THE CURRENT DEFLECTING WALL IN AN ESTUARINE HARBOUR

B. Hofland\textsuperscript{1}, H. Christiansen\textsuperscript{2}, R.A. Crowder\textsuperscript{3}, R. Kirby\textsuperscript{4}, C.W. van Leeuwen\textsuperscript{1}, J.C. Winterwerp\textsuperscript{1,5}

Full Affiliation(s)
\textsuperscript{1}Delft University of Technology, \textsuperscript{2}Strom- und Hafenbau Hamburg, \textsuperscript{3}Bradford University / Bullen Engineering, UK, \textsuperscript{4}Ravensrodd Consultants, UK, \textsuperscript{5}WL|Delft Hydraulics, NL

\textsuperscript{1}Correspondence: Delft University of Technology, Laboratory of Fluid Mechanics, PO BOX 5048, 2600 GA Delft, The Netherlands, Tel: (+31) 15 2784069, email: b.hofland@ct.tudelft.nl

ABSTRACT

Sedimentation is a serious problem for harbours around the globe. Sediment is transported into a harbour by various exchange mechanisms. A relatively new means to reduce harbour sedimentation of river harbours in tidal conditions in a passive manner is the Current Deflecting Wall (CDW). The main effect of a CDW in a harbour without density differences is that all the water that is needed for tidal filling is "caught" from the upper parts in the water column. This water contains little sediment. In order to determine whether a CDW can also work when density-induced exchange currents are present, laboratory experiments were executed. Several CDW configurations were optimised and compared visually. The configuration that seemed to decrease the exchange most was tested in detail. Especially the flood period was studied closely. During flood most river water enters the harbour basin due to tidal filling and the density current. During a large part of the flood period flow velocities in the flume are high enough for the CDW to function. With the CDW in place, the water that flows into the harbour during rising tide originates from the upper water layer in the flume. Hereby the influx of near bed water is substantially decreased. It also increases the density difference however, which causes a small extra exchange around high water slack. This effect is only minor when compared to the decrease of exchange of near bed water. It can be concluded that the CDW tested is able to decrease the influx of sediment due to density currents, but for quantification site-specific hydraulic modelling is required.

KEYWORDS

Current Deflecting Wall, siltation, density current, harbour design

INTRODUCTION

Sedimentation is a serious problem for harbours around the globe. Where ports are situated on tidal rivers and estuaries, the quantities of sediment deposited in harbour basins can be especially large. At the harbour basins of Hamburg, Germany, for instance, the sedimentation rate is in the order of 2 million cubic metres per year. Sedimentation decreases the depth of the harbour basin, so maintenance dredging is necessary on a regular basis to guarantee safe navigation. This dredging is often a large cost factor in harbour maintenance. Instead of taking the deposited material out of the harbour basin, it would be preferable to prevent the sediment from entering the harbour in the first place.

To achieve a reduction in sedimentation rate the causes for the sedimentation have to be known. Sediment is transported into an estuarine harbour by various transport mechanisms (Booij, 1986; Langendoen 1992), see Table 1. The first three processes are addressed in this paper. The fourth is not directly linked to the flow pattern. Going down this list, the processes
are less frequently present in harbours, but in general the magnitude of exchange caused by them (when present) increases.

| 1. Exchange in consequence of a velocity difference between river and harbour. |
| 2. Exchange in consequence of a net flow through the harbour entrance (tidal filling) |
| 3. An exchange flow driven by a density difference between harbour and river |
| 4. Gravity currents due to near-bed, high concentrations of suspended solids or fluid mud |

Table 1. Exchange processes in estuarine harbours.

A relatively new means to reduce harbour sedimentation in tidal conditions is the Current Deflecting Wall® (CDW). This is a vertical screen, curved in the horizontal plane, that is placed at the sea-side of the harbour entrance. The aim of a CDW is to alter the flow pattern in the entrance in such a way that the transport of sediments into the harbour is reduced. Until now the CDW had only been studied under tidal conditions, without the influence of density currents. A full-scale prototype, installed in the Port of Hamburg in 1990 has decreased the sedimentation rate (Winterwerp, 1993; Christiansen, 1997). More general research was conducted under the European second "Large Scale Facilities and Installations" programme (Crowder, 1999).

The main effect of a CDW in a harbour without density differences is that the volume of water required for tidal filling is "caught" by the CDW. With the use of a sill this water is collected from the upper part of the water column, which contains little sediment. Further, the turbulent mixing is influenced, which can also cause a reduction in exchange. This is because the CDW catches more water than needed for the tidal filling. The surplus flow pushes the mixing layer more into the river. Secondly the onset of flow separation (mixing layer) is moved to a point beyond the corner of the harbour entrance, and the stagnation point/zone is shifted more out of the harbour, hence the exchange is decreased. The separation of flow at the curved outer face of the CDW is also less fierce than flow separation at the corner of the harbour entrance. This reduces the width of the mixing layer. The eddy pattern is changed as well, but this can be either positive or negative with respect to harbour maintenance.

Figure 1. The new CDW and its components in the Delft Tidal Flume.

The particular topic addressed in the present research is that many harbours around the world have to cope with salinity-induced density currents. For the stratified conditions of the present research a new CDW was developed by H. Christiansen. (patented as CDW/SILL-SYSTEM®). The sill was extended beyond the CDW and covered half the water depth, see Figure 1.
EXPERIMENTAL SET-UP

Laboratory experiments were executed in the Delft Tidal Flume at WL|Delft Hydraulics (DTF). The DTF consists of a straight, prismatic flume (130x1x1 m³), which drains into a schematised sea with a surface area of 120 m². Water level and salinity in the basin can be controlled. The flume discharge can be varied in time in such a way that the effective length of the flume can be altered. The inflow of fresh water from the flume is removed from the sea basin by a skimmer. It is possible to simulate a wide range of estuarine systems. A description of the DTF is given in (Delft Hydraulics, 1986). For the experiments a harbour basin with a 45° angle to the flume was mounted 22 m upstream of the sea, with a surface area of 2.9 m². The experimental conditions, resembling those prevailing in the Scheldt River near Antwerp, are listed in Table 2.

<table>
<thead>
<tr>
<th>Tidal period</th>
<th>1000 s</th>
<th>Density at sea ((\rho_s))</th>
<th>1007 kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average flume discharge ((Q_r))</td>
<td>3.8 l/s</td>
<td>Density of river water ((\rho_r))</td>
<td>1000 kg/m³</td>
</tr>
<tr>
<td>Amplitude of flume velocity ((u_{r,max}))</td>
<td>0.20 m/s</td>
<td>Entrance width ((B))</td>
<td>1.00 m</td>
</tr>
<tr>
<td>Tidal range at sea</td>
<td>0.05 m</td>
<td>(Re_{max} = u_{r,max}h/\nu)</td>
<td>10,000</td>
</tr>
<tr>
<td>Average water depth ((h))</td>
<td>0.25 m</td>
<td>(Re_{E} = \Delta pghQ_r/\rho Bhu_{r,\text{rms}})</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 2. Experimental conditions.

The following measurements were conducted at various positions in the flume and the harbour basin: Electro Magnetic Velocity measurements (EMS), water level measurements, and salinity measurements (both at fixed depths and over the vertical by moving salinity probes). Special measurement techniques were:
- Dye Concentration Measurements (DCM): dye was injected in the flume/harbour, and its dispersion was monitored by video camera. The total dye mass in the harbour was calculated using digital image processing techniques.
- Particle Tracking Velocimetry (PTV): floating particles were supplied at the water surface, and the positions were recorded by video camera. Vector fields were made using digital image processing techniques.
- White metal plates with black tufts were placed on the bottom of the harbour entrance in order to visualise the flow pattern near the bed.

Only the exchange of water was determined in this research. A distinction was made between the total exchange of water between harbour and river, and the exchange of near-bed water between harbour and river. This helps to relate the water exchange to the actual sediment exchange in real harbour and river systems. Several CDW configurations were initially tested and compared visually. The configuration that seemed to decrease the exchange most was tested in detail, with and without a second sill on the river side (right side in Fig. 1) of the harbour entrance. As the configuration with an additional sill was found to work better, the performance of this one will mainly be discussed.

EXCHANGE PROCESSES – NO CDW

The variation over time of some important measured parameters is illustrated in Figure 2. The approximate periods when (and in which direction) the separate exchange mechanisms occur are depicted in the bars at the bottom of Figure 2.
Figure 2. Averaged flow characteristics during tidal cycle and subsequent division of tidal cycle in characteristic periods.

The water level indicates the magnitude of the tidal filling, $Q_{tf}$, which can be calculated by:
\[ Q_y = A_h \frac{d \zeta}{dt} \]  

Where \( A_h \) is the surface area of the harbour, and \( \zeta \) the water level. Tidal filling in the harbour occurs from \( t=950s \) to \( t=250s \) in the next tidal cycle (Fig. 2), and has an amplitude of 0.45 l/s. This causes a flow pattern that is relatively uniform over the width and depth of the entrance. The density current is related to a horizontal density gradient. Near-bed flow is directed towards the lowest density, and flow near the surface is in the opposite direction. When correcting the surface velocities in the entrance for the net flow (tidal filling), these also give an indication of the magnitude of the density current. The near-bed density current is directed into the harbour from 0 to 500s (Fig. 2). The density exchange discharge, \( Q_d \), has an amplitude of about 2 l/s.

Mixing is caused by the velocity difference between harbour and flume. It causes a gradient in the flow velocity over the width of the harbour, driving eddies in the basin. For harbours without density currents the exchange due to turbulent mixing, \( Q_{ex} \), is given by:

\[ a) \quad Q_{ex,0} = C u_r B_e h \]  

\[ b) \quad Q_{ex} = Q_{ex,0} - C_2 \frac{Q_y}{Q_{ex,0}} \]  

Where \( u_r \) is the river velocity, \( B_e \) is the width of the entrance, and \( h \) is the waterdepth (Booij, 1986; Van der Graaff, 1977). Values for the coefficient \( C \) amount to about \( 4 \times 10^{-2} \) for a rectangular entrance to \( 4 \times 10^{-4} \) for natural geometries (Van Schijndel, 1998). \( C_2 \) is in the order of 0.15-0.3. A net flow through the entrance reduces the mixing exchange as given by equation (2.b). Also density currents can suppress the mixing exchange (Langendoen, 1992). The magnitude of the turbulent mixing exchange (\( Q_{ex} = Q_{total} - Q_{tf} - Q_d \)) could not be determined, as the total exchange could not be determined. It is probably smaller than the exchange due to tidal filling. It can be seen in Figure 2 that the density current near the bed as well as the net flow are directed into the harbour from 0 to 300s. The largest amount of near-bed river water is entering the harbour during this period. This is also the period when the CDW functions, as the flow velocities in the river are sufficiently large and the flow is directed up-river.

The experiments and measurements are focussed on this period.

**RESULTS WITH CDW**

During flood

With a CDW present, the near-bed flow behind the sill diverges over the width of the harbour entrance. This feature is not present without the CDW (Fig. 3). The arrows in Figure 3.b emphasise the part of the flow going into the harbour and the part being directed into the
flume. Dye injected near the bottom of the flume, just upstream of the CDW is flowing past the harbour entrance with only a small amount entering the basin, as opposed to the situation without CDW. This flow pattern is observed during the flood period, when flow velocities in the flume are relatively high.

The observations and measurements helped to form an idea of the complex three-dimensional flow in the harbour entrance. In Figure 4 the flow situation during flood is schematically depicted. A similar pattern was observed without the second sill at the river-side of the harbour entrance.

![Figure 4. Schematic flow pattern in entrance during flood, with CDW present](image)

The CDW forces the flow into the harbour and against the out-going density current in the top layer. Behind the sill near the bed a low-pressure area develops because of separation. Due to the resulting pressure difference between the upper and lower parts of the water column behind the CDW, water captured by the CDW flows down and diverges at the bed behind the sill. This downward, diverging flow creates a counter clockwise vortex with a horizontal axis in front of the entrance. Such a vortex was observed over approximately half the water depth from the bed during the experiments. At high velocities it covers the entire entrance width. The presence of the vortex explains the existence of the stagnation-line over the width of the harbour entrance that was present behind the sill (see Fig. 3.b). Because of the vortex, water near the bed of the flume is hardly entering the harbour. Similar vortices are also observed behind submerged vanes (Marelius, 1998). These can more or less be compared to the sill under the CDW.

In order to quantify the total exchange, a constant flow of dye was injected into the flume, near the bed. The rate of change of the dye concentration in the harbour basin (measured by digital camera) was assumed to be proportional to the inflow of near-bed river water. The exchange discharges that were determined from these DCM results are lower than findings by other experiments and by the parallel PTV/EMS measurements. Relative differences between configurations can however be evaluated. The maximum reduction of the inflow of near-bed water (through the lower 25% of the water column) as calculated from the DCM results was approximately 90%, but varied over time (Fig. 5). The average reduction during the whole flood period was approximately 70%.

Lower average densities were observed in the harbour with a CDW (see Fig. 2). This can be explained as follows: Because of the CDW in combination with the sill, the dense water from the lower layer is to some extent kept out of the harbour during flood to some extent. Instead,
less saline water from the top layer is directed into the harbour. The result is a lower (average) density in the harbour.

![Graph of in-going discharge near the bed during periods from 925s to 250s in the next tidal cycle, calculated from DCM.](image)

**Figure 5.** In-going discharge near the bed during periods from 925s to 250s in the next tidal cycle, calculated from DCM.

**Around high water slack**

At about t=250s flow velocities in the river start to decrease substantially, and quite suddenly a large volume of near-bed river water (visualised with dye solution) enters the harbour basin over the entire entrance width. PTV measurements show that the surface velocities at this moment are higher with CDW than without, which indicates that the exchange discharge at this time has increased, compared to the reference configuration.

The increased density exchange discharge can be explained by the decreased salinity in the harbour (Fig. 2). The flume velocity has diminished at this time, so the CDW stops functioning and can no longer regulate the flow pattern. Now an extra inflow of saline water into the harbour occurs, as the salinity gradient is higher than at the same time in the reference case. Salinity and PTV measurements indicate an increase of the density discharge of about 5%.

**Ebb**

During the entire ebb period the driving force of the density current (density difference between harbour and river) is increased when the optimised CDW is applied. Because the density current at the bottom and the net flow are directed outward near the bed, this is not expected to have a large impact on the siltation rate.

**DISCUSSION**

It has been shown that it is possible to affect (decrease) the salinity induced density currents, which are partly responsible for the siltation of harbour basins. However, the present model set-up was a schematisation of a real harbour. Some of the schematisations might have affected the exchange processes between harbour and river, and the functioning of the CDW. An example is the ratio of the water depth to the width of the harbour entrance. For the present study this ratio was approximately 1:4. Often, this ratio is in the order of 1:15. Therefore the vortex might not be strong enough to exist over the entire harbour entrance width in reality.
The prismatic shape of the harbour entrance is also not realistic. Also, flow velocities in a real river could be insufficient for making a CDW effective. Because so many factors influence the flow in the harbour entrance, site specific hydraulic modelling remains necessary when designing a CDW.

Ultimately the siltation (reduction) in a harbour must be determined. Therefore the distribution of the sediment concentration over the vertical, which changes constantly during a tidal cycle, must be coupled to the flow pattern. Integrating this over a tidal cycle gives the total influx of sediment. Although no actual sediment was introduced in the experiments, it seems likely that a CDW can decrease the sediment influx even when a small gradient in the sediment concentration over the depth is present. The average reduction of 70% of the inflow of near-bed water during flood will most likely outweigh the minor increase of 5% of the total water exchange around high slack water.

CONCLUSION
From the results of the experiments it can be concluded that a CDW can influence the amount of sediment entering a harbour basin that is affected by density differences. The main function of the CDW tested, is that most of the water that flows into the harbour during rising tide originates from the upper water layer in the flume. Hereby the influx of near-bed water is substantially decreased. It also increases the density difference however, which causes a small and short duration extra exchange around high water slack. This effect is only minor when compared to the decrease of exchange of near bed water. The total inflow of river water during flood does not change with a CDW present.

Site-specific hydraulic modelling remains essential for determining the possible effect of a CDW on a specific harbour. A CDW can only function when the sediment concentration in the higher parts of a river is substantially less than in the lower parts.

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