CONTROLLING SEDIMENT ACCUMULATION BEHIND THE LOCKS OF ZANDVLIET AND BERENDRECHT

by

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1. DESCRIPTION OF THE SEDIMENT SUPPLY MECHANISM FROM THE RIVER SCHELDT TO THE DOCKS

1.1 Analysis of historical data

Before starting the measurement campaign, an inventory was made of the relevant historical data.

The lower Scheldt is that part of the Scheldt from the roadstead of Antwerp to the Dutch border. Sediment reaches the lower Scheldt from upstream as well as downstream. The silt tends preferably to settle in the access channels to the locks. Sedimentation-rates of 100 to 350 kg d.s./m^2/month (d.s.: dry sediment) were measured. The lower Scheldt can, in this respect, be regarded as a huge silt reservoir of unconsolidated silt. The access channel to the Zandvliet and Berendrecht locks has a surface area of 60 ha and computations proved the quasi-permanent presence of an unconsolidated silt volume of about 2 million m^3.

Past measurements to identify the sedimentation mechanism at work in the access channel to the locks proved the existence of density flows of salt water laden with silt. The presence of this saline wedge is most emphatic at high tide. The density flows, which are driven by small differences of salinity, may be reinforced by differences in suspension concentrations and a difference in temperature. Presumably, the same mechanism is at work during lock operations due to the contact between inrushing water of an average salinity which is always greater than the one of the less brackish water in the docks. Measurements show that, over a 12-month period, despite seasonal variations, there is always a salinity difference of 1.5 to 6 g/l between estuarine water in the Scheldt and the docks.

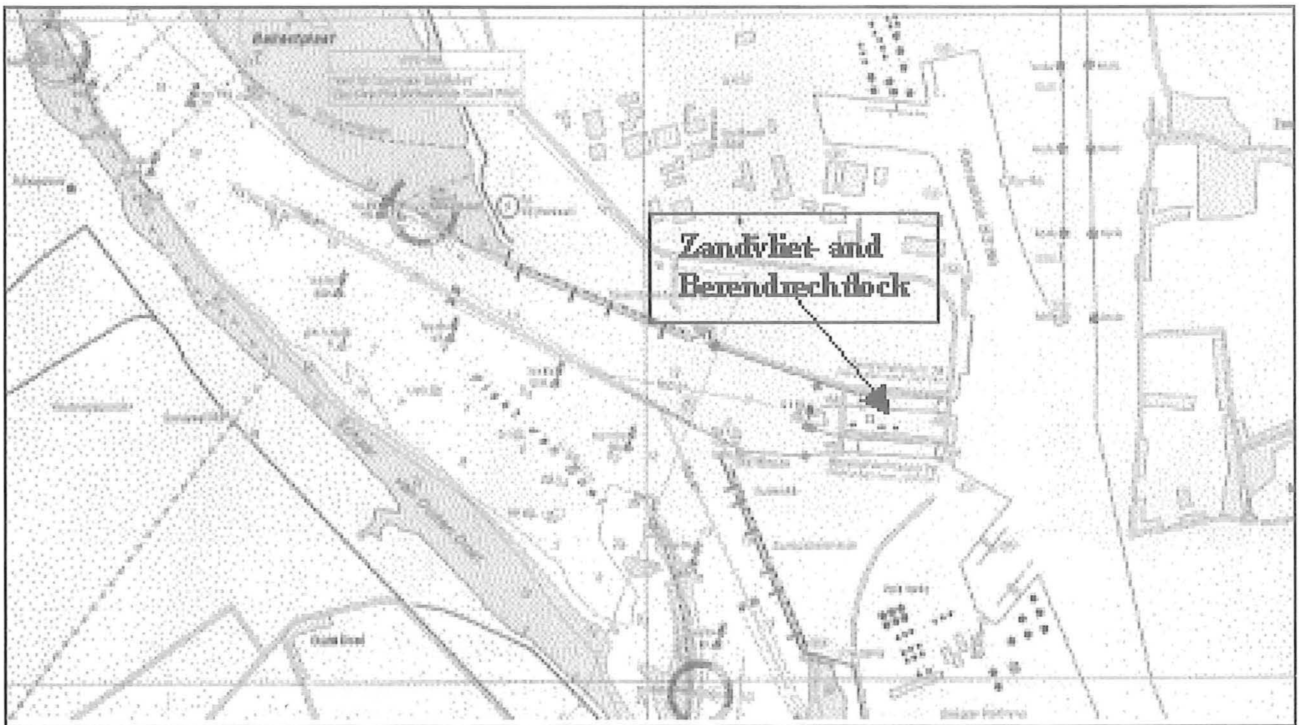


Fig. 1 Photo of the lower Scheldt

In order to maintain the water level in the docks, a thorough water balance is managed by the Port Authority of Antwerp. 400 to 1.000 Mm^3/year is evacuated from the docks to the river Scheldt while a mere 50 Mm^3/year is transferred, by gravity, from the river Scheldt to the docks. These water balance figures cannot explain the significant yearly estimated sedimentation-rate of approx. 200.000 to 350.000 tons of d.s./year within the dock's basin. The sediment-supply attributable to this water exchange operation is a merely 20.000 tons of d.s./year. Consequently other mechanisms of sediment transport are at work and should be identified.

The silt exchange mechanism is also influenced by other phenomena. The suspension concentration in the access channel to the locks and the river Scheldt fluctuates because of:

1. Natural variations.
   - tidal variations within a tidal-cycle (flood-ebb) and within a moon-cycle (Spring Tide, Neap Tide)
   - seasonal variations: variations of 100 to 1500 mg ds/l are possible over a period of one year and depending on the upstream discharge, the tidal coefficient, the hydrometeorological conditions,....
2. Man-made causes:
   - the influence of large ships entering the access channel and stirring up the fine-grained sediments.
   - The agitation-dredging of the sludge by scraper/bed-leveller works in the access channel.

The annual sedimentation in the turning basin in the port is estimated on the basis of dredging figures and bathymetric soundings and maps. So far these computations failed to give a confident and reliable prediction of the annual sediment-supply.

The analysis of the historical data didn't allow identifying and quantifying the sediment regime at work in the dock's turning basins. The historical analysis allowed to define the factors influencing this mechanism and to estimate sediment flux and sedimentation rate. Hence additional surveys and studies were found to be necessary. These are described hereafter.

1.2 A dedicated survey campaign to identify the sedimentation mechanism

To gain a clear understanding of the sedimentation mechanism, a sediment transport survey programme

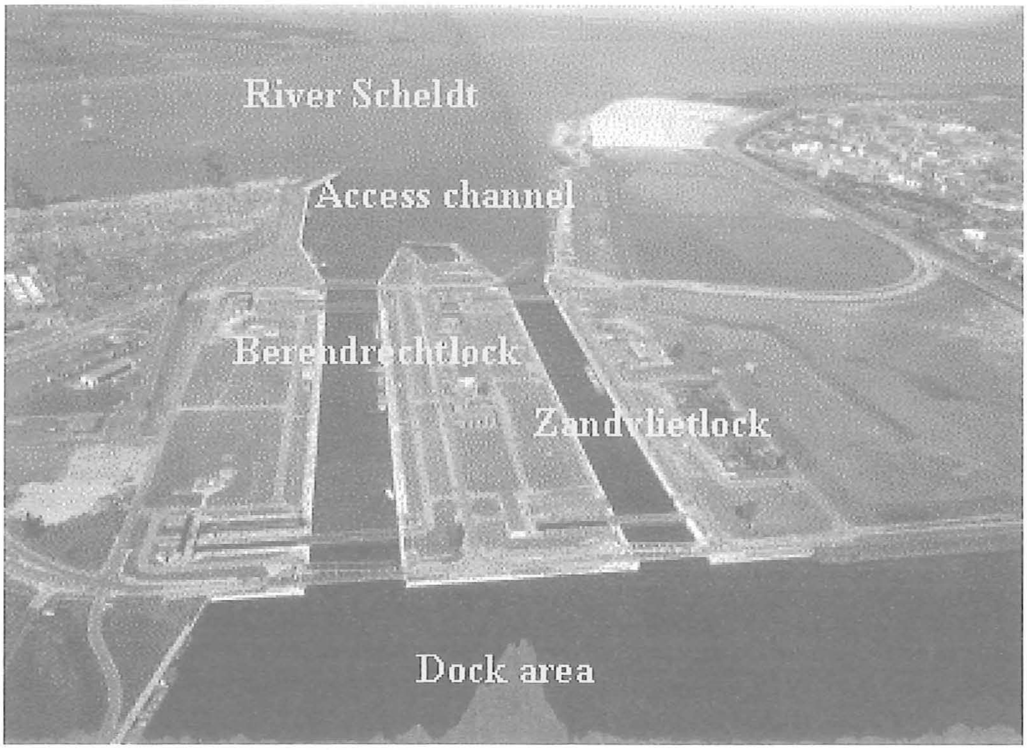


Fig. 2 Photo of the Zandvliet and Berendrecht locks

was executed in the access channel, the lock basin and the turning basin in the dock Kanaaldok. The results were used to validate a two-dimensional mathematical simulation of the sedimentation processes.

The main requisite of this survey was that vertical profiles be surveyed over the full water depth during various boundary conditions, e.g. different tidal levels, lock gate positions and navigational situations. Vertical profiles were surveyed for the following parameters: depth, current velocity and direction, conductivity, turbidity, salinity and temperature.

The measurements were made from the chartered hydrographic survey vessel "MS Argus" of the Rijkswaterstaat Vlissingen Survey Department and lasted for one week.The most important conclusions of the survey can be summarized as follows:

- Small differences in salinity were measured (differences of 2 to 7 g/l) between the access channel, lock basin and turning basin.
- Suspension concentration differences are much smaller; typical differences are in the order of 50 to 150 mgds/l.
- Current velocities of the nearbed flow are in the order of 0.5 m/s. Velocities of the upper parts of the water column are equivalent but in the opposite direction (from dock to Scheldt).
- Layer-thicknesses of the nearbed flow varies between 5 to 10 m in both locks.
- Density flows keeps on moving for 100 to 120 minutes.

These figures indicate that, on opening the lock gates, a density flow is generated whereby saline muddy water moves nearbed from Scheldt towards the docks and below less saline and sediment laden water, which moves from dock towards the Scheldt.

The nearbed density flux from the river Scheldt to the docks is quantified to some 1.5 to 3.0 x 10^{-5} tds/m^2.s. According sediment transport rates can reach 12 to 85 tds/locking operation.

Similarly has the upper part of the water column fluxes of ca. 5.10-6 tds/m^2.s from docks to the river Scheldt. The sediment transport is about 5 to 10 tds/locking operation.

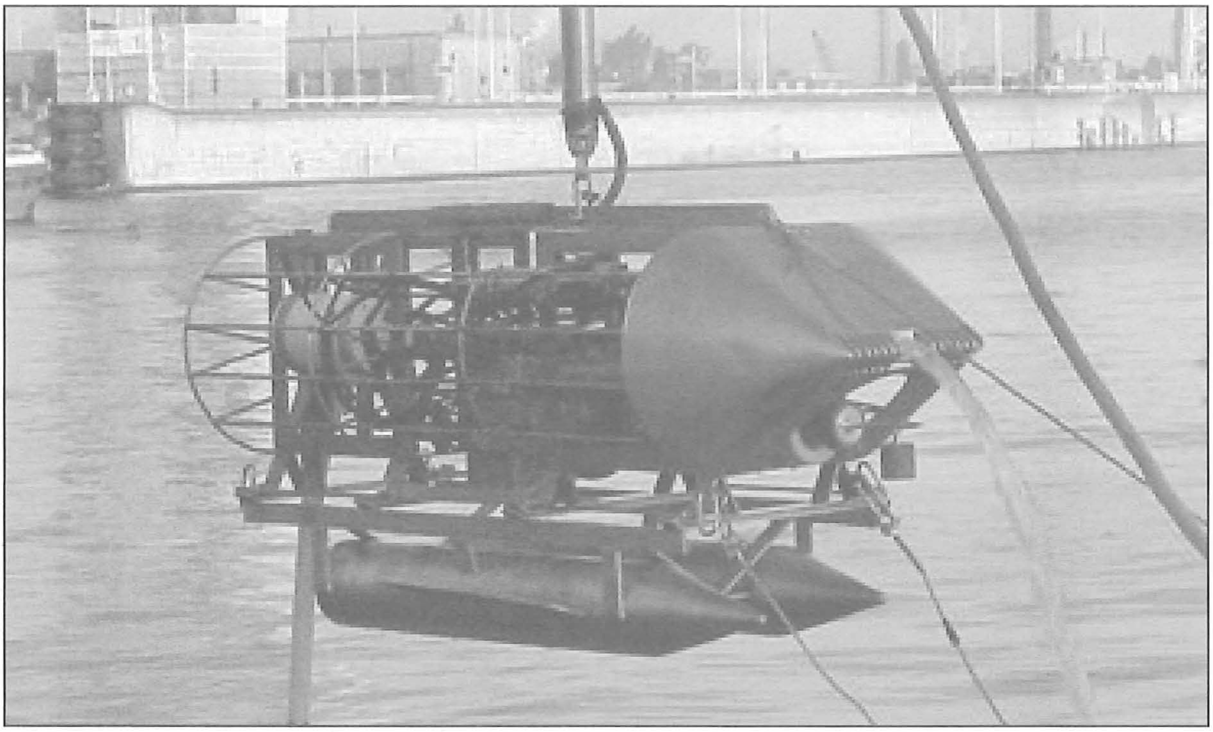


Fig. 3 Photo of the "measurement fish", fitted with salinity-, temperature-, density- and turbidity gauges

The characteristics of the density flow from the river Scheldt to the docks can hence be summarized as follows:

- Water-discharges of ca. 90 000 m^3/hour.
- Sediment fluxes of ca. 10 to 75 tds/locking operation.
- Suspension concentration of about 0.04 to 0.3 kgds/m^3. Salinities between 10 to 15 g/l.
- Current velocities of 0.10 to 0.50 m/s.

No significant influence of the passage of large vessels on the overall sediment-flux could be concluded from the survey results.

1.3 The two-dimensional hydrodynamic and sediment transport model

A 2D hydrodynamic and sediment transport model was developed, extending from the access channel to the turning basin of the locks. The effects of different lock gate movements were simulated. Each run generated computed profiles of velocity, salinity and turbidity over the entire cross-section.

After calibration and validation of the model by comparison with results from the in-situ measurements, 5 critical situations with different boundary conditions were simulated. The various conditions simulated were :

1. Extreme high salinity in the river Scheldt.
2. Extreme low salinity in the river Scheldt.
3. High turbidity (2 times the surveyed turbidity).
4. Extreme high turbidity (4 times the surveyed turbidity).
5. Combined extreme high salinity and high tidal level

The conclusions of the various simulations can be summarized as follows:

- The results of the mathematical simulations confirm the assumptions as to the driving force of the exchange mechanism of sediment, namely the salinity difference that exists between the river Scheldt and the docks.
- The higher the salinity difference, the greater the density flow.
- The turbidity is equally important, because it determines the sediment flux.

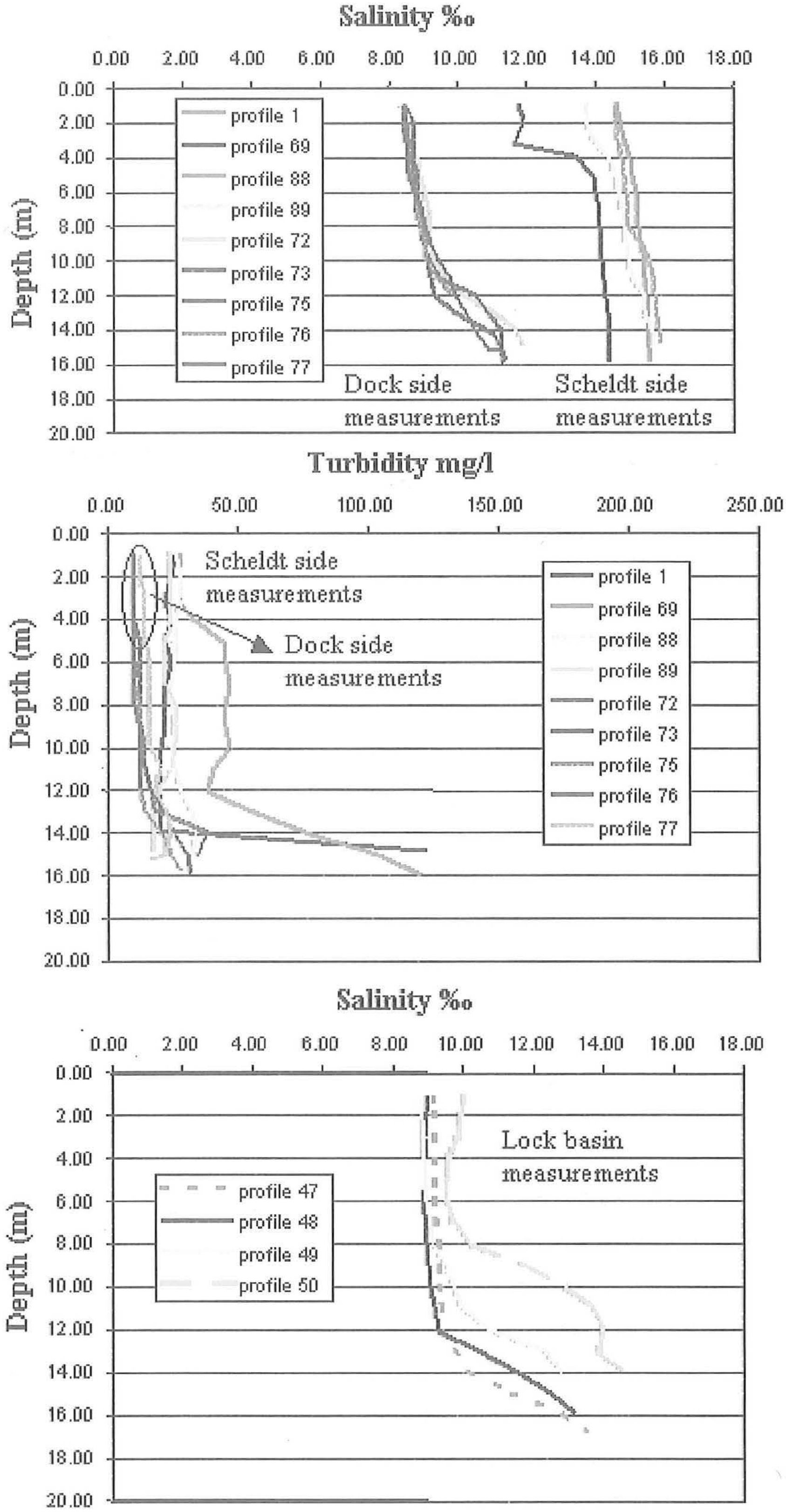


Fig. 4 Measured salinity and turbidity profiles and a sketch of the density flow

- The influence of the tidal level in the river Scheldt is of less importance. The high salinity difference combined with a high tidal level induces the most significant density flows.
- Current velocity and salinity profiles were easily validated by the model, confirming the relative simplicity of the process.
- Water exchange mechanism is characterized by certain inertia.
- The exchange is most intense in the first 90 minutes after opening the lock gate; the total exchange process lasts for more than 3 hours. The nearbed density flow is within a layer of 3 to 4 metres above the bed.

1.4 Conclusions of the survey campaign and of the mathematical simulation of the sediment supply mechanism

As a support to the functional design of a system dedicated to the prevention or reduction of sediment inflow via nearbed density flows, it is possible to draw the following conclusions from both the survey work and from the mathematical simulations :

- Each time the lock gate opens, a saline and silt-laden flow moves towards the docks; the nearbed density flow moves gravitary and is compensated by a near-surface freshwater flow.
- Small differences in salt concentration (differences from 2 to 7 g/l) are enough to initiate a density flow between the river Scheldt and the docks.
- The suspension concentration (50 and 150 mgds/l) in the lower parts of the water column is closely related to the nearbed density flow and is significant with respect to the overall sediment budget.
- The density flow velocities range between 0.2 and 0.5 m/s.
- The layer-thickness of the nearbed density flow varies between 5 to 8 m.
- The inertia period of the density flow is about 100 to 120 minutes.
- Figures on the nearbed density flow :
  - Density flows discharge at approx 90.000 m^3 /hour; the corresponding current velocity is 0.05 to 0.50 m/s (the average speed being 0.25 m/s).
  - Residual sediment transports over the whole lock chamber are between 10 and 75 tons of ds/locking operation for suspension-concentrations of 0,05 to 0,500 mgds/m^3 and fluxes of ca. 2.10^{-5} tds/m^2.
- Figures on the near-surface compensation flow:
  - Sediment flux is ca. 5.10^{-6} tds/m^2 corresponding to a sediment transport of 5 to 10 tds/ locking operation.

The density flow can be characterized as follows:

- The duration of the phenomena is 110 minutes.
- The silt concentration: 0.05 to 0.70 kg of ds/m^3.
- The salinity concentration: 8 to 15 g/l.
- The supply of sediment: 15 to 85 tds/locking operation.

1.5 Alternative systems identified to intercept nearbed density flow and to prevent sedimentation in the dock

Following systems were identified as potential systems able to capture or to intercept nearbed density flow and hence the nearbed suspension flux:

1. Floating silt barrier.
2. Current deflecting wall (CDW).
3. Air-bubble curtain.
4. Procedure to exchange the water in the lock basin with dock water during the lock cycle.
5. A density flow capturing device.
6. Close the lock gate as quickly as possible.

The above-mentioned systems were evaluated regarding their technical and economical feasibility. Below the summary of the multicriteria decision analysis is presented:

Consequently to these comparative study, it has been decided to withhold for further study and engineering the Density Flow Capturing Device, in combination with a fast closing of the lock gates immediately after vessels leave the lock chamber.

The conceptual system of the proposed Density Flow Capturing Device (DFCD) is presented on Figure 5.

	Expected Success Rate	Operational Reliability	Efficiency	Ruggedness	Operating cost	Payback time	Navigational impact	Total score
1. Floating silt barrier.	++	++	+	+	+	+	++	+
2. Current deflecting wall.	+	+	+	+++	+++	+	+	++
3. Air Bubble Curtain.	+++	+++	+	+++	++	+	++	+
4. Changing the water in the lock basin with dock water during the lock cycle.	+	+++	+++	+++	++	++	+	++
5. Density Flow Capturing Device.	+++	+++	+++	+++	++	++	++	+++
6. Close the lock gate as quickly as possible.	+++	+++	++	+++	+++	+++	+++	+++
Score: + = bad, ++ = moderate, +++ = good								

It is to be mentioned that the Zandvliet lock is yet provided with a funnel-shaped salt-water capturing device extractor, to the lock discharge and bypass pipe. The salt-water capturing system can, alternatively, be adopted to be used for capturing the salty silt-laden waters. This salt-water capturing device extractor was originally built to intercept saline bottom water and return it to the river Scheldt via the lock discharge/bypass pipe.

The Berendrecht lock wasn't equipped with an optional facility of the same type, so a new funnel-shaped pit must be dragged into position with a volume of 15.000 to 20.000 m³ to serve as a density flow catcher. A suction mouth system will ensure the necessary connection between the pit and the discharge pipe.

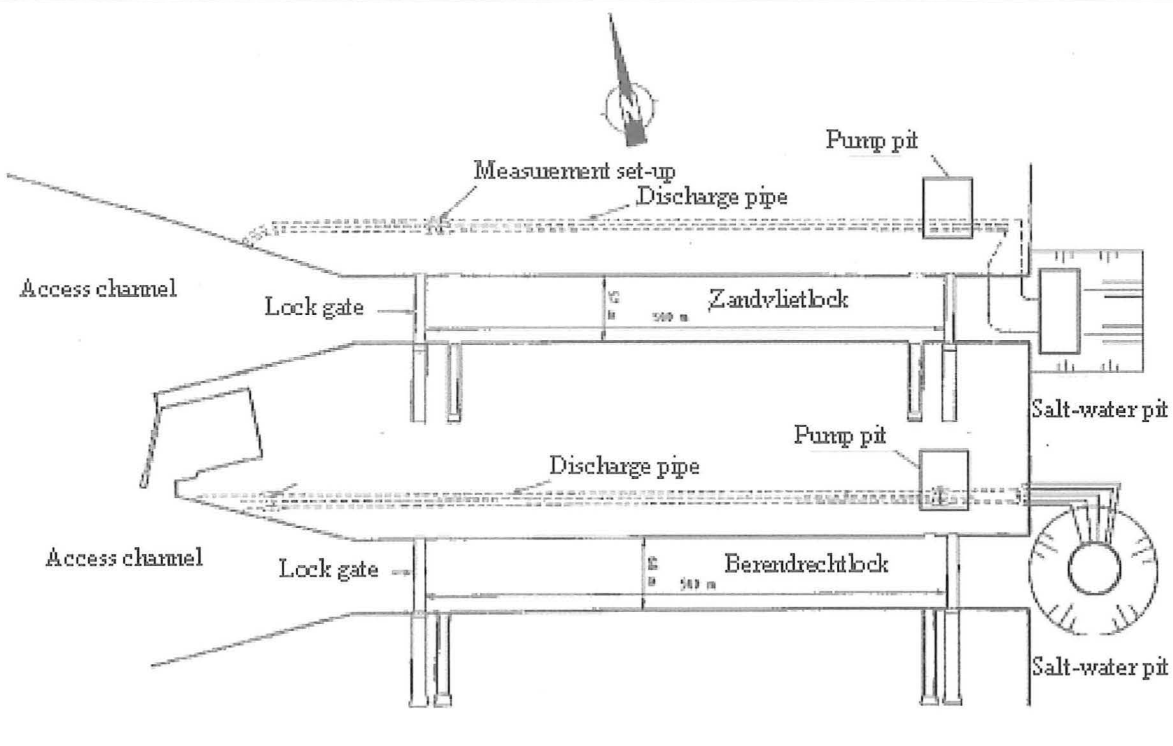


Fig. 5 Draft plan of the proposed Density Flow Capturing Device (DFCD)

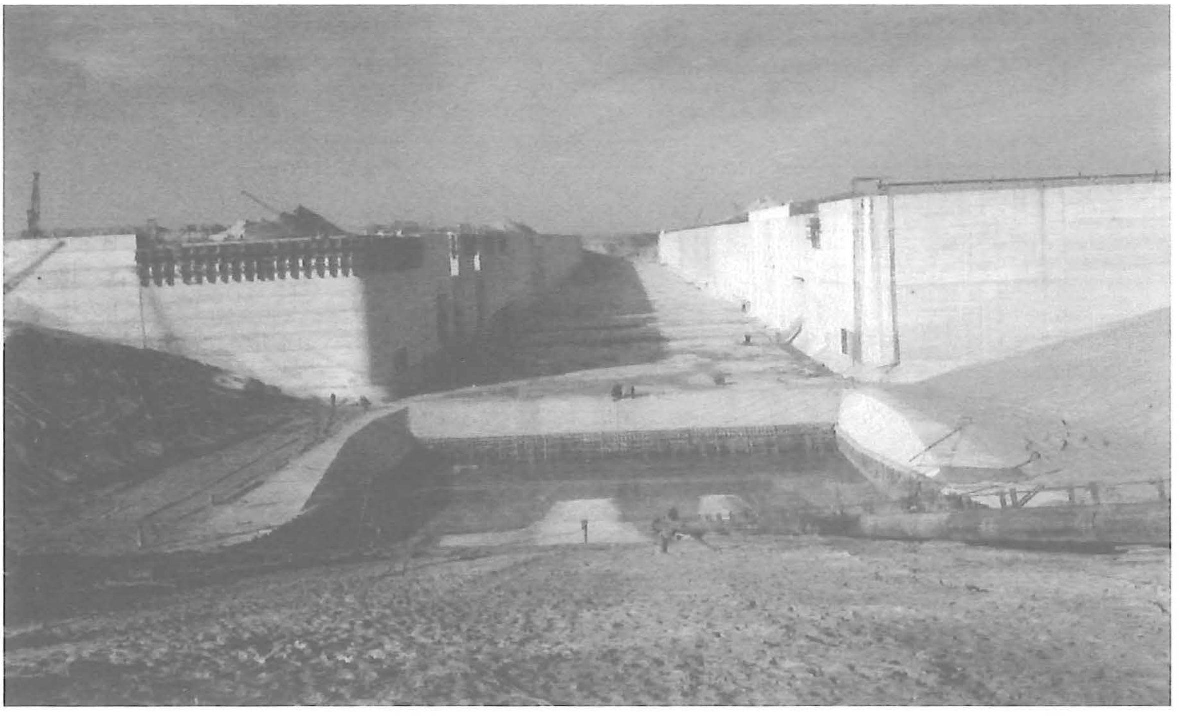


Fig. 6 Photo of the entrance of the salt water capturing device during construction of the Zandvliet lock

If and when the hydraulic gradient between the river Scheldt and the docks is large enough, gravitational hydraulic exchange can be induced.

Despite the possibility of generating high discharge, driven by gravity, the suggestion was made to force the return of the density flow by pumping. Propeller pumps or axial/radial pumps with a vertical axis in a dedicated pumping chamber are conceived in a by-pass configuration (bypassing the discharge pipes). The big advantage of the "by-pass" configuration is the ability of being able to discharge water by gravity and/or by pumping and the relative simplicity of construction.

The pump characteristics are the following:

- Design flow rate: 4 x 25.000 m^3/hour (four pumps for each lock). Main advantages: the operational reliability and the possible incorporation of a flow regulator, depending on the ratio of the gravitational fall to the pumped flow rate.
- Installed power: 4 x 500 kW.
- 4 cut-off valves.
- Driving mechanism for each pump: gearbox + magnetic coupling.
- Switch box with PLC-drive + magnetic switches.
- Frequency control to regulate the flow.

The pumps can be controlled in different ways:

- Manually.
- Activated by operation of the lock gate.
- Triggered by threshold measurements of the salinity and/or turbidity sensors in the salt water/density flow capture.

1.6 Cost-benefit analysis

A cost-benefit analysis was executed in order to help the decision-making by the Port Authority of Antwerp. The installation and infrastructural costs of building a DFCD and pump system for the Zandvliet lock, which is already equipped with a salt-water capture device and a discharge pipe, and for the Berendrecht lock equipped with a discharge pipe only:

Costs in EURO (x 10^3)	Zandvliet lock	Berendrecht lock
• Pumps (4*25 000 m³/h)	944	944
• Pipework	375	375
• Electric power supply, automation and instrumentation	371	371
• Discharge pipe + cut-off valves	50	50
• Pump pit	2 250	2 250
• Groundwork and revetment	250	250
• Pump housing and overhead crane	250	250
• Adaptation of the cut-off valve pit	250	250
• Construction of new intake		2 300
• Dredging work		200
• Design and contingency costs	1 185	1 810
Total cost	**5 925**	**9 050**

The total investment is estimated at ca. 15.000.000 euro. Assuming a depreciation period of 15 years and an interest rate of 6 %, the total depreciacion cost can be put at 1.500.000 euro/year.

The operating cost are estimated as follows:

	Costs in EURO (x 10^3)/year
• Total depreciation cost	1 542
• Energy consumption (2*5.7 MkWh/year * 0.1 EURO/kWh)	1 134
• Civil infrastructure - maintenance	125
• Electromechanical maintenance	210
	3 011

Using the survey data and the simulation results, total annual sediment transport transiting through Zandvliet and Berendrecht locks via nearbed density flows were computed and were evaluated at an annual transport of ca. 150.000 tds. This is quite similar to the rates deduced from the maintenance dredging in the Antwerp Docks, i.e. 150.000 to 200.000 tons of ds/year in the turning basin of the Zandvliet and Berendrecht locks.

The efficiency of the proposed system is estimated to be 60 %. Hence, 90.000 tds/year could, theoretically, be captured and returned via the discharge pipes to the river Scheldt; the unit price of this operation would therefore correspond to some EUR 33.5/tds.

The average dredging cost in the Port of Antwerp is ca. EUR 22/tds. Actually dredged material is disposed of in an underwater-facility, dredged in the bed of the Delwaide-dock; disposal cost is approximately EUR 20/tds. It's assumed that such relatively cheap equivalent disposal facilities cannot be implemented anymore in the future, because of the lack of storage space in the neighbourhood of harbours and because of the ever-tougher enviro-technological regulations. The total dredging and storage cost in the port of Antwerp, at current prices, is ca. EUR 42/tds.

Taking into account the above-mentioned storage costs, the proposed system seems to be more economical than the currently used dual strategy of dredging and storage. The fact that the storage costs will become more expensive in the future, strengthens the case for the suggested solution. In case gravity flow without pumping appears to be feasible as well, the DFCD-solution would, of course be tremendously more economic and more sustainable than the current dredging and disposal practice.

Moreover, would the original DFCD-solution open an era of a complete new approach to cost-effective and sustainable maintenance dredging management.

1.7 Other aspects of the proposed system

- Impact on the sedimentation process in the access channel

The proposed system actively transfers the inflowing sediment back to the access channel of the locks, viz. the sediment source. The returned volume of sediments is much lower than the sediment volume present within the river and access-channel. The sediment volume thus circulated is also less than the annual sediment volume in the access-channel and removed nearly constantly by agitation/bed levelling dredging. The study reveals great differences in the density flow flux (and, as a consequence, the sedimentation flux) between a flow from the Scheldt to the access channel and one from the access channel to the docks.

	from Scheldt to access channel	from access channel to docks
Density flow flux	ca. 2 kg d.s./m² sec	ca. 0.01 to 0.1 kg d.s./m² sec
Sedimentation flux	ca. 8 kg d.s. /m² day	ca. 1.6 kg d.s. /m² day

Consequently, the impact of recirculating sediments back to its origin, i.e. the access channel, would be negligible with respect to the sedimentation process in that same channel.

- The impact on navigation

The impact on navigation would be linked to the sidewards hydraulic flow on ships manoeuvring in the access-channel. This impact is supposed to be negligible because the backflow starts when the lock gate at the dockside is opened. The resulting turbulence at the outlet of the drainage pipe will not have an impact on ships berthed at that moment in the lock basin.

Moreover it is to be stressed that, at present, some 200 to 500 million m³ is yet being drained via these same discharge pipes in order to controll the water level in the docks; these current operations are executed nowadays and without any significant effect reported by pilots or navigators.

- The impact on the overall water balance of the harbour

The proposed solution helps to control the salinity-level of the dock water. The water level in the docks varies between TAW +4.10 m and 4.40 m (the target level is TAW +4.18 m. [TAW = the official Belgian topographic Chart Datum benchmark]).

Water level control is currently achieved by a correct balance between water intake from upstream canals (Albertkanaal,...), rainwater drainage system in the City and the river 't Schijn on one hand, and water discharge via the drainage pipes of the 4 main locks. In this respect, 400 to 1.000 million m³ of fresh water are drained annually from the docks to the river Scheldt via these discharge pipes; exact drainage discharge depends upon the upstream freshwater-discharge and water temperatures, and hence evaporation, in the summer.

The proposed solution will cause a discharge of ca. 500 million m³ (= 2.400 single ship transits * 200.000 m³/ship transit) from the docks to the Scheldt. This means a resultant discharge of nearly 40 million m³/month from the docks to the river Scheldt. Consequently, the proposed DFCD will discharge a water volume at the Zandvliet and Berendrecht locks equivalent to the actual annual discharge.

It has been recognized that the use of the DFCD solution during the drier months (June, July and August) may cause a water balance problem. This problem could be solved by the creation of a temporary water buffer during the months of April to May by keeping the water level artificially high and by allowing fresh surface water from the Scheldt into the docks .

2. FIELD-MEASUREMENTS TO CHECK THE EFFECTIVENESS OF THE SUGGESTED DFCD SOLUTION, POWERED BY GRAVITY

In order to check the effectiveness of the proposed DFCD-solution, another measurement campaign was undertaken. Over the past few years the salt water capture device behind the Zandvliet lock silted up due to the sediment inflow mechanism described above.

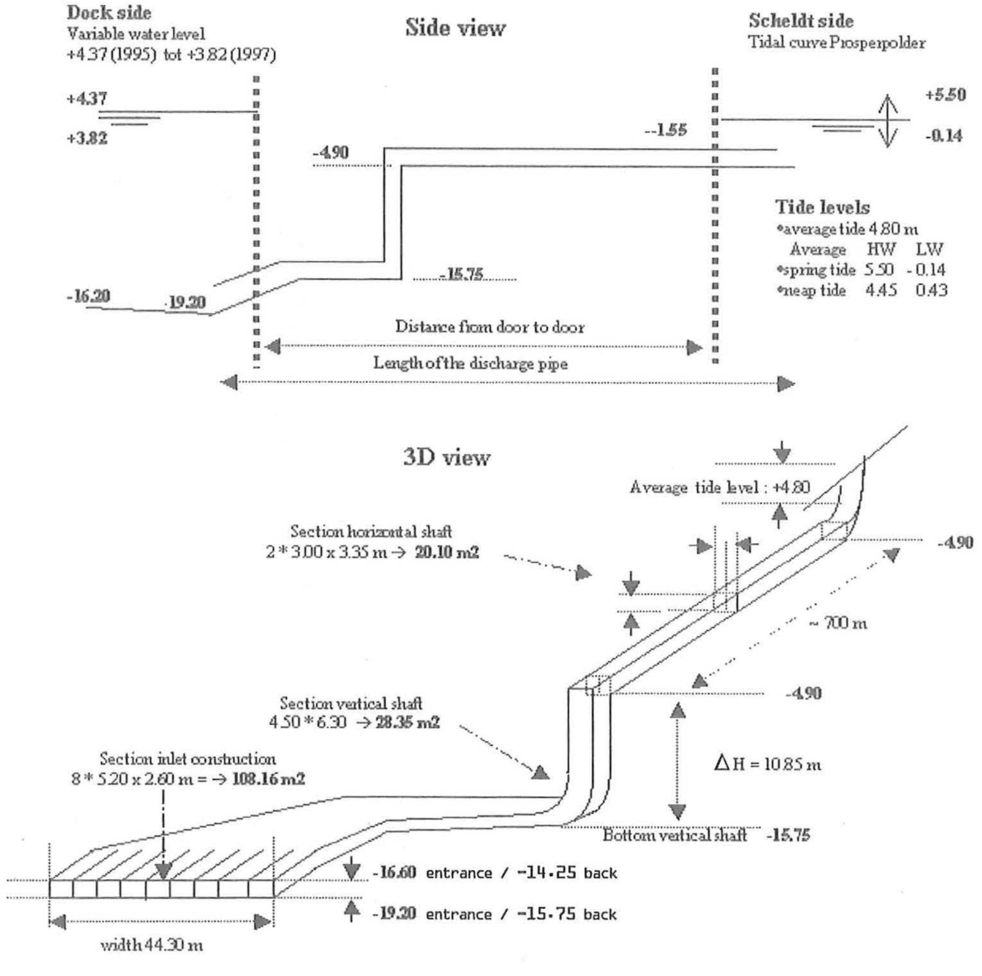
The complete infrastructure was surveyed and consequently cleaned by mechanical and hydraulic dredging. After these works, the salt-water capturing device including its very large inlet funnel was diver-inspected and all remaining obstacles were removed.

After that the field-measurements were executed. The objective of the measurement campaign was:

- To find the physical relationships between flow rate/discharge and hydraulic gradients between the river Scheldt and the dock.

$$Q = a * \sqrt{dh}$$

- To observe the sediment transport in the discharge pipe during the discharge operation.
- To investigate whether any relationship exists between the water level gradient and the sediment transport.
- To evaluate the overall technical feasibility of the DFCD under gravitational conditions (no pumping).



Schematic drawing of the discharge pipe construction

Fig. 7 A schematic view on the construction sequence for the discharge pipe

2.1 The measurement campaign

To prepare for the new measurement campaign, historical data from the previous measurement campaigns conducted in 1974 and 1990 were compiled. From the design of the discharge pipes and from these previous surveys, the following is thought to be relevant:

- The discharge pipe is composed of two identical horizontal pipes with a height of 3.40 m and a width of 3.40 m. The length of the discharge pipe is 720 m.
- There is a well-defined correlation between the water level gradient and the rate of flow in the discharge pipe. No mathematical equation was worked out.
- The correlation between sediment concentration and the water level gradient is less apparent.An influence of ship movements (stirring actions) near to the intake of the discharge pipe is suspected to affect this.
- The accuracy of the discharge-computations is evaluated at some 5 %; similarly, the accuracy for the sediment transport values, deduced from these surveys, is estimated at 10%.

Based on theoretical considerations and validations with the measurements from previous survey campaigns (1974 and 1990), the engineering team managed to formulate a unique equation between the water level gradient and the flow rate. In order to deduce extreme value discharge figures, extrapolations using the same equation were necessary.

Moreover, was it made possible to reduce the number of measuring sensors significantly, thanks to a thorough hydraulic analysis of current profiles and intercorrelation-computation between various survey data.

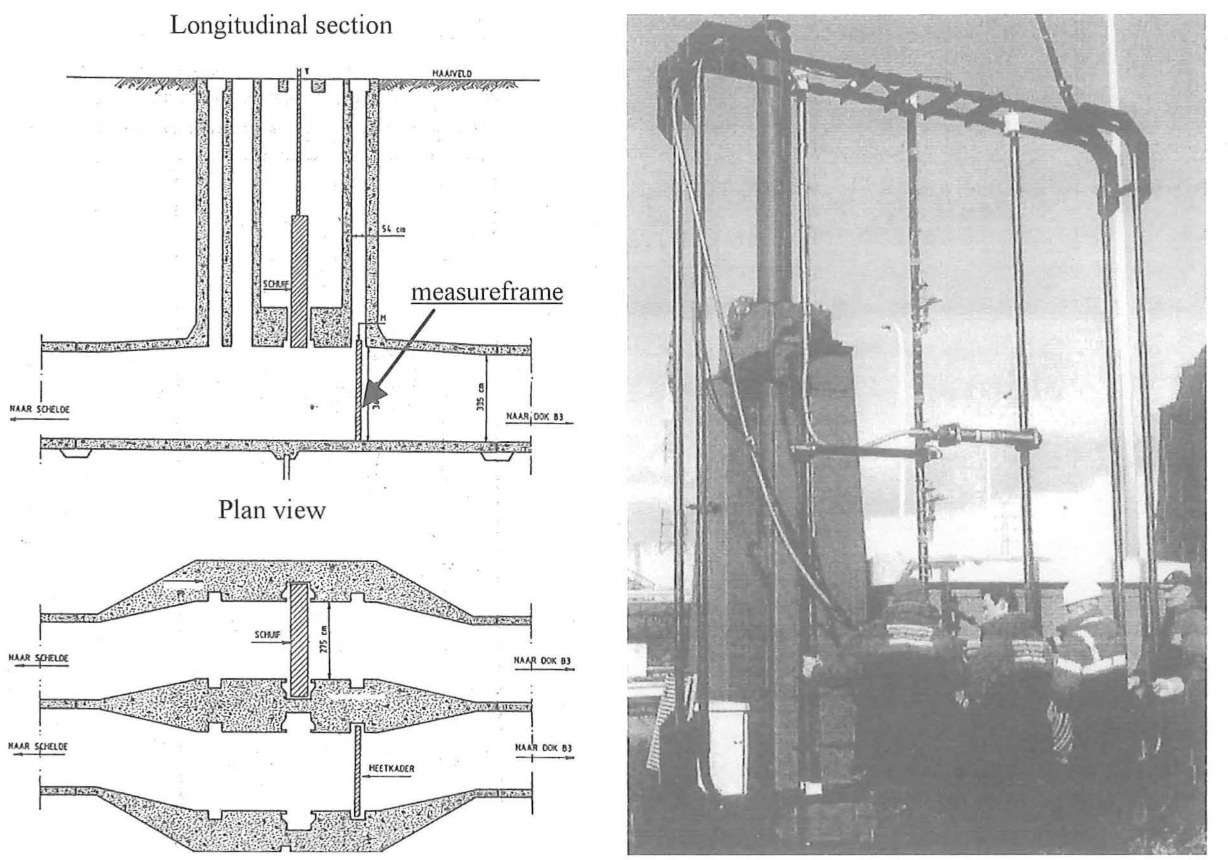


Fig. 8 Pipe sections for the discharge pipe and a photograph of the measuring frame

The measuring frame was equipped with three current velocity sensors, a silt monitor (turbidity gauge) and a pump to take water samples for the analysis of the sediment concentration.

The purpose of the velocity sensors positioned 0.6 m above the bottom and below the top of the discharge pipe is to indicate the average rate of flow. This could be deduced from the above-mentioned hydraulic analysis.

Water samples taken by the sampling pump were used to calibrate the turbidity gauge.

As for the density flow survey campaign, vessel traffic throughout the lock and the lock gate movements were monitored in order to assess their influence on the overall sediment transport.

The measurement campaign was undertaken at spring tide on the 12th of March 2001; the survey was done over 13 hours, during which the flow was oriented from dock to Scheldt river during 8 hours, and from Scheldt river to dock during 2 hours.

On the basis of the measurement campaigns in 1974 and 1990 and the theoretical study, a quadratic relationship was found to calculate the discharge originating from the water level gradient. A simplified model to calculate the flow rate in the discharge pipe is given below:

$$\Delta h = 4f\,\tfrac{1}{2}v_L^2\frac{L}{gD_L} + \frac{K_I}{g}\tfrac{1}{2}v_I^2 + \frac{K_U}{g}\tfrac{1}{2}v_U^2$$

$$\Delta h = 4f\,\tfrac{1}{2}\frac{Q^2}{gS_L^2}\frac{L}{D_L} + K_I\,\tfrac{1}{2}\frac{Q^2}{gS_I^2} + K_U\,\tfrac{1}{2}\frac{Q^2}{gS_U^2}$$

where:

- Δh water level difference [m]
- f friction coefficient according to *Nikuradse* (for a smooth walled pipe) [-]
- v_L velocity in the pipe [m/s]
- v_I velocity at the inlet of the pipe [m/s]
- v_U velocity at the outlet of the pipe [m/s]
- Q discharge [m³/s]
- g gravitational acceleration [m/s²]
- S_L cross-sectional area of the pipe [m²]
- S_I cross-sectional area of the inlet of the pipe [m²]
- S_U cross-sectional area of the outlet of the pipe [m²]
- L length of the discharge pipe [m]
- D_L hydraulic diameter [m]
- K_I hydraulic resistance coefficient of the intake structure [-]
- K_U hydraulic resistance coefficient of the outlet structure [-]

In this equation, $4f$ depends on Re (the Reynolds number) and, as a consequence, on $< v_I >$. The relative roughness of the concrete walled pipe of the Zandvliet lock x /D is max.: 3 mm / 3.4 m ≈ 0.001. The dependence of $4f$ on Re is, therefore, negligible whenever Re is greater than 3.105. Only for current velocities below 0.10 m/s does the friction factor become important. Hence, after assuming that for the average and extreme high conditions 4f is insignificantly affected by Re, it was found that the above-mentioned equation yielded a flow rate increasing proportionally with the square root of the water level difference, or hydraulic gradient.

These assumptions are to be validated by the field data.

Figure 9 on the following page shows the variance in the measured values.

The sediment concentrations of the water samples were used to calibrate the turbidity gauge. A correlation curve was plotted based on readings that were taken when the flow direction was from the dock to the river Scheldt; a good correlation (R2 =0.94) between turbidity gauge readings and sediment concentrations of water samples was concluded, ascertaining the reliability of these readings.

Furthermore, were the turbidity gauge readings during the whole survey continuously compared with the suspended solid concentration of water samples taken during this same survey.

Figure 10 on page 55 shows the variation in actual concentrations measured in the water sample compared to concentrations deduced from the calibrated turbidity gauge readings.

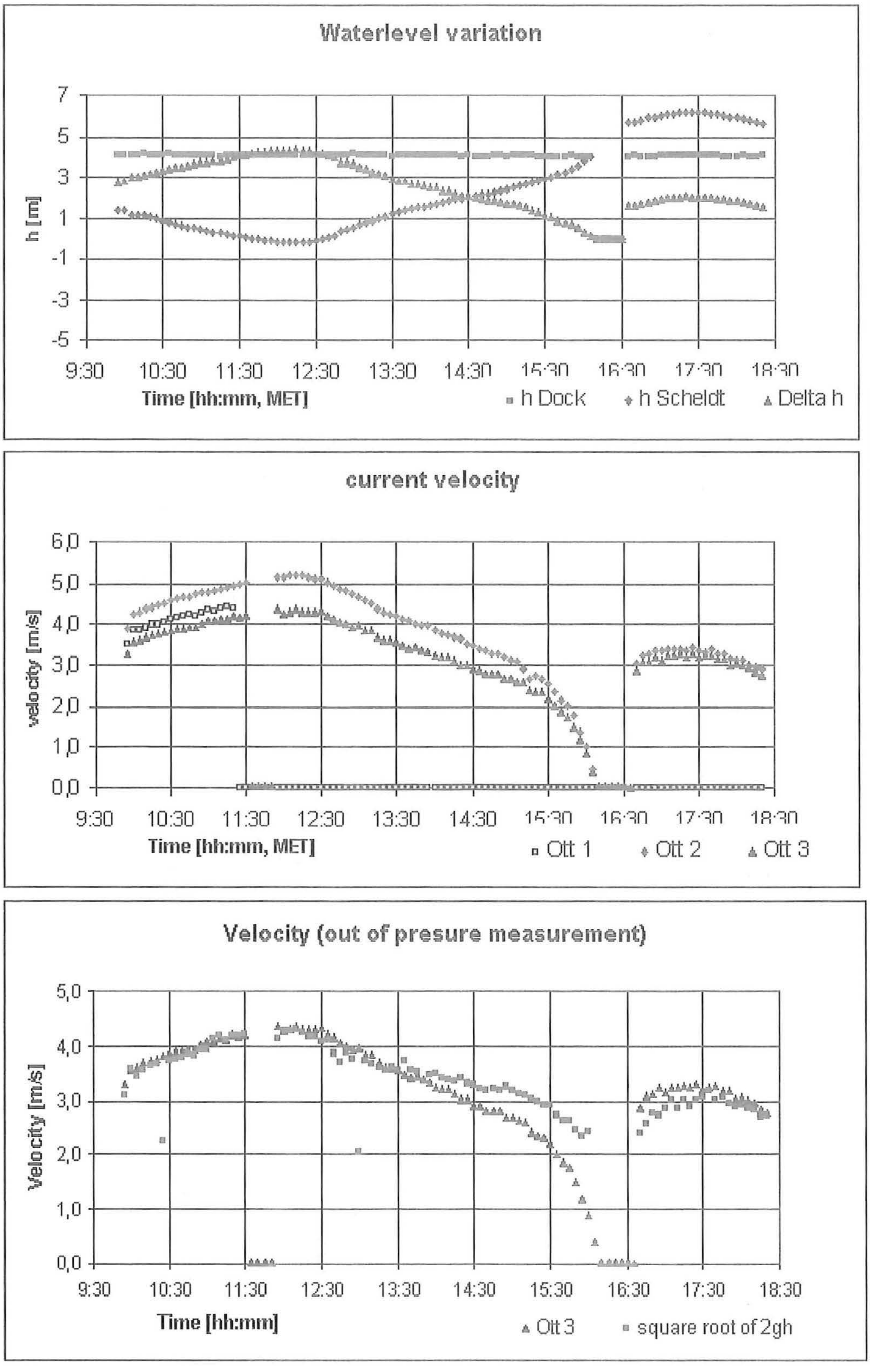


Fig. 9 Variations in water level readings in the river Scheldt and the docks; variance in measured current velocities in the discharge pipe; comparison of measured current velocities with computed current velocities derived from pressure sensor measurements

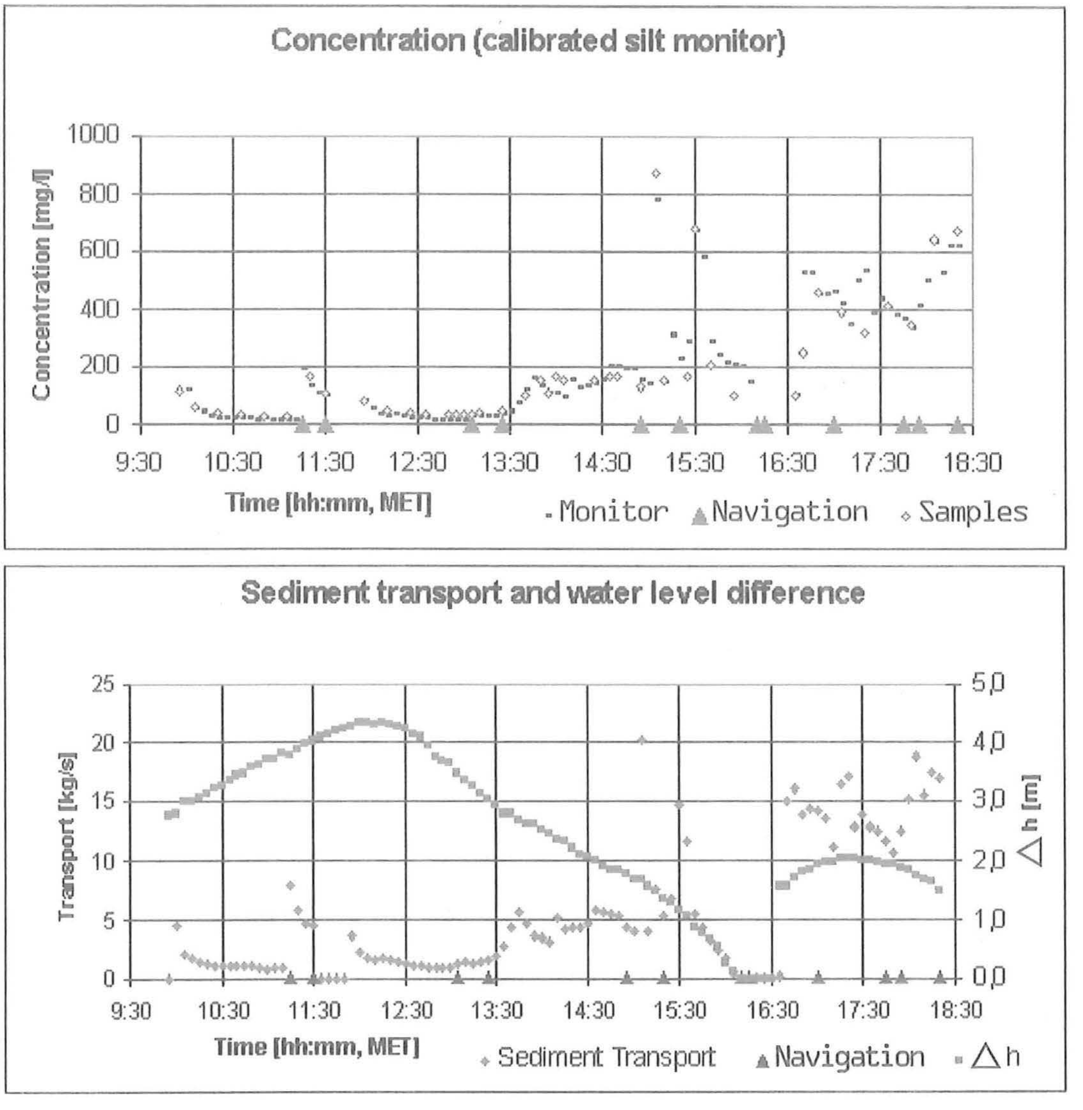


Fig. 10 Variations in sediment concentrations of the water samples compared to concentrations deduced from the turbidity gaugeand (ii) variations in sediment transport over time

Comparison between instantaneous turbidity values and vessel traffic, yielded the conclusion that bypassing vessels, passing along the intake of the discharge pipe, may induce short-living peaks in sediment concentration, and probably due to stirring as a result of propeller actions.

The current velocity within the discharge pipe was calculated from the water level within the gate valve chamber, measured by means of a pressure sensor. The velocity was deduced from the static energy head using Bernouilli's equation. The formula used is the following:

$$v = \sqrt{2gh}$$

where:

- v current velocity
- g gravitational acceleration
- h velocity head

Variations are found in:

- the absolute water level difference between the river Scheldt and the dock.
- the discharge derived from multiplying the average recorded current velocity (the current velocity measurement at gauge 3) with the cross-sectional area of the discharge pipe.
- The theoretical discharge is calculated using the formula:

$$Q = a * \sqrt{dh}$$

The constant 'a' will depend on the flow direction and is calculated by the least squares method using the square root of the water level difference versus the computed discharge derived from the average current velocity function.

The following table shows the results of the computations of the 'a' (hydraulic coefficient) value and the R^2 (correlation coefficient) value for the measurement campaigns undertaken on 12 March 2001 and June 1990 respectively:

- There are indications that the inlet of the salt-water capturing device of the Zandvliet lock was heavily obstructed by debris and by siltation affecting the hydraulic response significantly.

To obtain a reliable Q-h - relationship, the campaign must encompass the whole measurement range and not just the top of the curve.

The sediment transport is obtained by multiplying the flow rate and the sediment concentration deduced from the turbidity sensor readings.

The figure on the next page shows the variation in the suspension-sediment transport over time.

While the water is flowing from the dock to the river Scheldt, high peaks of sediment concentration are measured whenever large vessels pass near the intake of the discharge pipe. The unconsolidated fine-grained sediment is stirred up by the propeller-actions of the vessels and tugs; these local increases

Measurement date	Flow direction	a	R-square
12 March 2001	Dock to Scheldt	20.53	0.990
12 March 2001	Scheldt to Dock	22.54	0.885
June 1990	Dock to Scheldt	20.26	-
June 1990	Scheldt to Dock	20.50	-

Table of the calculated 'a' and R^2 values for the measurement campaigns of March 2001 and June 1990.

The R2 value for the flow going from the river Scheldt to the dock is smaller than the one for the flow from dock to river Scheldt. This can be explained by the variations in tidal coefficients and the status of the salt-water capture device (+ its intake):

- The measurement of March 2001 was taken at spring tide, whilst the measurements of June 1990 were done at an intermediate tidal coefficient. During spring tide, the water level rise is rapid (illustrated by a steep tidal curve during the flood period). The recorded variation in the water level difference was too small to calculate a reliable correlation when the water flowed to the dock from the river Scheldt.

in suspension concentrations are evenso visible on the water surface. The table below shows such measured peaks in sediment concentration as a function of increased vessel traffic activity.

From 16:35 onwards, the flow was directed from the river Scheldt to the dock and was measured in a similar way. From that very moment, no more effects were recorded attributable to vessels passing the inlet pipe in the access channel of the lock. The following table shows the measured peaks in sediment concentration w.r.t. increased navigational activity.

Time*	Name of vessel	Dimensions (length, width and draught)	Lockage direction	Concentration peak (mg/l)
9:21	Med Viaredgio	176.60 / 22.90 / 6.50	D > S	124
11:14	Alicia Rotterdam	167.90 / 22.90 / 6.50	D > S	192
11:32	Christiaan C	52.00 / 6.70 /	D > S	-
13:07	Polarstern	154.00 / 24.00 / 8.00	S > D	204
13:27	Eben Haezer	38.30 / 6.60 /	S > D	204
13:27	Chamsin	108.50 / 11.40 /	S > D	204
13:27	Vigila	110.00 / 11.50 /	S > D	204
14:57	Inovator	209.50 / 32.20 / 12.50	D > S	781
15:18	Veldhoven	110.00 / 11.50 /	D > S	679

* time of entry into the lock basin

The total transported volume of water and sediment over the full duration of the measurement campaign was calculated by way of an indication.

Flow direction	Volume (10^3 m^3)	Sediment (10^3 kg)	Average concentration (mg/l)
discharge from dock to Scheldt.	709.5	72.1	102
inflow from Scheldt to the dock area.	194.3	91.0	468

2.2 Main conclusions of the measurement campaign

The following main conclusions regarding the field measurement campaigns can yet be drawn:

- The tests indicated the feasibility to hydraulically flush the salt-water and sediment-laden water, captured by the salt-water capturing device on the bottom of the dock-side of the Zandvliet lock back to the river Scheldt, i.e. its origin, hence confirming the feasibility of tackling the dock-sedimentation problem at its source.
- There is no significant relationship between the water level difference and the sediment concentration or transport.
- The sediment transport towards the dock is significantly higher than when the flow is outflowing to the Scheldt river, confirming previous findings that suspension-concentrations in the river are significantly higher than in the dock waters.
- When the flow is directed from the dock to the river Scheldt, distinct sediment concentration peaks are observed within the discharge pipe during periods of increased vessel traffic close to the intake of the salt-water capturing device.
- The measurement campaign results concluded that it is feasible and strongly recommended to flush the salt-water capturing device by gravity during every lockage from the Scheldt to the dock, in order to intercept both salt-water and suspended solid penetration in the dock.

3. TRANSPORT OF SUSPENDED SLUDGE VIA THE SALT-WATER CAPTURING DEVICE ASSISTED BY WATER INJECTION DREDGING

The discharge test proved the feasibility of flushing undesired salt-water and sediment-laden water via the discharge pipe back to its origin in the river Scheldt. The question was raised whether the above-mentioned device could also be operated as a DFCD and if suspension-load backflow could be increased when assisted by water-injection of the sediment-deposits on the bed of the docks.

Fig. 11 Photo of the water injection dredger

After mobilisation of a water-injection dredger on the site, a new measurement-campaign took place on the 19th July, 2001. The same measurement arrays and equipment were used as in the trial of 12th March, 2001, with the exception of the current velocity gauge array, which was simplified.

Maintenance dredging or comparable dredging work, in terms of soil type, can often be carried out by a water injection dredging vessel, instead of conventional dredging equipment. During water injection dredging, water is injected, at high pressure, into the sediment, thereby creating a water-sediment mixture with fluid properties and with extremely low viscosities. The layer-thickness of such an artificially created density flow may, depending on the soil properties, vary between one and three metres.

Because of its higher density, this density flow will flow according to gravitational forces and will prefereably flow to lower-lying areas of the basin, such as the salt-water capturing device in front of the Zandvliet Lock This density flow will drag away the remobilised sediments, which in this case, will be captured and discharged via the discharge funnel and pipe back to the river Scheldt.

Much valuable experience has yet been gained on various Dutch and overseas projects using a water injection dredging plant. On several of these operations, conducted in cooperation with the Dutch Ministry of Public Works, extensive *in-situ* measurements were made to ascertain environmental conditions during the dredging process, such as soil properties, turbidity, dispersion of the sediment, current velocities and safe working methods. From the experimental and test results, thus obtained, a computational model of artificially created density flows could be developed.

From these previous works, it could also be concluded that local working conditions and the overall geometry of the site will play a crucial role in the success of a production process. The water-injection system is patented according to applicable laws in the following countries and/or areas : Europe (except Belgium) and the United States of America.

Detailed study of relevant publications, model tests[1] and practical experience have afforded a deep and close insight into the theory and practice of water injection dredging. Several conclusions concerning this dredging method are listed below:

[1] Trials of prof. Dr. Kuenen (1942) and the hydraulic laboratory of Delft.

- The water injection process, jet penetration, jet dispersal, density or turbidity current and sedimentation process can all be described by mathematical formulae. These can be used to calculate dredging outputs and productions in specific situations, just as for a classical dredging.
- Where the fluidised sediments are transported not only by a density current but also by dispersion and cross-currents, e.g. at the mouth of the harbour, computational models can be used to estimate the likely dispersal of the material.
- Knowledge of the prevailing conditions is essential for reliable results and may have a marked effect on the performance of a water injection vessel. The most important of these are:
  - characteristics of the soil.
  - geometry and bathymetry of the dredging area[2] (any potential sand bars or slopes). Small overdepths have a huge impact on the dispersion behaviour of a density current. They can take variations in height in their stride, provided the velocity of the current is strong enough and the sediments are fine-grained. Similarly, it was shown that a large proportion of this density current could, with little loss of flux, move over a sand bar (e.g. the case of the ferry harbour at Texel, the Netherlands).
  - existing currents. The resulting density current is capable of moving against a tidal current (e.g. the case of Epon harbour).

The water injection dredger MS CIRA was mobilised for the test in the Zandvliet Lock area on the dock side. A chronological description of the movements of the MS CIRA in the dock is given below.

Figure 12 on the next page shows the suspended-solid concentration variations in the discharge pipe measured with the turbidity gauge.

The concentration of the incoming water (that flows into the dock) is ca. 110 mg/l. This concentration is much lower than the measurements that were logged in March 2001. In the summer, water from the river Scheldt is brought into the docks using the discharge pipe – the reason being that the dock water level, in summer, is generally lower than the target water level. In August 1998 a total river Scheldt water volume of 47 million m^3 was flowed into the docks. The estimated sediment transport over the summer months, assuming an average sediment concentration of 100 mg/l, is 3.300 tds. The same operation executed in March, when the average sediment concentration is 400 mg/l, would have given rise to a sediment transport of 12.000 tds.

The cumulative amount of dry matter conveyed through the discharge pipe CT(T), expressed in tds, at any given point in time, can be calculated using the following formula:

Period	The Cira's movements	The sediment concentration
07:37 – 07:55	Not in action yet The gate of the discharge pipe is opened.	Decreases gradually to 40 mg/l
07:55 – 09:30	Water injection of the sediments in the neighbourhood of the salt-water capturing device.	Fluctuates and increases rapidly with max. values of 4.000 mg/l
09:30 – 10:00	Not active.	Decreases gradually to 150 mg/l
10:10 – ca. 11:50	Active between the locks of Zandvliet and Berendrecht.	Fluctuates and increases rapidly with max. values of 7.000 mg/l
11:50 – 12:10	Not active.	Decreases gradually to 180 mg/l
12:10 – ca. 13:40	Active in the turning basin. Sailing long stretches at a time.	Quite constant and high values with maximum values of 7.000 mg/l
13:40 – 15:30	Not active. The flow in the discharge pipe is from the river Scheldt to the dock.	Decreases gradually and then stabilizes at ca. 110 mg/l.

[2] Trials in the Haringvliet (Netherlands) in 1994 proved that highly contaminated sludge could be transported from a higher located dredging location to a lower temporary deposit site. 210 000 m^3 of *in-situ* consolidated clay material was transported over a distance of ca. 2 km in 20 hours.

$$CT(T) = 10^{-6} \sum_{t=T_0}^{T} Q(t).C(t).\Delta t(t)$$

where:

Q(t) Water discharge through the discharge pipe, expressed in m³/s, at a certain point in time, t.

C(t) *Average* Sediment concentration in mg/l at a certain point in time t.

T_0 The measurement starting time.

$\Delta t(t)$ Time interval between successive measurements at a certain point in time t

10^{-3} is a correcting factor for the conversion from mg/l to kg/m³.

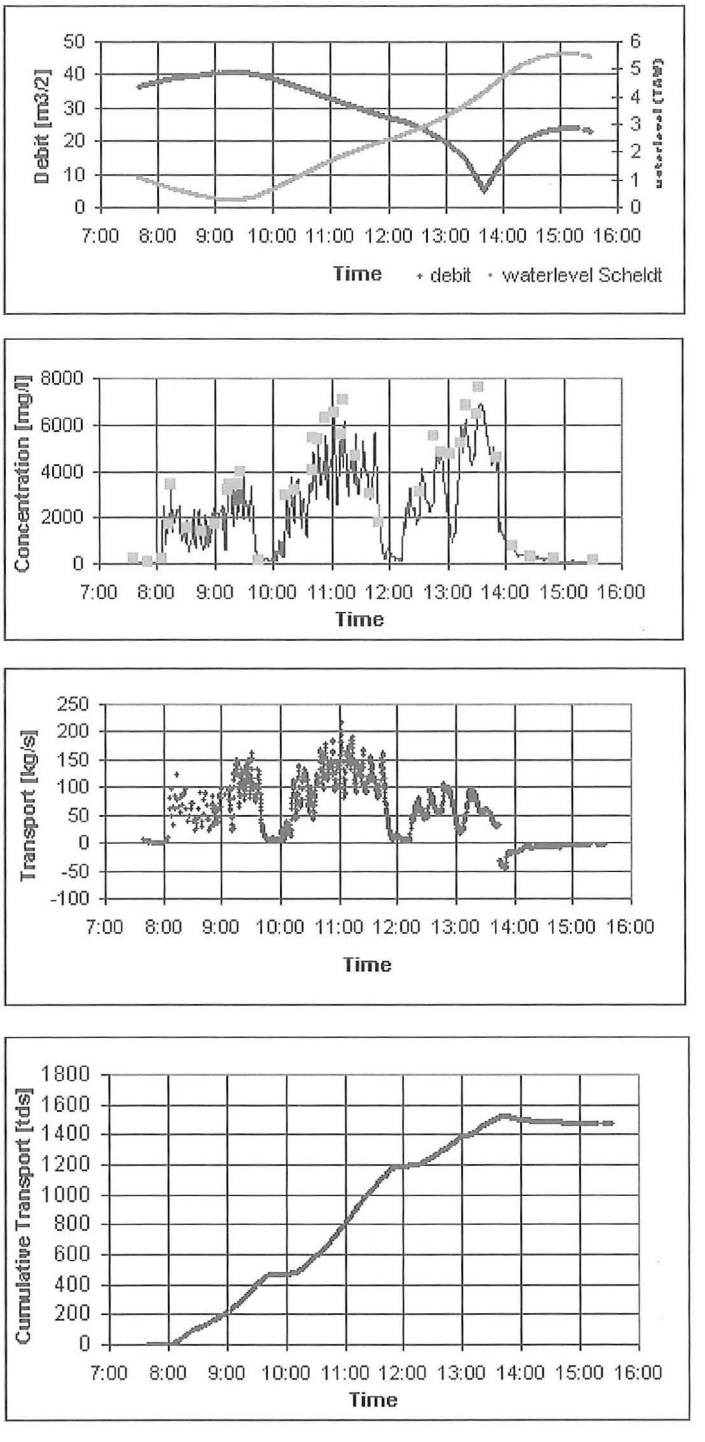


Fig. 12 Calibrated measurements of the turbidity gauge (blue dots); the red dots represent the measured sediment concentrations, derived from water samples. The cumulative transport curve (CT)

The cumulative transport curve (CT) clearly increases when the MS CIRA is active. In between operations, the cumulative curve increases at an extremely slow rate, indicating that no density flow and/or sediment supply is achieved anymore. After 13:44 the cumulative transport curve decreases because of the change in flow direction. The maximum value that was obtained is 1.530 tds.

The measurement campaign confirmed the feasibility of using the salt-water capturing device as a DFCD (Density Flow Capturing Device), to capture efficiently both salt-water and sediment-laden bottom waters and to recirculate them back via the discharge pipe to the river Scheldt; the tests proved also that this process could favourably be enhanced, with the help of a water injection system. The dredging activity took about 5 hours and implied three dredging campaigns, clearly visible on the recorded plots of the sediment concentration.

The 3 pre-requisites (a theoretical description of water injection dredging, in-situ experience and adequate instrumentation aboard the dredging vessel) explain how sediment can be transported, along a pre-constructed wedge, towards the intake funnel of the discharge pipe.

4. CONCLUSIONS

The purpose of the study was to find out what hydro-sedimentological mechanisms are causing the sedimentation patterns in the docks of the port of Antwerp and whether practical solutions could be found to prevent or reduce such a siltation.

The study identified and quantified the exchange mechanism between the river Scheldt and the docks of the Port of Antwerp which, for the most part, are located behind large sea locks. In order to prepare for the measurement campaign, historical data on the sedimentation problem in the access channel of the Zandvliet- and Berendrecht locks and in the turning basin behind the locks, were collected and evaluated.

Several parameters were surveyed *in-situ* which, supposedly, were the driving forces for the mechanism and diffusion kinetics of the system. During the measurement campaign, information was collected on the salinity, density, temperature, turbidity and tidal levels of the water in the river Scheldt (access-channel to the lock), the lock chamber and the dock (turning circle in the Kanaaldok).

The survey data clearly identified and quantified the saline water and sediment-laden bottom waters acting as a density flow which penetrates the lock chamber at each gate-opening; during the opening of the Scheldt river gate, the saline and sediment-laden water penetrates as a density flow into the lock chamber dragging huge amounts of sediments (order of magnitude ca 50 tds/locking operation). After opening the dock side gate, exactly the same density flow operates from lock chamber into the dock. These surveys confirmed the existence of one of the major mechanisms causing the siltation of the docks in the Port of Antwerp.

The *in-situ* measurements were also used to build and calibrate a 2D hydrodynamic transportation model, which was validated against the survey results. Mathematical simulations were then run using different sets of boundary conditions. The process of density flow appears to be easily simulable and the simulations helped to confirm and quantify the density flow and the overall yearly sediment balance in the area. This sediment balance coincides with the Port Authority's perception of required maintenance dredging effort, hence validating the overall figures regarding sediment exchange between the river Scheldt and the docks.

It could be concluded from the aforementioned survey, simulations and studies that each time the lock gate is opened, a saline and silt-laden current moves towards the docks, as a nearbed density flow. Small differences in salt concentration between the river Scheldt and the docks are triggering this density flow. The suspension-load of this nearbed density flow and the suspension-concentration difference are the main cause of sediment supply to the docks. The density flow discharges at ca 90.000 m^3/hour, with a corresponding average speed of approx. 0.25 m/s. The sediment flux generated by this nearbed density flow is ca. 2.10^{-5} tds/m^2 and corresponds to a sediment supply of 10 to 70 tds/locking operation.

The insight thus gained into the theory of the exchange mechanism enabled to find possible solutions to prevent or to reduce the sediment-inflow by such density flows. From various technical solutions identified, the method whereby a dedicated Density Flow Capturing Device - named DFCD in this publication - in combination with an appropriated procedure for closing the lock gates immediately after each locking operation was selected as the best feasible one from a technical and environmental point of view.

A conceptual front end engineering of the pumping installation was made, enabling to assess the technical feasibility and the corresponding preliminary Bills of Quantities for the construction works.

A cost-benefit analysis was also made to gauge the client's interest in the proposed solution. The proposed system appears to be economically attractive, taking into account the investment and maintenance cost of the new installation compared to the present dredging and dredge disposal technique in the port of Antwerp. The side effects of the system on the sedimentation process in the access channel, on shipping and on the overall water balance of the port were also considered. The effects were negligible and can be solved by low-cost counter-measures.

The alternative to use the DFCD in a pure gravitational mode, without any need for implementing large-scale pumping devices, was investigated as well. Such an alternative would, of course, be even much more attractive from the economical point of view and would allow the Port Authority to implement the new maintenance dredging strategy at once. To check this feasibility on the field, dedicated extra measurement campaigns were executed.

These survey campaigns, where dedicated measurements were made in the lock discharge pipe, proved the existence of a simple mathematical relationship between the discharge and the hydraulic gradient between the river Scheldt and the docks. There is no significant relationship between the water level difference and the sediment transport in the discharge pipe. The sediment transport towards the dock is significantly higher than when the flow is outgoing to the Scheldt. While the flow is outgoing from the dock to the river Scheldt, high peaks of sediment concentration are measured whenever large vessels pass too near to the intake to the sludge extractor. The measurement campaign ascertained the feasibility for a gravitational use of the Density Flow Capturing Device in the Zandvliet lock.

The discharge trial proved the feasibility of capturing the sediment-laden density flow via the Salt-Water Capturing system and flow-back to the river Scheldt. In the last trial, a measurement campaign proved the feasibility of using the Salt Water Capturing Device to convey suspended sludge through the discharge pipe into the river Scheldt, with the help of a water injection system.

The three pre-requisites (a theoretical description of water injection dredging, in-situ experience and adequate instrumentation aboard the dredging vessel) explain how sediment can be transported, along a pre-constructed wedge, towards the intake structure of the discharge pipe.

The work presented in this paper is a successful combination of hydrographic surveying, computational modelling and conceptual engineering. The *in-situ* investigations furnished hard evidence of near-bed density flows (a saline wedge), laden with silt. That sediment transport regime is now recognized as the single most important source of siltation in the Port of Antwerp. The proposed solutions to prevent excessive sedimentation were developed and evaluated financially and theoretically. Validation tests were performed, using the salt-water capture infrastructure of the Zandvliet lock. Finally, an innovative combination of an existing dredging technique (water injection dredging) and the existing discharge pipe connected to the salt-water capture infrastructure of the Zandvliet lock have been employed successfully to dredge sediment in the turning basin of the Zandvliet lock that passed near to the salt extractor. Furthermore, the dispersion pattern of this silt within the dock areas causes these sediments to be contaminated by industrial and domestic waste-water effluents; hence, the port is faced with a dual problem (maintenance dredging and the management of contaminated dredged material).

Hopefully, this paper will be a meaningful contribution to the design of locks built in places in the world where sediment exchange mechanisms are to be feared, and with good reason.

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SUMMARY

The port facilities and docks at the Port of Antwerp lie, for the most part, behind large maritime locks. The Boudewijn, Van Cauwelaert, Zandvliet and Berendrecht locks rank among the largest locks in the world and are used more than 9.000 times a year. Each lock operation necessarily involves a physical contact between the freshwater in the port's docks and the brackish water in the river Scheldt. The engineers at the Port of Antwerp Authority, assisted by the engineering consultants at Haecon and S.A. Kamminga b.v., have carried out an in-depth survey and study of the water exchange mechanisms within these locks. These study activities included survey techniques, computational modelling and conceptual engineering. The in-situ investigations furnished hard evidence of near-bed density flows (a saline wedge), laden with silt. That sediment transport regime is now recognized as the most important source of siltation in the Port of Antwerp. The dispersion pattern of this silt within the dock areas exposes these sediments to contamination by industrial and domestic waste-water effluents; hence, the Port is faced with a dual problem: the maintenance dredging and the management of contaminated dredged material. With that in mind, the study team came up with a handful of technically feasible solutions to control these density flows and, hence, the port's siltation. Conceptual solutions were developed, costed and ranked according to their technical-economic feasibility. Finally, real-time validation tests were performed in situ, using the salt-water capture infrastructure of the Zandvliet lock.

RÉSUMÉ

Les entrepôts et les services portuaires du Port d'Anvers sont, pour la plupart, situés derrière les grandes écluses maritimes. Les écluses de Boudewijn, Van Cauwelaert, Zandvliet et Berendrecht figurent parmi les plus importantes au monde et fonctionnent plus de 9.000 fois par an. Chaque manœuvre d'écluse implique nécessairement un contact physique entre l'eau douce dans les entrepôts du port et les eaux saumâtres de la rivière Escaut. Les ingénieurs du Port d'Anvers, assistés par les consultants d'Haecon et de S.A. Kamminga b.v., ont effectué une enquête et une étude approfondies des mouvements d'eau à l'intérieur de ces écluses. Ces études comportent des techniques d'enquête, des modèles informatiques et une conception d'ingénierie.

Les investigations sur le site ont montré avec une nette évidence la présence en profondeur de courants denses (une couche saline) chargés de matières en suspension. Ce processus de transport de sédiments est aujourd'hui reconnu comme la plus importante source d'envasement du Port d'Anvers. Les modalités de dispersion de ces matières dans le périmètre des écluses exposent ces sédiments à une contamination par les effluents d'eaux usées industrielles et urbaines ; c'est pourquoi le Port doit faire face à un double problème : d'une part la gestion des dragages et d'autre part la gestion des produits de ces dragages qui sont contaminés.

Dans ces conditions, l'équipe d'étude a conçu un ensemble de solutions réalistes en vue de contrôler ces courants denses et, par conséquent, l'envasement du port. Des solutions conceptuelles ont été développées, chiffrées et classées en fonction de leur faisabilité technico-économique. Finalement, des test de validation en temps réel ont été réalisés in situ, en utilisant les installations de prise d'eau salée de l'écluse de Zandvliet.

ZUSAMMENFASSUNG

Die Hafeneinrichtungen und Docks im Hafen von Antwerpen liegen zum größten Teil hinter großen Seeschleusen. Die Boudewijn-, Van Cauwelaert-, Zandvliet- und Berendrecht Schleusen zählen zu den größten Schleusen der Welt und werden mehr als 9.000 Mal pro Jahr benutzt. Jede Schleusung bewirkt notwendigerweise einen physischen Kontakt zwischen dem Süßwasser in den Hafendocks und dem Brackwasser in dem Fluss Schelde. Die Ingenieure der Hafenbehörde von Antwerpen haben mit der Unterstützung der Beratungsingenieure von Haecon und S. A. Kamminga B. V. eine Tiefenvermessung und eine Studie zum Wasseraustausch-Mechanismus innerhalb dieser Schleusen durchgeführt. Die Arbeiten dieser Studie umfassten Vermessungstechniken, Berechnungsmodelle und konzeptionelle Ingenieurarbeiten. Die in-situ Untersuchungen lieferten einen starken Beweis für sohlnahen Schwemmsand transportierenden Dichtefluss (salzer Keil). Dieses Sedimenttransport-Regime wird als wichtigste Quelle für die Verschlickung des Hafens von Antwerpen angesehen. Das Verteilungsmuster dieses Schwemmsands innerhalb der Dockbereiche setzt diese Sedimente der Kontamination durch industrielle und häusliche Abwässer aus; also sieht sich der Hafen einem doppeltem Problem gegenüber: der Unterhaltungsbaggerung und dem Umgang mit kontaminiertem Baggergut. Vor diesem Hintergrund schlug das Untersuchungs-team einige technisch durchführbare Lösung vor, um diesen Dichtefluss - und damit die Verschlickung des Hafens zu kontrollieren. Konzeptionelle Lösungen wurden entwickelt, kostenmäßig geschätzt und hinsichtlich ihrer technisch-ökonomischen Machbarkeit gewichtet. Schließlich wurden *in situ* Echtzeit-Validierungs-Tests unter Verwendung des Salzwassereintrags der Zandvliet Schleuse durchgeführt.