

Stilling Basin Optimization for a Combined Inlet-Outlet Sluice in the Framework of the Sigmaplan

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ABSTRACT: Within the framework of the so-called Actualised Sigmaplan, i.e. the masterplan to create a sustainable Schelde estuary, flood control areas (FCA) are setup in well-chosen polders along the tidal part of the river Schelde and its tributaries. In some of these FCAs a semi-diurnal, controlled reduced tide (CRT) is introduced, by means of simple inlet and outlet sluices. Nowadays, it is preferred to combine inlet and outlet sluices in one single structure, in which the inlet culverts are situated on top of the outlet culverts. At inflow, energy is dissipated by means of a vertical drop and a stilling basin. In this paper, results are presented of a physical model study (scale 1:8) aiming at the optimization of the inlet configuration, i.e. the stilling basin, starting from the desktop design of the in- and outlet construction for FCA-CRT Bergenmeersen.

Keywords: Actualised Sigmaplan, inlet sluice, vertical drop, stilling basin, hydraulic jump, physical model

1 FLOOD CONTROL AREA – REDUCED TIDE AREA (FCA-CRT)

After a major flooding in the north of Belgium (Flanders) in 1976, a masterplan – the so-called Sigmaplan – was elaborated in 1977 to mitigate storm surges in the Schelde estuary as to increase the level of safety. Due to changing physical circumstances and new insights in water management, the Sigmaplan was profoundly updated in 2005 – i.e. the so-called Actualised Sigmaplan. The Actualised Sigmaplan aims at satisfying both safety and ecological needs along the tidal part of the river Schelde and its tributaries in a sustainable way. Therefore, different restoration techniques are elaborated which combine safety with estuarine restoration, e.g. dike strengthening together with more space for the river, flood control areas (FCAs) with or without a controlled reduced tide (CRT), non-tidal wetlands, etc. In this paper, only flood control areas with a controlled reduced tide (abbreviated: FCA-CRTs) are considered.

During storm surges, FCA-CRTs are filled via a lowered levee (referred to as “overflow dike” in Figure 1). On average, this takes place once or twice a year depending on the level of the overflow dike. In addition, a well-designed system with inlet and outlet sluices allows limited semi-diurnal water exchange between the estuary and the FCA-CRT. The goal is to obtain inundation characteristics in the polder which are similar to natural tidal marshes along the estuary, in order to restore estuarine habitats which have disappeared over the past two centuries or degraded (elsewhere) in the estuary (Cox et al., 2006 ; Maris et al., 2007).

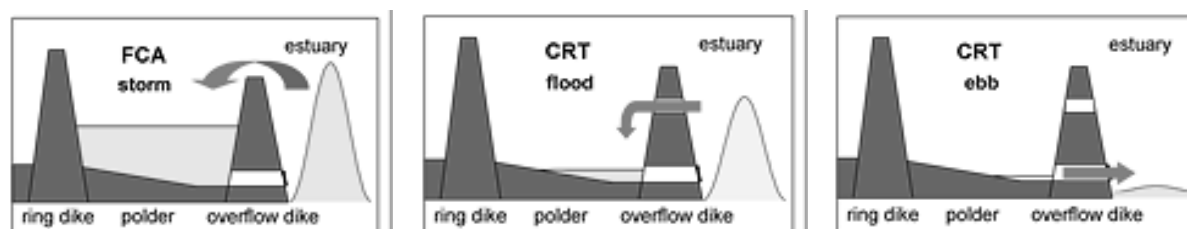


Figure 1. Working principles of a flood control area with controlled reduced tide (FCA-CRT): during storm surge (left) and in normal tidal conditions (middle and right).

2 COMBINED INLET-OUTLET SLUICE FOR FCA-CRT FUNCTIONING

An overview of the different types of sluice systems that have been designed, built and/or are under construction for FCA-CRTs in Flanders, is given in a companion paper (De Mulder et al., 2013). At first, the sluice system was setup with adjacent inlet and outlet sluice constructions. Nowadays it is preferred to combine inlet and outlet sluices in one single construction. Combining the inlet and outlet in one structure is believed to offer some important advantages, both from the structural and ecological point of view (IMDC, 2008).

Figure 2 provides a sketch of a combined inlet-outlet sluice. The inlet culverts are placed on top of the outlet culverts. The inflow can be adjusted by placing a stop log wall on the floor slab of the inlet culvert. The outlet culverts are equipped with flap gates in order to drain the FCA-CRT when the Schelde level is lower than the FCA-CRT level. After passing the stop log wall the incoming water drops vertically and plunges into the stilling basin underneath. The latter is formed by a concrete slab lowered with respect to the floor slab of the outlet culverts in order to assure that a certain water level is provided in the stilling basin.

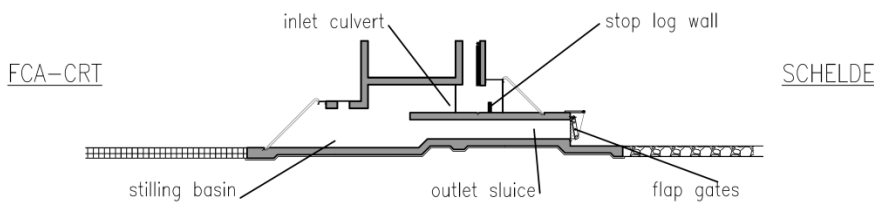


Figure 2. Schematic view of a combined inlet-outlet construction.

3 DESIGN OF FCA-CRT BERGENMEERSEN

The future FCA-CRT Bergenmeersen has an area of about 38 ha and is situated in the freshwater part of the Schelde estuary (Figure 3). The agency in charge of the design and construction of the FCA-CRT is Waterwegen & Zeekanaal nv. Different parties were involved in the design of the FCA-CRT Bergenmeersen. Only the parties involved in the design of the combined inlet and outlet structure are mentioned explicitly below.

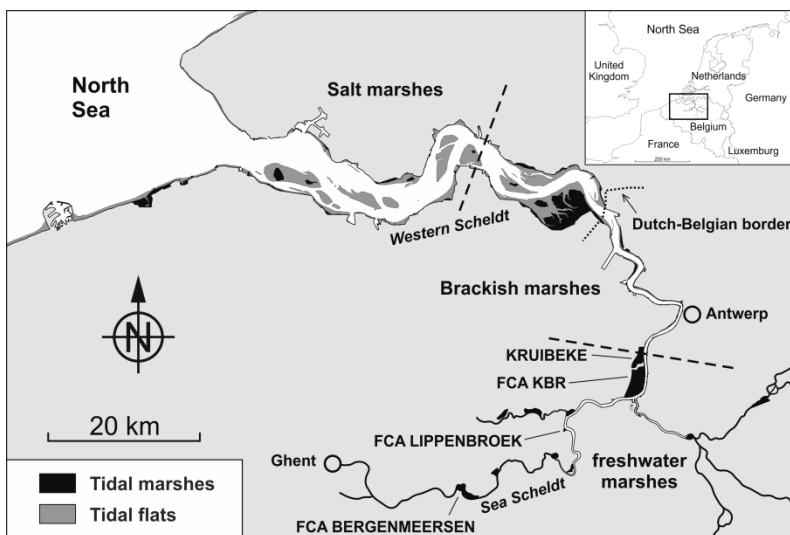


Figure 3. Location of FCA-CRT Bergenmeersen in the Schelde estuary.

By means of a numerical model study at Flanders Hydraulics Research (Coen et al., 2010), the required sill levels and (total) cross-sectional areas of the inlet and outlet culverts have been determined, in order to obtain a suitable reduced tide, i.e. aiming for a profound springtide/neap tide cycle, in the polder. The numerical model study was carried out using Mike 11, a 1-D unsteady river flow model from the DHI group. Within Mike 11, a FCA-CRT is modeled using a combination of branches. The sluices are modeled using the built-in culvert unit of MIKE 11. Culvert model parameters are calibrated following in situ discharge measurements at pilot project Lippenbroek (Peeters et al., 2009).

Given the optimal configuration of inlet and outlet culverts, a 5 month period of “normal” tidal conditions has been simulated numerically, supplemented with some shorter simulation periods of storm surges. Figure 4 contains all times series of predicted water levels in the FCA-CRT (abbreviated as: CRT level) as a function of the water level in the Schelde near Bergenmeersen. Both water levels are expressed (in m AD) with respect to the Belgian datum level (i.e. the so-called reference level TAW, which is approximately the mean level of low water along the Belgian North Sea coast).

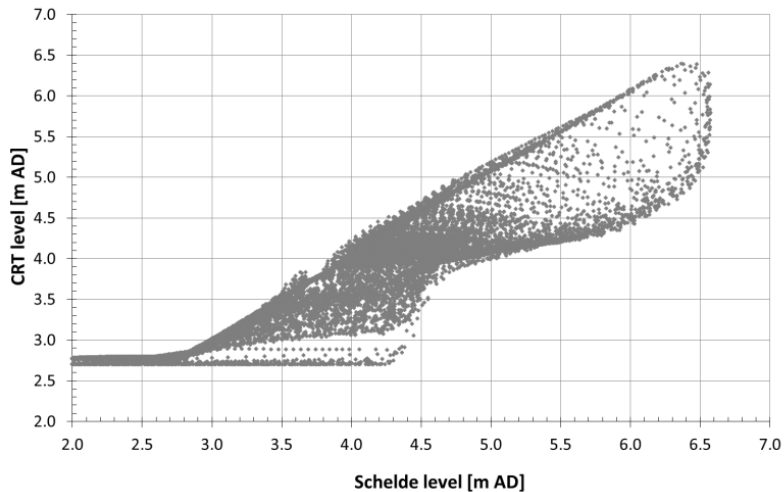


Figure 4. Numerical simulations predicted CRT levels in function of Schelde level.

The detailed structural design of the combined inlet-outlet sluice has been subcontracted by the agency (Waterwegen en Zeekanaal nv) to the consulting engineering company IMDC nv. The dimensions of the stilling basin have been determined based upon formulae in literature (IMDC, 2010). The dimensioning of the length and the depth of the stilling basin is based on a comparison of formulas mentioned in Chow (1982), French (1986), Sinniger and Hager (1989) and Ritzema (1994). The outcome of the desktop design is shown in Figure 5.

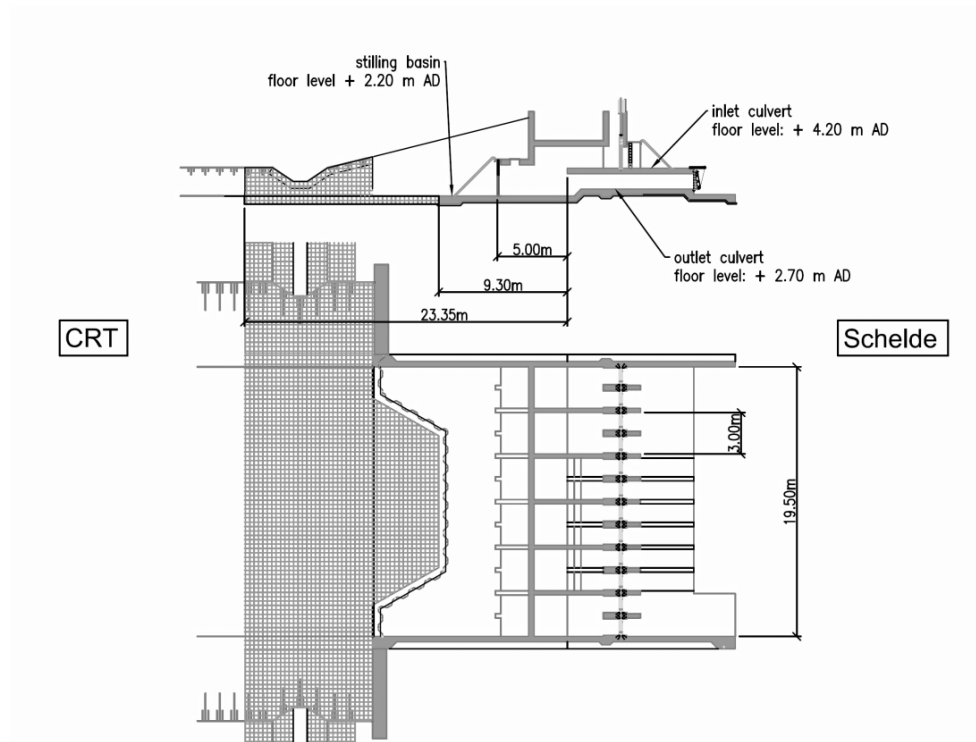


Figure 5 . Combined inlet-outlet sluice for FCA-CRT Bergenmeersen designed by IMDC nv.

The characteristic culvert dimensions corresponding to the desktop design in Figure 5 are summarized in Table 1.

Table 1. Characteristic culvert dimensions for FCA-CRT Bergenmeersen.

FCA-CRT Bergenmeersen					
Inlet culverts	Number of culverts	6	Outlet culverts	Number of culverts	3
	Culvert width	3.0 m		Culvert width	3.0 m
	Culvert height	1.6 m		Culvert height	1.1 m

Note in Figure 5 that:

- The drop height from the floor level of the inlet culvert to the floor level of the stilling basin is 2.0 m.
- The brink of the inlet culvert floor slab where the water starts dropping vertically (further abbreviated as: the brink), is used underneath (and in Figure 4) as a reference point to measure (horizontal) distances.
- The floor level of the stilling basin is proposed to be 0.50 m below the floor level of the outlet culvert. At 5.0 m downstream of the brink, the 6 inlet culverts are combined into one stilling basin. The combined stilling basin has parallel (i.e. non-diverging) sidewalls, which end at 19.0 m downstream of the brink (where they are attached to a wing wall).
- In the center of the construction, the concrete floor slab of the stilling basin ends at 9.3 m downstream of the brink (though the slab is extended somewhat further downstream at the edges of the construction). Between 9.3 m and 23.4 m downstream of the brink bottom protection is provided by gabions.

To be able to relate some characteristic levels in the design of the FCA-CRT to the tidal characteristics of the river Schelde near Bergenmeersen, Table 2 is provided.

Table 2. Characteristic levels for FCA-CRT Bergenmeersen.

FCA-CRT Bergenmeersen			Tidal river characteristics	
Ring dike	Crest level	+8.00 m AD	MHW	+6.2 m AD (extreme spring)
Levee	Crest level	+8.00 m AD		+5.3 m AD (spring)
Overflow dike	Crest level	+6.40 m AD		+5.0 m AD (mean) +4.7 m AD (neap)
Inlet culverts	Level of culvert ceiling	+5.80 m AD	MLW	+2.2 m AD (spring)
	Crest level of stop log walls	+4.4 to +5.7 m AD*		+2.1 m AD (mean)
	Level of culvert floor	+4.20 m AD		+2.0 m AD (neap)
Outlet culverts	Level of culvert ceiling	+3.80 m AD		
	Level of culvert floor	+2.70 m AD		
Polder	Mean elevation	+3.7 m AD		

* Range of stop log crest levels considered during design. Levels to be tuned when FCA-CRT is in operation.

The extreme spring tide referred to in Table 2, is defined as the level which is exceeded on average three times per year. Knowing that the corresponding water level is +6.2 m AD, this means that in such conditions the water level in the Schelde is 2.0 m above the floor of the inlet culvert. Similarly, from Table 2 and Figure 5 can be found that the water level in the Schelde is 1.1 m above the floor of the inlet culvert at mean spring tide. The corresponding specific discharges are equal to be 4.4 m³/s/m (extreme spring tide) and 1.8 m³/s/m (mean spring tide).

4 PHYSICAL SCALE MODEL

Both the agency and the consulting engineers preferred the desktop design (Figure 5) to be tested in a scale model, before the design would be approved for construction. Therefore, a physical model study was initiated at Flanders Hydraulics Research.

Because several designs of combined inlet-outlet sluices for other FCA-CRTs than Bergenmeersen are coming up in near future, the idea was to setup a flexible scale model in order to test different designs consecutively without major intermediate model (re)construction efforts. Moreover, the scale model setup should also allow the identification of possible flaws with and an optimization of a design.

To this end, the geometry of the design is somewhat simplified. Basically, a so-called 2DV model is aimed at, with a geometrical scale 1:8 for the vertical and longitudinal dimensions. The lateral direction is not relevant in a 2DV model. The model is built in a narrowed section of the large flow flume at Flanders Hydraulics Research. This flow flume has a length of 57.0 m, a width of 2.40 m, a height of 1.40 m and a maximum discharge of approximately 0.4 m³/s. The dimensions of the narrowed section are: a length of 15.0 m, a width of 0.56 m and a height of 1.0 m. In order to allow an optimal visualisation of the flow patterns, one side of the narrowed channel is transparent. By means of exchangeable plates fixed on movable mechanical lifts, a wide range of geometrical arrangements can be addressed (Figure 6). Aeration of the falling jet is provided by two tubes mounted under the ceiling of the outlet culvert in the model. These tubes are in connection with the atmospheric pressure. The aeration method to be applied in the prototype has not been decided yet.

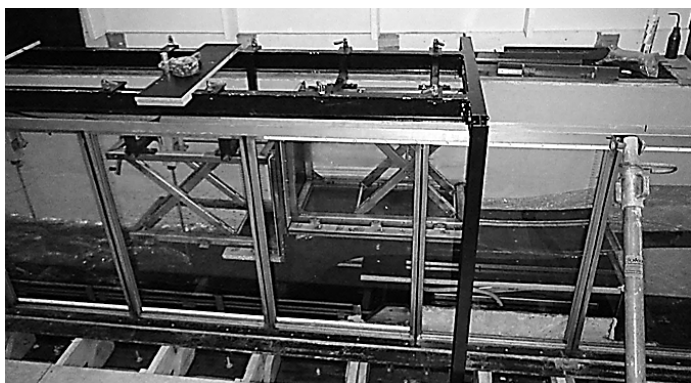


Figure 6. Possible adjustments scale model geometry.

The following measurement equipment is used in the physical model study:

- 2 electronic floaters to measure the water level upstream and downstream of the narrowed model section,
- 4 wave height meters to measure the water level on 4 locations in the model section,
- 3 electromagnetic discharge meters on the supply conduits,
- 2 electromagnetic velocimeters to measure a point velocity in the stilling basin.

Besides the electronic registrations, also visual registrations are carried out:

- drop length,
- end of the hydraulic jump,
- water level in the outlet culvert.

5 EXPERIMENTS

This section of the paper presents scale model results for the combined inlet-outlet sluice which has been designed for FCA-CRT Bergenmeersen. The main focus was on inflows into the FCA-CRT, since these require most energy to be dissipated. Moreover, fixing the location of the hydraulic jump (downstream of the vertical drop) in the stilling basin for the combinations of water levels in the FCA-CRT (further abbreviated to: CRT level) and given water levels in the river Schelde (further abbreviated to: Schelde level) is looked at. When the hydraulic jump can be located above the concrete slab of the stilling basin, the velocity above the bottom protection (gabions) downstream of the slab will be limited and erosion downstream of the construction will be limited.

First the results of the desktop design will be presented. Then the results of some optimization efforts will be presented. Most of these experiments have been carried out with aeration of the falling jet in the vertical drop, though some comparative measurements without aeration did not show noticeable differences as far as the hydraulic jump is concerned.

5.1 Desktop design

The first geometry tested was the (original) desktop design. Figure 7 presents the flow pattern in the stilling basin with a Schelde level of + 6.20 m AD (this is an extreme spring tide with an occurrence of approximately three times a year) and three different levels in the CRT.

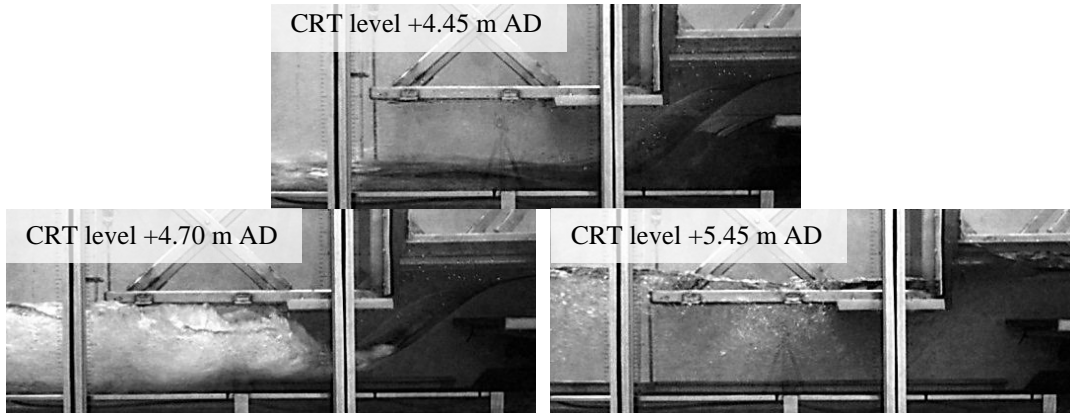


Figure 7. Illustration of flow pattern for a Schelde level of + 6.20 m AD and three different CRT levels:
top: CRT level + 4.45 m AD → supercritical flow downstream of drop
bottom left: CRT level + 4.70 m AD → hydraulic jump fixed
bottom right: CRT level + 5.45 m AD → culvert drowned.

For a Schelde level of + 6.20 m AD, Figure 8 shows the near bottom velocity at 10 m downstream of the drop as a function of the CRT level. The near bottom velocity at 10 m is used as the design velocity for the gabions downstream of the structure. (Notice indeed in Figure 5, that the bottom protection starts at a distance of 9.3 m downstream of the drop in the center of the construction.)

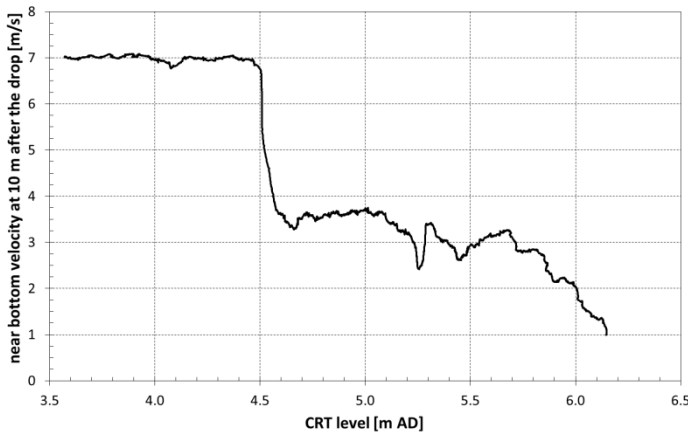


Figure 8. Near bottom velocity in function of the CRT level with a Schelde level + 6.20 m AD at 10 m downstream of the drop (note that the velocimeter is limited to 7 m/s).

Figure 8 shows a sudden drop of the near bottom velocity at a CRT level of + 4.50 m AD. This is caused by the transformation of supercritical to subcritical flow by means of a hydraulic jump. After this transition, the velocity remains at an almost constant level until the inlet sluice is drowned (Figure 7 below) and the discharge decreases. The CRT level at which the jump starts directly downstream of the drop is further referred to in this paper as the conjugate CRT level.

Figure 9 presents the measured conjugate CRT level as a function of the Schelde level. For comparison purposes, the conjugate CRT level calculated with the Bélanger equation (Bélanger, 1949) is also shown in Figure 9.

Bélanger equation:

$$Y_2 = Y_1 \cdot \frac{1}{2} \cdot \left(\sqrt{1 + 8 \cdot Fr_1^2} - 1 \right) \quad (1)$$

where Fr_1 = Froude number upstream of the jump, Y_1 and Y_2 = water levels upstream and downstream of the jump respectively Y_1 can be calculated with the formula by Rand (1955):

$$Y_1 = \Delta z \cdot 0.54 \cdot \left(\frac{q^{2/3}}{g^{1/3} \cdot \Delta z} \right)^{1.275} \quad (2)$$

where Δz = drop height, q = discharge per unit width, g = gravity acceleration.

Also the equation of the water depth upstream and downstream of the jump by Chanson (2002) and the equation of the water depth downstream of the jump by Rand (1955) were evaluated. The difference between the three analytical formulae is a maximum of 0.1 m. The numerical results by Coen et al. (2010), presented earlier in Figure 4, are used to verify that during operation the CRT level is continuously above the conjugate CRT level.

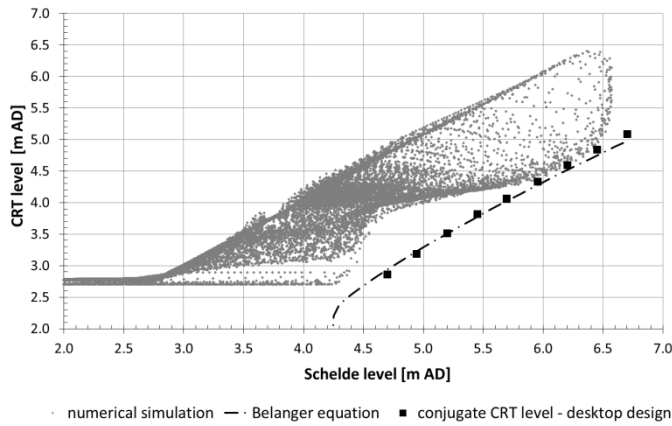


Figure 9. Comparison of predicted CRT levels during operation with the conjugate CRT level.

Figure 9 shows that the CRT levels during operation (predicted with the numerical model) are continuously above the conjugate CRT level. This means that the supercritical flow is transformed into subcritical flow in the area before the gabions (i.e. above the concrete floor slab of the stilling basin). At a Schelde level around + 6.20 m AD, however, there is no margin between the minimum predicted CRT level and the measured conjugate CRT level. Therefore, several optimization efforts have been made to increase that margin. Changes to the stilling basin geometry are made, some of which are classical in the hydraulic literature.

5.2 Gabion sill

Tests are carried out with a gabion sill with height 0.25 m and 0.50 m at a distance of 14 m and 19 m downstream of the drop. Because the floor level of the outlet culvert is situated 0.50 m above the floor level of the stilling basin, the maximum height of the gabion sill is limited to 0.50 m. Figure 10 left shows the near bottom velocity in function of the CRT level at a Schelde level + 6.20 m AD. Figure 10 right presents the measured conjugate CRT level in function of the Schelde level and compares this level with the predicted CRT levels.

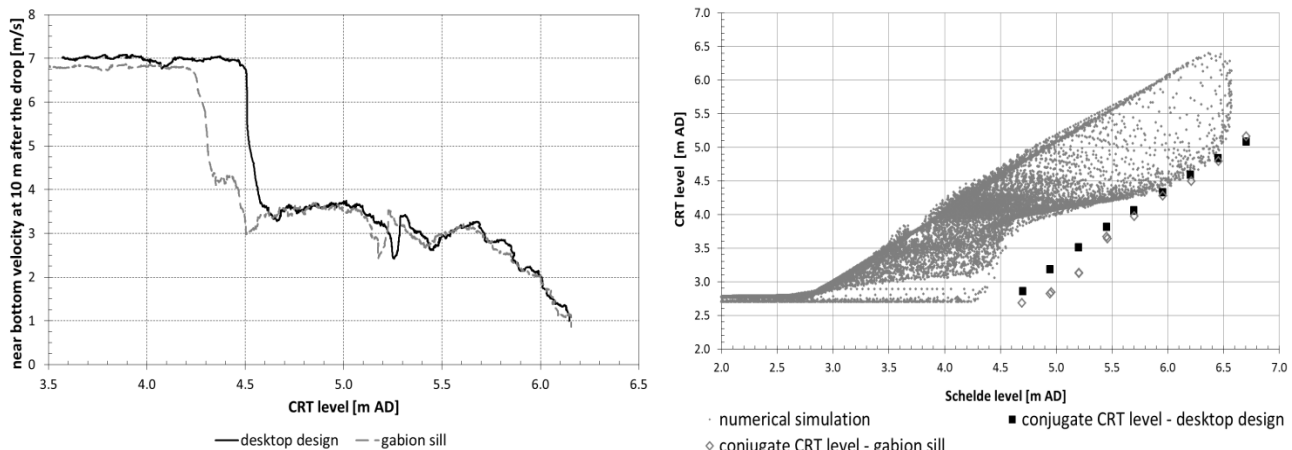


Figure 10. Left: Near bottom velocity in function of the CRT level with a Schelde level + 6.20 m AD at x=10 m at x=10 m when using a gabion sill with height 0.50 m at 14 m downstream of the drop (notice that the velocity meter is limited to 7 m/s); Right: Comparison of predicted CRT levels during operation with the conjugate CRT level.

Notice in Figure 10 left that a gabion sill has only a limited effect on advancing the transformation from supercritical to subcritical flow. Figure 10 right shows that a gabion sill only has a considerable effect on advancing the hydraulic jump for Schelde levels below + 5.50 m AD.

5.3 Deepening the stilling basin

Figure 11 left shows the near bottom velocity at a distance of 10.0 m downstream of the drop in function of the CRT level with a Schelde level of +6.20 m AD when increasing the stilling basin depth from 0.50 m to 1.00 m below the outlet culvert invert level. Figure 11 right presents the measured conjugate CRT level as a function of the Schelde level when the stilling basin is deepened and compares this level

with the predicted CRT levels. For comparison purposes, the conjugate CRT level (re)calculated with the Bélanger equation for the deepened stilling basin, is also shown in Figure 11.

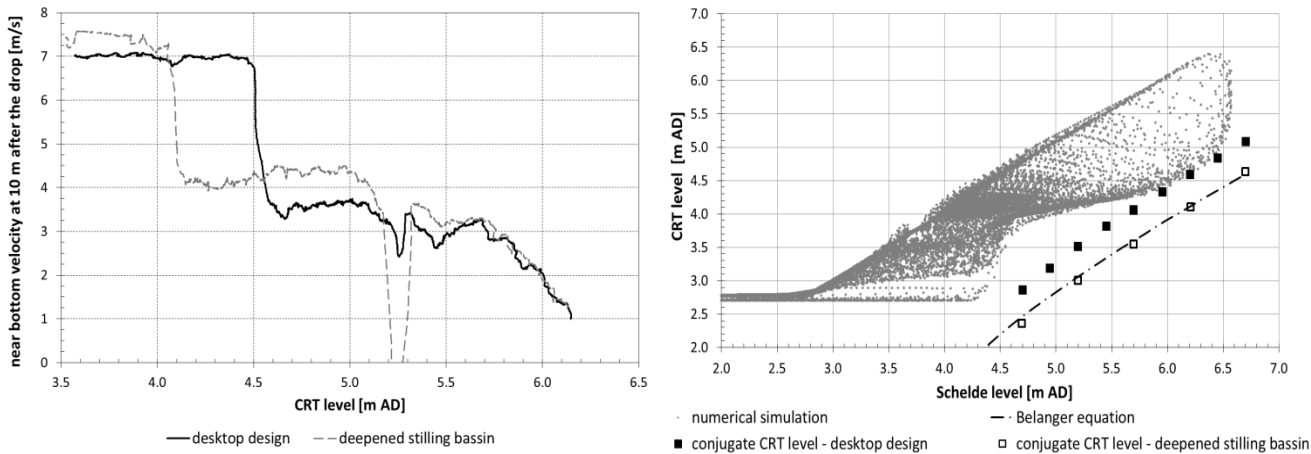


Figure 11. Left: Near bottom velocity in function of the CRT level with a Schelde level of + 6.20 m AD at $x=10$ m downstream of the drop when deepening the stilling basin to 1.0 m (notice that the velocity meter is limited to 7 m/s) ; Right: Comparison of predicted CRT levels during operation.

Figure 11 left shows that deepening the stilling basin to 1.0 m reduces the conjugate water level by about 0.45 m. Figure 11 right shows that deepening the stilling basin reduces the conjugate CRT level by 0.4 m to 0.5 m for the entire range of Schelde levels, and provides a margin with the predicted CRT levels.

5.4 Baffle beam

The effect of adding a beam at a distance of 5.0 m downstream of the drop was studied. The beam will be further referred to as a “baffle beam”, since it can be interpreted as a set of baffle blocks with zero spacing in the spanwise direction. The baffle beam dissipates part of the drop energy and due to this, the conjugate CRT level decreases. The maximum height of the baffle beam must be below the floor level of the outlet culvert and thus is limited to 0.5 m. In the scale model, baffle beams with height 0.25 m and 0.50 m were tested. Figure 12 shows the flow pattern downstream of the drop with a CRT level of + 4.45 m AD and a Schelde level of + 6.20 m AD when using a baffle beam with a height of 0.50 m.

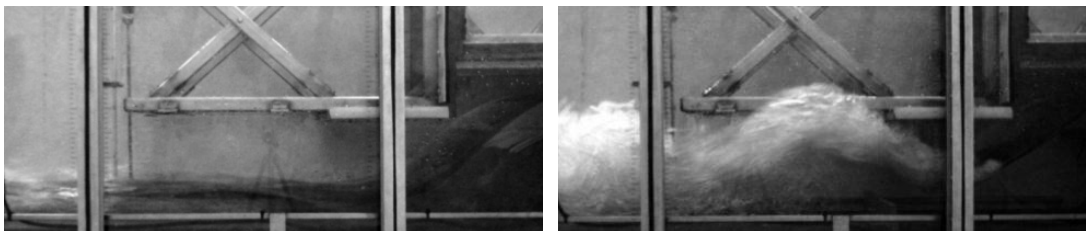


Figure 12. Flow pattern in the stilling basin (CRT level + 4.45 m AD / Schelde level + 6.20 m AD) Left : desktop design ; Right : baffle beam with height 0.50 m at 5.0 m downstream of the drop.

Notice in Figure 12 that the baffle beam deviates the supercritical flow in the upward direction. Through the dissipation of energy with the baffle beam, the water downstream of the baffle beam is transformed to subcritical flow with a lower conjugate CRT level.

Figure 13 left presents the near bottom velocity downstream of the drop in function of the CRT level with a Schelde level of + 6.20 m AD, when a baffle beam with a height of 0.50 m is placed at 5.0 m downstream of the drop. Because the transformation to subcritical flow is not a clear hydraulic jump, the near bottom velocity is also given at 7.5 m and 12 m downstream of the drop. Figure 13 right shows the measured conjugate CRT level as a function of the Schelde level when a baffle beam with height 0.25 m and 0.50 m is used and compares this level with the predicted CRT levels.

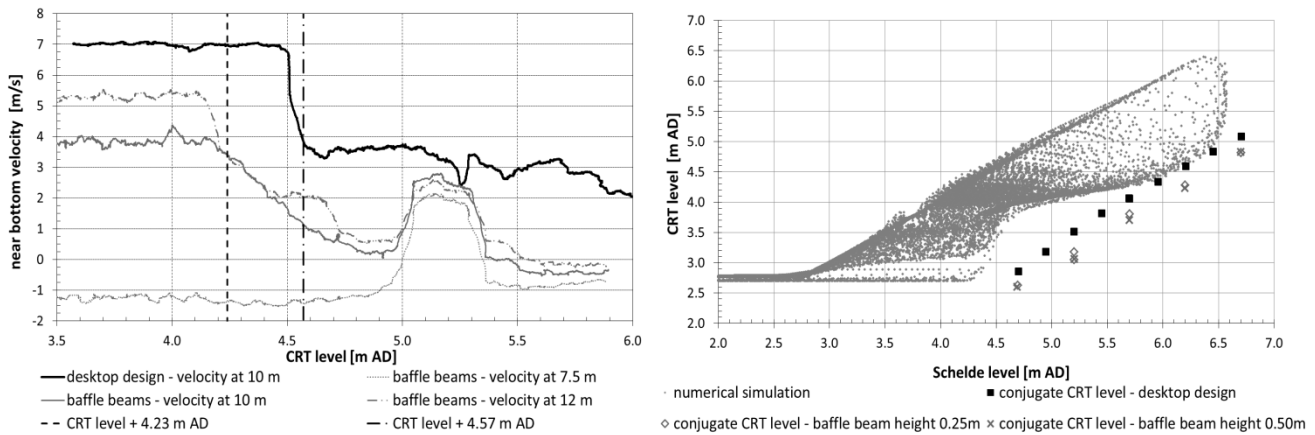


Figure 13. Left Near bottom velocity in function of the CRT level with a Schelde level of + 6.20 m AD at $x=7.5$ m, 10.0 m and 12.0 m downstream of the drop when using a baffle beam with height 0.50 m at 5.0 m downstream of the drop (notice that the velocity meter is limited to 7 m/s) ; Right Comparison of predicted CRT levels during operation with the conjugate CRT level.

Notice in Figure 13 left that a baffle beam advances the transformation from supercritical to subcritical flow. Because the energy is partly dissipated, the velocity is lower for the full range of Schelde levels. When the CRT level rises, the drop length increases, see Figure 14. At a CRT level of + 5.10 m AD the drop goes beyond the baffle beam. Consequently, the velocity rises to a value almost equal to the velocity for the desktop design. For a CRT level equal to + 5.30 m AD the ceiling of the stilling basin is drowned (Figure 7). The falling jet now bumps into the vertical wall downstream of the inlet culvert and is redirected towards the baffle beam. The interaction between the jet and the baffle beam positively influences the near bottom velocity downstream of the baffle beam.



Figure 14. Flow pattern downstream of a sudden drop in a rectangular channel (Vischer & Hager, 1995).

The use of a baffle beam decreases the conjugate CRT level for the full range of Schelde levels. The baffle beams with a height of 0.25 m and 0.50 m result in an almost similar decrease of the conjugate CRT level.

During the tests, an unstable flow pattern was noticed using the baffle beams. For a Schelde level of + 6.20 m AD this unstable flow pattern occurs between CRT levels + 4.50 m AD and + 4.90 m AD. Between these two levels the flow pattern changes constantly between the distinct patterns shown in Figure 15.

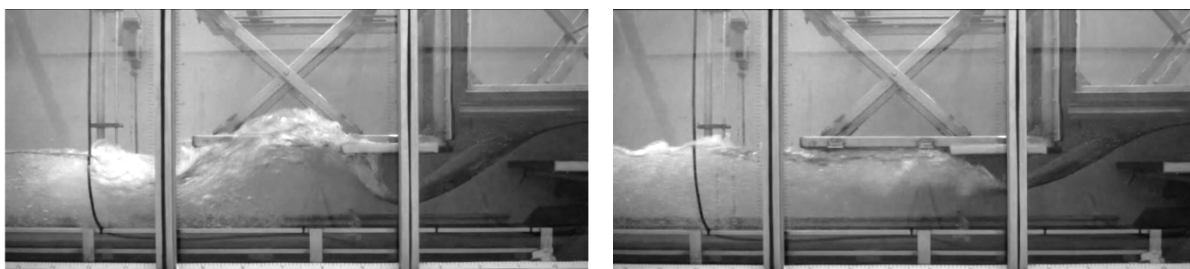


Figure 15. Unstable flow patterns when using a baffle beam with height 0.50 m (CRT level + 4.60 m AD / Schelde level + 6.20 m AD).

5.5 Baffle blocks

Peterka (1984) and Thompson & Kilgore (2006) advice to use baffle blocks instead of one baffle beam for energy dissipation. Baffle blocks reduce the length of the jump and the conjugate water level. Based on the literature formula for dimensioning the baffle blocks, blocks with a height of 0.66 m, a width of 0.56 m and a distance between the blocks of 0.56 m are recommended for a Schelde level of + 6.20 m AD. In the scale model, blocks with a height of 0.50 m and 0.75 m were tested. The width and the distance between the blocks for both type of baffle blocks was 0.50 m. The baffle blocks do not obstruct the

whole area, therefore it is permitted that the height is above the floor level of the outlet culvert. Figure 16 presents the flow pattern for baffle blocks with a height of 0.50 m, a CRT level of + 4.45 m AD and a Schelde level of + 6.20 m AD.

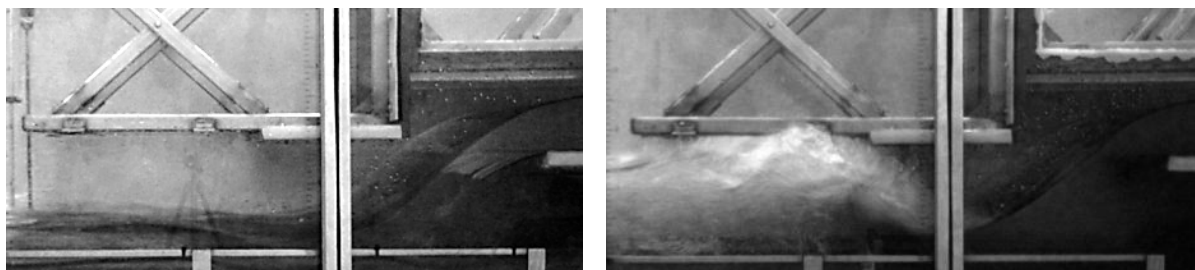


Figure 16. Flow pattern in stilling basin (CRT level + 4.45 m AD / Schelde level + 6.20 m AD)
 Left : desktop design ; Right : baffle blocks with height 0.50 m at 5.0 m downstream of the drop.

When using baffle blocks, the hydraulic energy is partly dissipated. For this configuration the jump starts at a lower conjugate CRT level. It is also noticed that baffle blocks result in a greater energy dissipation when compared to a baffle beam. The aforementioned unstable flow pattern with the baffle beam was not noticed. Figure 17 left presents the near bottom velocity after the drop in function of the CRT level with a Schelde level of + 6.20 m AD when baffle blocks with height 0.50 m are placed at 5.0 m downstream of the drop. Because the transformation is not a clear hydraulic jump, the near bottom velocity is also given at 7.5 m and 12.0 m downstream of the drop. Figure 17 right presents the influence of baffle blocks with height 0.50 m and 0.75 m on the conjugate CRT level as a function of the Schelde level. According to Thompson & Kilgore (2006) the conjugate CRT level can be reduced to 85 % when using baffle blocks. In Figure 17 right a line is plotted indicating 85% of the conjugate CRT level calculated with the Bélanger equation.

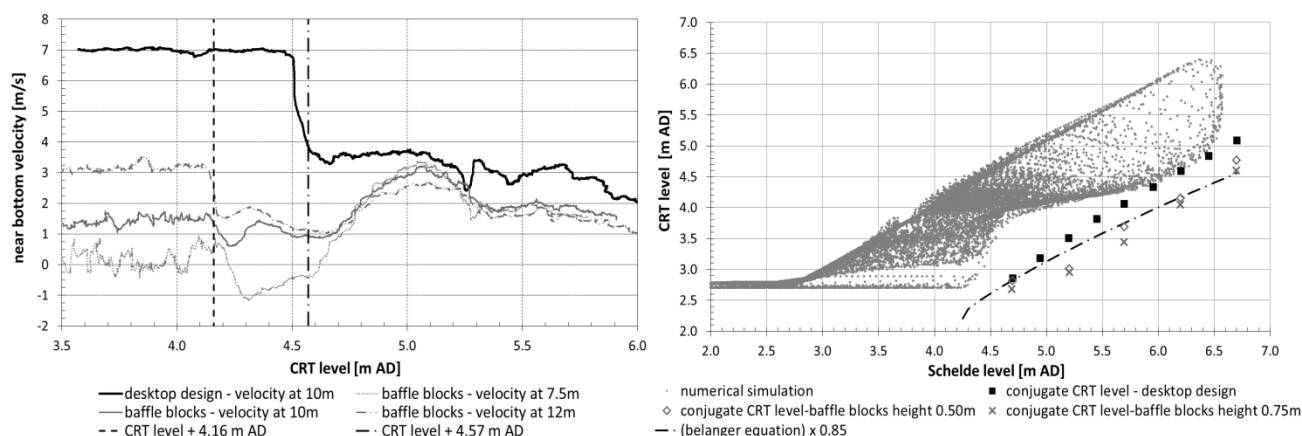


Figure 17. Left: Near bottom velocity in function of the CRT level with a Schelde level + 6.20 m AD at $x=7.5$ m, 10.0 m and 12.0 m downstream of the drop when using baffle blocks with height 0.50 m at 5.0 m after the drop (notice that the velocimeter is limited to 7 m/s) ; Right: Comparison of predicted CRT levels during operation with the conjugate CRT level when using baffle blocks.

In Figure 17 left it should be noticed that the near bottom velocity decreases for the full range of Schelde levels when using baffle blocks. If the representative velocity for the desktop design is used to determine the effectiveness, it can be stated that baffle blocks reduce the conjugate CRT level by 0.4 m. Similarly to the case of one baffle beam, a rise in near bottom velocity is noticed for CRT levels from + 5.0 m AD. Figure 17 right shows that baffle blocks reduce the conjugate CRT level over the full range of Schelde levels. The effect of baffle blocks with height 0.50 m and 0.75 m on the conjugate CRT level is similar. The conjugate CRT level at the design discharge of the baffle blocks (corresponding to a Schelde level of + 6.20 m AD) is approximately 15 % lower than the value for a normal hydraulic jump without baffle blocks.

6 CONCLUSION

Within the framework of the Sigmaplan, different flood control areas with controlled reduced tide (FCA-CRTs) are being setup along the Schelde estuary. To introduce the reduced tide in the polder, simple inlet and outlet sluices are relied upon. Most recently, combined inlet-outlet sluices are being advocated. In such structures the inlet culverts are on top of the outlet culverts. During inflow, a falling jet drops from the floor slab of the inlet culvert and plunges into a stilling basin. The energy of the plunging jet is additionally dissipated by means of a hydraulic jump.

In this paper, a physical model study is described to test a desktop design of such a structure for a specific case, i.e. FCA-CRT Bergenmeersen. The desktop design turns out to be satisfactory. Yet, at inflow discharges corresponding to an extreme spring tide (i.e. a Schelde level of +6.20 m AD which is exceeded on average three times per year), there is only a small margin in terms of fixing the location of the hydraulic jump above the concrete slab of the stilling basin. Therefore, some optimization efforts have been carried out to increase that margin, by adding some obstacles in the stilling basin or by modifying the basin geometry: (i) adding a gabion sill, (ii) deepening the stilling basin, (iii) adding a baffle beam and (iv) adding baffle blocks.

It turned out that adding a gabion sill does not increase the margin at extreme spring tide levels. Deepening the stilling basin increases the margin over the full range of Schelde levels (but this design modification is not applicable in practice, since the preparatory work for the construction of the prototype is in a too advanced stage). The same goes for adding a baffle beam, though in some range of CRT levels (i.e. tailwater depths) an unstable flow pattern was observed. The use of baffle blocks gives the best results for fixing the location of the hydraulic jump and no unstable flow patterns are observed.

For the designs with a non-obstructed hydraulic jump (i.e. a design without sill, beams, blocks, ...), there was a good correlation between the literature formulae and the scale model results. Peterka (1984) and Thompson & Kilgore (2006) present formulae for dimensioning baffle blocks and state that when using baffle blocks (according to this formulae) the conjugate CRT level may be lowered to 85 %. This was – for the design discharge of the baffle blocks – confirmed by the scale model results.

Notwithstanding the abovementioned optimization efforts, it was decided by the agency to retain the original desktop design. This decision was motivated by the fact that the predicted CRT levels do (though marginally) exceed the conjugate CRT level and the preparation of the construction in the field was already in an advanced stage. In addition, the agency reckoned that - if during operation of the FCA-CRT unacceptable circumstances would be encountered - there are still means to elegantly modify the stilling basin geometry without major constructional efforts. Adding a baffle beam in the stop log recesses seems to be the most likely solution.

Of course, the lessons learned from the abovementioned optimization efforts will be taken into account for the design of the upcoming FCA-CRT projects.

NOTATION

Y_1	Water level upstream of hydraulic jump [m]
Y_2	Conjugate water level downstream of hydraulic jump [m]
Fr_1	Froude number upstream of hydraulic jump [-]
q	Discharge per unit width [m^2/s]
g	Gravity acceleration [m/s^2]
Δz	Drop height [m]

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