

MODELLING STORM SURGES AND FORECAST
EFFECTS IN DESIGNING THE ROTTERDAM
STORM SURGE BARRIER

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Abstract

In 1989 the Dutch government decided to build a storm surge barrier in the New Waterway near Rotterdam being a good and cheap alternative for the necessary strengthening of dikes along the lower regions of the Dutch rivers Rhine and Meuse. To be feasible the barrier had to meet several goals. The most important ones being :

- * closing frequency less then once every 10 years now and once every 5 years after 50 years from now (including 25 cm sea-level rise)
- * prescribed reduction of design water-levels at two representative locations, being Rotterdam and Dordrecht.

These and other parameters are calculated by means of a probabilistic calculation method. This method involves a mathematical open-channel network model of which the results are combined with the statistical properties of input parameters. A risk-analysis of the performance of the barrier is included. Finally the model is adapted to study operational aspects.

1. Introduction

The project area is situated in the southwest of the Netherlands as shown in figures 1 and 2. In figure 2 the dikes are shown, which were to be reinforced as a consequence of the Delta plan. This plan was

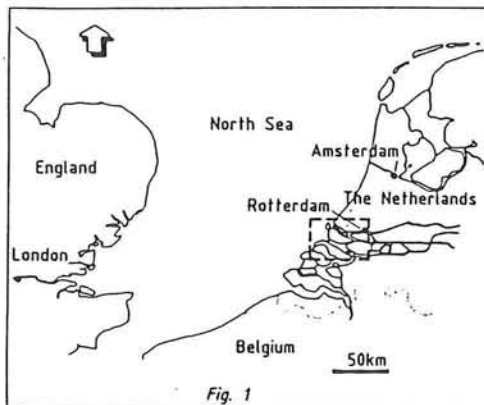


Fig. 1

developed after the flood of 1953. It included shortening of the coast line by closing a number of tidal inlets and to strengthen remaining dikes. By the time of 1985 most of this plan has been completed : still about 200 km of dikes had to be strengthened. A re-examination of design water-levels (DWL) led to higher values than those originally calculated.

This implied very costly construction works in densely populated or otherwise complicated areas. Therefore, in 1987 the Dutch government initiated a study to consider a storm surge barrier near Rotterdam. This barrier should meet two main goals. Firstly the DWL should be reduced significantly to avoid problems

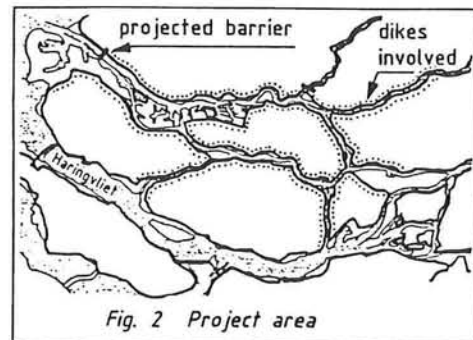


Fig. 2 Project area

related to dike reconstruction works. The prescribed reductions of DWL are based on the situation in the areas, which would be most affected by the reconstruction works. These areas are the cities of Rotterdam and Dordrecht. Secondly the presence of Rotterdam harbour doesn't allow the barrier to be closed too often. The closing frequency of the barrier should (on average) be less than once every 10 years now and less than once every 5 years after 50 years from now. The latter

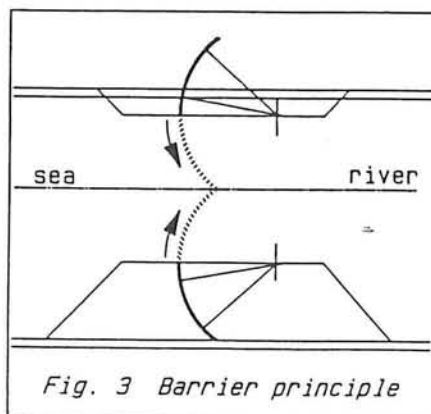


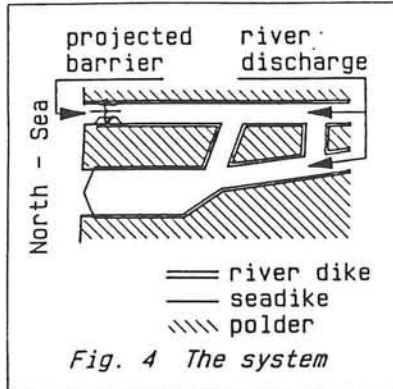
Fig. 3 Barrier principle

situation includes a sea-level rise of 25 centimetres. From several predesigns a final choice was made at the end of 1989. The selected barrier design features two semi-circular doors. The barrier is closed by rotating the floating doors into the river (figure 3) and lowering the entire construction to the river bottom by filling ballast tanks with water. This paper deals with hydraulic

aspects of this barrier and the influence of reliability of the barrier on DWL and operational aspects.

2. Hydraulic aspects

2.1 The hydraulic system



In figure 4 the hydraulic system is shown in a schematic form. Basically there are two river branches with several connections. The southern branch runs into the large Haringvliet estuary. This estuary is separated from the sea by a barrage with large discharge sluices. The northern branch runs freely into the sea

via the city of Rotterdam and the New Waterway. Tidal movement and therefore storm surges enter the system through this northern branch.

Close to the river-mouth the water-level is determined completely by tidal movement combined with storm surge effects. Figure 5 shows that the water-level at the river-mouth can be constructed as a combination of astronomical tide and a storm surge. The maximum sea water-level (MSWL) is influenced by five parameters: astronomical tide, duration, shape and height of the storm surge and phase difference between storm surge and astronomical tide. This number of variables can be reduced. The variation of the astronomical tide at Hoek van Holland is so small, that a mean tidal curve will

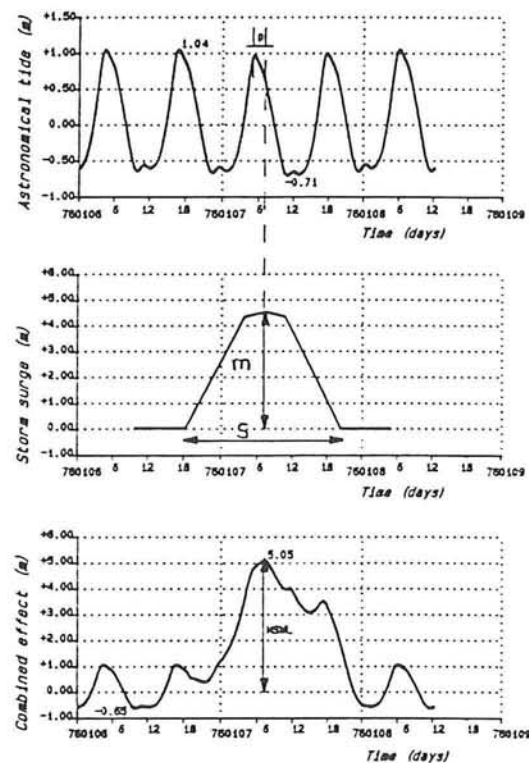


Figure 5

be used. Secondly the shape of the storm surge is considered to be constant as shown in figure 5.

The incoming tidal wave is damped travelling upstream and phase differences occur, as shown in figure 6. In this intermediate region the water-levels are determined by both tidal movement and river discharge.

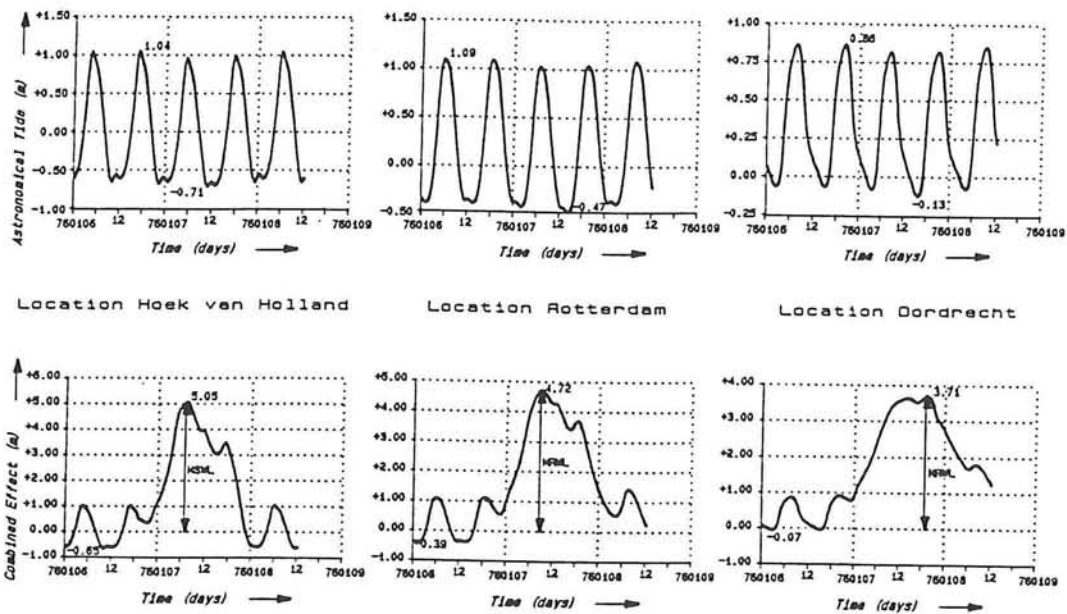


Figure 6

The relation between MSWL, river discharge and maximum river water-level (MRWL) is shown in figure 7. This figure shows lines of equal MRWL at Rotterdam and Dordrecht as a function of river discharge and MSWL. In these graphs the values of duration and phase difference of the storm surge are kept constant at 29 and 4.5 hours.

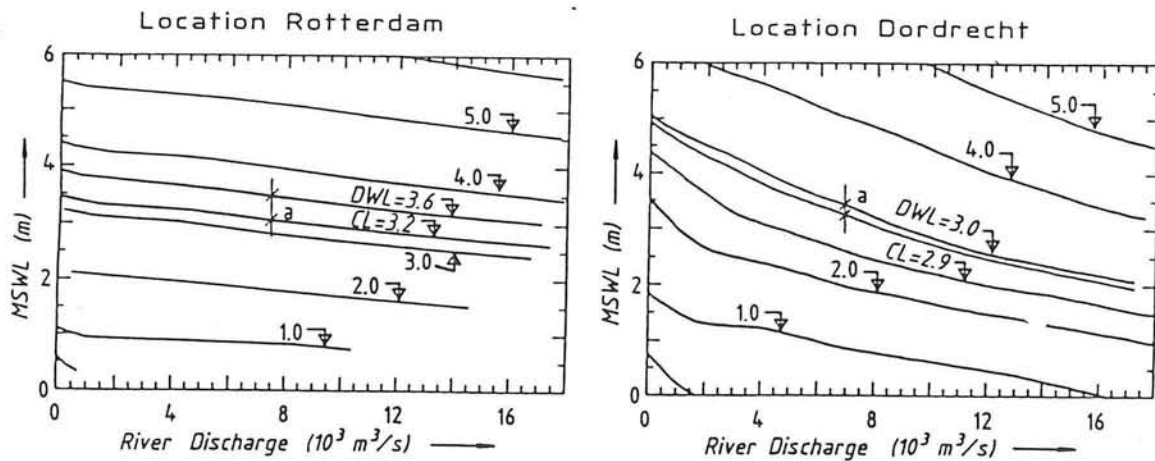


Figure 7

The hydraulic conditions in the project area are governed by four variables. Three variables determine the boundary condition at the river-mouth (MSWL). These variables are duration (s), height (m) and phase difference (p) of the storm surge. The fourth variable is the river discharge (q), which in combination with the MSWL, determines the MRWL. The river discharge varies on a much larger time scale than storm

surges do. Therefore this variable can be treated as a constant during a storm surge. The four governing variables are considered to be independent. This method of determining water-levels is an extension of the usual approach, which is based on only two governing variables: storm surge height and river discharge. The parameters storm surge duration and phase difference are assumed to be constant (29 and 4.5 hours). For the situation without a barrier the results of both calculation methods don't differ very much.

2.2 The effect of the barrier

The effects of the barrier on water-levels in the hydraulic system are twofold. One effect is the reduction of water-levels because the storm surges can't enter the system any more. On the other hand there is an increase of water-levels in the system because of the accumulation of river discharge. To calculate the total balance of effects the hydraulic system has been modelled by a mathematical open-channel network model. The schematization of the system is conform figure 2 and consists of about 200 branches and nodes. This model has been in use for a long time to predict water-levels on a daily basis. The barrier should reduce the DWL at Rotterdam and Dordrecht. The prescribed DWL are 3.60 meter above NAP for Rotterdam and 3.00 meter above NAP for Dordrecht. In order to reach this goal the barrier has to be closed whenever the predicted maximum sea water-level (PMSL), given the actual river discharge, would result in a exceedance of the DWL at one of the locations. In order to have some freeboard regarding the effects of inaccuracy of the PMSL (see paragraph 3) a critical water-level (CL) is introduced. This level is somewhat lower than the DWL. The margin between DWL and CL is 40 cm for the location of Rotterdam and 10 cm for the location of Dordrecht. The reason for these different margins is the fact, that Dordrecht is about twice as far from the North Sea as Rotterdam and therefore less sensitive to sea-level variation. This means, that the margin, which is strongly influenced by the accuracy of the PMSL, can be somewhat smaller at Dordrecht. It should be kept in mind, that both DWL and CL are fixed water-levels at the locations Rotterdam and Dordrecht. Figure 6 can be used to transform the CL into a

river discharge dependent criterion $CL(q)$ for the location Hoek van Holland for which also the PMSL is given.

In figure 8 the effect of the barrier is shown for the locations of Rotterdam and Dordrecht for a specific storm surge and river discharge. In figure 9 the effect of the barrier on the relation between MSWL, river discharge and MRWL is shown. In figure 9 the thick line represents the closing criterion $CL(q)$. Below this line figure 9 is exactly the same as figure 7. Above this line the barrier is closed and this reduces the MRWL significantly compared with figure 7. Only for very high river discharges the effect of the barrier is less significant.

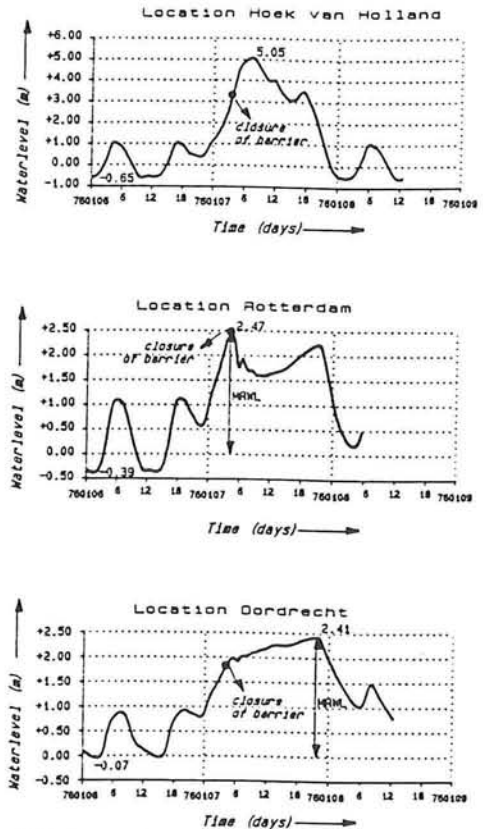


Figure 8

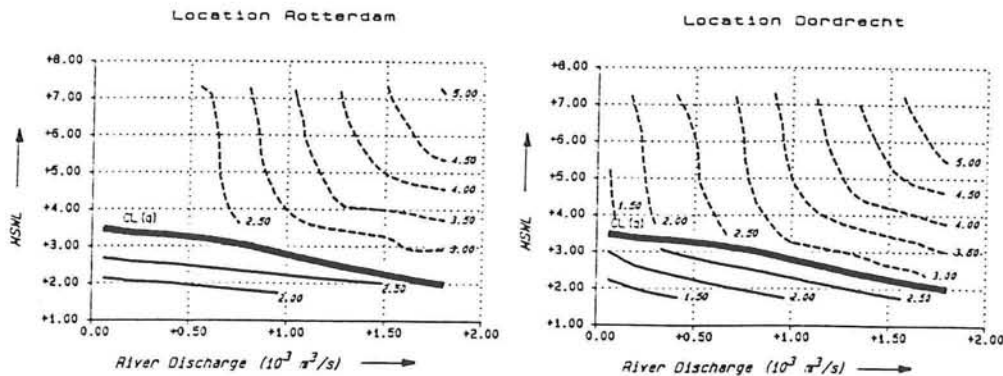


Figure 9

2.3 Calculation of statistical aspects

So far only hydraulics have been discussed. The link with statistics however has to be made because of the probabilistic design procedure of the barrier and the definition of DWL. A DWL is a water-level which has a prescribed frequency of exceedance. The DWL is the most important factor in designing a dike. The prescribed frequency varies along the

country depending on the type of threat (sea/river/lake), population density and economical activities. For Rotterdam this frequency is 1/10000 per year whilst for Dordrecht this frequency is 1/4000 per year for the situation without a barrier and 1/2000 per year for the situation with a barrier. This increased design frequency is based on the reduction of the threat by storm surges.

By means of the hydraulic network-model, mentioned in the previous paragraph, the probability distribution functions of the boundary conditions are transformed into probability distribution functions of the water-levels in the hydraulic system. From these functions the DWL can be calculated easily. This method can also be applied to calculate design discharges, velocities and hydraulic head of the barrier. The transformation of probability distribution functions can be determined by a numerical solution of the following equation :

$$P(MRWL > X) = \int \int \int \int_{MRWL=X}^{MRWL=\infty} f(m, s, p, q) dm ds dp dq$$

In this equation $f(m,s,p,q)$ is the combined probability distribution function of the stochastic variables m, s, p and q . The probability distributions of river discharge and storm surge duration are directly derived from recordings during the last century. The probability of storm surge height and the phase difference are determined in such a way, that the calculated probability distribution of the MSWL shows a good agreement with the historical data and its extrapolation.

3. Reliability aspects

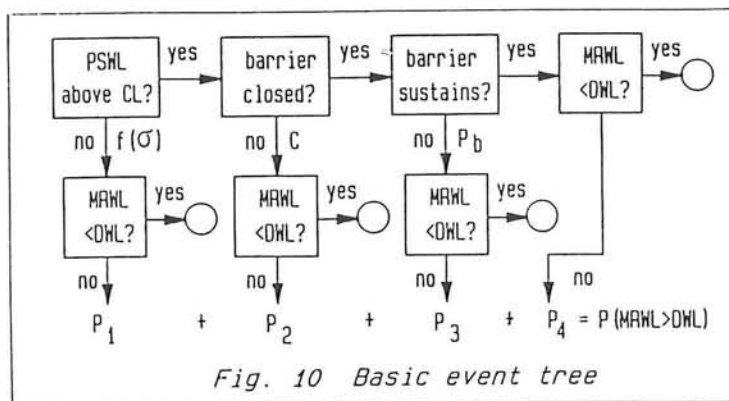


Fig. 10 Basic event tree

The beneficial effect of the barrier on MRWL is strongly influenced by functional and structural reliability of the barrier. To investigate these influences a risk-analysis has been carried

out. In figure 10 an event tree is shown with all possible branches leading to a MRWL exceeding the DWL. At the top of the figure the 'normal' sequence of events is shown. That is a good prediction, a correct decision, a properly functioning barrier, which is strong enough to withstand the forces, mostly generated by the hydraulic head. This leaves four points where something can go wrong:

- * a PMSL lower than the $CL(q)$, so the barrier is not closed, but an actual MRWL higher than the DWL at either Rotterdam or Dordrecht.
- * a PMSL higher than the $CL(q)$, but the barrier is not closed and as a consequence MRWL can be higher than DWL.
- * a PMSL higher than the $CL(q)$, the barrier is closed, but collapses due to the enormous (hydraulic) load. As a consequence the MRWL can be higher than DWL.
- * even if everything functions well, there is still a possibility that the MRWL is higher than DWL.

4. Design conditions/calculations

4.1 Calculation method

For a numerical integration the probability distribution functions of the boundary conditions have to be sampled. Combining the four sampled probability distribution functions, yields a total number of hydraulic calculations to be made. The total number of calculations is set at 6900, which is sufficient for accurate results. The results of these calculations are stored in a database. This database contains the following information : the boundary condition and its probability density, the MSWL, the MRWL at each node of the network model, the hydraulic head and maximum discharges in specific branches of the network model. Two of these databases are made. One database contains information for the situation without a barrier. The other database contains information for the situation with a barrier, which is being closed for every storm surge. By reading both databases and determining if the barrier should have been closed [by comparing the MSWL and the $CL(q)$] a choice for the 'open' or 'closed' data can be made. After reading both databases the probability distribution functions of all

data can be constructed. Because of this separation between calculation and selection, several values for $CL(q)$ and other reliability parameters (see next paragraph) can be used without having to make an extensive calculation. This is very convenient for a sensitivity analysis.

4.2 Integration of reliability aspects

The separation between calculation and selection also offers the possibility of integration of the reliability aspects. By integrating the event tree of figure 10 into the selection program, a probability for each situation ('open' or 'closed') can be calculated. This probability is determined by the $CL(q)$, the accuracy of the PMSL, the unreliability of the barrier (C) and the probability of collapse of the barrier (P_b). If the barrier collapses, the data for the 'open' situation is assumed to be valid. The unreliability C is the probability of not closing the barrier given the fact that the PMSL exceeds the $CL(q)$.

It is clear that the parameters $CL(q)$, the accuracy of the PMSL, the unreliability C and the probability of collapse P_b play a central role in determining the effect of the barrier in terms of DWL and closing frequency. The presented calculation method also provides the possibility of setting targets considering closing criterion, accuracy of PMSL, unreliability and structural strength.

4.3 Sensitivity analysis

Already in an early stage of the project the permissible probability of collapse was fixed at 10^{-6} in any one year. Considering the frequency of DWL for Rotterdam (10^{-4} per year) the effect of P_b can be neglected. The closing criterion $CL(q)$ is set to such a level that the closing frequency is tolerable. This leaves the accuracy and the unreliability as variables. A sensitivity analysis has been carried out considering these two parameters. Initially, the accuracy was set to the properties determined by an analysis of predicted MSWL during the last decades. This analysis showed that the difference between predicted and measured

MSWL could be assumed to have a normal probability distribution with an average (μ) of -20 cm and a standard deviation (σ) of 25 cm. This means that the predictions were on average on the safe side. In figure 11 the sensitivity of the DWL at Rotterdam for the σ is shown. This line shows a very large sensitivity to σ . By using von Kalman filtering, based on on-line measurements during the passage

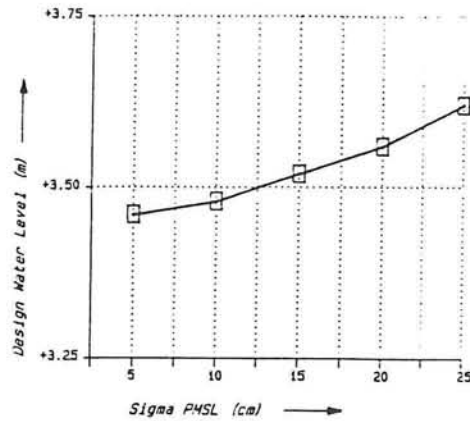


Figure 11

of the

storm at the British east coast and platforms in the North Sea, one believes that σ can be reduced to 15 cm. This value is used for design calculations of the storm surge barrier. The sensitivity of the DWL at Rotterdam for the unreliability is shown in figure 12. This figure shows a sharp increase of sensitivity for values of C larger than 10^{-3} . Therefore the maximum value of C was set to 10^{-3} .

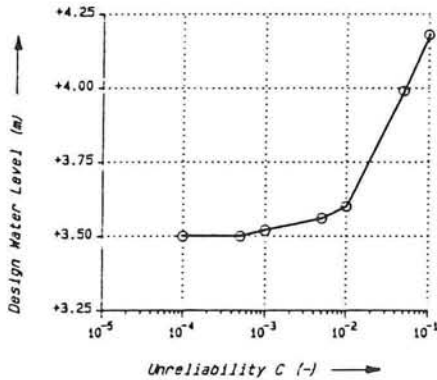


Figure 12

4.4 Results

In the figure 13 the results of a complete calculation for the situation without a barrier are shown. In this figure the probability of exceeding certain water-levels at the locations Hoek van Holland, Rotterdam and Dordrecht is shown. The DWL for these locations are 5.15, 4.80, 3.78 meters. In figure 14 the same lines are shown for the situation with a storm surge barrier. The DWL for Rotterdam and Dordrecht are reduced to 3.52 and 3.15 meters.

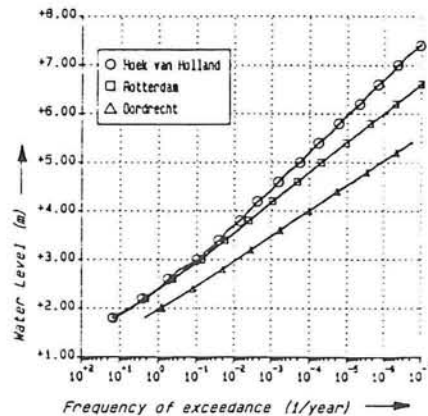


Figure 13

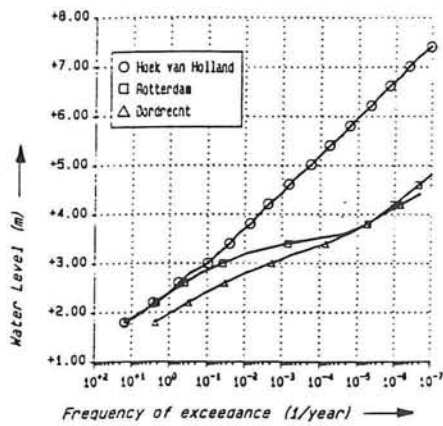


Figure 14

These results show that the prescribed reduction of DWL for the location Dordrecht is not achieved, according to the calculation method with four variables. However, for the calculation of DWL the method with two variables has been applied for all dike reconstruction works up till now. For reasons of continuity this method will be applied for the final stage of the dike reconstruction works as well. Another calculation with only the variables storm surge height and river discharge reduces the DWL for the location Dordrecht to 2.90 meter above NAP. For the location Rotterdam the DWL is reduced to 3.46 meter above NAP. For the situation with a barrier the difference between the results of both calculation methods are increased. Especially for locations, which are relatively far away from the sea. These locations suffer the most from the negative effect of the barrier.

5. Operational aspects

5.1 Specific problems related to operational use of the barrier

During operation decisions have to be made about the closing and opening of the barrier. For both decisions criteria have been set. To close the barrier the PMSL must be higher than the $CL(q)$ and a closing condition (CC) must be actually reached. In the current design the CC depends on the river discharge. For low discharges the CC is a water-level of 2.00 meter above NAP and for high discharges the CC is the local zero inflow condition. It is obvious that these conditions can be met several times during a storm. To prevent high water-levels by unnecessary long closures of the barrier (accumulation of discharge) the closure starts at the last CC before the sea water-level exceeds $CL(q)$.

To open the barrier a opening condition (OC) must be reached and the PMSL may not exceed the DWL any more. The OC is defined to be the

moment when the water-levels on both sides of the barrier are equal. Non-exceedance of the DWL is guaranteed if the PMSL does not exceed the $CL(q)$ any more.

The involvement of predicted water-levels causes some problems. If predictions were precise it would be very easy to pick the right moment to close and open the barrier. In practice however predictions are inaccurate (increasing with time) and also only available for a limited time ahead (at the most 18 hours). This implies that every occurrence of CC or OC in a specific storm is a potential closing or opening moment. Which moment is chosen depends on the outcome of the predicted water-levels. The use of predicted water-levels may even cause the barrier not to be closed at all at the last CC; for example if the predicted (last) CC does not occur in reality. Since this is thought to be unacceptable an extra possibility for closing the barrier is

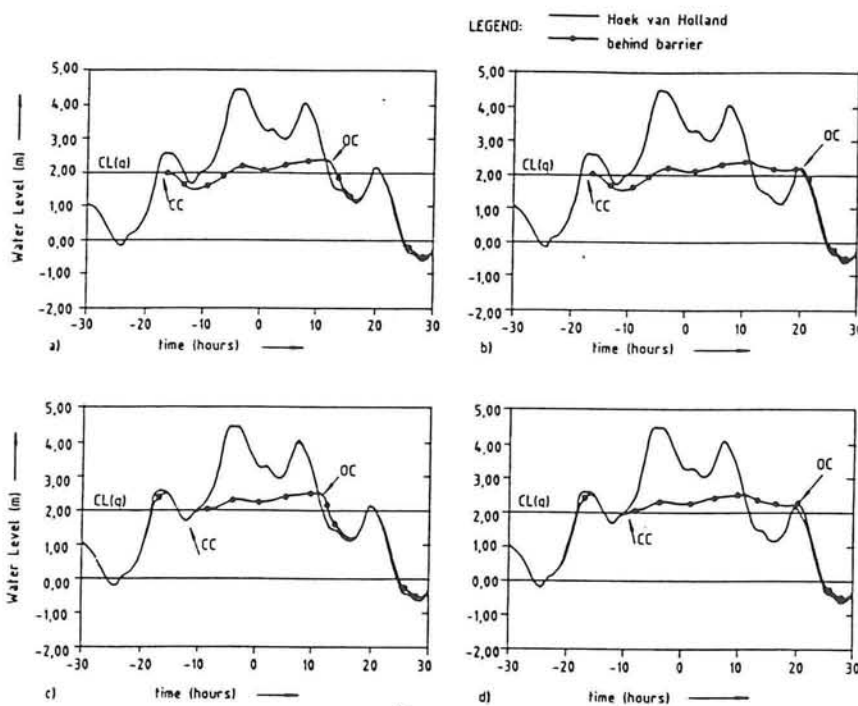


Figure 15

introduced at the lowest water-level after the last CC. Figure 15 illustrates four possibilities for a single storm: so-called realizations. In this case there are two CC that can be combined with two OC. Combination c) illustrates the optimum choice. The model described in the previous paragraphs only includes the optimum closure and opening of the barrier [combination c) in figure 15]. Since other closure or opening moments may generate different MRWL and loads on the barrier a model is developed to include the effect of all possible realizations. The calculation scheme is described in the next paragraph.

introduced at the lowest water-level after the last CC. Figure 15 illustrates four possibilities for a single storm: so-called realizations. In this case there are two CC that can be combined with two OC. Combination c) illustrates the

The calculation method to determine DWL and loads is roughly the same as described in paragraph 4.1. The hydraulic model is used to calculate the water-levels. For every storm all realizations are included. The procedure to generate all realizations for a storm is shown in figure 16.

For every realization the resulting MRWL and loads are determined and stored in a database. The statistical calculation to derive DWL and design loads is based again on numerical integration of all possible combinations. However the important difference with the method described in paragraph 4.1 is that for a single storm more realizations are possible and this requires an extra integration over realizations. The

conditional probability of the realization (for a given storm) is calculated. At the current CC the probability of satisfying the criteria for closing is calculated and the same procedure is followed for the OC with respect to the criteria for opening. In principle more than one predicted high water is considered in calculating this probability. An analysis of predictions during the last decades showed that these predictions were independent. The conditional probability of a realization will depend on the $CL(q)$ level, the height of individual high waters and the accuracy of the predicted water-levels. The probability of a realization is calculated by multiplying the conditional probability with the probability of the boundary conditions. Initially a very fast and simplified open channel network model was used because of calculation time. It appeared that by taking into account realizations the number of calculations increased with a factor 3.5. In the future the more complex model described in section 2.2 will be used. The preliminary results in the next paragraph are based on calculations with the simplified model.

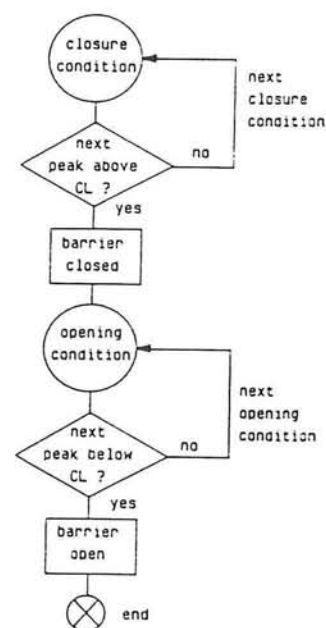


Figure 16

5.3 Preliminary results

The analysis with the model described in section 5.2 was focused on the influence of the operational decisions on DWL and design loads. When a σ of 0.25 meter was used for the accuracy of water-level predictions the following results were found.

- * an 30% increase in closing frequency resulting from more potential closures for every storm
- * no influence on DWL at the representative locations compared to the previous analysis (also including $\sigma = 0.25$ meter)
- * no influence on the positive design head over the barrier
- * an increased negative design head over the barrier (20%) resulting from closures at an earlier moment and/or opening at a later moment.

Influences at other locations and for other parameters could not be determined with the simplified model. This will be analyzed with the complex model.

6. Conclusions

- * The use of large numerical models does not necessarily rule out the use of probabilistic design methods.
- * The accuracy of the predictions of water-levels is of vital importance for the performance of the storm surge barrier.
- * The calculation method of DWL should be based on all governing variables. Reducing the number of variables is only tolerable after a sensitivity analysis. Based on such an analysis the significant value of the variable can be used in the calculation of DWL.
- * The effect of actually operating the storm surge barrier should be included in the design process, also in the phase of determining the boundary conditions.

7. Acknowledgements

It is obvious that the study presented in this paper involves an enormous number of computations. Most of this work is done by mr. Henk de Deugd also from Rijkswaterstaat. The authors are duly grateful for this.

Abbreviations and symbols used in this paper

C	= unreliability	NAP	= reference water-level
CC	= closing condition	OC	= opening condition
CL	= critical water-level at Rotterdam and Dordrecht	p	= phase difference
CL(q)	= critical water-level at Hoek van Holland.	Pb	= probability of collapse
DWL	= design water-level	PMSL	= predicted maximum sea water-level
MRWL	= maximum river water- level	σ	= standard deviation of error in PMSL
MSWL	= maximum sea water-level	q	= river discharge
m	= storm surge height	s	= duration of the storm surge
μ	= average of error in PMSL		

