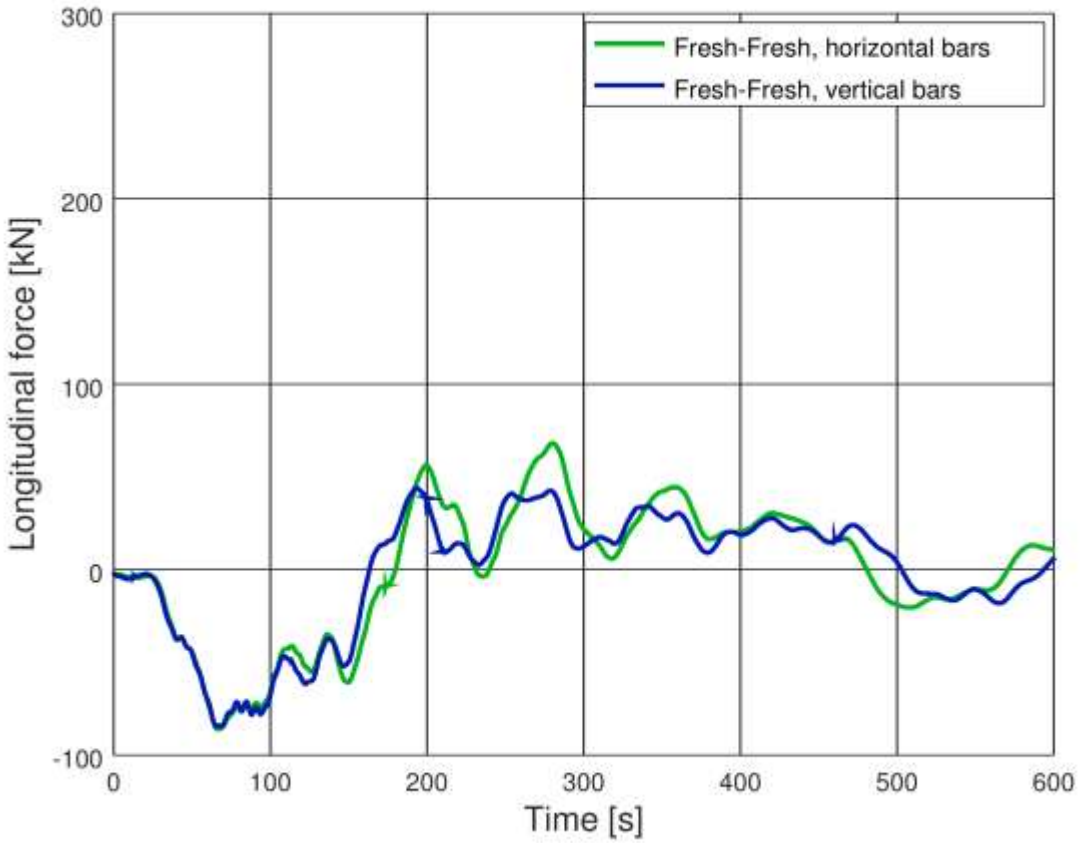
Validation of the numerical model

Fresh water hydrodynamics: Validation with data of the lock „Holtenau“ at the eastern end of the Kiel-Canal

- **Very good** agreement with **flow rates** of physical model
- **Very good** agreement with **water levels** of physical model
- **Acceptable** agreement with **ship forces** of physical model

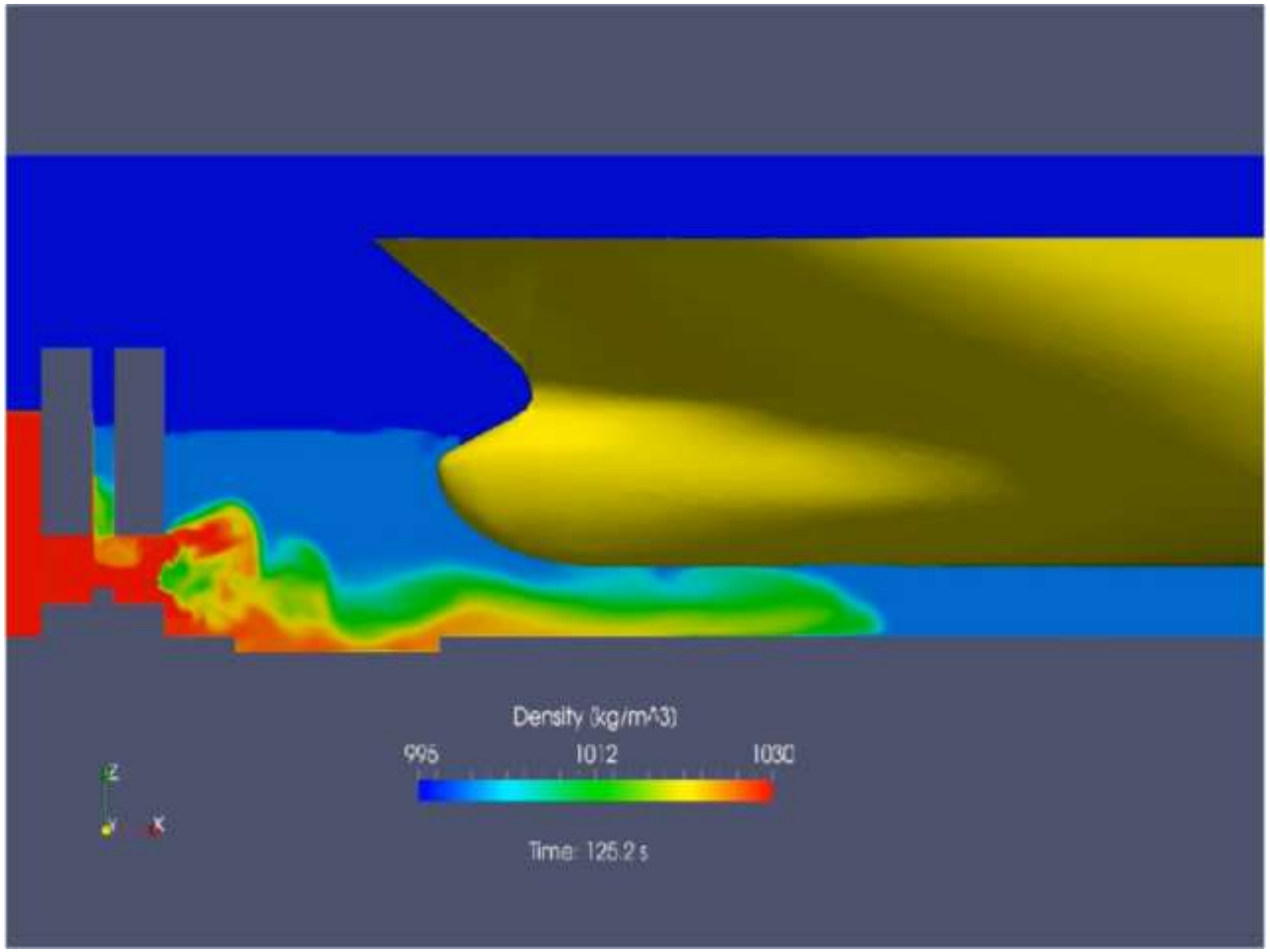
Note: Numerical model was only set up, but ***not „calibrated“!***

Filling with fresh water



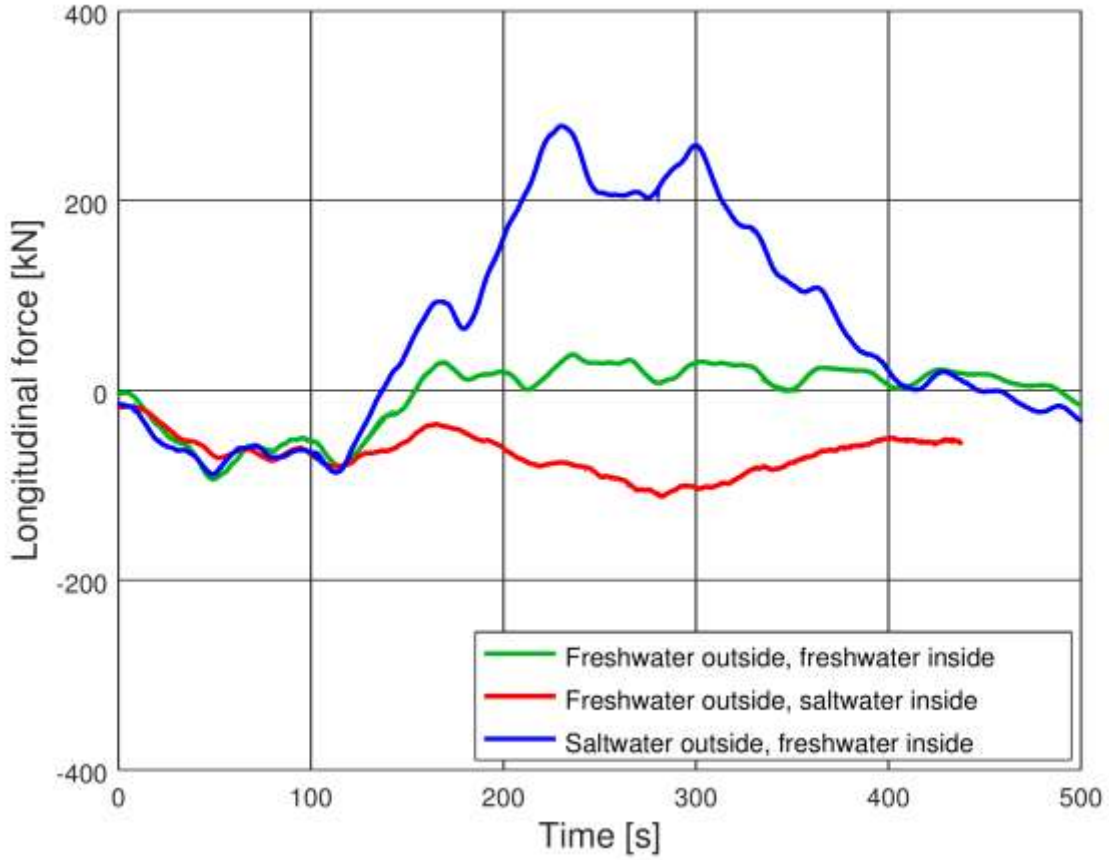
Comparison of longitudinal forces

The new lock at Brunsbüttel: Filling simulations



Computed flow field: Saltwater entering a chamber filled with freshwater

The new lock at Brunsbüttel: Filling simulations

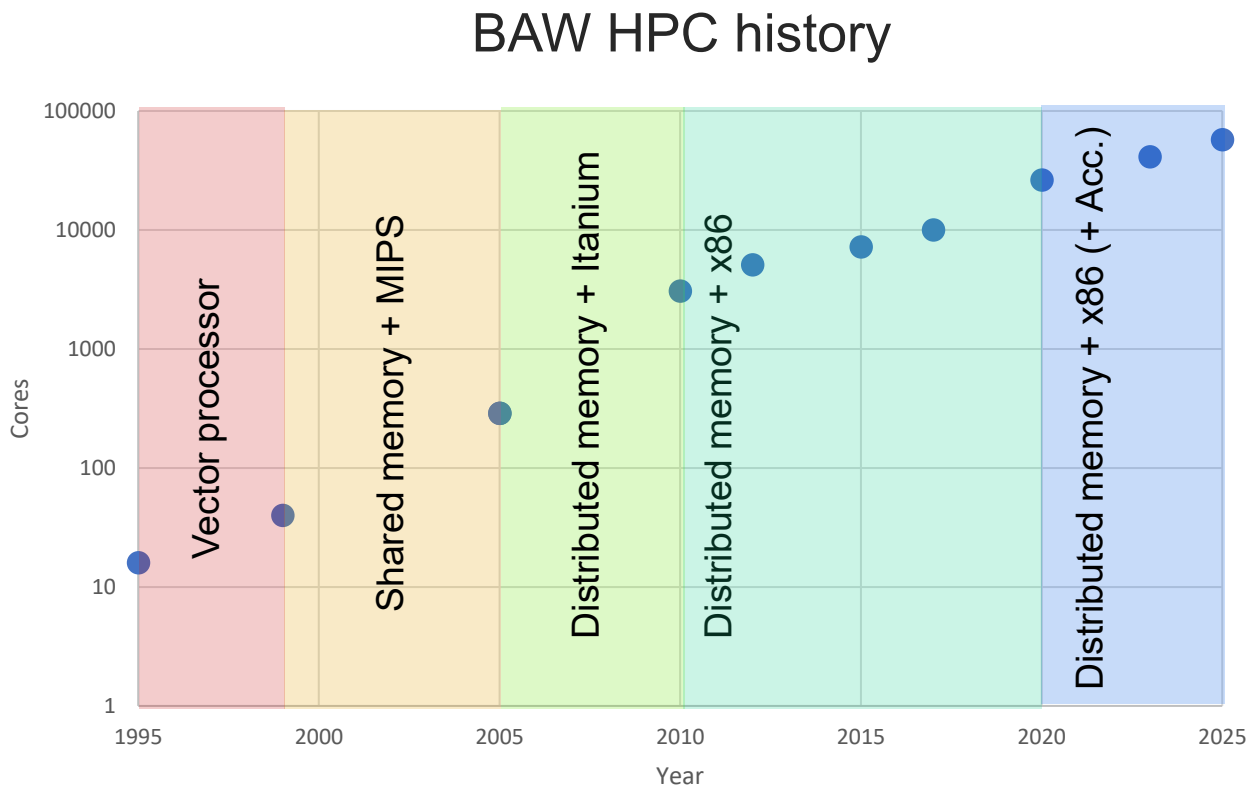


Computed forces on vessel for filling with salt- or freshwater and smooth valve schedule

Summary and conclusions lock filling simulations

- A numerical model based on OpenFOAM was set up that incorporates **moving valves, moving vessel, moving water surface** and the impact of **density differences**
- Validation of the numerical model shows **good agreement for all flow patterns** even without calibration, but could be better for the forces on the vessel
- Simulation results have shown the **importance** to take **density differences** into account
- Simulation results have shown that the mixing at the lock head helps only little to minimize the effects of **density differences** on the vessel

Fish … and chips



Installed HPC CPU cores in BAW (Karlsruhe branch)

New system

Commissioning 2026:

37.376 Compute Cores

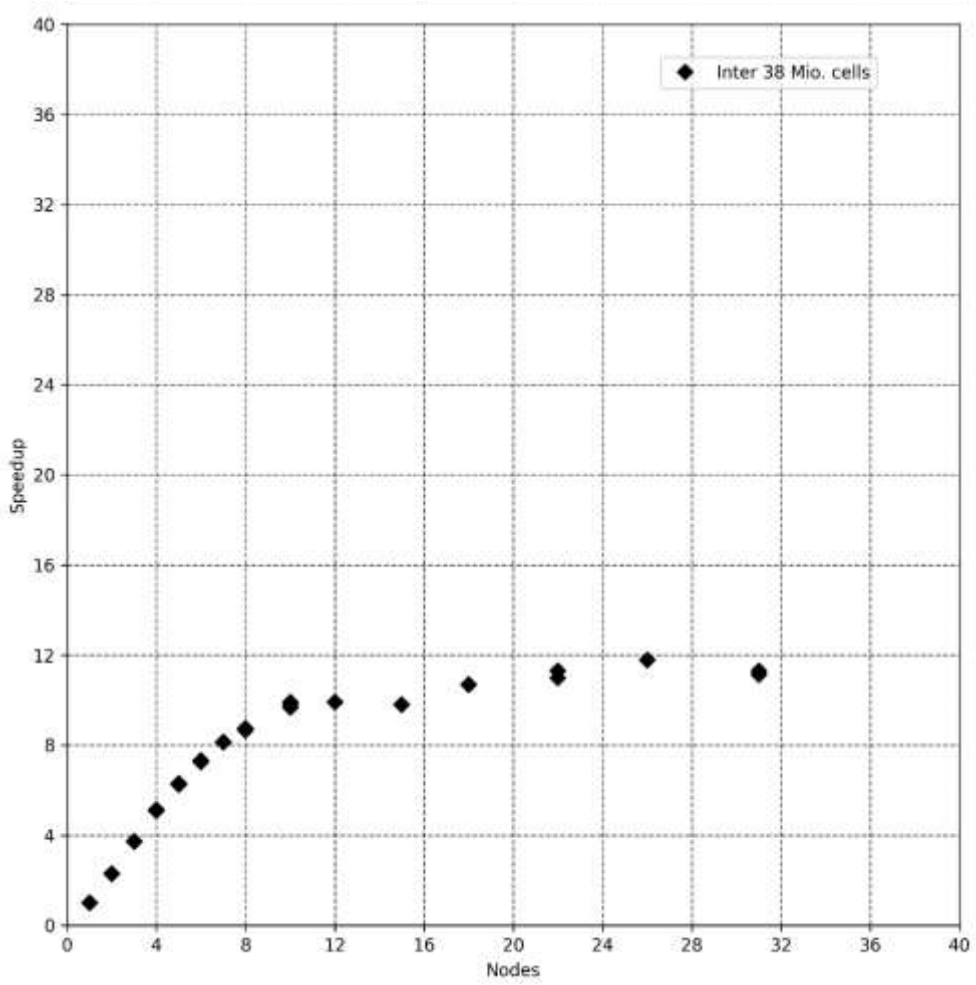
112 TB RAM

15 GPU nodes (Nvidia L4)

5 AI nodes (Nvidia H100)

1 + 1 + 0,5 PB storage

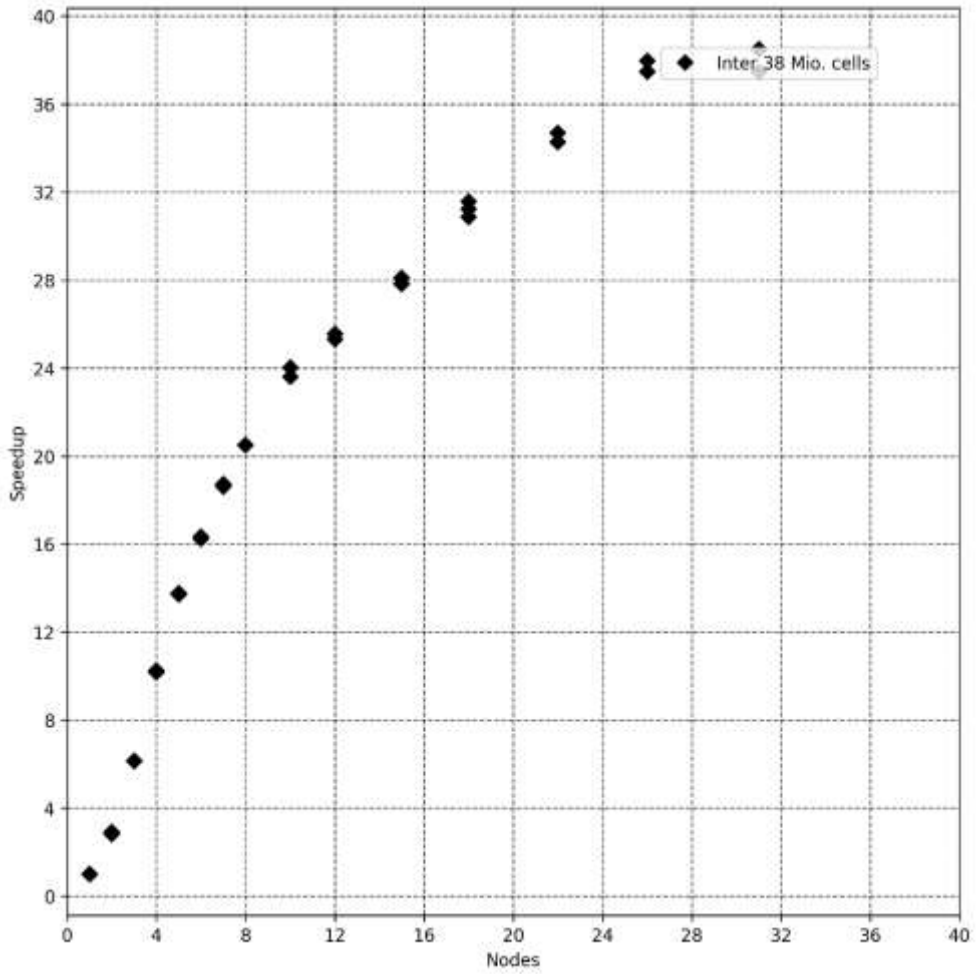
Parts of the commissioning tests: Scaling tests



GAMG preconditioned BiCGStab

- interFoam
- 38 Mio. cells
- Compact domain
- Multilevel decomposition (Scotch)
  - ⇒ n Nodes
  - ⇒ 2 CPUs
  - ⇒ 128 Cores

Parts of the commissioning tests: Scaling tests



DIC preconditioned PCG

- interFoam
- 38 Mio. cells
- Compact domain
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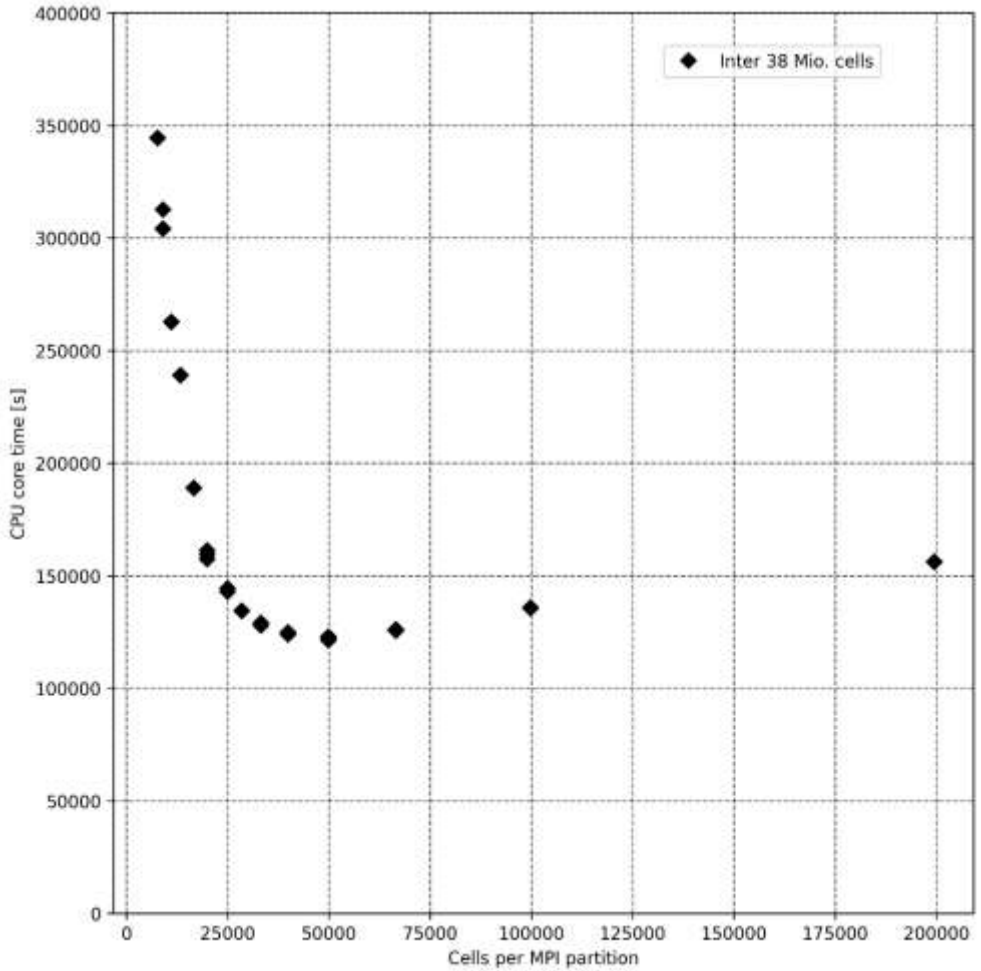
  - ⇒ n Nodes
  - ⇒ 2 CPUs
  - ⇒ 128 Cores

Parts of the commissioning tests: Scaling tests



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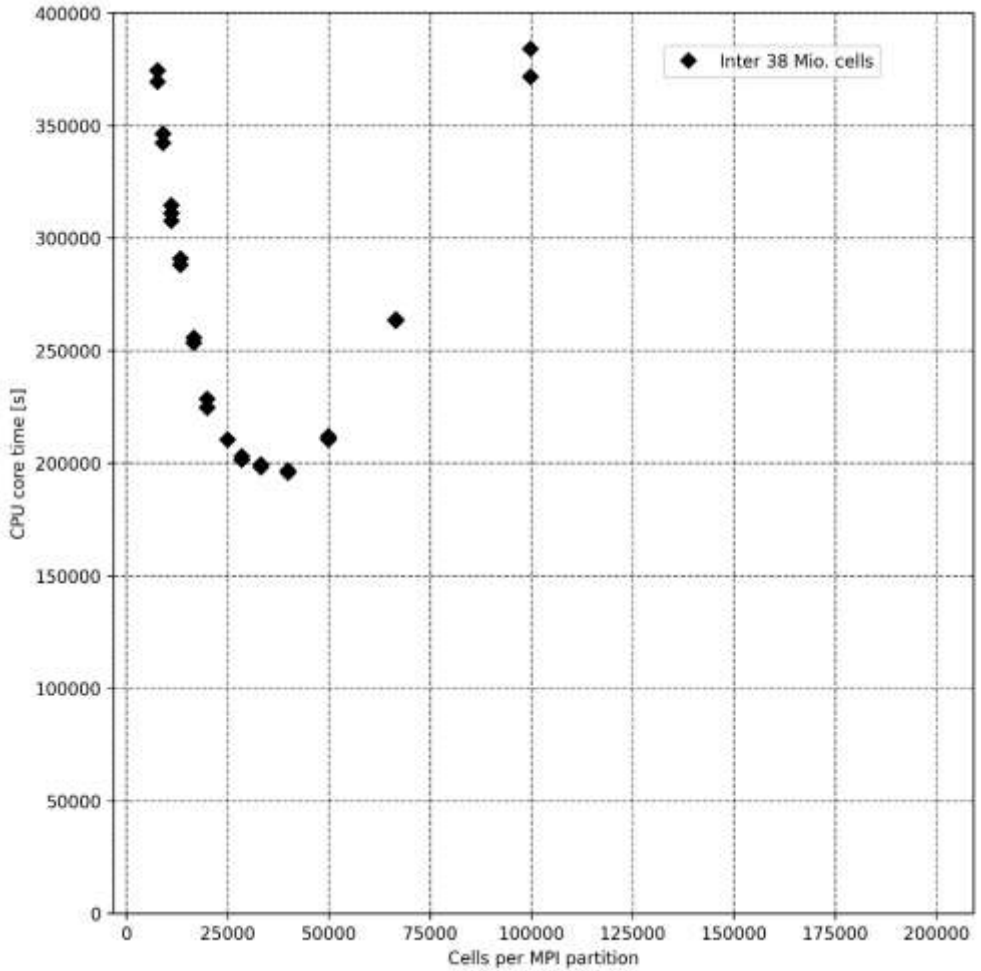
~125000 core seconds

Wide range optimum:

90% performance: ~25000-100000 cells/core

Parts of the commissioning tests: Scaling tests



DIC preconditioned PCG

- interFoam
- 38 Mio. cells
- Compact domain
- Multilevel decomposition (Scotch)
  - ⇒ n Nodes
  - ⇒ 2 CPUs
  - ⇒ 128 Cores

~200000 core seconds

Narrow range optimum:

90% performance: ~20000-50000 cells/core

… but the scaling looks impressive!

Summary

- Waterway engineering offers many challenging questions
- Sometimes it is most challenging to understand the underlying physics
- Different numerical methods are required for different questions
- OpenFOAM is a very valuable tool due to its versatility …

  … but not the answer to everything

Thanks!

(For all the fish)

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