Optimizing a cooling water outfall inside the Maasvlakte 2 port extension - dealing with conflicting requirements

Martijn P.C. de Jong[1,2], Arnout C. Bijlsma[1], and Aron Ament[3]
[1] Deltares, P.O. Box 177, 2600 MH, Delft, The Netherlands
[2] martijn.dejong@deltares.nl, +31 (0)88 335 8596
[2] Port of Rotterdam, P.O. Box 6622, 3002 AP, Rotterdam, The Netherlands

Abstract

Presently, a large power plant in the Port of Rotterdam discharges its cooling water through a permeable breakwater directly into the North Sea. The future Maasvlakte 2 port extension (MV2) will encompass this outfall location and in the new layout nautical activities are planned nearby. This may lead to conflicting requirements, since the nautical activities require moderate flow conditions, and thus the application of a strong diffusor structure, while the cooling water circuit of the plant requires that the hydraulic losses over such a diffuser are limited. Therefore, a feasibility study has been performed to optimize the hydrodynamic integration of the cooling water outfall in the design of MV2 to ensure that the different port functionalities can take place in an optimal way within the space available. The specific hydrodynamic requirements were analyzed and verified for a number of diffusor scenarios based on output from numerical computations with a shallow-water flow model. The results confirm the feasibility of the plans. Furthermore, they provide the information required for the Rotterdam Port Authority to decide on an optimized design for this part of the port extension.

Keywords: port layout optimization, industrial and nautical activities, 3D flow modeling, outfalls

1 Introduction

Presently, a power plant located at the western edge of the Port of Rotterdam discharges its cooling water through a permeable breakwater directly into the North Sea. Figure 1 shows this part of the harbor with the inset depicting the present situation around the outfall location. The curved breakwater was originally designed to protect the Maasvlakte 1 port region from waves from the North Sea. Its top layer consists of large concrete blocks (2.55 m edge). The resulting permeability means that effectively the breakwater now also functions as a diffusor for the cooling water discharge.

The future port extension Maasvlakte 2 (MV2) will surround this outfall location. Figure 2 on the next page shows the design of the overall MV2 Master Plan. This plan includes a Service Basin (SB) directly adjacent to the outfall location (black circle). In the original version of this plan the section of the breakwater directly around the outfall location (solid black line) would remain in place to keep functioning as a diffusor.

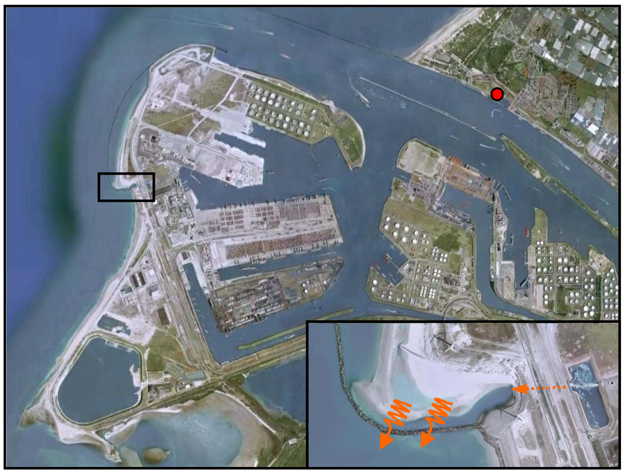

Figure 1: present situation Port of Rotterdam.

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Dekker *et al.* (2009), referred to in more detail below, described a hydrodynamic analysis of this situation. They concluded that the breakwater, or another diffusor structure with similar characteristics, will be required to achieve acceptable flow conditions for the nautical activities foreseen in the SB.

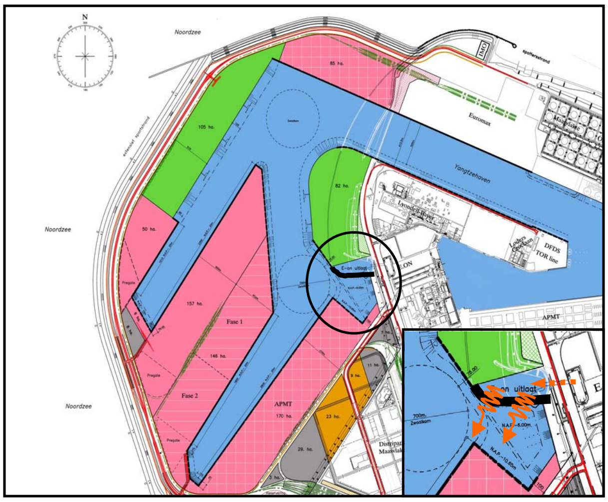


Figure 2: Master Plan of the MV2 port extension.

In a later design stage, the Rotterdam Port Authority developed an alternative plan of the area surrounding the outfall location. Figure 3 shows a detail of this plan, in which a new compact diffusor replaces the breakwater to leave more space for nautical activities.

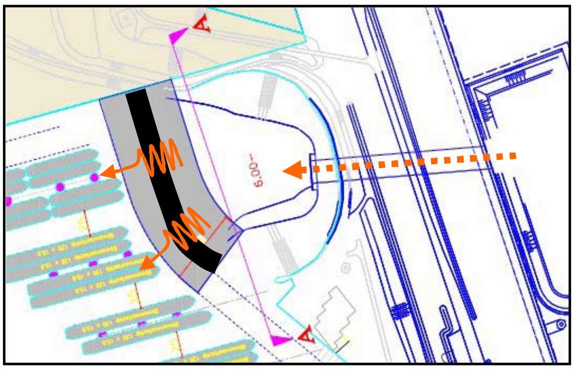


Figure 3: new compact diffusor in updated plan.

Although a smaller diffusor leads to a more efficient use of harbor space, the associated intensified use of the SB makes an optimal integration of functional requirements even more critical than for the original plans (Figure 2), considered in Dekker *et al.* (2009). This particularly applies to nautical activities (moored and maneuvering vessels), which require a strong diffuser to ensure moderate local flow velocities and gradients, and the (possibly conflicting) requirement of a limited head loss over such a diffusor structure in view of the cooling capacity of the power plant. Therefore, the aim of the present study was to optimize the integration of the cooling water outfall as part of the design of MV2 to ensure that the different port functionalities can take place adequately and efficiently within the space available.

2 Flow modeling

Model setup

The flow conditions inside and around the SB have been determined via a series of coupled hydrodynamic models based on Delft3D-FLOW. This approach was described in detail by Dekker *et al.* (2009), so only the main elements are summarized here. The starting point of the numerical modeling was a 3D model describing the greater port area, a part of the southern North Sea, and the local river branches (Bijlsma *et al.* 2004). The second step was a 3D model of the western section of the Port of Rotterdam (Nolte and Kleissen, 2006). The final model step was a detailed 3D model covering only the areas of MV1 and MV2, with a resolution of up to about 10 m. The 3D models were used to simulate the stratified flow during spring tide caused by density differences due to river runoff and the increased temperature of the cooling water ($\Delta T = 8$°C, maximum future discharge: 90 m^3/s).

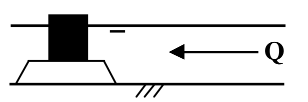
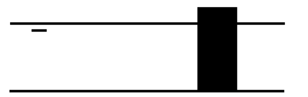
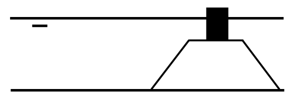
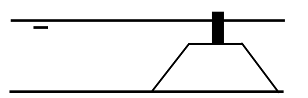
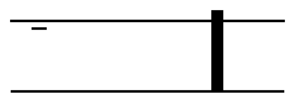
In view of the study aims, this numerical modeling approach focuses on describing the flow field at some distance of the diffuser. In such an approach the small-scale flow through the diffuser structure cannot be fully resolved. This is required in view model efficiency and is acceptable because it is not of main interest in the present study. However, it means that the effect of the diffuser must be represented in the numerical model by parameterization methods (hydraulic structure options). Dekker *et al.* (2009) calibrated and validated a number of such methods available in Delft3D-FLOW. They preferred an approach based on a constant resistance over the vertical, which has also been applied in the present study.

Considered diffusors

The computations for the present study described the existing breakwater situation (450 m length) with a uniform bathymetry as a reference (Scenario 0, layout shown in Figure 2) and four scenarios covering different permeability characteristics and sill heights of a new compact (125 m length), dedicated diffusor (Scenario 1a to 1d, layout depicted in Figure 3).

Table 1 summarizes these scenarios, with levels defined relative to the local reference level (approximately mean sea level). The table includes the values used for the dimensionless energy loss coefficient C_{loss}, which is the main parameter for describing the resistance caused by the diffusor. The diagrams visualize the differences between the alternatives by illustrating the level of the sill and the resistance (shown as width) of each structure.

Table 1: overview of considered diffusors.

scenario \ parameters		sill level (m)	C_{loss} (-)
0		-4	160
1a		-6 (no sill)	160
1b		-2	55
1c		-2	15
1d		-6 (no sill)	15

All scenarios included a uniform bottom level of -6 m in the SB area, including the section enclosed by the diffusor. The original situation included a higher and non-uniform bottom level (Figure 1). It was expected that the lower future depth would cause a part of the sediment, assumed to be present in the core of the breakwater, to flush out, resulting in an effective sill height of -4 m in Scenario 0 (Table 1).

Considering different sill heights in the simulations for the compact diffuser combined with a number of different diffusor loss coefficients (C_{loss}), provided an optimal range of degrees of freedom for the design choices that need to be made. In addition, the sill also has a hydrodynamic function, since it is enhances the mixing and spreading of the flow in the area enclosed by the diffusor.

3 Flow patterns

The calculated flow patterns were evaluated on their suitability for nautical activities. This evaluation focused on the flow patterns in the top layer of the model and on root-mean-square (RMS) flow fields averaged over the draught of the different types of vessels that are expected to visit the SB. These latter fields indicate the forces that the currents exert on the vessels.

Only the computed results for the new compact diffusor are presented here in detail, since these form the most recent results and because they supplement the results of the reference scenario presented in Dekker *et al.* (2009).

Maximum flow velocities due to the cooling water discharge occur during low water and in the upper level of the water column. Therefore, the flow fields in the top computational layer at low water are presented here to illustrate the results of the computations and the nautical evaluation. Similar flow patterns were found for the depth-averaged fields, only with decreasing velocities for increasing draughts.

Figure 4 shows the range of the results by presenting output for the most transparent (Scenario 1d, smallest resistance) and for the least transparent compact diffusor (Scenario 1b, largest resistance). These scenarios correspond to the largest and smallest diffuser heights over the sill, leading to the highest and lowest flow velocities in the SB.

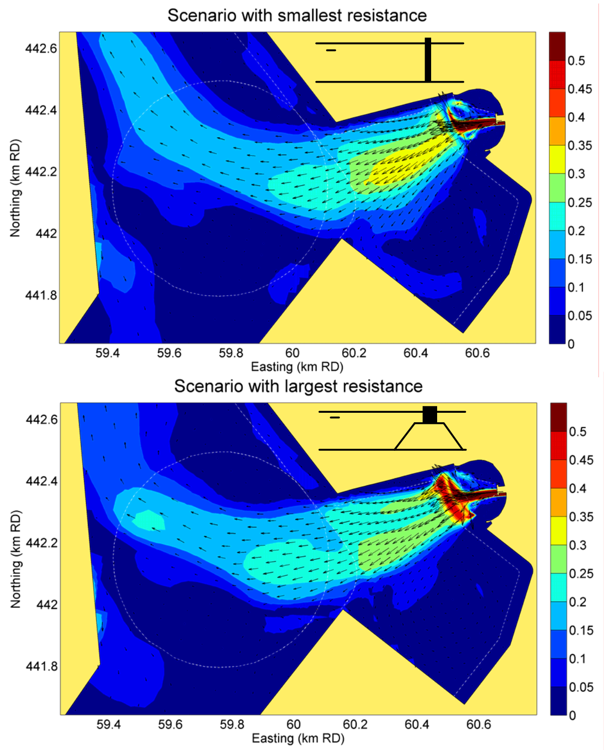


Figure 4: flow patterns at low water (m/s).

The results for the diffusor with the smallest resistance (top panel) show somewhat higher flow velocities in the SB than the scenario with the largest resistance (bottom panel). An evaluation of these results showed that in both cases all planned nautical activities in the SB can be expected to proceed with only limited interference due to the flow velocities and gradients caused by the outfall discharge through the diffusor.

4 Head loss over the diffusor

Background of the evaluation

The cooling water circuit of the power plant requires a sufficiently small (external) head difference between the point of the cooling water intake and the outfall location. The computations showed that in the future situation the averaged head difference due to the tide will be limited (<0.01 m) and therefore the head loss across the diffusor will dominate the problem.

The sections below first describe an analysis of the instantaneous head loss, used to describe and interpret the behavior of the hydrodynamic system. It is followed by an evaluation of the averaged head loss across the diffusor. The outcome of this latter step is compared to the formal design criteria, based on the 72 h average head loss, which are a function of the ambient water temperature: $T < 12$ °C: <0.50 m, 12 °C < T < 15 °C: <0.29 m, $T > 15$ °C: <0.05 m.

Instantaneous head loss

The top panel of Figure 5 shows the results of a theoretical evaluation of the head loss over the diffuser (reproduced from Dekker *et al.*, 2009), assuming stationary and spatially uniform (1D) conditions. The x axis shows the instantaneous head loss and the y axis shows an ambient water level, which here represents the water level in the SB. Results are shown for different combinations of sill levels, and permeabilities n. The latter parameter is part of a theoretical head loss formulation to derive C_{loss}, with higher values for n corresponding to a higher permeability of the breakwater or diffusor. The figure indicates that the combination of a low permeability of the breakwater and a high sill level results in high head losses across the diffusor. Largest head losses occur around low tide. This is because in that situation the height of the water column over the sill is minimal.

The bottom panel of Figure 5 shows that the head loss derived from the results computed with Delft3D-FLOW for the different scenarios as listed in Table 1 reproduce the trends as found in the theoretical results. The presented head loss was determined by comparing the water level at a representative location in the area enclosed by the diffusor and at one in the SB. The figure shows sequential combinations of instantaneous water levels and head losses over the diffusor, describing the evolution of these coupled parameters over time. The results are shown for the last three tidal cycles, which is the time interval of the computations available for analysis.

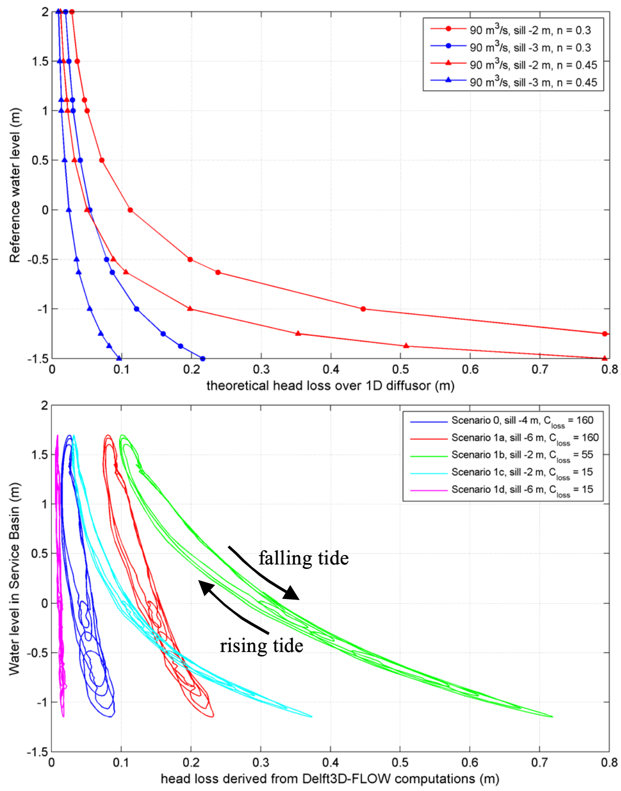


Figure 5: theoretical (top) and computed (bottom) instantaneous head losses.

The large loop from high to low tide that is present in the numerical results of each scenario is a hysteresis effect. This occurs because the instantaneous head loss for a given water level in the SB is different for a rising tide than for a falling tide (indicated in the bottom panel of Figure 5). During rising tide the discharge through the diffuser and the resulting head loss will be slightly reduced because the discharge is (partly) stored in the area behind the diffuser to follow the rising tide level outside. During falling tide the opposite situation will occur. This effect could not be taken into account in the theoretical analysis of the head loss, since that situation assumed quasi-stationary conditions.

The more erratic behavior around low water that is visible in the bottom panel of Figure 5 is because those tidal levels differed more strongly from day to day, due to the daily inequality and because of non-stationary meteorological conditions. Furthermore, the different smaller ‘loops’ around low water in the results for each scenario are due to the occurrence of double low waters (in Dutch: ‘aggers’) at this location. The results further show, as predicted by the theoretical results, that the head loss will particularly be critical during low water, since under those conditions the highest values occur. Also at that water level, the largest sensitivity to diffusor characteristics is found, leading to a large range of possible outcomes.

Average head loss for the computed situation

The criteria for the maximum allowable head loss, mentioned above, use an averaging interval of 72 h. The three tidal cycles in the computations following the initialization stage (about 37 h) were therefore used to give an *indication* of the 72 h average head loss. Table 2 presents the results of the comparison of these values with the criteria. In this table the green color indicates acceptable conditions, orange is around the criterion (within expected model accuracy) and red corresponds to unacceptable situations.

Table 2: evaluation of diffusor scenarios.

Scen.	average head loss	> 15°C < 0.05 m	15°C - 12°C < 0.29 m	< 12°C < 0.5 m
0	0.046 m			
1a	0.143 m			
1b	0.327 m			
1c	0.128 m			
1d	0.012 m			

The results show that not all scenarios considered in the present study are acceptable. The reference situation, Scenario 0, corresponds to a feasible situation, although the head loss is very close to the strictest criterion. The outcome for Scenario 1a to 1d shows that it is possible to select diffusor characteristics that will result in an acceptable averaged head loss, while the evaluation in Section 3 showed that at the same time the flow conditions are acceptable for nautical activities. This indicates that a compact diffusor is feasible.

On the other hand, besides that this evaluation does not cover 72 hours, these results might not be (fully) representative for the actual criterion because the daily inequality might not be fully averaged out. Furthermore, it is only one realization, i.e. one specific combination of tidal water levels and meteorological influences.

Average head loss based on archived data

An extended analysis was made to overcome the limitations mentioned above by combining long term archived measurements and the computed results shown in the bottom panel of Figure 5. The extended analysis is based on ten years of archived measured water levels and surface water temperatures near the main harbor entrance (near Hook of Holland, indicated by the red dot in Figure 1). These data inherently include a large range of different tidal and meteorological influences such as wind-induced set-up.

The measured water levels were taken as an approximate description of the water levels in the future SB, while the surface water temperatures were taken to approximate the temperature of the ambient water at the intake. This is obviously not exact but it was considered a suitable approach in the present feasibility study, since here the influence of realistic *variations* in these parameters for this area are considered.

The key to the extended analysis is a trend that is fitted through the results for each scenario presented in the bottom panel of Figure 5. By expressing this trend for the head loss as a function of the water level, the measured time series of water levels can be converted to a ten years time series of head losses. These are then used to determine 72 h averaged values by applying a moving averaging window. To evaluate the outcome, the daily surface water temperature values were converted to a day-to-day criterion for the average head loss based on the criteria mentioned above.

Results of this analysis are illustrated here based on the output for Scenario 1b. This particular scenario was selected because it shows the most pronounced head losses.

Figure 6 depicts the results for a typical year. The black line, representing the 72 h averaged head loss, shows that more severe weather conditions during winter cause relatively large variations, while the summer months correspond to relatively stable averaged head losses. The green line presents the value derived from Delft3D-FLOW, indicating that the computations considered a representative situation.

The red line in Figure 6 indicates the day-to-day criterion for the maximum 72 h averaged head loss. A similar trend was found for each year, clearly showing the distinction between summer and winter months. Fortunately, the largest peaks in the averaged head loss occur during the winter months, when the intake water is relatively cold and a large head loss is acceptable. However, during all summer months the daily criterion is exceeded in this scenario, even though fluctuations are small.

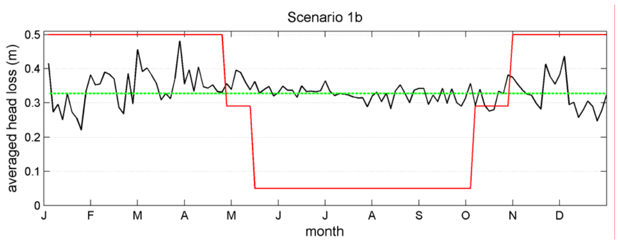


Figure 6: example of one year of averaged head losses.

The strictest criterion during the summer months applies for about 40% of the time. This is reflected in the scores of most scenarios using a compact diffusor. This summer-winter separation, i.e. unacceptable-acceptable, was found for most considered scenarios.

Scenario 1d, with the most transparent diffusor settings, did not exceed the criterion and shows that, also when realistic variations of the water level and of the surface temperature are taken into account, it is feasible to apply a compact diffusor.

5 Conclusions

This study was carried out to optimize the implementation of an existing cooling water outfall in the future Maasvlakte 2 port extension of the Port of Rotterdam. This optimization included the evaluation of the feasibility of a compact, dedicated diffusor that could replace the breakwater that presently acts as a diffusor.

The feasibility of such a plan depends on whether the different local functionalities can be facilitated alongside each other. This particularly applies to the power plant operations, which require a limited head loss over the diffusor, and to nearby nautical activities, which require a sufficiently strong diffuser to ensure moderate flow conditions. Requirements for both these functionalities have been considered in this study.

The results indicate that both the remaining section of the existing breakwater as well as a compact diffusor will be feasible options in the Maasvlakte 2 port extension. Computations show acceptable velocities and flow patterns for the foreseen local nautical activities. Analyses of the head losses over the diffusor show that the breakwater meets the criteria and that there is enough freedom in design parameters of a compact diffusor to ensure that the head losses remain sufficiently small while ensuring acceptable flow fields. Additional analyses of the head losses using long-term archived measurements showed that also seasonal variations and storm conditions will not result in unacceptable situations.

These findings therefore provided a sound basis for the Port Authorities to decide on a final design of this section of the Maasvlakte 2 port extension, in which different port functionalities can now be facilitated in an optimized way.

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