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Underwater structures against sedimentation at a ship berth in a tidal River

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ABSTRACT

Siltation is a permanent problem in harbours at tidal rivers and in estuaries causing continuous maintenance dredging to guarantee safe navigation. 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.

A technical solution (sheet pile wall), minimizing sedimentation near the berth of a deep drafted ship to secure manoeuvrability, is presented.

The hydrodynamic situation at the tidal part of a river was simulated, using RMA2 and MIKE3 hydrodynamic models. Relevant physical processes of sediment transport, erosion and deposition were modelled using SED2D. 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 can 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 modelled it is pointed out which modelling capabilities are necessary to find critical flux conditions and how they influence the overall design of the structure.

The results of the simulations and the final recommendations for the ship berth are discussed. Finally, the results of a subsequent monitoring are presented.

1. INTRODUCTION

To secure manoeuvrability 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 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.

An example of sedimentation in a deep draft ship berth without a sheet pile wall at the Weser/Lesum river in Germany is shown in Fig. 1. The depth changed from –11m below datum to –7.5m after 1 year.

The tidal river berth is located at the lower tidal part of the Lesum River (Fig. 2), flowing into the Weser River. The Weser River ends up in the southern part of the North Sea.

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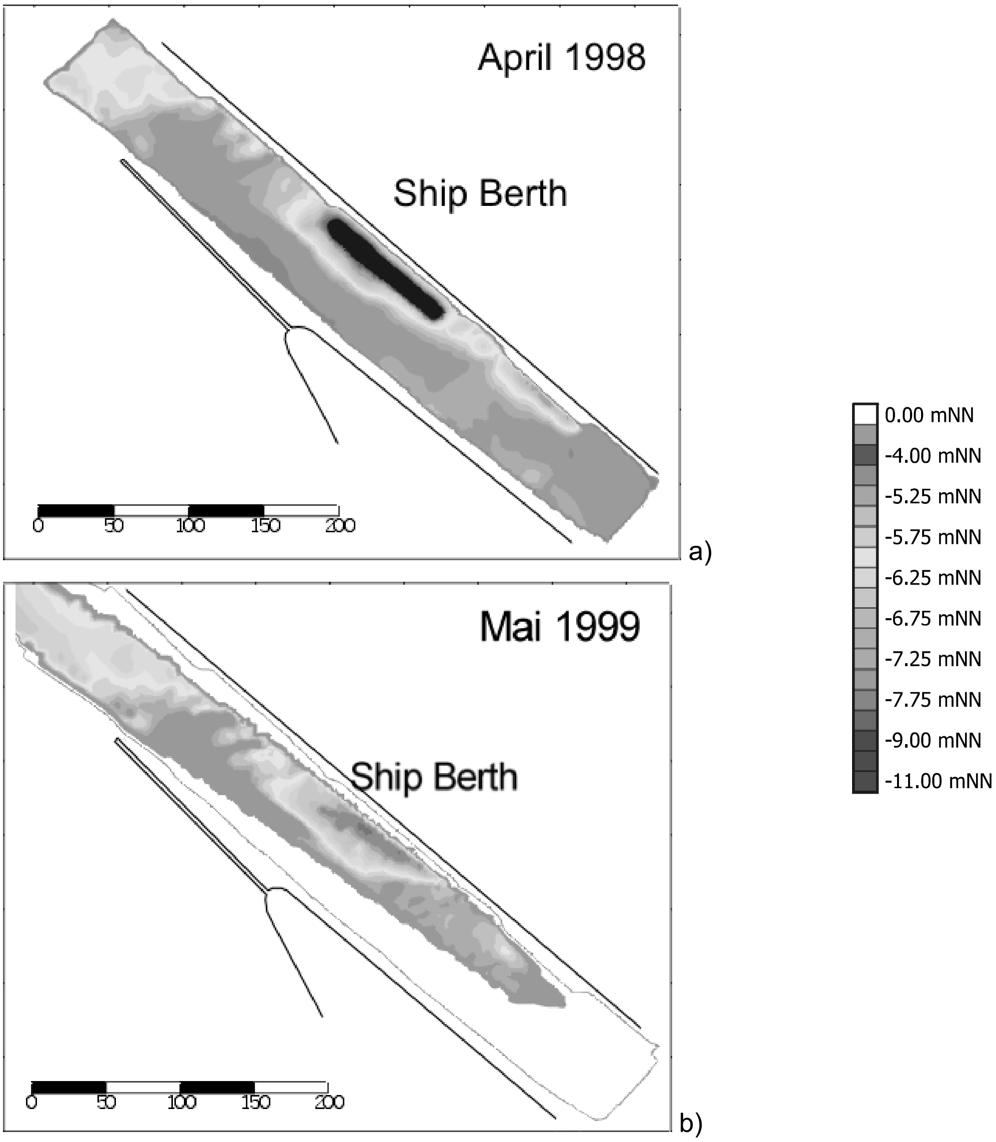

Figure 1: Water Depth at a deep draft Ship Berth situated at the River Weser/Lesum in Germany a) April 1998, b) April 1999

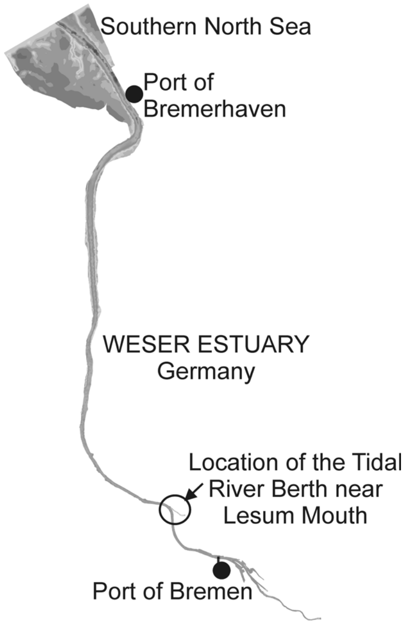

Figure 2: Area of Investigation and Location of the Tidal River Berth

2. MODELLING TECHNOLOGY

2.1 Hydrodynamic Simulation

2.1.1 RMA2 Version 4.3

RMA2 is a 2D FE scheme for sub critical free-surface flow developed at the Waterway Experiment Station, US Army Corps of Engineer (WES). It 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 modelled 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 up winding and in cases of high Peclet-numbers.

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 set-up. 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. 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 which hinders practical work and complicates 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.

2.1.2 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.

The node centred FD ADI solver is a stable and accurate scheme. 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=Δy =2m, 6m,18m from nested to coarse grid, Δz=1m). 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 optimised alternating scheme.

Flexibility of implemented space discretisation (staggered grid with $\Delta x=\Delta y$=const.) is limited, although nested grid functionality is available. Setting up bathymetry is simple, if nesting is off. 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=constant. Automatic time step length adaptation by evaluation of former time steps for example would speed up the solver for long term simulations and reduce data output significantly.

2.2 Sediment transport Simulation with SED2D 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).

3. TIDAL RIVER BERTH NEAR LESUM MOUTH

The tidal river berth is located at the lower tidal part of the Lesum River (Fig. 3). 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).

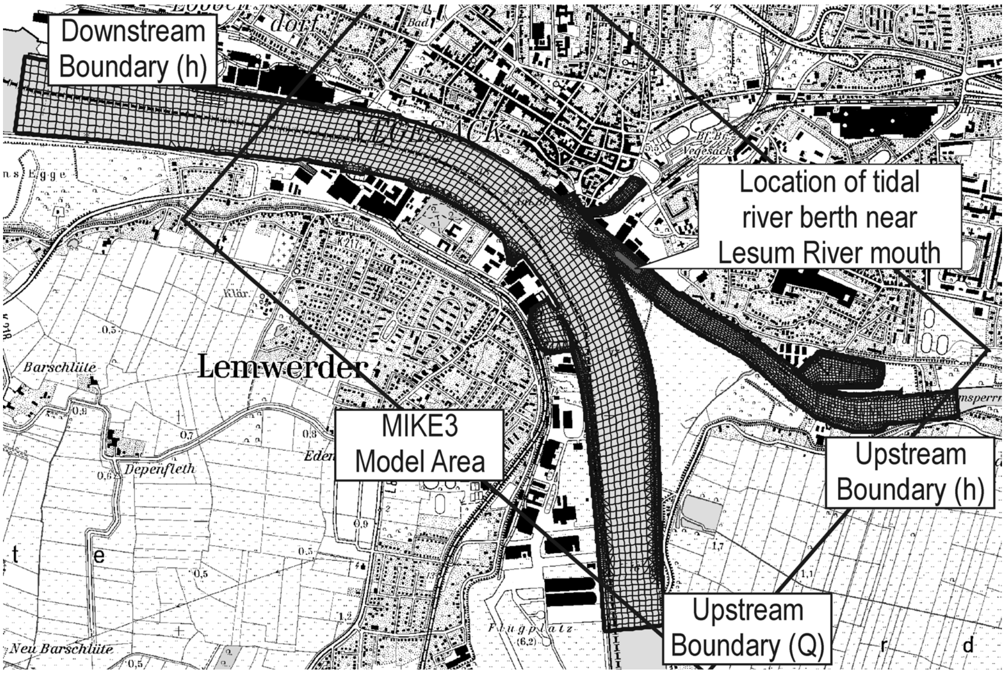

Figure 3: Model area: FE-Mesh (RMA2/SED2D: combined triangular/quadratic Mesh, Element Size 2-1200m^2, 7235 Elements) and FD-Mesh (MIKE3: Grid Dimension: nx=167, ny=90; Grid Resolution: dx=dy=18m, 6m, 2m (nested); Rotation: 41°)

3.2 Underwater Sheet Pile Wall

Dimensions and location of the sheet pile wall near the mouth are shown in Fig. 3 (location) and Fig. 4 (height, length). The sheet pile Wall is about 160 m long. The top of the wall is about 2m above the existing ground level. On the downstream side, the wall is lowered to 1m above existing ground to allow the ship entering the ship berth during high water ("entrance", Fig. 4).

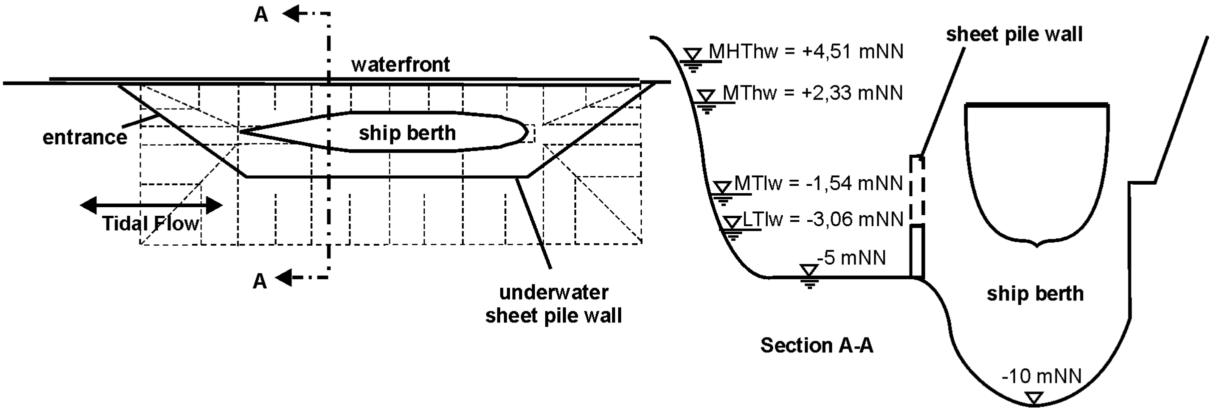

Figure 4: Sheet Pile Wall dimensions, Ship Position and Mean Water Levels

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 was 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 negligible, due to a berm dividing Lesum River mouth and lower Weser River.

Boundary conditions (Fig. 3, Fig. 5) were selected from field records for a hydrodynamic situation with high sediment input from the upper Lesum River.

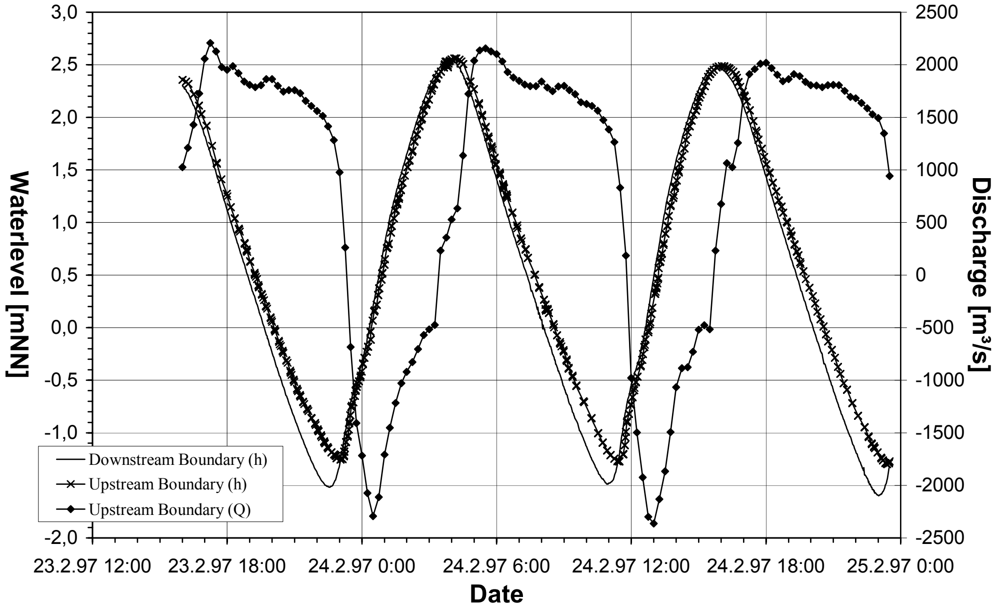

Figure 5: Boundary conditions for the investigated Hydrodynamic Situation

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. 1.

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

Table 1: Main Model Parameters

4. RESULTS OF THE 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 period/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 CS2 and CS3 (Fig. 6), due to their importance for bed building flow characteristics around the berth. These cross sections are defined as a view from up- to downstream (from Lesum River to Weser River).

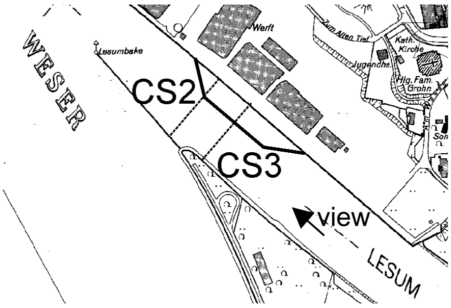

Figure 6: Selected Cross Sections for evaluation of Hydrodynamic Situation

Current profiles around the berth are mainly influenced by the profile reduction (11% for MThw, 25% for MTlw), caused by the underwater sheet pile wall and the ship body. The distance between ship and quay was fixed.

There is a minimal shift of the velocity profiles to the centre of the cross sections and a local increase of flow velocities during the flood Period T2 induced by the sheet pile wall (Fig. 7 and 9). The overall maximum velocity is increased for 3cm/s. Local velocities on the left bank of the Lesum River (located from -30 m to -50 m in cross section CS3, Fig. 9) are increasing for 15-30 cm/s.

While entering the critical range of 60-70 cm/s they could have an impact on the left river bank by eroding parts of the bottom. A slope failure could be the result.

The minimal shift of the velocity profiles to the centre of the cross sections is also shown during the ebb period T4 (Fig. 8 and 10). The overall maximum velocity is increased for 22cm/s. The main ebb stream is situated in the middle of the Lesum River. The velocities are up to 25 cm/s higher than before, but there is not such an increased impact on the river bank as shown in Period T2.

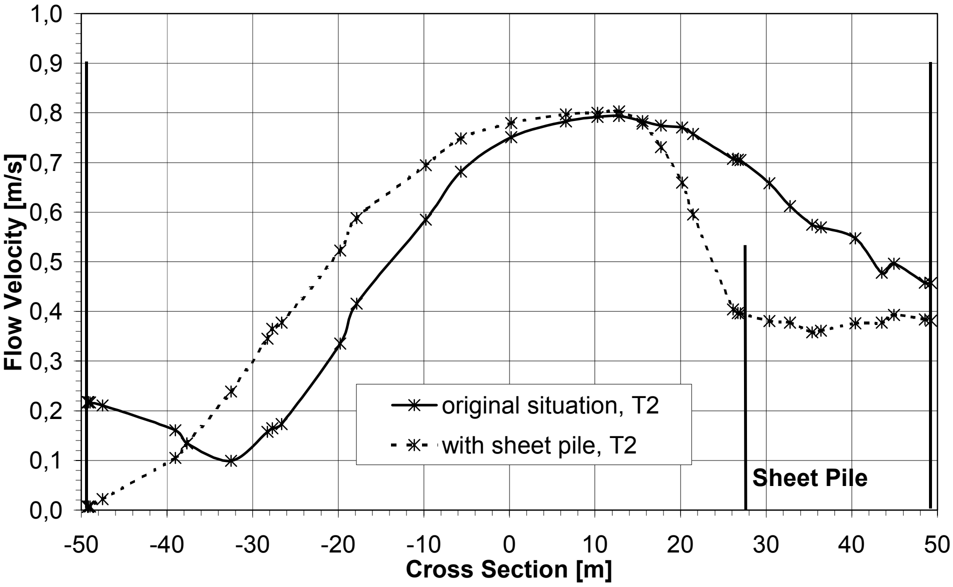

Figure 7: Velocity Profiles in Cross Section CS2 for T2 (fully developed Flood Period)

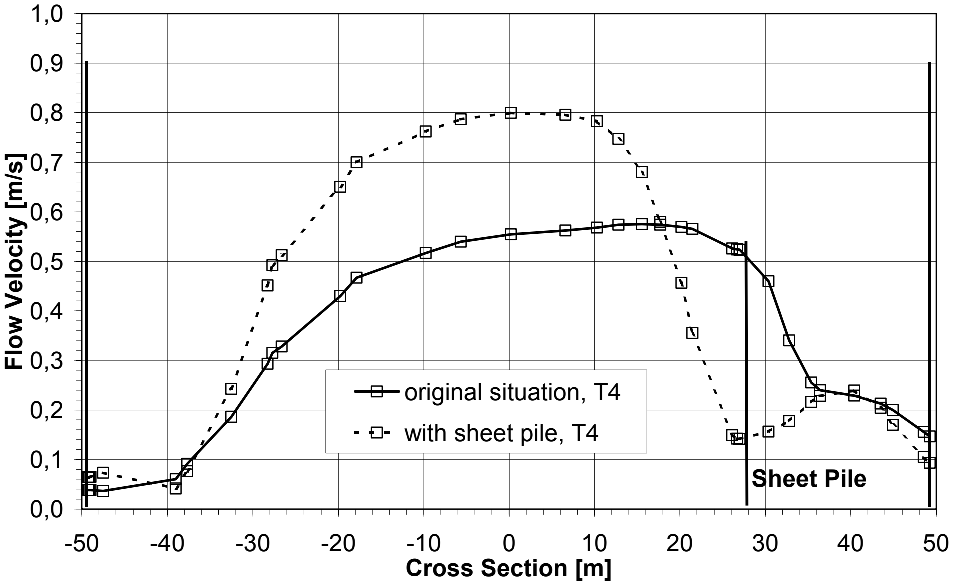

Figure 8: Velocity Profiles in Cross Section CS2 for T4 (fully developed Ebb Period)

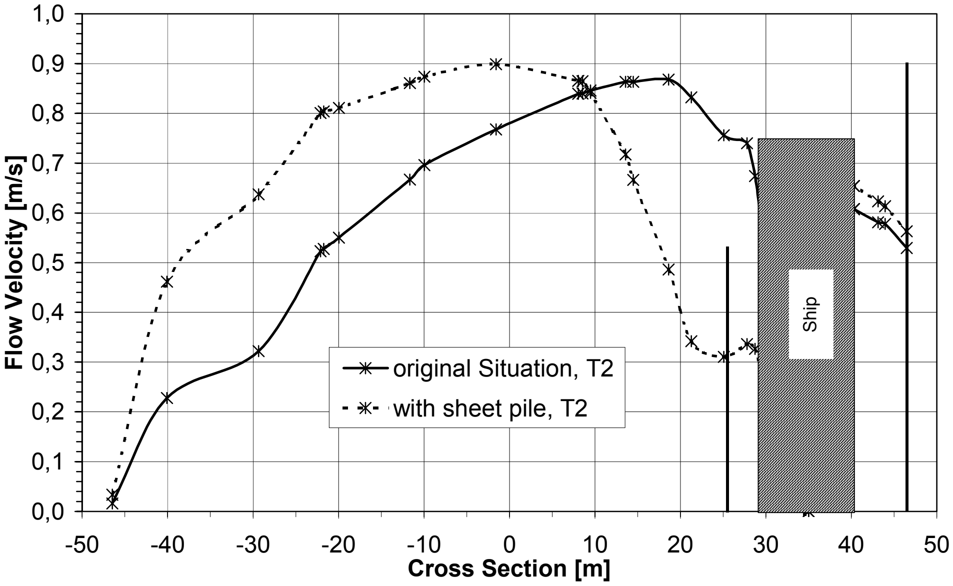

Figure 9: Velocity Profiles in Cross Section CS3 for T2 (fully developed Flood Period)

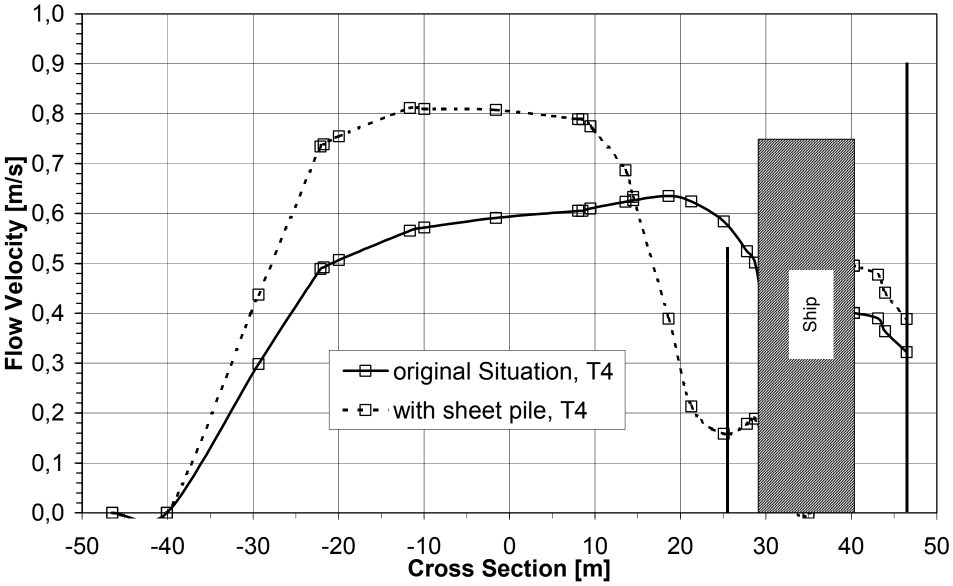

Figure 10: Velocity Profiles in Cross Section CS3 for T4 (fully developed Ebb Period)

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. 11), because the berm between Weser and Lesum River minimizes sand transport during flood periods. In the original situation no erosion occurs. After construction of the sheet pile wall sedimentation upstream the berth is lower (E-S1, Fig. 11). Additionally, an erosion area along the berth occurs (E-E1, Fig. 11). The eroded sediment is deposited downstream the berth (E-S2, Fig. 11).

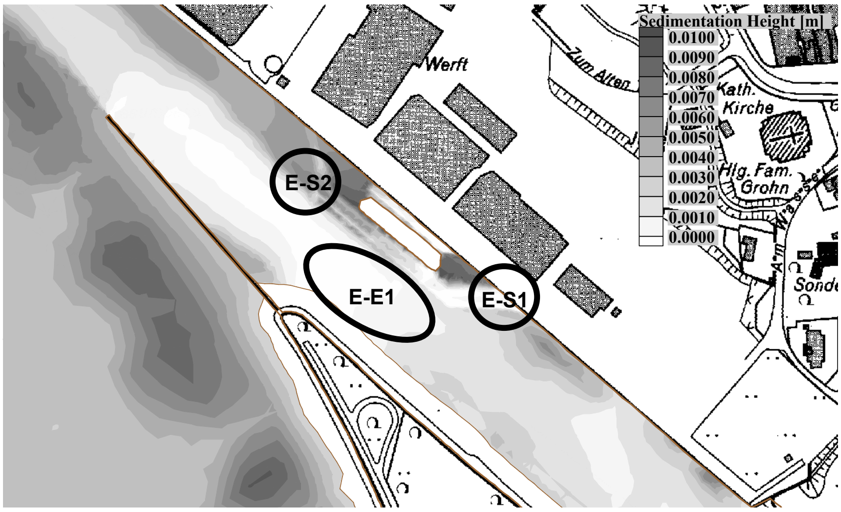

Figure 11: Sedimentation/Erosion during Ebb Period around/in the Sheet Piled Berth

5. RESULTS OF THE 3D APPROACH

Verification of the hydrodynamic situation (here only for T4: ebb tide fully developed) using MIKE3 shows flow guidance around the structure (Fig. 12).

Near the top of the structure a vertical component v_z=0.3-0.35m/s occurs (Fig. 13, P1). Vertical sediment transport overtopping the structure could be possible ($v_z > w_s$).

Near the bottom of Lesum River, the vertical velocity component v_z is reduced to 10 cm/s. The resulting area of critical vertical flow velocities (w_s = 0,09m/s) starts 1 m above the bottom. Thus a partial sediment input to the structure is possible.

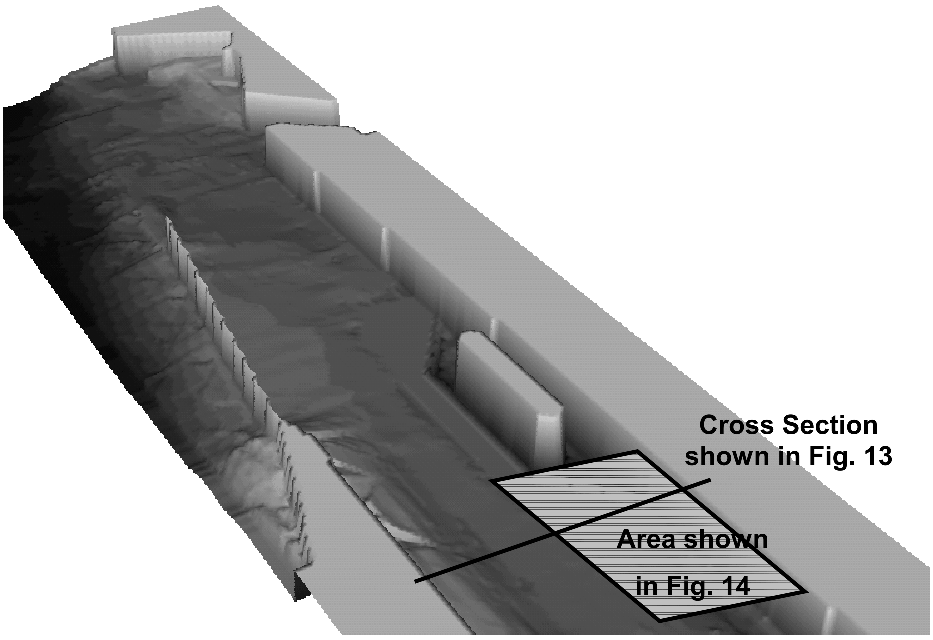

Figure 12: Position of the following Cross Section and Bottom Layer upstream the Underwater Sheet Pile Wall

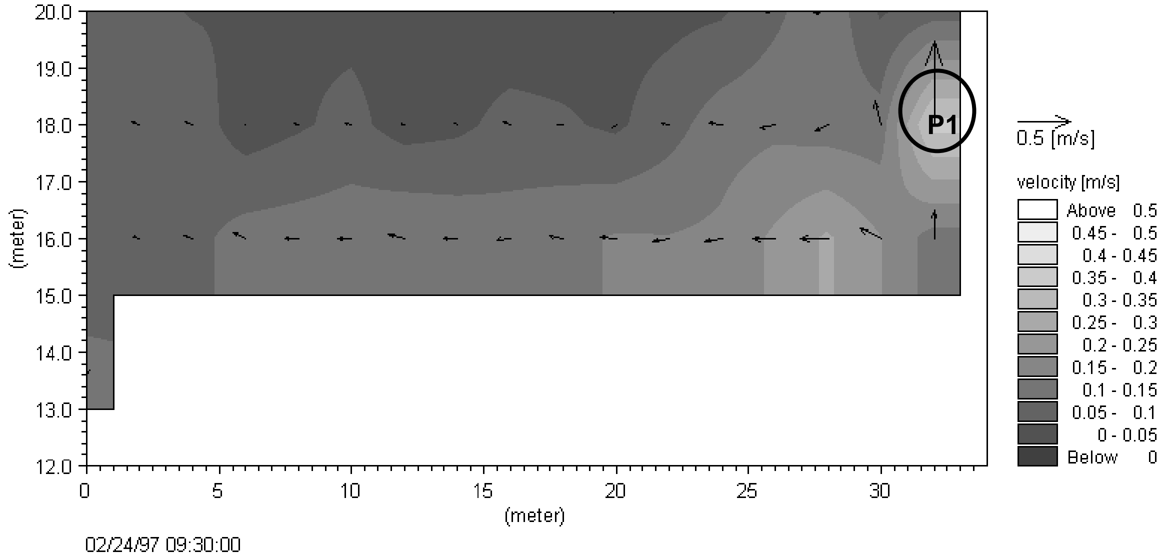

Figure 13: Flow Velocities in a Cross Section perpendicular to the Waterfront 5m upstream the Underwater Sheet Pile Wall

Flow velocities upstream the structure show a critical level (Fig. 14, P2). Eroded sediment is guided by the structure and deposited downstream the berth. Influence of the quay slows down flow velocities and prevents erosion in this area (Fig. 14, P3).

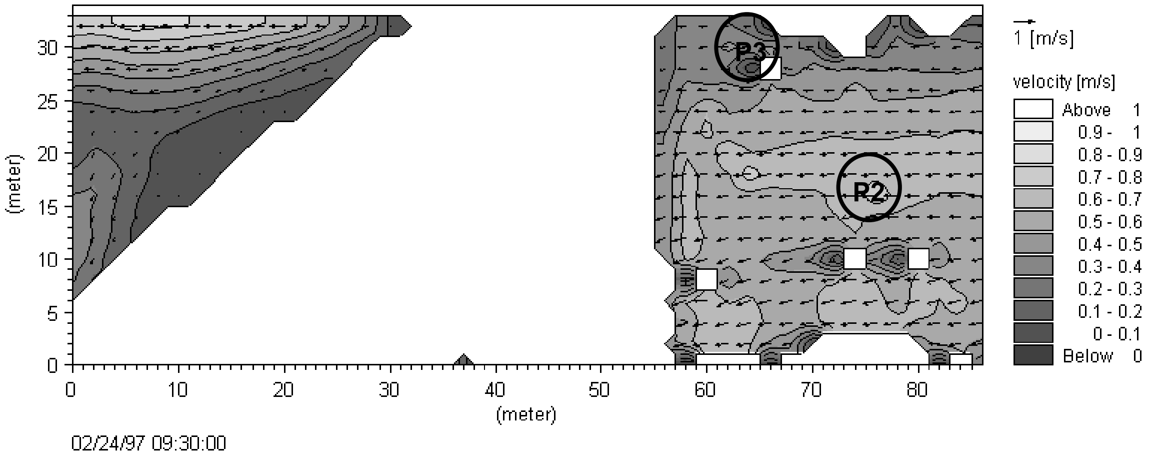

Figure 14: Flow Velocities near the Bottom upstream the Underwater Sheet Pile Wall (white Area is higher than displayed Bottom Layer)

6. MONITORING

Higher flow velocities in the Lesum River during higher discharges may cause erosion along the left river bank and may result in a slope failure. For this reason an additional monitoring program was established after construction of the wall in June 2002.

The bathymetry of the Lesum River was monitored with echo sounding. Additionally the berth around the sailing ship was monitored by the crew with a hand lead, to proof the efficiency of the sheet pile wall.

Fig. 15 shows changes after 1 month. There is low erosion in the centre of the river and along the sheet pile wall. Sedimentation In front of and behind the ship berth appears.

Fig. 16 shows the situation after 4 month. There is little sedimentation in front of and behind the ship berth. Erosion takes place in the centre of the river parallel to the sheet pile wall. Additionally sedimentation occurs near the corners of the sheet pile wall. The left river bank will be stable. The monitoring can be reduced to twice a year.

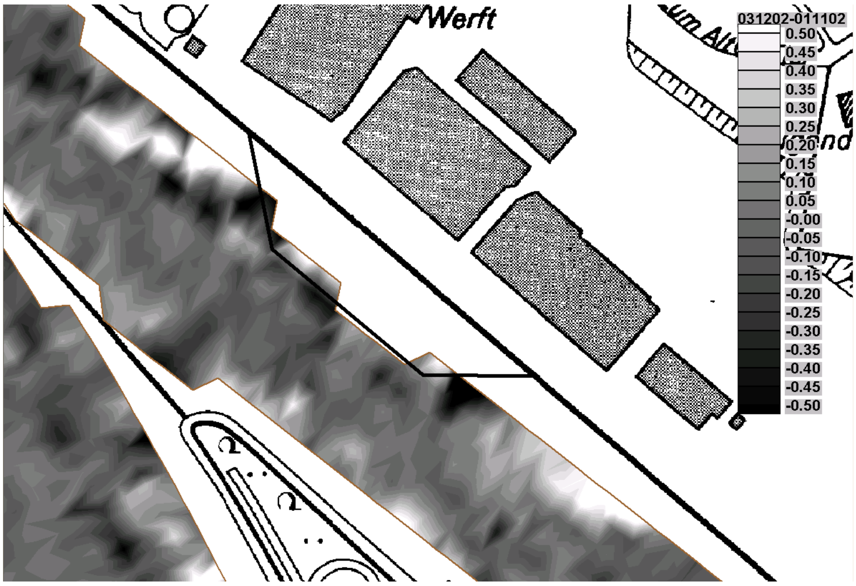

Figure 15: Sedimentation (+) and Erosion (-) after 1 Month of monitoring around the Sheet Piled Berth (in m)

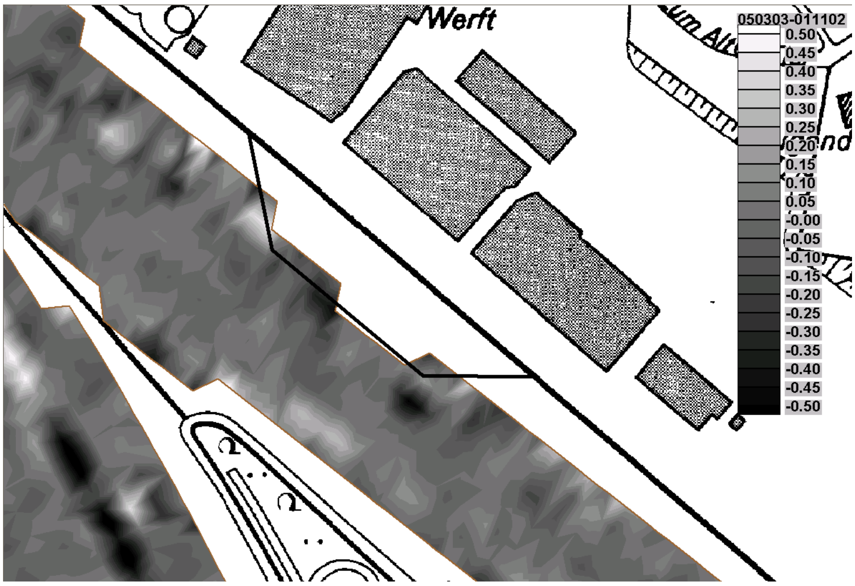

Figure 16: Sedimentation (+) and Erosion (-) after 4 Month of monitoring around the Sheet Piled Berth (in m)

Soundings around the sailing ship were carried out with a hand lead once in a month at locations defined in Fig. 17. The water depths in March 2003 are shown in Tab. 2. In Tab. 3 the differences of the following soundings to march 2003 are shown.

Figure 17: Location of Sounding Points

On the river side, the middle section of the ship (pos, 6.8) is eroded (Tab. 3), which levels out a former sedimentation from a flood event.

Sedimentation at stern and bow of the ship proves that hydrodynamic results were fairly calculated by indicating an area with $v_z \approx w_s$.

On the waterfront side of the sailing ship (b) is less sedimentation. Even near the stern is some erosion (Tab. 3, pos. 11+12).

The extreme sedimentation shown in Fig. 1 in the berth is not present any more.

Sailing ship "Deutschland", hand lead from 19.03.2003/10.40 Uhr [mNN]				Sailing ship "Deutschland", hand lead from 30.04.2003/10.10 Uhr [mNN]				Sailing ship "Deutschland", hand lead from 28.05.2003/08.55 Uhr [mNN]				Sailing ship "Deutschland", hand lead from 26.06.2003/07.50 Uhr [mNN]			
1a	-9,40	1b	-9,80	1a	-9,50	1b	-9,80	1a	-9,42	1b	-9,82	1a	-9,53	1b	-9,73
2a	-9,30	2b	-9,30	2a	-8,70	2b	-9,40	2a	-8,72	2b	-9,02	2a	-8,63	2b	-9,13
3a	-9,50	3b	-8,90	3a	-8,90	3b	-8,80	3a	-8,82	3b	-8,72	3a	-9,43	3b	-8,63
4a	-9,70	4b	-7,90	4a	-9,50	4b	-8,10	4a	-9,42	4b	-7,82	4a	-9,43	4b	-8,13
5a	-9,70	5b	-7,80	5a	-9,70	5b	-7,80	5a	-9,62	5b	-7,82	5a	-9,53	5b	-7,63
6a	-9,10	6b	-7,80	6a	-9,70	6b	-7,70	6a	-9,32	6b	-7,72	6a	-9,63	6b	-7,73
7a	-8,90	7b	-7,80	7a	-9,60	7b	-7,70	7a	-9,72	7b	-7,72	7a	-9,83	7b	-7,73
8a	-9,10	8b	-7,90	8a	-9,50	8b	-7,80	8a	-9,62	8b	-7,82	8a	-9,63	8b	-7,73
9a	-9,10	9b	-7,90	9a	-8,90	9b	-7,80	9a	-8,92	9b	-7,92	9a	-9,13	9b	-7,83
10a	-9,00	10b	-7,70	10a	-9,00	10b	-7,60	10a	-8,82	10b	-7,72	10a	-9,03	10b	-7,63
11a	-8,30	11b	-8,00	11a	-7,90	11b	-7,90	11a	-7,92	11b	-8,52	11a	-7,73	11b	-8,33
12a	-7,50	12b	-8,50	12a	-7,50	12b	-8,40	12a	-7,62	12b	-8,52	12a	-7,43	12b	-8,83
13a	-7,70	13b	-8,80	13a	-7,30	13b	-8,70	13a	-7,62	13b	-8,72	13a	-7,33	13b	-8,53
H	-8,60			H	-8,40			H	-8,02			H	-7,73		

Table 2: Water Depth at the different Sounding Points around the Sailing Ship in March 2003 and the three successive Months

Sailing ship "Deutschland", hand lead from 19.03.2003/10.40 Uhr [mNN]				Sailing ship "Deutschland", difference from 19.04.03 to 30.04.03				Sailing ship "Deutschland", difference from 19.03.03 to 28.05.03				Sailing ship "Deutschland", difference from19.03.03 to 26.06.03			
1a	-9,40	1b	-9,80	1a	-0,10	1b	0,00	1a	-0,02	1b	-0,02	1a	-0,13	1b	0,07
2a	-9,30	2b	-9,30	2a	0,60	2b	-0,10	2a	0,58	2b	0,28	2a	0,67	2b	0,17
3a	-9,50	3b	-8,90	3a	0,60	3b	0,10	3a	0,68	3b	0,18	3a	0,07	3b	0,27
4a	-9,70	4b	-7,90	4a	0,20	4b	-0,20	4a	0,28	4b	0,08	4a	0,27	4b	-0,23
5a	-9,70	5b	-7,80	5a	0,00	5b	0,00	5a	0,08	5b	-0,02	5a	0,17	5b	0,17
6a	-9,10	6b	-7,80	6a	-0,60	6b	0,10	6a	-0,22	6b	0,08	6a	-0,53	6b	0,07
7a	-8,90	7b	-7,80	7a	-0,70	7b	0,10	7a	-0,82	7b	0,08	7a	-0,93	7b	0,07
8a	-9,10	8b	-7,90	8a	-0,40	8b	0,10	8a	-0,52	8b	0,08	8a	-0,53	8b	0,17
9a	-9,10	9b	-7,90	9a	0,20	9b	0,10	9a	0,18	9b	-0,02	9a	-0,03	9b	0,07
10a	-9,00	10b	-7,70	10a	0,00	10b	0,10	10a	0,18	10b	-0,02	10a	-0,03	10b	0,07
11a	-8,30	11b	-8,00	11a	0,40	11b	0,10	11a	0,38	11b	-0,52	11a	0,57	11b	-0,33
12a	-7,50	12b	-8,50	12a	0,00	12b	0,10	12a	-0,12	12b	-0,02	12a	0,07	12b	-0,33
13a	-7,70	13b	-8,80	13a	0,40	13b	0,10	13a	0,08	13b	0,08	13a	0,37	13b	0,27
H	-8,60			H	0,20			H	0,58			H	0,87		
				Δh_{mean} = 0,05				Δh_{mean} = 0,04				Δh_{mean} = 0,02			

Table 3: Water Depth at the different Sounding Points around the Sailing Ship in March 2003 and its change during the three successive Months

7. CONCLUSIONS

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

The used 2D/3D modelling techniques helped to find a nearly optimal design of the sheet pile wall. 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 catchments.

The effects of the sheet pile wall were determined by a monitoring program, which documents same effects as computed (Fig. 11, Fig. 15).

The sedimentation inside the ship berth is reduced to a minimum.