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Securing Manoeuverability of a Deep Draft Ship in a Sediment loaded Tidal River Berth

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Abstract

Sedimentation near a deep draft ship berth at a tidal river cannot be avoided due to tidal currents and turbulent processes. But reductions in sedimentation can significantly decrease maintenance dredging costs. Transport and deposition of sediments in a tidal environment depend on factors like sediment size, settling velocity, tides and is controlled by unsteady current velocities and stochastic turbulent processes.

A technical solution, minimizing sedimentation near the berth of a deep drafted ship to secure manoeuverability, is presented. The hydrodynamic situation at the tidal part of a river was simulated, using MIKE3 HD and RMA2 hydrodynamic models. Exchange of sediment-loaded waters entering the berth could be significantly reduced with a flow-guiding sheet pile wall. Relevant physical processes (sediment transport, erosion and deposition) were modelled using RMA2/SED2D. Thus, reduction of sedimentation was verified using MIKE3 HD to get a look to hydrodynamics around the sheet pile wall.

To understand the process of sedimentation near the ship it is important to know the dynamic behaviour of the tidal environment and resulting hydrodynamics, also influenced by varying discharges from the upstream non-tidal part of the river system. It is shown that near bed sand transport could be guided. However, the structure described above act as a sediment trap for suspended material. Applicability and sensitivity of the different models is compared. Besides technical aspects of the construction to be modeled it is pointed out which modeling capabilities are necessary to find critical flux conditions in the model domain and how they influence the overall design of the structure.

1 Introduction

Many harbours, ship landings and berths are located at tidal rivers, where sedimentation and deposition of fine (silt) and coarser sediments (sand) are major factors for maintenance. Operation requires permanent and safe approach channel and berth area, which means independence of bed morphology changing with erosion and deposition in the tidal river itself and the local berth area. To secure manoeuverability of a deep draft ship and minimizing dredging activities at the berth, an underwater sheet pile wall can be used to guide flow and sediments. Sediment transport for this solution was simulated using MIKE3 and RMA2/SED2D. Quality of model results strongly depends on knowledge about basic physical processes, which is limited but not discussed here, and mathematical description and solution of the designated problem class.
The work presented, is an analysis to minimize sedimentation nearby an underwater sheet pile wall around the berth of a deep draft ship and a comparative analysis of used numerical 2D/3D models.

2 Modeling Technology

Due to certificated models chosen here, the reader may refer to literature.

2.1 RMA2/SED2D

2.1.1 RMA2 Version 4.3

RMA2 is a 2D FE scheme for sub critical free-surface flow, solves the Reynolds form of the Navier-Stokes equations. Derivatives in time are replaced by a non linear finite difference approximation. The solution is fully implicit, solved by Newton-Raphson non linear iteration. Turbulence is modeled by eddy viscosity (constant for materials or coupled to velocities by Peclet-Number). Stability of the method is critical, due to explicit linearization of advective terms without upwinding and in cases of high Peclet-numbers.

2.1.2 SED2D-WES Version 1.2

SED2D-WES can be applied to cohesive (clayey) and non cohesive (sandy) sediments. The model considers a single grain size solving the 2D convection-diffusion equation. Processes can be grouped into motion (diffusion coefficients), erosion (erosion rate for particle by particle erosion and mass failure of a bed layer), and deposition (critical bed shear stress).

2.1.3 Discretisation of Space and Time

Space discretisation is based on several FE types (one dimensional elements or two dimensional either triangular or rectangular). The used FE-solution can lead to extremely dense meshes. Due to mesh quality and job times, this is limited in practice for tidal conditions. Solver stability is not checked during mesh setup. Thus, enormous problems occur getting the model stable incorporating hydraulic structures (e.g. underwater sheet pile wall). Mesh design can easily be adapted for local areas using finite elements, having in mind that mixing of element types and rapid variation of element sizes influences solver stability extremely. Modeling moving structures (e.g. lock gates, weirs) is not possible and would one of the major topics for improvement. Automatic re-discretisation of the model area depending on morphological changes is limited due to stability of the numerical scheme.

Discretisation of time is based on an internal scheme, not able to incorporate common time formats (e.g. "1999/02/03 14:15:56") directly, which hinders practical work and coupling of different models to simulate physical process interaction (e.g. wave current interaction). Time step length should be more than 5min to get the model stable for discharge change at slack water.

2.2 MIKE3 Version 2000b

Model philosophy of MIKE3 builds a consequent improvement of the MIKE21 (2D) software suite, to solve the unsteady 3D flow equations. A direct relation between hydrodynamic module (HD) and mud transport module (MT) is implemented, ignoring loop backs to the hydrodynamics in the case of morphological changes during time steps, which is not relevant due to necessary time step length (Courant Criterion).

2.2.1 Hydrodynamic Module (HD)

The node centered FD ADI solver is a stable and accurate scheme. Code is implemented using C^{++} and FORTRAN90, which guarantees moderate job times (Tab. 1). Stability is obtained by limiting the "numerical momentum" (Courant Criterion). Setting up local models with high discretisation in space (e.g. to evaluate hydrodynamics and/or scour near a sheet pile wall) leads to Δt=2s-10s (Δx variation=2m, 6m,18m from nested to coarse). The used up/down sweeps (used directions – left to right, up/down, right to left, down/up - to solve governing equations) are able to limit numerical diffusion to a minimum, due to the optimized alternating scheme.

Table 1. Job times for different hydrodynamic solver packages.

Solver	Project Area	Machine	Tides	Nodes/sec	Job Time
MIKE21	Ems Estuary	SUN Ultra 10	28	72.000	45h
MIKE21	Weser Estuary	SUN Ultra 10	52	72.000	45h
MIKE3	Ems Estuary	PC 800 Mhz	3	64.000	12h
MIKE3	Weser/Lesum	PC 800 Mhz	1	69.000	80h
RMA2	Port of Bremen	ORIGIN 200	6	168	18h
RMA2	Weser/Lesum	ORIGIN 200	6	297	12h

2.2.2 Discretisation of Space and Time

Flexibility of implemented space discretisation (staggered grid with $\Delta x = \Delta y =$const.) is limited, although nested grid functionality is available, but not automatically done after defining nested areas. Setting up bathymetry is simple, if nesting is off. Future development should cover import facilities from GIS systems and/or interpolation schemes using x-y-z data. Discretisation over the depth is based on layers (Δz=const., except the bottom layer, which is adopted automatically after specifying number of layers and Δz). The implemented space discretisation should be arranged more flexible, introducing Δx and Δy matrixes and variable Δz.

All modules are working with Δt=const. (using a real world format, JJ:MM:HH:SS). Automatic time step length adaption by evaluation of former time steps would speed up the solver for long term simulations and reduce data output significantly.

3 Tidal River Berth near Lesum Mouth

3.1 Model Area

The tidal river berth is located at the lower tidal part of the Lesum River (Fig. 1, Fig. 2). The model covers an area between Lower Weser km 16 and km 20, including the tidal part of the Lesum River from the Lesum Storm Surge Barrier (Lesum km 8) to the mouth (Lesum km 10).

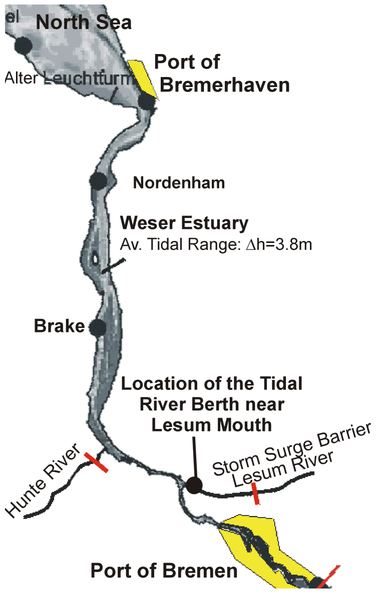


Figure 1: Area of investigation and location of the tidal river berth.

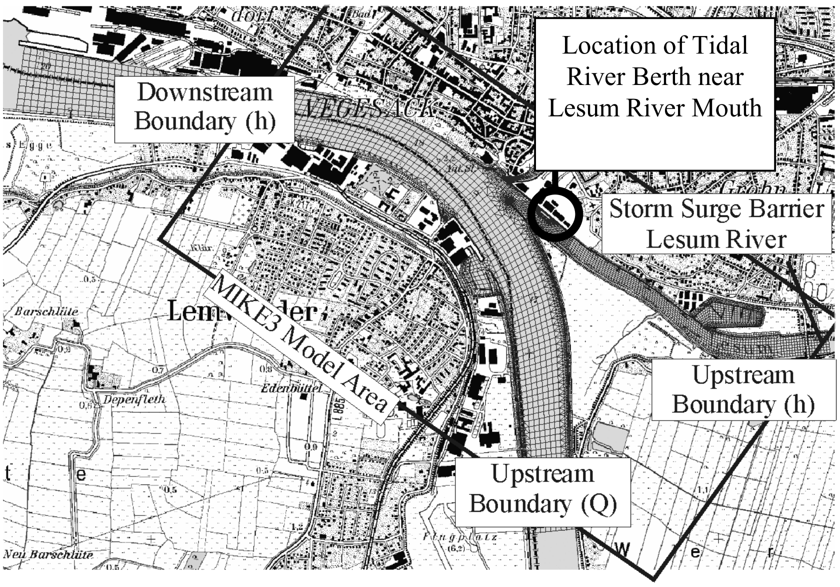


Figure 2: Model area: FE-Mesh (RMA2/SED2D: combined triangular/quadratic mesh, element size 2-1200m^2, 7235 elements) and FD-mesh (MIKE3: starting point 3473253,5892911; grid dimension: nx=167, ny=90; grid resolution: dx=dy=18m, 6m, 2m (nested); rotation: 41°).

3.2 Underwater Sheet Pile Wall

Dimensions (height, length etc., Fig. 3) and location (Fig. 2) of the sheet pile wall near the mouth were determined using a 1D pre-model (ship and sheet pile wall were modeled as block structure) for mean discharge and tidal conditions.

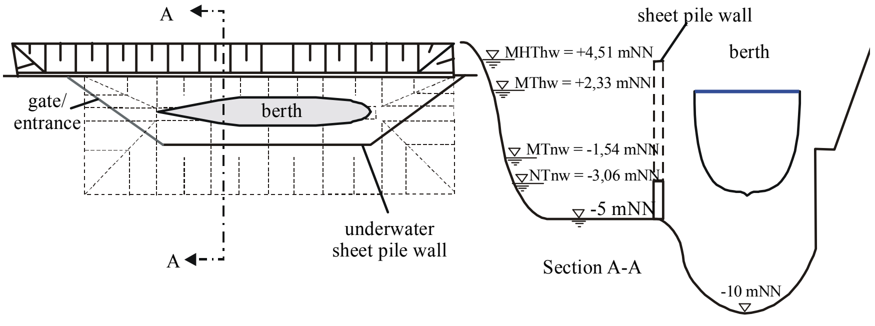


Figure 3: Sheet pile wall dimensions, ship position and mean water levels.

3.3 Model Philosophy, Boundary Conditions and Calibration

In a first step RMA2/SED2D were used to model hydrodynamics and sediment transport near/around and into the berth to estimate wall dimensions (necessary height, length, nearest distance from ship, angle to quay).

MIKE3 were used to calculate and verify 3D effects (distribution of v_z over the depth) near the sheet pile, responsible for sediment transport near and above the wall.

Grain size distributions clearly indicated sand, coming from the upper (non tidal) part of the Lesum river, introduced during ebb periods only for higher discharge rates, and transported to the lower Weser River. Sediment transport from the Weser River to the area of investigation is neglectable, due to a berm deviding Lesum River mouth and lower Weser River.

Boundary conditions (Fig. 2, Fig. 4) were selected from field records for a hydrodynamic situation with high sediment input from the upper Lesum River.

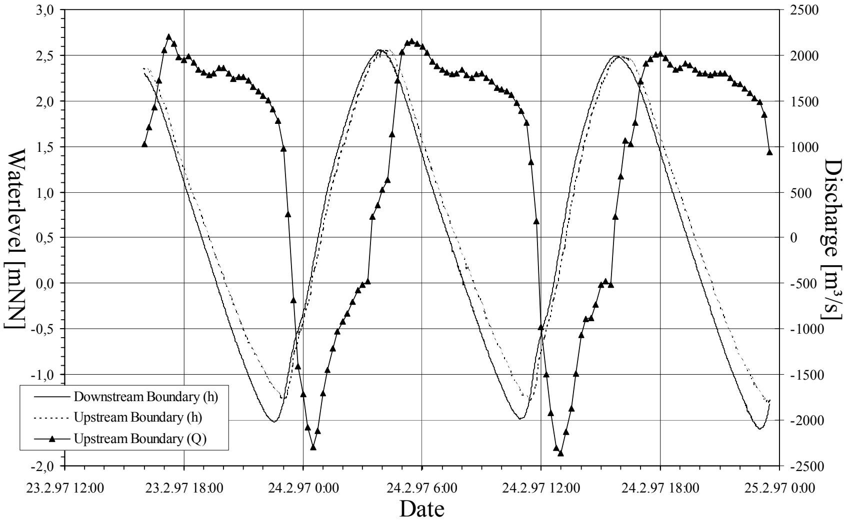


Figure 4: Boundary conditions for the investigated hydrodynamic situation.

Hydrodynamics were calibrated using results of a former physical model. Sediment input for the above described hydrodynamic situation was estimated by a regional model and checked against sediment balances calculated from echo soundings. Main model parameters are summarized in Tab. 2.

Table 2. Main model parameters.

RMA2	Manning-Number [-] River: 0.030 Harbours: 0.025 Embankments: 0.035	E [m^2/s] Calculated by Peclet-Number	Flood/Dry Check 0.08m/0.18m
SED2D	d = 0.6mm	c_I = 0.016 [kg/m^3]	w_s [m/s] = 0.09 [m/s]
MIKE3	k_s = 0.05m No. of Layers = 10 k-ε Model (vertical) c_μ=0.09, $c_{1\varepsilon}$=1.44, $c_{2\varepsilon}$=1.92, σ_k=1, σ_ε=1.3	Δt = 1 [s] Δz = 1 [m] k = 1e-007 [m^2/s^2] c_s = 0.4 [-]	Flood/Dry Check 0.2m/0.3m ε = 5e-010 [m^2/s^3e] T = 10 [°C]

4 System Layout using a 2D Approach

4.1 Hydrodynamic Effects of Sheet Pile Wall and Ship

Four characteristic hydrodynamic situations can be distinguished during the selected tide (T1: begin of flood period/duration: 1h,T2: fully developed flood/duration: 3,5h, T3: begin of ebb period/duration: 1h, T4: fully developed ebb period/duration: 6h). Only T2 and T4 are shown for the selected cross sections CR2 and CR3 (Fig. 5), due to their importance for bed building flow characteristics around the berth.

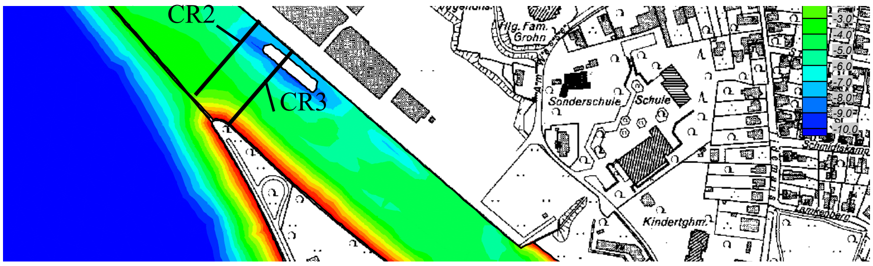


Fig. 5: Selected cross sections for evaluation of hydrodynamic situation.

Current profiles around the berth are mainly influenced by the profile reduction (11% for MThw, 25% for MTnw) caused by the underwater sheet pile wall and the ship body. The distance between ship and quay was fixed. Optimization of the angle between sheet pile wall and quay (35°) to guide the flow around the structure resulted in a minimal shift of the velocity profiles to the center of the cross sections and a local increase of flow velocities ($\Delta v_{max,}$=25cm/s during flood, Fig. 6 and Δv_{max}=11cm/s during ebb, Fig. 7).

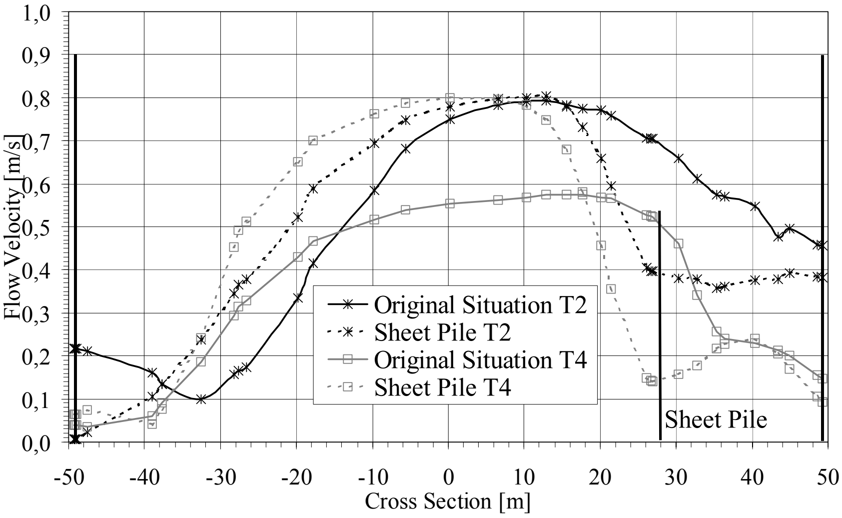


Fig. 6: Velocity profiles in cross section CR2 for T2 and T4.

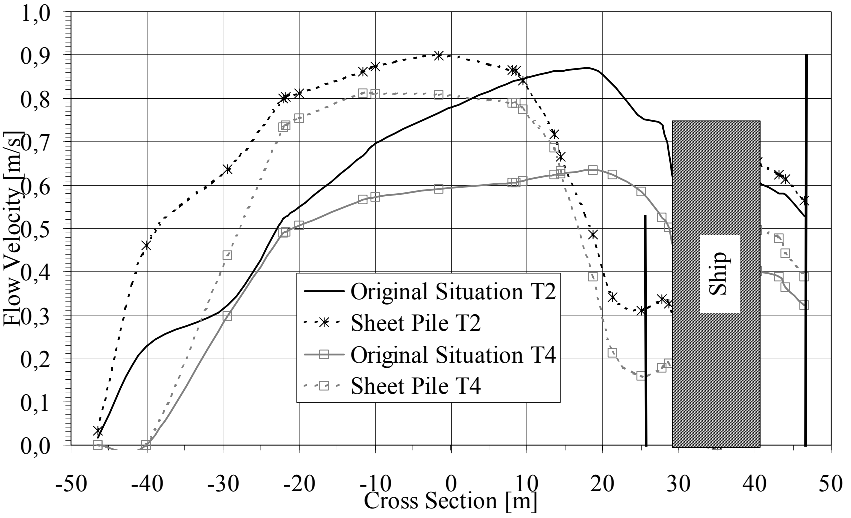


Fig. 7: Velocity profiles in cross section CR3 for T2 and T4.

4.2 Sedimentation inside the Sheet Pile Wall

Sedimentation and erosion phenomena around the sheet piled berth are discussed for the ebb period only (Fig. 8, Fig. 9), because the berm between Weser and Lesum River minimizes sand transport during flood periods. In the original situation no erosion occurs (Fig. 8). After construction of the sheet pile wall sedimentation upstream the berth is lower (E-S1, Fig. 9). Additionally, an erosion area along the berth occurs up (E-E1, Fig. 9). The eroded sediment is deposited downstream the berth (E-S2, Fig. 9)

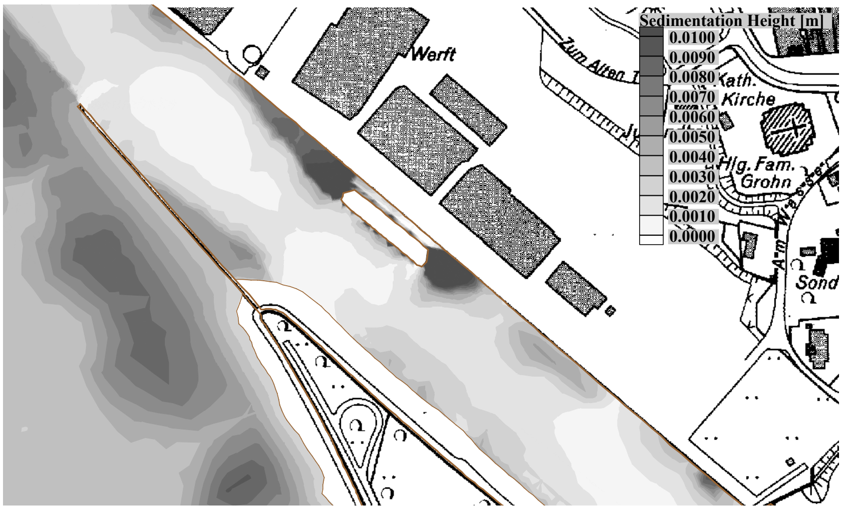


Fig. 8: Sedimentation during ebb period around the ship (original situation).

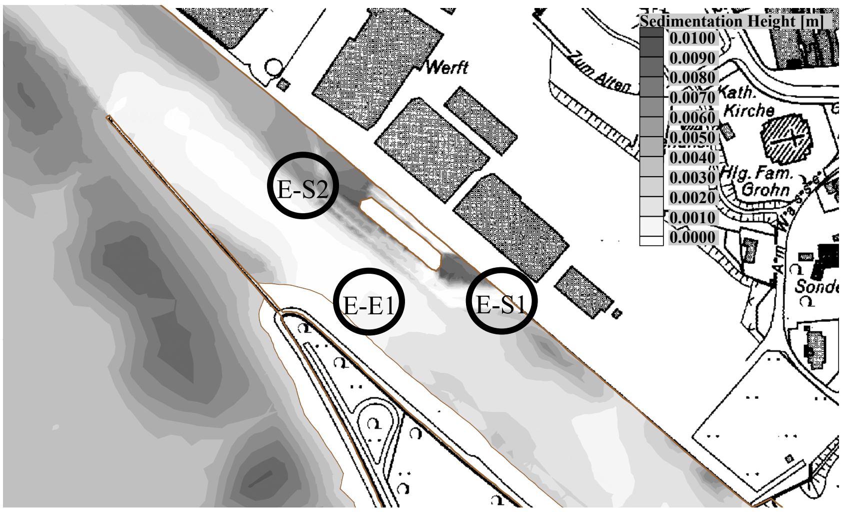


Fig. 9: Sedimentation/erosion during ebb period around/in the sheet piled berth.

5 Verification using a 3D Approach

Verification of the hydrodynamic situation (here only for T4: ebb tide fully developed) using MIKE3 shows flow guidance around the structure (Fig. 10). Near the top of the structure a vertical component v_z=0.3-0.35m/s occurs (Fig. 10, P1). Thus, vertical sediment transport overtopping the structure is partially hindered (v_z<w_s at the bottom).

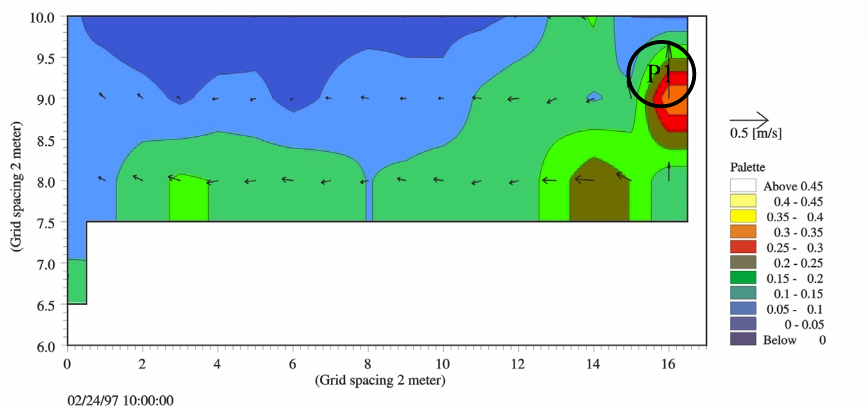


Fig. 10: Flow velocities in a cross section perpendicular to the quay 5m upstream the underwater sheet pile wall.

Flow velocities 0.5m above the bottom show a critical level (Fig. 11, P2). Eroded sediment is guided by the structure and deposited downstream the berth. Influence of the quay (slip function) slows down flow velocities and prevents erosion in this area.

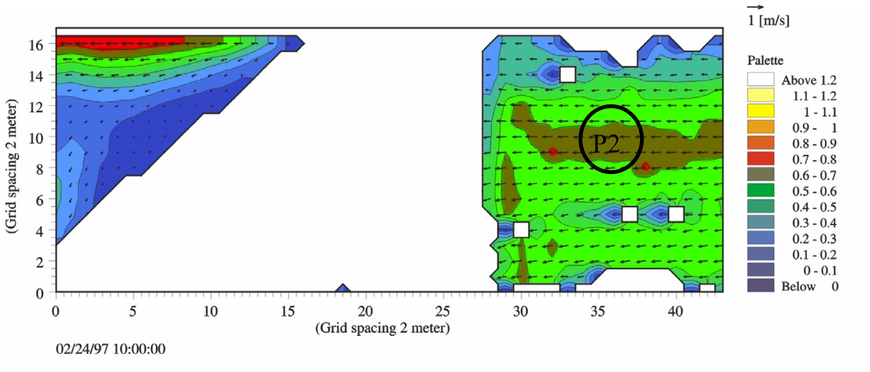
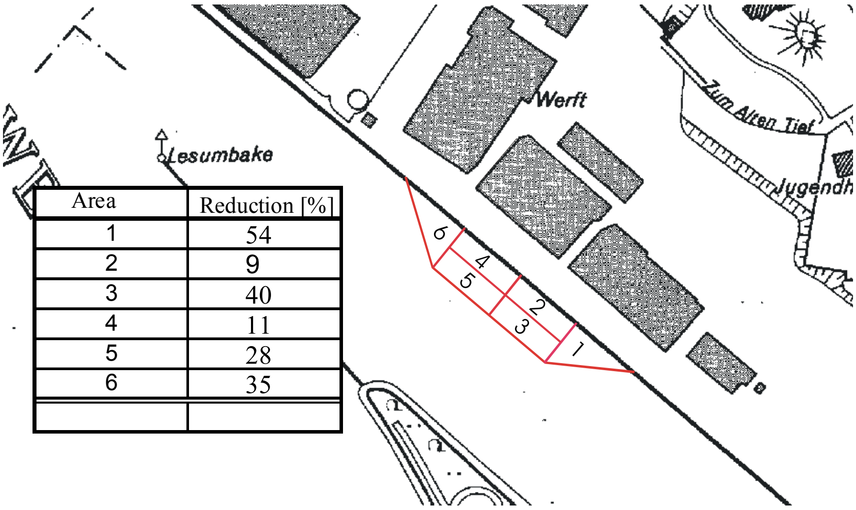


Fig. 11: Flow velocities near the bottom upstream the underwater sheet pile wall (white area is higher than displayed bottom layer).

6 Conclusions

The presented technical solution of an underwater sheet pile wall around a tidal river berth shows significant reduction of sedimentation (Fig. 12).



Area	Reduction [%]
1	54
2	9
3	40
4	11
5	28
6	35

Figure 12: Reduction of sedimentation inside the berth.

Used 2D/3D modeling techniques helped to find an "quasi" optimal design. Flow effects guiding sediment around the structure were identified using a 3D approach, securing that vertical flow velocities upstream the structure are lower than settling velocities of sediment approaching from the upper catchment.