SAFETY STANDARDS FOR STORM SURGE BARRIERS

A framework for deriving a requirement for structural failure of storm surge barriers

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Safety standards for storm surge barriers

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by

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Cover Figure: Eastern Scheldt Barrier.

Preface

This report is written as part of the master's programme in Civil Engineering at the Delft University of Technology, it serves as the completion of a Master Thesis. The report is intended for readers that are interested in flood risk related safety standards for storm surge barriers in the Netherlands. Prior knowledge regarding this topic helps for understanding the calculations presented in this study.

I express my gratitude to the people that supported me during the writing of this thesis. I would like to thank Cong Mai Van and Richard Jorissen for their support throughout all the stages of this thesis. I am grateful to Bram van Prooijen for his critical review of the report. Rijkswaterstaat provided me with the motivation, the tools, and the opportunities to conduct this thesis, for which I would like to thank Alexander Bakker and Jesse Simonse in particular. I am grateful to Vincent Vuik and Wouter Jan Klerk for their guidance in developing and applying the framework.

Sam De Bruijn,

Delft, September 2025

Summary

This report studies the ability of flood defences to reduce the risk of flooding. Storm surge barriers are a specific type of flood defence. Their function is to reduce the hydraulic loads, the water levels and the wave conditions on the dikes located behind the storm surge barrier. Safety standards for flood defences are established to ensure a minimum level of safety, accounting for the performance of flood defences, which is determined by their probability of failure.

The applicable requirements for storm surge barriers have developed over time. Various assumptions have been made in deriving these requirements, because the applicable standards for flood defences and the corresponding methods to assess their safety have developed. Specifically, assumptions have been made regarding the influence of storm surge barrier performance on the failure probability of dikes. The objective of this study is to build a framework that includes this relationship in a requirement for storm surge barriers.

The framework is built by analysing the relationships that define the flood protection system. It is considered that a reduction in storm surge barrier performance increases the water levels in front of dikes, which increases the dike failure probability and the risk of flooding. The framework built in this study calculates a requirement for structural failure of storm surge barriers based on an economic optimisation at flood protection system level. The dike failure probability is calculated by expressing storm surge barrier performance in terms of water levels in front of the dike and by representing the resistance of a dike to a certain water level using fragility curves. In the next step, investment functions are used to translate failure probabilities into costs to determine the minimum, and therefore optimum, costs at flood protection system level.

The framework is first applied in a generic context to outline the steps and potential applications of the framework. Second, the framework is applied to a schematised representation of the Eastern Scheldt, focusing on the case-specific aspects. The framework is applied to identify the criteria that should be considered in safety standards for storm surge barriers. A requirement for storm surge barriers considers the dike failure probability as a function of storm surge barrier performance. The maximum allowed dike failure probability relates to the maximum allowed consequences of flooding. Furthermore, the variation in dike investment costs compared to the variation in storm surge barrier investment costs is important to derive a requirement that corresponds to an economically optimum flood protection system.

Contents

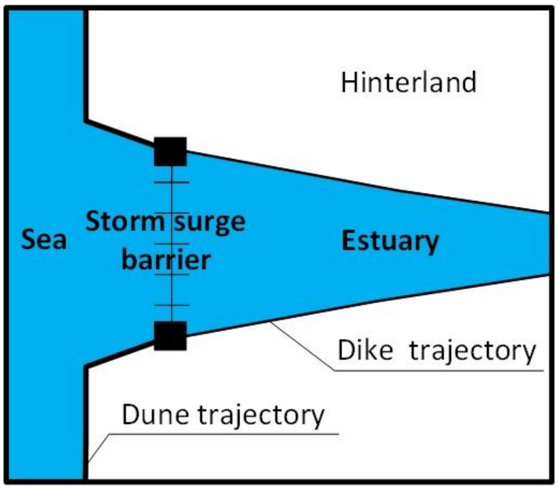
1. Introduction

1.1. Research context

The function of flood defences is to reduce the risk of flooding. They do so by resisting hydraulic loads, which are water levels and wave conditions. In other words, flood defences are designed to prevent water levels and waves from reaching and damaging the area behind them. There are various types of flood defences, each of them has its own role within the flood protection systems shown in Figure 3. Dunes and dikes are located in front of the hinterland; they protect the hinterland directly against hydraulic loads. Figure 1 shows an example of a dike section in the Netherlands. Dunes, typically found along the Dutch coast, are sandy shorelines that function as flood defences.

Figure 1 [Left]: Example of a dike in the Netherlands. Figure 2 [Right]: Eastern Scheldt Barrier.

A storm surge barrier (SSB) is a specific type of flood defence, as it is not constructed to directly protect the hinterland, its function is to reduce the hydraulic loads on dikes. A storm surge barrier does so by closing when a high water level occurs or is predicted. This allows for tidal exchange when the storm surge barrier is opened. As a result of these closure procedures, the maximum water level in the estuary that acts as a load on dikes is reduced. This flood protection system is schematised in Figure 3. The Eastern Scheldt Barrier, an example of a storm surge barrier, is shown in Figure 2.



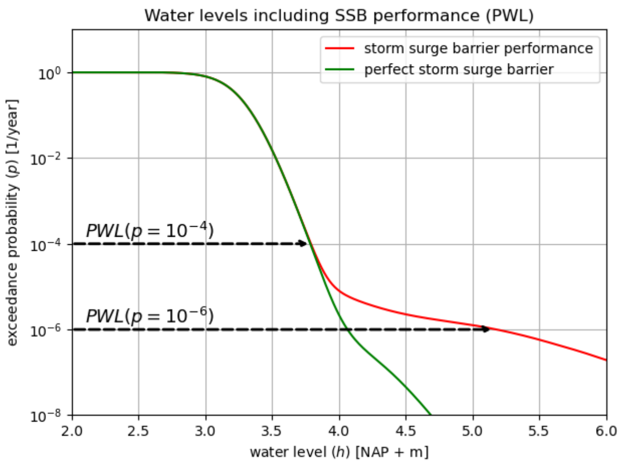


Figure 3 [Left]: Schematisation of a flood protection system with a storm surge barrier. Figure 4 [Right]: Example of water levels at the Eastern Scheldt, location Oesterdam, as a function of storm surge barrier performance using Prespeil.

A storm surge barrier reduces the hydraulic loads, the effectiveness in reducing the hydraulic loads is described by its performance. The performance is limited by the fact that a storm surge barrier does not function perfectly, it is possible that a storm surge barrier is not fully closed during high water. As such, storm surge barrier performance accounts for its probability of failure; the probability that the structure does not fulfil its water-retaining function. There are various causes for a storm surge barrier not performing perfectly. One of these failure mechanisms is the fact that structural parts of a storm surge barrier can fail due to the hydraulic loads acting on the structure. Structural failure is correspondingly defined as loss of water-retaining function by failure of structural parts of the flood defence. In other words, it is possible that structural components of the storm surge barrier fail to prevent water from passing the structure.

The performance of storm surge barriers can be expressed in terms of water levels, of which an example is shown in Figure 4. The performance level (prestatiepeil) is the water level corresponding to a certain exceedance probability, the water level distribution shown in Figure 4 shows a series of water levels calculated while accounting for the fact that a storm surge barrier does not function perfectly. This is illustrated in Figure 4, the red curve, the curve that is determined by its performance, estimates a higher water level than the green curve, the curve that assumes a perfect storm surge barrier. The lower the exceedance probability, which means the larger the expected period over which a certain event is expected to occur, the larger the difference in water level between the two curves.

The probability of failure of a storm surge barrier must be reasonably low to effectively reduce the estuary hydraulic loads. Therefore, a maximum allowable probability of such an event taking place is defined. Such a defined minimum expected performance is prescribed by safety standards. Safety standards ensure that structures are assessed against the probability of a certain unfavourable event occurring. A requirement allows for assessing the performance of storm surge barriers. Additionally, requirements for storm surge barriers define the hydraulic loads that must be accounted for in designing and assessing dikes. It defines which assumed reduction in hydraulic loads is accounted for when verifying the required strength of dikes. Defining requirements for storm surge barriers is thus essential for establishing the context for designing and assessing dikes.

1.2. Problem description

The safety standards used for assessing storm surge barriers in the Netherlands have developed over time. These safety standards can be confusing, as the maximum allowed probability of failure is assigned to different criteria that define failure. Furthermore, these safety standards hold various assumptions. The influence of storm surge barrier performance on the design and assessment of dikes is not derived explicitly, as concluded from the literature review, which is stated in the knowledge gap in Section 2.5. Structural failure of storm surge barriers is of particular interest, as requirements are based on specific assumptions regarding this failure mechanism. This failure mechanism has been treated differently than other storm surge barrier failure mechanisms in safety standards, which introduces additional definitions.

Two recent developments are relevant with respect to safety standards for storm surge barriers and are therefore included in this study.

- New safety standards for designing and assessing flood defences in the Netherlands were introduced in 2017. These new safety standards have introduced additional definitions concerning the effect of storm surge barrier failure on flood risk.
- The water level distributions derived in OBT (2022) for the Eastern Scheldt, of which an example is shown in Figure 4, provide insights into the influence of the performance of the Eastern Scheldt Barrier, and structural failure in particular, on the resulting water levels behind the Eastern Scheldt Barrier.

1.3. Research objective

The objective of this study is to build a framework that calculates the effect of structural reliability of storm surge barriers on dike failure probabilities and that derives a requirement based on this effect. The framework is used to identify criteria that influence this effect and consequently the derived requirement. These criteria are identified for storm surge barriers in the Netherlands in the context of flood risk.

The following main research question is formulated.

What criteria should be considered in safety standards for storm surge barriers?

Three sub-questions are formulated to address the main research question.

1. What criteria have been used in safety standards for storm surge barriers?
2. What aspects describe the effect of storm surge barrier performance on flood risk?
3. What criteria should be considered in a requirement for structural failure of the Eastern Scheldt Barrier?

1.4. Research methodology

Literature is reviewed to identify the criteria that have been used in safety standards for storm surge barriers. This review outlines the definitions and assumptions underlying these safety standards, including the specific definitions and assumptions for different failure mechanisms of storm surge barriers. Based on the literature review, a knowledge gap is identified. This knowledge gap is consulted to identify the aspects to include in the framework.

The framework reflects the relationships that describe the effect of storm surge barrier performance on flood risk. The framework captures the effect of storm surge barrier failure on water levels and the influence of these water levels on the failure probability of dikes along the estuary. The framework provides a mathematical description of these relationships, which is used to derive a requirement for structural failure of storm surge barriers.

The framework is applied to identify the criteria that should be considered in safety standards for storm surge barriers. The framework is applied first in a generic context, focusing on a description of relevant relationships. Furthermore, the relevant aspects to consider in applying the framework are identified. As a next step, the framework is applied to the case study, the characteristics of the Eastern Scheldt are schematised to derive a requirement for structural failure of the Eastern Scheldt Barrier. Based on this application, in combination with a description of the requirements and assessment of the storm surge barrier, the relevant criteria for a requirement for structural failure of the Eastern Scheldt Barrier are discussed.

1.5. Structure report

The first chapter of this report introduces the topic. The second chapter discusses safety standards for storm surge barriers in the Netherlands. The third chapter develops the framework after examining the influence of storm surge barrier performance on the risk of flooding. The fourth chapter applies the framework in a generic context. The fifth chapter applies the framework to the case study. The steps taken regarding the application of the framework are discussed in the sixth chapter. The last chapter presents conclusions and recommendations.

2. Reviewing safety standards

This chapter reviews safety standards for flood defences, with the focus on storm surge barriers. The findings presented in the first three sections are used to present and discuss the requirements for structural failure of the Eastern Scheldt Barrier. In the last section, a knowledge gap is formulated.

2.1. Safety standards for flood defences

This section discusses the old and the new safety standards for flood defences. Leidraad Kunstwerken (LK, 2003) outlines failure mechanisms for storm surge barriers based on the return period of the hydraulic loads defined in safety standards. Werkwijzer Ontwerpen Waterkerende Kunstwerken (WOWK, 2018) includes methods for calculating failure probabilities for flood defences and for the distribution of the maximum allowed failure probability across failure mechanisms.

2.1.1. Introduction on safety standards for flood defences

Hydraulic loads are used for designing and assessing flood defences. In the old safety standards, as applied before 2017, a single exceedance value was used for designing and assessing flood defences in the Netherlands. This included the derivation of one value with a certain return period. This return period was derived per area protected by flood defences and was established by law in Wet op de Waterkering (1996). For example, for the dikes along the Eastern Scheldt, a return period of 4000 years was enforced. Consequently, the dikes along the Eastern Scheldt were designed and assessed to resist the hydraulic loads predicted to occur once in 4000 years.

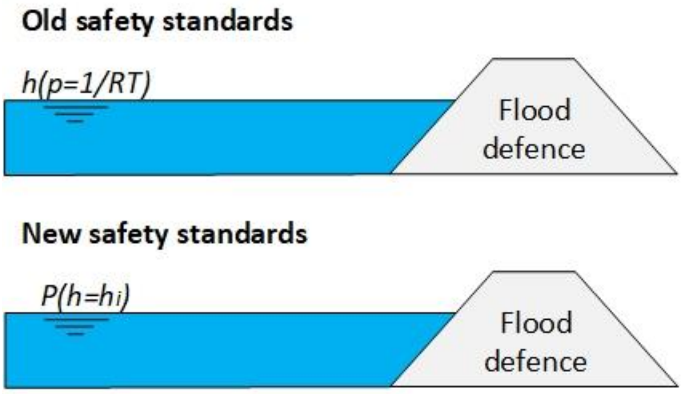


Figure 5: The old safety standards define a return period (RT) of the hydraulic loads. The new safety standards relate to the uncertainty in the occurrence of a certain load (h_i).

Since 2017, safety standards for flood defences in the Netherlands require failure probabilities to be calculated explicitly. In fact, safety standards for flood defences based on failure probabilities were already calculated and proposed based on an economic optimisation in van Dantzig (1956). However, in practice the exceedance probabilities of hydraulic loads were used for designing and assessing flood defences under the old safety standards. The difference between the old and the new safety standards is schematised in Figure 5. In the new safety standards, the complete water level distribution, including the probability of occurrence of water levels, is directly used in designing and assessing flood defences.

Furthermore, the maximum allowed failure probability of flood defences located directly in front of the hinterland is in the new standards explicitly calculated based on the consequences of flooding. This is done by determining the strictest of three criteria (Slootjes & van der Most, 2016).

- **Economic optimisation:** A maximum allowed failure probability is determined based on an optimisation that considers investment costs and risk related costs, which reflects an aversion to high economic damage resulting from flooding.
- **Individual risk:** A maximum allowed failure probability is determined based on the maximum allowed probability of dying due to a flood per person, which reflects an aversion to someone dying resulting from flooding.
- **Societal risk:** A maximum allowed failure probability is determined based on the maximum allowed probability of a certain number of people dying due to a flood, which reflects an aversion to multiple people dying due to a certain flood.

Safety standards for flood defences in the Netherlands are expressed in two failure parameters (Slootjes & van der Most, 2016). These two failure probabilities are assigned to each flood defence trajectory, which is defined as a certain stretch of flood defence along the waterline.

- **Maximum allowable annual probability of failure (Ondergrens):** Failure probability that must not be exceeded. A minimum required reliability.
- **Signal value (Signaleringswaarde):** Probability used for indicating the need to maintain and reinforce flood defences.

2.1.2. Old safety standards for flood defences

LK (2003) defines requirements for moveable flood defences that apply to storm surge barriers. This safety standard prescribes requirements for three failure mechanisms of storm surge barriers. LK (2003) defines these three failure mechanisms as follows.

- **Structural failure:** Failure of structural components resulting in loss of water-retaining function measured at hydraulic boundary conditions corresponding to the safety standard.
- **Operational failure:** Non-closure resulting in exceedance of the maximum inflowing volume.
- **Overtopping failure:** Water passing a closed object resulting in exceedance of the maximum inflowing volume.

In practice, tailored approaches were used to assess storm surge barriers. Fault trees represent the events that lead to the occurrence of the top event and therefore allow for specifying the unique characteristics of storm surge barriers. This approach is exemplified by two examples.

The failure probabilities for different components of the Maeslant Barrier, as derived from design documents, are presented in van Wonderen (2003). Rijkswaterstaat (1986) describes the fault tree used in the design of the Eastern Scheldt Barrier, which includes the calculation of the total failure probability resulting from different failure mechanisms. This fault tree is discussed in more detail in Section 2.4.

Table 1 presents two criteria that are used for defining requirements in LK (2003). The maximum allowable annual failure probabilities per failure mechanism are derived via Equation 1.

$$P_{req,m} = P_{req} * \omega_m \qquad \textit{Equation 1}$$

- $P_{req,m}$ [1/year]: Maximum allowed failure probability of failure mechanism.
- P_{req} [1/year]: Safety standard, return period of hydraulic loads.
- ω_m [-]: Distribution factor of failure mechanisms.

Table 1: Requirements for storm surge barriers in LK (2003).

Criterion	**Failure mechanism (m)**	**ω [-]**
The probability of structural failure must be small because of the uncontrollable situations associated with erosion of the bed protection that result in severe flooding. The structural failure probability must be insignificant compared to the maximum allowed failure probability of the two other failure mechanisms.	Structural failure	0.01
The probability that failure of a storm surge barrier leads to exceeding a maximum inflowing volume must be small. This maximum inflowing volume relates to the storage capacity of the water body, or, in other words, to the maximum allowable estuary water level.	Operational failure Overtopping failure	0.1 1

There are two approaches to check whether the requirement presented in Equation 1 is met. Both approaches are explained using the limit state function presented in Equation 2.

$$Z = R - S \qquad \textit{Equation 2}$$

- Z: Limit state function, failure for $Z < 0$.
- R: Resistance.
- S: Load.

The first approach is a fully probabilistic method. The calculations are performed while considering uncertainty in both load and strength. The failure probability is defined as the probability that the limit state function is smaller than zero ($P(Z < 0)$). This calculated failure probability is verified against the maximum allowed probability of failure per failure mechanism, as defined in Table 1.

The second approach is a semi-probabilistic method. In this method, the safety standard is translated into design values and safety factors per event. The design water level, the load as a function of the safety standard, is used for deriving the required strength of the structure, such that the limit state is greater than zero ($Z(P_{req}) > 0$).

2.1.3. New safety standards for flood defences

WOWK (2018) is a follow-up on LK (2003), including recommendations on using failure probabilities when designing and assessing water-retaining structures. This is reflected in the definition of failure; the maximum inflow of volume is related to the consequences of inflowing volume (i.e., economic damage or fatalities) instead of exceeding a threshold water level.

Equation 3 is used for designing and assessing flood defences according to the new safety standards. The failure probability of a flood defence is distributed over different failure mechanisms. A prescribed distribution of failure mechanisms is shown in Figure 6. A length effect is prescribed per failure mechanism of flood defences.

$$P_{req,m} = \frac{P_{req} * \omega_m}{N_m}$$ *Equation 3*

- $P_{req,m}$ [1/year]: Maximum allowed failure probability of failure mechanism at cross section level.
- P_{req} [1/year]: Safety standard, maximum allowed probability of failure, of flood defence trajectory.
- ω_m [-]: Distribution factor of failure mechanisms.
- N_m [-]: The length effect considers the variations in load and resistance along a flood defence trajectory per failure mechanism. Load and resistance are not the same for every inspected cross section.

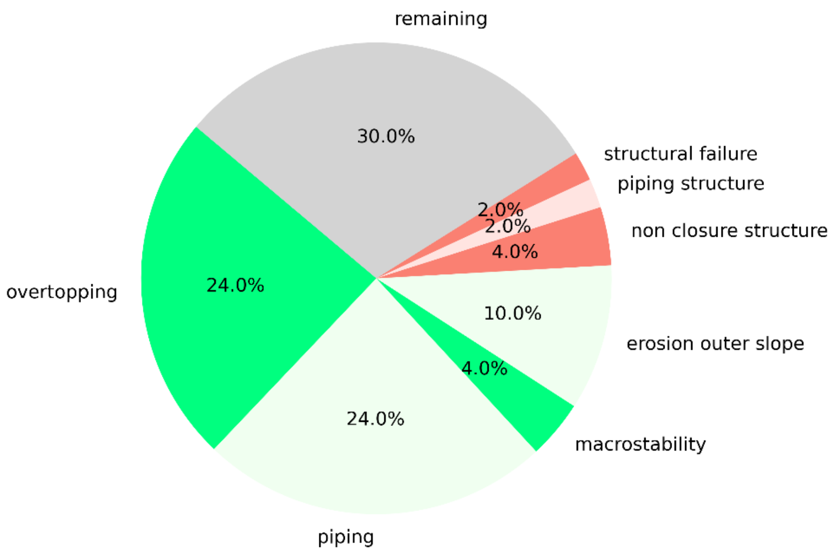


Figure 6: Default distribution of the maximum allowed failure probability across failure mechanisms as prescribed for dike trajectories in Handreiking ontwerpen met overstromingskansen (2014).

So far, the standards of the Water Act (Waterwet) have been discussed. When designing water-retaining structures, both the Water Act and the Building Decree (Bouwbesluit) are to be used. The Building Decree imposes the design of structural components, including components with a non-water-retaining function. So, if a structural component fulfils a water-retaining function, a check on both the Water Act and the Building Decree is important. Such a check is relevant on two scales; the Water Act is imposed at trajectory level, and the Building Decree is imposed per component and per structure (WOWK, 2018).

Another difference between the two standards is the reference period used in requirements. The Water Act defines requirements that must be complied with every year, the annual failure probability must every year be lower than as maximally allowed. The Building Decree defines requirements with respect to the lifetime of the structure, the total failure probability during the entire lifetime of the structure is assessed (WOWK, 2018).

In the Building Decree, the reliability index, a measure for the level of safety used in design, is used to determine load and resistance. This reliability index is based on the consequence class, the larger the consequences, the higher the consequence class, the higher the required reliability index, and the higher the load used in designing structural components.

WOWK (2018) shows how the maximum allowed failure probability is used to determine loads for designing structural components according to the Water Act using safety factors. Consequently, the semi-probabilistic design is governed by the stricter of the two standards. These design principles are summarised in Figure 7.

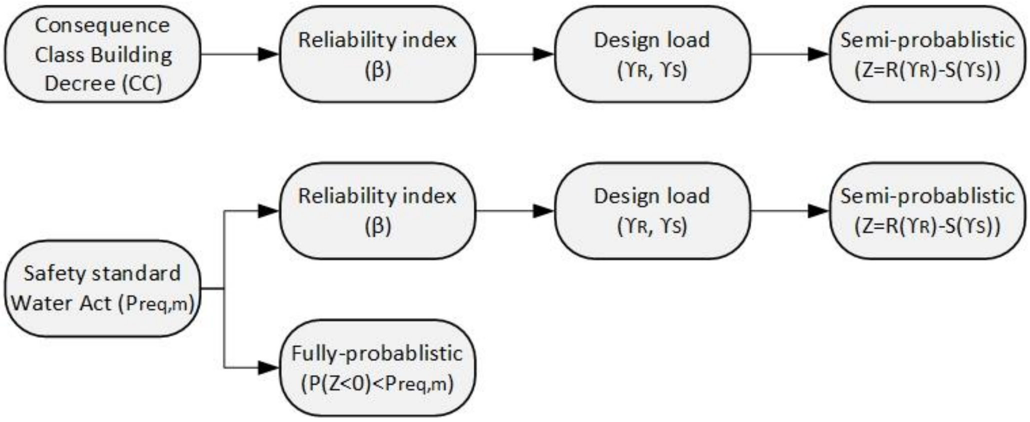


Figure 7: Design methods for structural failure of flood defences via Building Decree and Water Act.

2.2. Safety standards for storm surge barriers

This section discusses safety standards for storm surge barriers. The approach and formulas used for calculating a safety standard for storm surge barriers are important for the safety standards as established in Dutch law.

2.2.1. Approach for deriving safety standards for storm surge barriers

For deriving safety standards for storm surge barriers, the effect of storm surge barrier performance on the hydraulic loads on dikes is considered. Safety standards are in Jongejan (2015) derived to allow for neglecting the contribution of storm surge barrier performance to the dike failure probability. Two reasons are identified that explain why this approach is considered.

- The failure probabilities of dikes, and thus the safety standards of dikes, do not need to be recalculated for considering the effect of a different storm surge barrier performance. In other words, this approach aligns with the dike safety standards that have been derived while accounting for a certain storm surge barrier performance.
- It is assumed that the investments in keeping the storm surge barrier up to standard are lower than the investments in dike strengthening prevented by keeping the storm surge barrier up to standard. In other words, it is assumed economically preferable to have a negligible storm surge barrier failure probability.

2.2.2. Derivation of safety standards for storm surge barriers

A safety standard that calculates the maximum allowed annual probability of failure for storm surge barriers is derived in Jongejan (2015). A safety standard is derived based on the assumption that the failure probability of a storm surge barrier ($\mathrm{P(F_{SSB})}$) must have a small influence on the calculated failure probability of dikes ($\mathrm{P(F_{dike})}$). This principle is illustrated in Figure 8, the probability of a scenario where both dike and storm surge barrier fail ($\mathrm{P(F_{dike}) \cap P(F_{SSB})}$) must be small with respect to the probability of the scenario where the dike fails, while the storm surge barrier does not fail ($\mathrm{P(F_{dike}) \cap P(\overline{F_{SSB}})}$).

$$\mathrm{P(F_{dike}) = P(F_{dike}) \cap P(F_{SSB}) + P(F_{dike}) \cap P(\overline{F_{SSB}}) =} \\ \mathrm{P(F_{dike}|F_{SSB}) * P(F_{SSB}) + P(F_{dike}|\overline{F_{SSB}}) * P(\overline{F_{SSB}})} \qquad \textit{Equation 4}$$

A criterion is correspondingly defined by stating that the left term in Equation 4 must be less than 10 per cent of the right term of this equation, as shown in Equation 5. This threshold assumes that the probability of flooding can practically not be calculated within this margin of 10 per cent (Jongejan, 2015).

$$P(F_{dike}|F_{SSB}) * P(F_{SSB}) < 0.1 * P(F_{dike}|\overline{F_{SSB}}) * P(\overline{F_{SSB}})$$ *Equation 5*

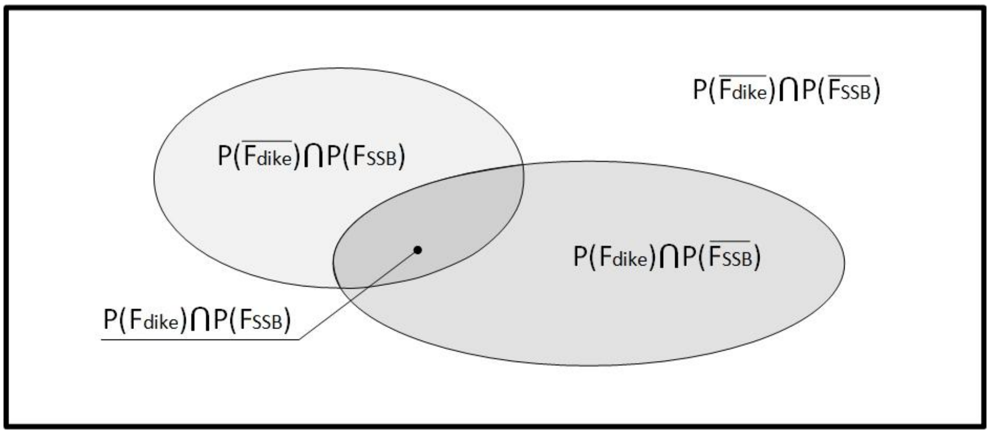


Figure 8: Venn diagram illustrating the failure scenarios for a flood protection system with a storm surge barrier.

The expression in Equation 5 is simplified further. The probability of storm surge barrier failure is assumed to be small ($P(\overline{F_{SSB}}) = 1$). The maximum allowable annual probability of failure ($P_{req,dike}$) is assigned to the dike failure probability given no storm surge barrier failure ($P(F_{dike}|\overline{F_{SSB}})$), implying that the dike failure probability is fully governed by this term. As a result of these assumptions, a maximum allowable failure probability for a storm surge barrier is derived via Equation 6.

$$P_{req,SSB} = \frac{P_{req,dike}}{10 * P(F_{dike}|F_{SSB})}$$ *Equation 6*

- $P_{req,SSB}$ [1/year]: Maximum allowed annual probability of storm surge barrier failure.
- $P_{req,dike}$ [1/year]: Maximum allowed annual probability of dike failure. This parameter is determined by the strictest safety standard of the dike trajectories along the estuary.
- $P(F_{dike}|F_{SSB})$ [-]: The conditional failure probability of a dike given failure of the storm surge barrier.

2.2.3. Safety standards for operational failure of storm surge barriers

For storm surge barriers, it is considered infeasible to neglect the effect of the operational failure probability on the hinterland (Kramer & van der Most, 2014). An additional requirement is prescribed for operational failure of storm surge barriers. The requirement defined by Equation 6 applies to failure in closed state, implying that failure due to non-closure is not assessed via this safety standard.

This additional safety standard for operational failure models the probability of non-closure in the hydraulic loads behind the storm surge barrier. These hydraulic loads, thus the hydraulic loads including the effect of operational failure, are used when designing and assessing dikes. For storm surge barriers that allow for defining a unique relationship between storm surge barrier failure and resulting water levels, a criterion is defined by the maximum allowable probability of non-closure of storm surge barriers per request. This maximum allowed operational failure probability determines the hydraulic loads used for designing and assessing dikes (Jongejan, 2015).

This unique relationship cannot be defined for the Eastern Scheldt Barrier. Therefore, a tailored approach is used that assesses operational failure while considering all sixty-two gates of the Eastern Scheldt barrier. This approach is described in Subsection 2.3.1.

2.3. Safety standards based on estuary water levels

Storm surge barrier performance is described in terms of resulting water levels. Subsection 2.3.1 discusses the calculation of water levels at the Eastern Scheldt. A requirement is derived by expressing the performance of the Eastern Scheldt Barrier in terms of water levels at the Eastern Scheldt. Subsection 2.3.2 describes a tool that is used in the Netherlands for calculating water levels. Hydra-NL is used for deriving hydraulic boundary conditions that are used for designing and assessing flood defences.

2.3.1. Water levels at the Eastern Scheldt

The water levels as a function of storm surge barrier performance are used for assessing the performance of the Eastern Scheldt Barrier by accounting for the number of gates that fail per storm event. These water levels are in recent studies calculated using Prespeil (Saman, 2017). This model uses hydraulic boundary conditions at sea, wind conditions, and failure probabilities of the storm surge barrier to calculate water levels in front of dikes along the Eastern Scheldt.

Two approaches for interpreting the results are discussed, the difference between the approaches is explained by the new safety standards in place since 2017. In the old safety standards, a single water level corresponding to the return period established by law was derived. The performance levels (prestatiepeilen) were derived for locations along the Eastern Scheldt in van Manen (2008), these water levels are shown in Figure 10.

This study found that for the most normative location along the Eastern Scheldt, the water level corresponding to a 4000-year return period was 8 cm higher than the water level for modelling a perfect storm surge barrier. Furthermore, the calculated water levels were lower than the water levels used at that time for designing and assessing flood defences. For the normative location, the water level used for assessing flood defences prescribed in Hydraulische Randvoorwaarden (2001) was 8 cm higher than the water level that accounts for storm surge barrier performance that is shown in Figure 10.

	Bemand	Onbemand
0 schuiven	9.71E-01	9.13E-01
1 schuif	2.53E-02	7.75E-02
2 schuiven	1.27E-03	4.09E-03
3-5 schuiven	9.33E-05	1.24E-03
6-10 schuiven	3.13E-04	6.96E-04
11-16 schuiven	3.89E-04	5.40E-04
Halve kering	1.83E-03	1.89E-03
Driekwart kering	1.39E-07	2.79E-07
Hele kering	2.08E-04	7.19E-04

Locatie	Huidig prestatiepeil
Roompot Buiten	4,86
Roompot Binnen	3,15
Burghsluis	3,16
Wemeldinge	3,48
Rattekaai	3,77
Marollegat	3,82
Stavenisse	3,43
Philipsdam West	3,62
Colijnsplaat	3,20
Zeelandbrug Noord	3,22

Figure 9 [Left]: Prespeil input: Non-closure probabilities for different numbers of gates that fail, with and without staff availability (van Manen, 2008). Figure 10 [Right]: Prespeil output: Performance water levels per location along the Eastern Scheldt in metres above NAP (van Manen, 2008).

The water level distributions as a function of storm surge barrier performance were revisited in OBT (2022), including an interpretation of the water level distributions conforming to the new safety standards. The water levels are produced based on the same principles as used in van Manen (2008). Prespeil was built based on the same database of hydraulic boundary conditions (i.e., IMPLIC). The non-closure probabilities of the storm surge barrier shown in Figure 9 are updated based on recent studies.

A notable difference between the two approaches is the inclusion of structural failure probabilities. The structural reliability was included in deriving water level distributions in OBT (2022). In van Manen (2008), the structural reliability was not included in the derivation of water levels, under the implicit assumption that it does not influence the results (Vuik et al., 2021).

The performance of the Eastern Scheldt Barrier is assessed according to the following criterion (Duits & Vuik, 2022):

The performance level (prestatiepeil) may not exceed the assessment level (beoordelingspeil) in the hinterland.

This interpretation is understood graphically via Figure 11; the green dotted curve may not be exceeded by the red curve at the intersection of the black dotted lines. This criterion must be fulfilled for all selected locations along the Eastern Scheldt. An explanation of the curves and terms in Figure 11 is listed.

- **Reference level (Referentiepeil, green):** Water level for assuming a perfect storm surge barrier.
- **Assessment level (Beoordelingspeil, green dotted):** Reference level including a 0.1-metre operation margin (beheerruimte).
- **Performance level (Prestatiepeil E-M, blue):** Water level resulting from electrical (E), and mechanical (M) failure.
- **Performance level (Prestatiepeil E-M-S, red):** Water level resulting from storm surge barrier failure. Thus, including electrical (E), mechanical (M), and structural failure (S).
- **Maximum allowable annual probability of failure (Ondergrens, black dotted):** Failure probability of dike trajectory that must not be exceeded.
- **Signal value (Signaleringswaarde, black dotted):** Standard for dike trajectories used for indicating the need to maintain and reinforce flood defences.

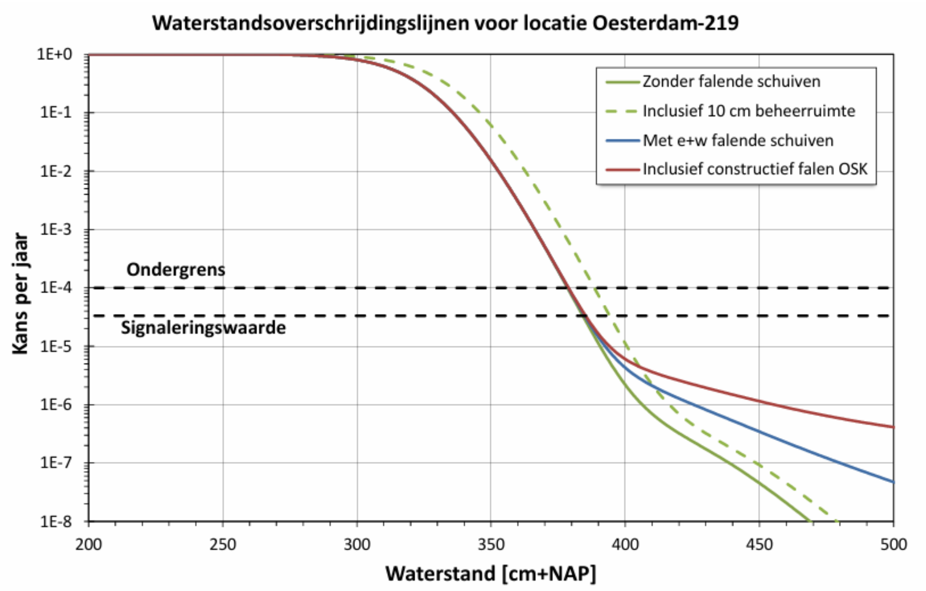


Figure 11: Prespeil output: Water level distribution including storm surge barrier performance at the Eastern Scheldt, location Oesterdam (Duits & Vuik, 2022). The exceedance probability is plotted against water level.

This safety criterion verifies the magnitude of the effect of storm surge barrier performance at the two probabilities defined by the safety standards for all flood defence trajectories along the estuary. The maximum allowable magnitude of this effect is defined by a practical 0.1-metre operation margin. This 0.1-metre operation margin is an agreement between the responsible authorities for both dikes and storm surge barrier (Vuik et al., 2021). It is the maximum allowed increase in water levels that must be provided and operated by the responsible authority of the Eastern Scheldt Barrier.

2.3.2. Water levels calculated using Hydra-NL

Hydra-NL is a tool for probabilistically assessing flood risk for dikes in the Netherlands (Duits, 2020). It provides water level distributions for various locations in the Netherlands. Hydra-NL provides similar results as Prespeil for the Eastern Scheldt; however, it does not consider structural failure in deriving hydraulic boundary conditions. Hydra-NL calculates the hydraulic boundary conditions as a function of mechanical and electrical failure (E-M failure), of which an example is presented in Figure 12. Hydra-NL uses a different database (i.e., WAQUA) than Prespeil (i.e., IMPLIC). Therefore, the water level calculated per exceedance probability differs between Prespeil and Hydra-NL.

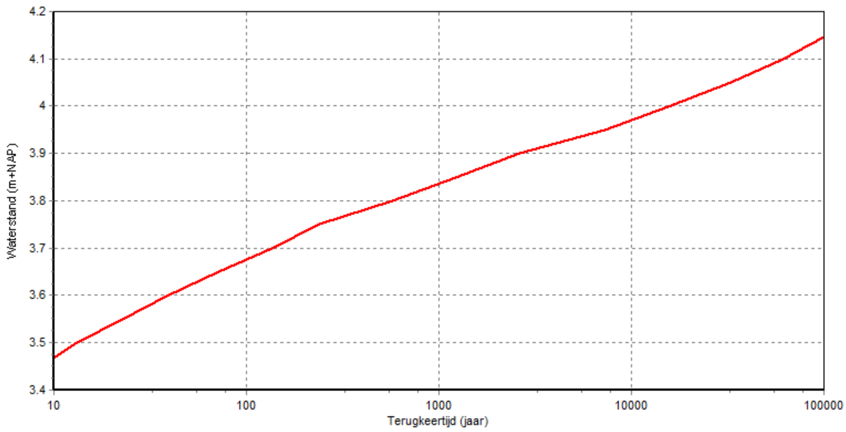


Figure 12: Water level [NAP + m] as a function of return period [year] calculated for a location near Oesterdam via Hydra-NL.

Hydra-NL is used in this study for providing insights into the effect of different storm surge barrier failure scenarios on hydraulic boundary conditions. This is done by altering the input file containing non-closure probabilities presented in Table 2. This allows for calculating hydraulic loads, water level, wave height, and wave period as a function of the operational reliability of the Eastern Scheldt Barrier. The assessment mode in Hydra-NL is used in this study for performing calculations.

Table 2: Non-closure probabilities on demand of the Eastern Scheldt Barrier in Hydra-NL, presented for different fractions of the total of sixty-two gates that fail with and without staff availability.

Number of gates that fail	**0**	**16**	**31**	**62**
Staff available	9.99E-01	1.15E-03	1.70E-04	2.05E-05
No staff available	9.95E-01	3.58E-03	2.31E-04	7.53E-04

2.4. Safety standards for structural failure of the Eastern Scheldt Barrier

The requirements and corresponding definitions for structural failure of storm surge barriers have developed over time. This section presents a timeline of the established safety standards for structural failure of the Eastern Scheldt Barrier. The five moments in the timeline presented in Figure 13 are discussed in this section.

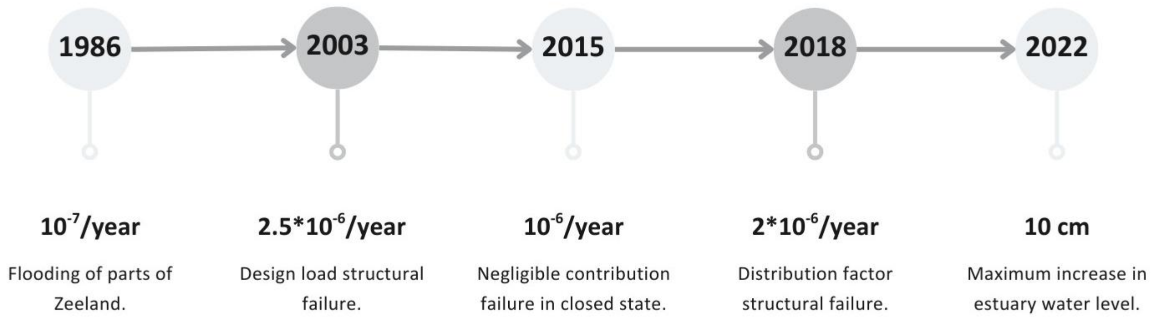


Figure 13: Timeline illustrating the development of the requirement for structural failure of the Eastern Scheldt Barrier.

Flooding of parts of Zeeland

The original design of the Eastern Scheldt Barrier was verified against the occurrence of the top event: flooding of parts of the province of Zeeland. A fault tree identifies the events leading to the occurrence of the top event. Rijkswaterstaat (1986) describes the fault tree used in designing the Eastern Scheldt Barrier. The maximum allowed annual probability of occurrence of this top event is calculated using Equation 7.

$$P_{flood,req} = \frac{IR_{req}}{N_{flood}} = \frac{10^{-4}}{10^{3}} = 10^{-7}$$ *Equation 7*

- $P_{flood,req}$ [1/year]: The maximum allowable annual probability of flooding.
- $IR_{req} = 10^{-4}$ [person/year]: The maximum allowable annual individual risk of dying.
- $N_{flood} = 1000$ [person]: The number of fatalities that are estimated if the top event takes place.

This requirement is satisfied when the assembled failure probability, the failure probability as a function of all events contributing to the occurrence of the top event, is lower than 10^{-7}. Events related to structural failure were integrated in the fault tree. One of the two events in Table 3 must occur to trigger the top event. The first event relates to loss of water-retaining function, the second event concerns an increase in estuary water level.

Table 3: Events contributing to flooding of parts of Zeeland in Rijkswaterstaat (1986).

Event	Contributing failure events
A flood occurs due to failure of the storm surge barrier, causing immediate failure of dikes close to the storm surge barrier.	Failure probability of $0.9*10^{-7}$ for failure of top layer or piers leading to failure of the dams that connect the storm surge barrier to the adjacent islands.
The water level in the estuary exceeds the threshold value: NAP + 4.3 m.	Failure probability based on the events contributing to an increase in estuary water level. The operational failure probability depends on the closure procedure.

The structure was designed to comply with the requirement in Equation 7. This was done by defining maximum allowable probabilities of failure of events within the fault tree. The Eastern Scheldt Barrier was designed to withstand the hydraulic loads corresponding to the 4000-year return period. Safety factors were used to correct for the maximum allowed failure probability of events within the fault tree.

Design load structural failure

LK (2003) includes requirements for storm surge barrier failure mechanisms. These requirements were derived relative to the safety standard; this safety standard corresponds to the return period of the hydraulic loads used for designing and assessing flood defences. For the Eastern Scheldt Barrier, a maximum allowed probability of structural failure is derived via Equation 1.

$$P_{req,sf} = P_{req} * \ \omega_{sf} = \frac{1}{4000} * 0.01 = 2.5 * 10^{-6}$$

Equation 1

- $P_{req,sf}$ [1/year]: Maximum allowed failure probability of structural failure.
- $P_{req} = \frac{1}{4000}$ [1/year]: Safety standard for hydraulic loads from the North Sea (van der Want, 2010).
- $\omega_{sf} = 0.01$ [-]: Distribution factor for structural failure (see Table 1).

A low distribution factor implies that the allowed probability of structural failure is low relative to other storm surge barrier failure mechanisms. This safety standard is implemented in the design via safety factors. Hydraulic loads are corrected to ensure a sufficiently safe approximation (LK, 2003). Structural failure is not assessed for hydraulic loads with larger return periods than the one defined by the safety standard, which corresponds to the definition of structural failure provided in Subsection 2.1.2.

Negligible contribution failure in closed state

The maximum allowed probability of storm surge barrier failure derived in Jongejan (2015) is important, as it examines the relation between dike failure probability and storm surge barrier performance. This step is essential because the philosophy of assessing flood defences based on failure probabilities is embedded in the new safety standard. Therefore, it is not sufficient anymore to relate storm surge barrier performance solely to estuary water levels.

A requirement is calculated using Equation 6, it calculates the maximum allowed annual probability of storm surge barrier failure. Three assumptions are made in deriving and assessing this safety standard for the Eastern Scheldt Barrier.

$$P_{req,SSB} = \frac{P_{req,dike}}{10 * P(F_{dike}|F_{SSB})} = \frac{\frac{1}{3000}}{10 * \frac{1}{3}} = 10^{-4}$$

Equation 6

- $P_{req,SSB}$ [1/year]: Maximum allowed annual probability of storm surge barrier failure. In the assessment in OBT (2022), it is assumed that failure in closed state occurs if at least 1 of the total sixty-two gates fails. This definition corresponds to loss of water-retaining function.
- $P_{req,dike} = \frac{1}{3000}$ [1/year]: Maximum allowed annual probability of dike failure, as determined in 2015 (Jongejan, 2015). Currently, the normative dike safety standard equals 1 in 10,000 years (see Table A.3). This implies that the maximum allowed probability of storm surge barrier failure is lower when the current dike safety standards are plugged into the equation.
- $P(F_{dike}|F_{SSB}) = \frac{1}{3}$ [-]: The conditional failure probability of a dike given failure of the storm surge barrier (Jongejan, 2015).

This required maximum allowed failure probability is defined in the Water Act; this means that the value of 10^{-4} is enforced by law for failure in closed state. It is assumed that complying with this requirement allows for neglecting the effect of failure in closed state when calculating the dike failure probability. A requirement for structural failure is derived using distribution factors. For a distribution factor of 1 per cent, as defined in LK (2003), the maximum allowed annual probability of structural failure is derived at 10^{-6}.

The influence of storm surge barrier performance on the dike failure probability is fully captured through the estimated conditional failure probability (i.e., $P(F_{dike}|F_{SSB})$). This estimate is supported by a sensitivity study that considers the sensitivity of this requirement to changes in this conditional failure probability. For example, a less strict requirement, a maximum allowed annual probability of storm surge barrier failure of 1 in 3,000, is derived for a conditional failure probability equal to 1 in 6 (Jongejan, 2015).

Distribution factor structural failure

A requirement for structural failure from WOWK (2018) is derived based on the requirement established in Jongejan (2015) for storm surge barriers. WOWK (2018) prescribes the distribution of the safety standards derived for flood defence trajectories over different failure mechanisms. This is shown in Equation 8 for structural failure, which is the same equation as Equation 3 but includes a correlation factor. Note that the distribution factor for structural failure is in the same order of magnitude as the one prescribed in LK (2003), although its interpretation is different.

$$P_{req,sf} = \frac{P_{req,SSB} * \omega_{sf} * c}{N_{sf}} = \frac{10^{-4} * 0.02 * 3}{3} = 2 * 10^{-6}$$ *Equation 8*

- $P_{req,sf}$ [1/year]: Maximum allowed failure probability of structural failure at cross section level.
- $P_{req,SSB} = 10^{-4}$ [1/year]: Maximum allowed failure probability of storm surge barrier, according to Equation 6.
- $\omega_{sf} = 0.02$ [-]: Distribution factor structural failure (see Figure 6).
- $c = 3$ [-]: Correlation factor between overtopping and structural failure via WOWK (2018). This factor allows for calculating the probability of structural failure given no overtopping failure.
- $N_{sf} = 3$ [-]: Length effect via WOWK (2018). A small length effect for structural failure implies a small variation in load and strength over the flood defence trajectory.

This safety standard corresponds to a probabilistic assessment of the structural failure probability of the storm surge barrier. A small distribution factor is recommended for structural failure of structures within a flood defence trajectory, since 2 per cent of the total safety standard is prescribed for this failure mechanism. As part of assessment, it is possible to change the distribution factor. The distribution factor is prescribed but is not a strict requirement. The flood defence must ultimately be verified against the safety standard for the flood defence trajectory, as derived via Equation 6. For example, an explicit distribution of failure probability over failure mechanisms is not considered in the assessment performed in OBT (2022), the length effects and relevant failure mechanisms are considered in the calculated failure probability in closed state of the flood defence trajectory.

Maximum increase in estuary water level
The Eastern Scheldt Barrier is assessed based on estuary water levels. A criterion imposes the maximum allowed increase in water level resulting from the storm surge barrier not performing perfectly. This additional requirement, the requirement defined in Equation 6 is still in place, explicitly evaluates the consequences of storm surge barrier performance by calculating the resulting water levels. Furthermore, this requirement does not require the number of gates that fail to be included in a definition for storm surge barrier failure. In OBT (2022), a criterion is defined as a maximum allowed increase of 10 centimetres in water level resulting from storm surge barrier performance. The calculated water levels include contributions of all storm surge barrier failure mechanisms.

It is not possible to apply this criterion to the entire water level distribution, because the water levels with a low probability of occurrence are higher when storm surge barrier performance is accounted for. This is illustrated in Figure 11, the red curve surpasses the green dotted curve for a certain exceedance probability smaller than the signal value. The requirement for the Eastern Scheldt is assessed at the two exceedance probabilities defined in dike safety standards: the maximum allowable annual probability of failure and the probability corresponding to the signal value. It is noted that these two probabilities are defined at trajectory level, whereas the water level distributions are calculated per dike cross section. A distribution of the failure probability at trajectory level across dike sections and failure mechanisms according to Equation 3 is not made in this requirement.

Based on this discussion, it is concluded that this criterion aligns with the old safety standards, as the hydraulic loads are solely assessed at the frequencies corresponding to the dike safety standards at trajectory level. According to the new safety standards, the entire water level distribution is used when calculating the failure probability of flood defences. Therefore, this criterion does not consider an explicit translation of storm surge barrier performance towards dike failure probabilities.

2.5. Knowledge gap

In the new safety standards, flood defences are assessed based on their probability of failure. The dike failure probability, which is determined by the hydraulic loads used in designing and assessing dikes, depends on the performance of a storm surge barrier. Based on the literature reviewed in this chapter, it is concluded that in requirements for storm surge barriers no explicit calculations are made on the effect of the performance of a storm surge barrier on the resulting dike failure probability or on the consequences of flooding. The framework presented in Section 3.3 outlines the steps to include these explicit calculations in deriving requirements for storm surge barriers.

3. Building the framework

This chapter presents a framework that provides the steps to calculate a requirement for storm surge barrier performance. The framework is built based on relevant definitions and theory, which are discussed in this chapter. The framework is presented and described mathematically in the third section. The last section discusses the limitations of the framework.

3.1. Definition of failure for flood defences

For describing the flood protection system, it is important to understand the definition of failure for flood defences. The most recent definitions are listed in Artikel 2.0c of Besluit kwaliteit leefomgeving (2025). A distinction is made between defining failure for storm surge barriers and for dike trajectories. For dike trajectories, the maximum allowable annual probability of failure is defined as follows:

The maximum allowable annual probability of loss of water-retaining function, leading to flooding of the area protected by the dike trajectory in such a way that it results in fatalities or substantial economic damage.

Failure of dikes thus relates directly to the consequences of flooding. For defining storm surge barrier failure, it is understood that loss of water-retaining function does not directly lead to an increase in fatalities or economic damage. The maximum allowable annual probability of failure is defined as follows (Besluit kwaliteit leefomgeving, 2025):

The maximum allowable annual probability of loss of water-retaining function, leading to a substantial increase in hydraulic loads on the dike trajectories behind the storm surge barrier.

This criterion defines the function of a storm surge barrier; it reduces the hydraulic loads on dikes. A precise definition of “a substantial increase in hydraulic loads’’ is not provided, interpretations of this criterion differ per case.

The limit state function described by Equation 2 relates solely to loss of function, a translation towards risk is not included. The calculation of a failure probability for a certain failure mechanism is understood in this context. The limit state function is in line with the failure definition for dike trajectories when assuming that loss of water-retaining function directly results in a flood. The following definitions correspond to the use of limit state functions, which is the approach followed in this report.

- **Flood defence failure:** Loss of water-retaining function.
- **Failure probability:** The annual probability of loss of function.
- **Maximum allowable probability of failure:** The safety standards for flood defences as reported in Appendix II of Besluit kwaliteit leefomgeving (2025).
- **Flood:** Loss of water-retaining function, resulting in consequences.
- **Consequences:** Substantial economic damage and/or fatalities due to a flood.
- **Flood risk:** The product of failure probabilities and consequences.

3.2. Description of elements flood protection system

The fault tree depicted in Figure 14 presents the events that cause flooding for flood protection systems with a storm surge barrier. The fault tree highlights that the studied combination of failure of a storm surge barrier and failure of a dike trajectory is one event that leads to a flood, this event is highlighted by the bolded line in Figure 14. It is important to note that an area can flood without failure of a storm surge barrier. In fact, the failure probability of a dike depends on whether the storm surge barrier has failed and to what extent failure influences the hydraulic loads on the dike.

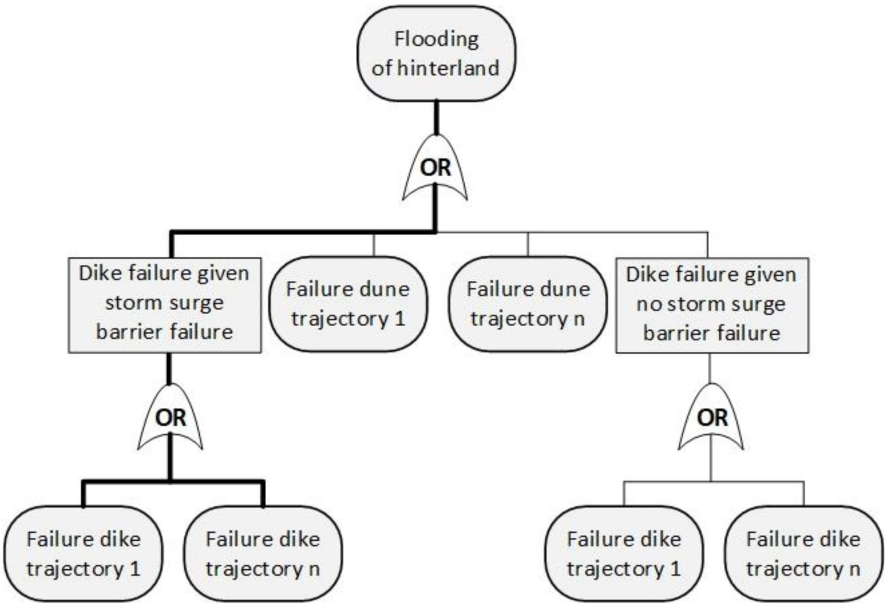


Figure 14: Fault tree depicting events that lead to flooding. The elements of the flood protection system are identified from Figure 3.

The event of interest in this study considers the cross section shown in Figure 15. The flood protection system is defined such that the consequences of flooding for the hinterland depend on the characteristics of the elements in front of the hinterland. This section describes the aspects of the elements of the flood protection system that are relevant for this study. The system consists of four elements: storm surge barrier, water level, dike, and hinterland. The following definitions are used for describing the elements depicted in Figure 15.

- **Failure mechanism:** Failure of flood defences is initiated by failure mechanisms. Failure is defined as the load exceeding the resistance, as expressed by Equation 2.
- **Load:** The parameters that increase the probability of failure of flood defences. For flood defences, relevant hydraulic loads are water levels and waves.
- **Resistance:** The parameters that reduce the probability of failure of flood defences. The geometry and material strength of flood defences determine the resistance.

Figure 15: Cross section depicting the elements of the flood protection system.

3.2.1. First line of flood protection system: Storm surge barrier

The moveable parts of storm surge barriers can fail due to three failure mechanisms, as identified in Subsection 2.1.2. The relevant aspects of these failure mechanisms are listed below.

- **Structural failure:** Structural components are designed to withstand offshore hydraulic boundary conditions.
- **Operational failure:** Non-closure during operation of gates depends on mechanical and electrical failure. Failure is assumed to be independent of hydraulic loads.
- **Overtopping failure:** The height of the structure must be sufficient to resist overtopping failure due to hydraulic loads.

Structural failure is specified further as failure of the storm surge barrier is caused by failure of a component of the structure, which implies failure of a gate of the structure. This scheme is illustrated in Figure 16. Failure of structural components induces failure of the flood defence trajectory and increases the hydraulic loads behind the storm surge barrier. The structural components are therefore designed to resist the offshore hydraulic boundary conditions. The resistance of structural components to failure is increased by increasing the material strength and changing the geometry of these components.

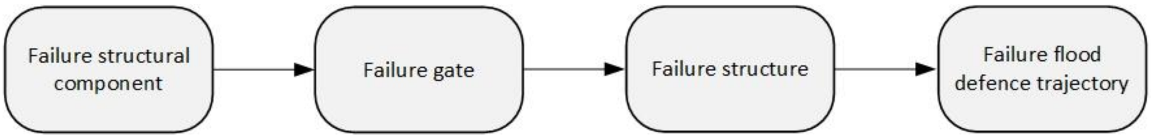


Figure 16: Steps from failure of a structural component towards failure of a flood defence trajectory.

3.2.2. Hydraulic loads behind storm surge barrier

The hydraulic loads behind the storm surge barrier are a result of its performance, accounting for the significance of the reduction in offshore hydraulic loads. When translating these loads to a location in front of a dike, other aspects are relevant. Three of these aspects are listed.

- Water levels are influenced by wind setup, which is an increase in water level by the wind pushing up the water level in the direction of the wind (Jonkman et al., 2021).
- Water levels are influenced by the inflow and outflow of water via rivers and canals.
- Wind waves are generated as wind strikes over a certain fetch, which is the length of the water body over which the wind strikes. Wave characteristics are influenced by the water depth, the wind speed, and the fetch along this direction.

3.2.3. Second line of flood protection system: Dike

A dike trajectory consists of multiple dike sections; each section is classified as geotechnical or structural. Dike failure is defined as the load exceeding the resistance, according to Equation 2. The material properties and cross-sectional profiles, which define the resistance to dike failure, vary between these sections. The hydraulic loads on dikes are influenced by the aspects described in Subsection 3.2.2.

There are various failure mechanisms that initiate dike failure. Failure mechanisms for geotechnical dike sections are shown in Figure 17. It is noted that these failure mechanisms are also applicable to geotechnical dam sections, the only difference is the presence of water behind the dam section. Failure of any dike cross section due to any failure mechanism leads to dike failure. This report discusses a limited number of dike failure mechanisms; the dike failure mechanisms used in applying the framework are described in Appendix B.

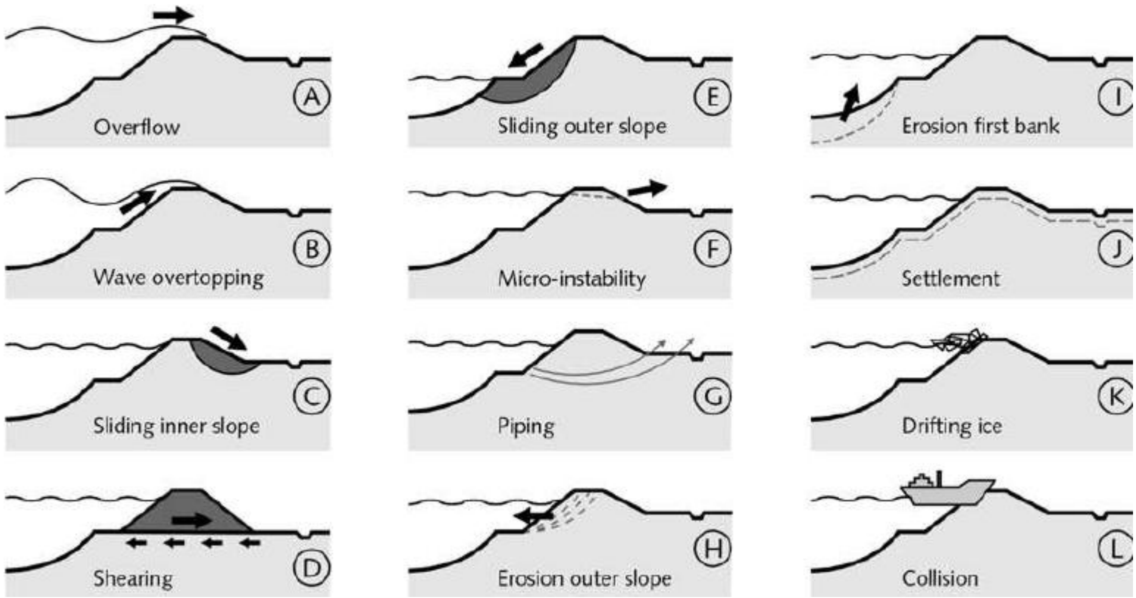


Figure 17: Overview of dike failure mechanisms (TAW, 1998).

3.2.4. Consequences of dike failure for the hinterland

The hinterland is relevant because a flood is defined when dike failure results in fatalities or substantial economic damage, as stated in Section 3.1. The risk of flooding is determined by the probability of dike failure and the consequences of flooding. The consequences of flooding are determined by two aspects.

- **Vulnerability to flooding:** The presence of consequences in the hinterland. For example, evacuation reduces the vulnerability to flooding.
- **Significance of flooding:** The significance of consequences in the hinterland. For example, floodproof buildings reduce the significance of flooding.

3.3. Description framework

The framework incorporates the performance of a storm surge barrier in calculating the failure probability of the dikes located behind the storm surge barrier. It is assumed that this effect should be considered when deriving a requirement for the performance of storm surge barriers. This framework includes the steps towards the derivation of an optimal structural failure probability. This is done by translating failure probabilities into costs. A mathematical description of the framework is provided after the generic steps to perform the calculations are outlined.

3.3.1. Generic description framework

The elements of the flood protection system described in Section 3.2 are used for identifying the steps of the framework. Storm surge barrier performance is included in the water level distribution in front of dikes, describing the first two elements of the flood protection system. The third element, the dike, resists the hydraulic loads in front of it. A step towards flooding, and thus towards consequences for the hinterland, is not considered explicitly but is considered by the maximum allowable annual probability of failure of dike trajectories.

Six steps are identified to determine a requirement for storm surge barrier performance based on an economic optimisation. A generic expression of these steps is provided.

1. Estimate the water level distribution (load) as a function of storm surge barrier performance.
2. Estimate the strength (resistance) of the dike behind the storm surge barrier.
3. Calculate the dike failure probability based on load and resistance.
4. Estimate the costs to strengthen the dike to comply with the dike safety standard.
5. Estimate the costs to maintain a certain storm surge barrier performance.
6. Determine the storm surge barrier performance corresponding to minimal total costs, while considering the investment costs for the entire length of dike along the estuary.

The generalised steps to derive a requirement based on a criterion that assesses the validity of neglecting the effect of storm surge barrier performance on the dike failure probability are outlined.

1. Estimate the water level distribution (load) as a function of storm surge barrier performance.
2. Estimate the strength (resistance) of the dike behind the storm surge barrier.
3. Calculate the dike failure probability based on load and resistance.
4. Define a criterion to assess the validity of neglecting the effect of the storm surge barrier failure probability (e.g., Equation 5).
5. Determine the storm surge barrier performance that just complies with the criterion defined in step 4, while considering the entire length of dike along the estuary.

The first three steps of both schemes are identical. These three steps are necessary to calculate the dike failure probability as a function of storm surge barrier performance. Further steps are required to translate these failure probability calculations into a requirement for storm surge barrier performance.

3.3.2. Mathematical description framework

The framework presented in this subsection captures the steps described in Subsection 3.3.1. Two input curves are used for calculating the failure probability of a dike behind a storm surge barrier. These two curves represent load and resistance in the framework: a water level distribution as a function of storm surge barrier performance and a fragility curve. Deriving water level distributions requires modelling efforts, fragility curves are constructed based on dike characteristics. Investment functions are used to calculate an economically optimum structural failure probability; these investment functions must be estimated per case.

1. **Water level distribution:** Storm surge barrier performance is captured in the water level distribution; different curves represent different failure scenarios of the storm surge barrier.
2. **Fragility curve:** Describes the resistance of the dike to failure by providing the conditional probability of failure for a given water level per dike failure mechanism.
3. **Investment function:** Translates the failure probabilities of dike and storm surge barrier into costs to maintain the corresponding safety standard.

The framework visualised in Figure 18 is described mathematically in 5 steps. Figure 18 shows the calculations performed for the input functions shown on the left side of the figure. These five steps are described mathematically in the remainder of this subsection.

0. Assume relationship between storm surge barrier performance and water level distribution.
1. Translating water level exceedance curve into probability density function.
2. Calculating dike failure probability per failure mechanism.
3. Translating cross section failure probability into trajectory failure probability.
4. Calculating the required investment to comply with the dike safety standard.
5. Searching for an optimal storm surge barrier structural failure probability.

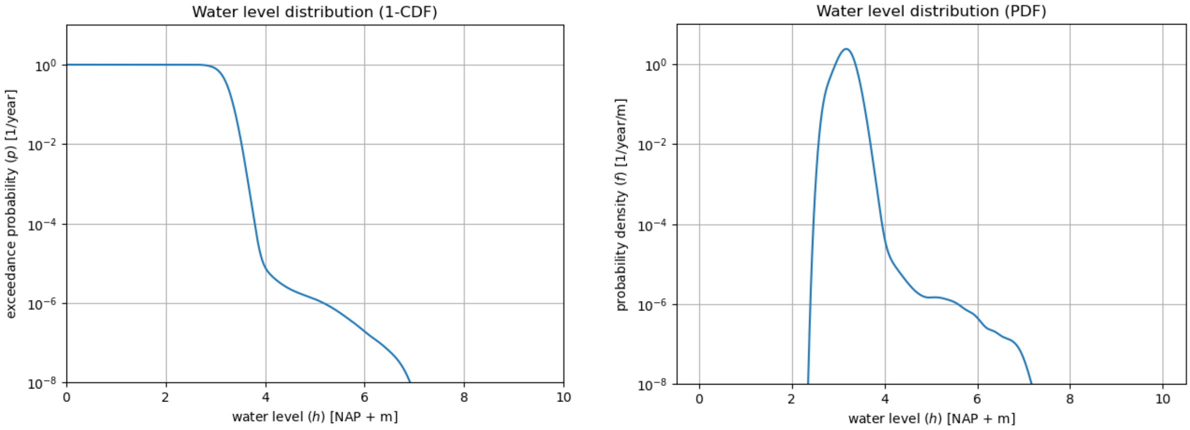


Figure 18 [1a-b]: Water level distribution as a function of storm surge barrier performance.

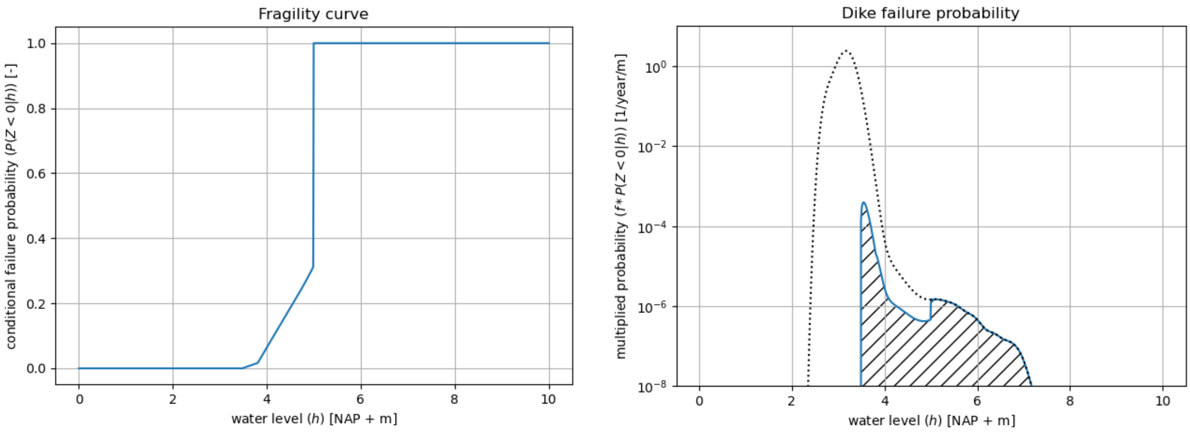


Figure 18 [2a-b]: Dike failure probability calculated using fragility curves.

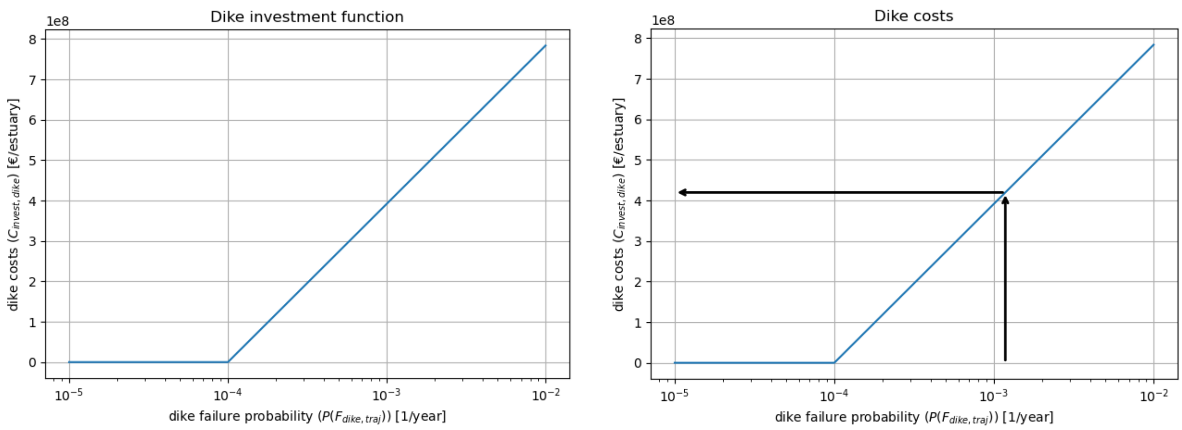


Figure 18 [3a-b]: Dike costs as a function of the dike failure probability at dike trajectory level.

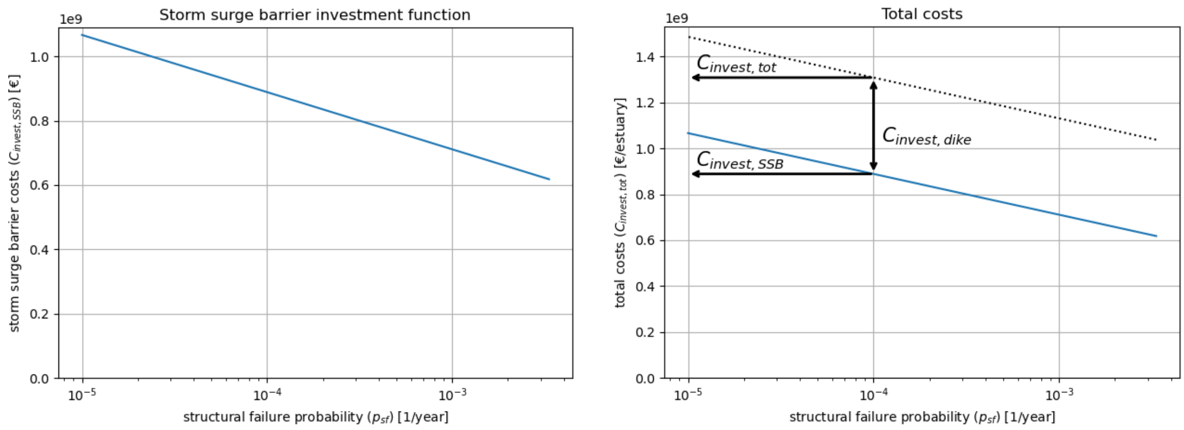


Figure 18 [4a-b]: Total costs at flood protection system level as a function of the storm surge barrier structural failure probability.

Step 0. Assume relationship between storm surge barrier performance and water level distribution.

The five steps of the framework are performed after estimating the relationship between storm surge barrier performance and resulting water levels. In this way, the water level distribution is described as a function of storm surge barrier performance. An optimisation problem evaluates the performance of the storm surge barrier, including both operational failure and structural failure. To calculate only the optimal structural failure probability, the operational reliability must be assumed.

Step 1. Translating water level exceedance curve into probability density function.

Water level distributions are commonly presented by the exceedance probability as a function of water level, as for example shown in Section 2.3. Equation 9 shows the translation from exceedance probability to probability density function.

$$f(h) = \frac{dF(h)}{dh} = \frac{d(1-p(h))}{dh} = -\frac{dp(h)}{dh}$$ *Equation 9*

- h [NAP + m]: Water level.
- $f(h)$ [1/year/m]: Probability density function (PDF) water level distribution.
- $F(h)$ [1/year]: Cumulative distribution function (CDF) water level distribution.
- $p(h) = 1 - F(h)$ [1/year]: Exceedance probability (1-CDF) water level distribution.

Step 2. Calculating dike failure probability per failure mechanism.

The dike failure probability is calculated by multiplying the fragility curve and the water level distribution and then constructing the area under the graph, as presented in Equation 10.

$$P_m(Z < 0) = \int_{-\infty}^{\infty} f(h) * P_m(Z < 0|h) * dh$$ *Equation 10*

A discretised version of this equation is presented in Equation 11. This equation approximates Equation 10 for calculating over a small step in water level.

$$P_m(Z < 0) = \sum_{h=h_1}^{h_n} f(h) * P_m(Z < 0|h) * \Delta h$$ *Equation 11*

- h [NAP + m]: Water level.
- Δh [m]: Increment in water level of the discretised water level distribution.
- $P_m(Z < 0)$ [1/year]: Failure probability dike failure mechanism.
- $f(h)$ [1/year/m]: Probability density function (PDF) water level distribution.
- $P_m(Z < 0|h)$ [-]: Fragility curve providing the failure probability of a dike failure mechanism per water level.

Step 3. Translating cross section failure probability into trajectory failure probability.
The dike failure probability is calculated at cross section level per failure mechanism. Safety standards are defined at trajectory level for all failure mechanisms. A translation is made, which is presented in Equation 12. In this equation, the dike failure mechanisms are assumed to be independent; the contributions of the failure mechanisms are summed. The same assumption is made in assessing dikes in practice, as discussed in Appendix A (A.1).

$$P(F_{dike,traj}) = \sum_{m=m_1}^{m_n} P_m(Z < 0) * N_m$$ *Equation 12*

- m_i: Dike failure mechanism.
- $P(F_{dike,traj})$ [1/year]: Dike failure probability at trajectory level.
- $P_m(Z < 0)$ [1/year]: Failure probability dike failure mechanism.
- N_m [-]: Length effect corresponding to dike failure mechanism.

Step 4. Calculating the required investment to comply with the dike safety standard.
A dike needs to be reinforced when the calculated dike failure probability exceeds the maximum allowed probability of failure. The dike reinforcement costs are calculated as a function of the ratio between the calculated failure probability and the safety standard, as depicted in Equation 13. This equation is applied to the length of dike that is considered representative for the calculations performed in the first three steps.

$$\frac{C_{invest,dike,s}}{L_{estuary}} = C_{dike,fact10} * \log_{10}\left(\frac{P(F_{dike,traj})}{P_{req,dike}}\right) + C_{dike,base}$$ *Equation 13*

- $P(F_{dike,traj})$ [1/year]: Dike failure probability at trajectory level.
- $C_{invest,dike,s}$ [€]: The investment required to reinforce a dike section along the estuary.
- $L_{estuary}$ [km]: Representative length of dike along the estuary.
- $C_{dike,fact10}$ [€/km]: Dike investment to reduce the dike failure probability by a factor of 10.
- $P_{req,dike}$ [1/year]: Maximum allowable annual probability of dike failure.
- $C_{dike,base}$ [€/km]: Costs to initiate dike reinforcement.

Step 5. Searching for an optimal storm surge barrier structural failure probability.
For an optimal structural failure probability of the storm surge barrier, the sum of dike investment costs and storm surge barrier investment costs at estuary level is minimal, which is expressed in Equation 14.

$$C_{invest,tot}^{opt} = \min_{p_{sf}}(C_{invest,SSB}(p_{sf}) + \sum_{s=s_1}^{s_n} C_{invest,dike,s}(p_{sf})) = \min_{p_{sf}} C_{invest,tot}(p_{sf})$$ *Equation 14*

- p_{sf} [1/year]: Structural failure probability storm surge barrier.
- s_i [-]: Dike section along the estuary.
- $C_{invest,tot}^{opt}$ [€]: The optimal and thus minimum costs corresponding to the optimal storm surge barrier structural failure probability (p_{sf}^{opt}).
- $C_{invest,dike,s}$ [€]: The investment required to reinforce a dike section along the estuary.
- $C_{invest,SSB}$ [€]: The investment to maintain a certain structural failure probability of the storm surge barrier (SSB).
- $C_{invest,tot}$ [€]: The total investment costs, the sum of the two contributions.

3.4. Discussion of limitations framework

This section discusses the limitations of the framework. The first subsection addresses the schematisation of the consequences of flooding used in the framework. The second subsection highlights that the aspects considered in the framework relate to flood risk, which is according to the scope of this study, while non flood risk related aspects also influence the required level of safety of structural components of a storm surge barrier.

3.4.1. Schematisation of consequences of flooding

A criterion that accounts for the consequences of dike failure is interpreted in the framework by calculating the investment needed to meet the dike safety standard. This approach implies that it is not economically optimal to reduce the dike failure probability below this safety standard. This assumption is not necessarily valid when the risk related costs, the costs resulting from flooding, are considered.

Flood risk is calculated as a function of a certain strength of both dike and storm surge barrier, as outlined in Equation 15. This analysis results in safety standards for storm surge barrier and dike after iterating for various reliabilities of the elements. When taking this approach, a dike failure probability smaller than the current safety standard may end up being economically favourable due to lower risk related costs. A simplification is thus made in this study by not considering that a different requirement for storm surge barrier failure may result in a different dike safety standard.

$$C_{invest,tot}^{opt} = \min_{p_{sf},p_{df}}(C_{invest,SSB}(p_{sf}) + \sum_{s=s_1}^{s_n} C_{invest,dike,s}(p_{df,s}) + C_{risk,s}(p_{sf}, p_{df,s}))$$ *Equation 15*

- p_{sf} [1/year]: Structural failure probability storm surge barrier.
- $p_{df,s}$ [1/year]: Dike failure probability of dike section.
- s_i [-]: Dike section along the estuary.
- $C_{invest,tot}^{opt}$ [€]: The optimal and thus minimum costs corresponding to the optimal storm surge barrier structural failure probability (p_{sf}^{opt}), and the optimal dike failure probability of dike sections ($p_{df,s}^{opt}$).
- $C_{invest,SSB}$ [€]: The investment to maintain a certain structural failure probability of the storm surge barrier (SSB).
- $C_{invest,dike,s}$ [€]: The investment to obtain a certain dike failure probability for a dike section along the estuary.
- $C_{risk,s}$ [€]: The risk expressed in costs, a function of probability and monetised consequences of flooding for a dike section along the estuary.

When performing an economic optimisation for flood protection systems using Equation 14 or Equation 15, it should be checked that the requirements for individual risk and societal risk are met. An iterative step is required when a different performance of the storm surge barrier results in a different dike safety standard (Jongejan, 2015). Thus, the number of fatalities, the number of victims, and the economic damage need to be modelled per scenario. The safety standard is determined solely by the optimal system configuration under the assumption that an increase in storm surge barrier failure probability does not result in exceedance of the maximum allowed consequences of flooding.

Theoretically, safety standards for both dike and storm surge barriers are derived by describing the costs at flood protection system level and analysing the flood risk at this system level (Kramer & van der Most, 2014). The minimum total costs that do not lead to exceeding the maximum allowed consequences of flooding are searched for. A generic description of the steps to perform such a problem is listed below.

1. Estimate the water level distribution (load) as a function of storm surge barrier performance.
2. Assume the strength (resistance) of the dike behind the storm surge barrier.
3. Calculate the consequences of flooding for each combination of load and resistance (i.e., risk related costs, individual risk, and societal risk).
4. Proceed with the next steps if the maximum allowed consequences of flooding are not exceeded.
5. Estimate the costs to achieve a certain dike safety standard.
6. Estimate the costs to maintain a certain storm surge barrier performance.
7. Determine the combination of dike safety standard and storm surge barrier performance corresponding to minimal total costs, while considering the investment costs for the entire length of dike along the estuary.

The difference between these steps and the steps listed in Subsection 3.3.1 is the explicit calculation of flood risk. The costs associated with a certain dike safety standard are calculated instead of the costs to comply with a predefined dike safety standard. The framework described in Section 3.3 takes the dike safety standards in Appendix II of Besluit kwaliteit leefomgeving (2025) as a starting point.

3.4.2. Safety criteria for non flood risk related aspects

The framework is built in the context of flood risk, focusing on the effects in terms of hydraulic loads and dike failure probabilities. A requirement for structural failure is imposed by the Building Decree but is not explicitly considered in the safety assessment of storm surge barriers. Deriving a requirement based on flood risk may result in a less strict requirement for structural failure. Increasing the allowed structural failure probability can have a limited impact on flood risk under the Water Act, however, the Building Decree requires a minimum level of structural reliability.

An argument for demanding a sufficient level of safety for the structural components of a storm surge barrier is that storm surge barriers fulfil other functions that must be preserved. For example, if a road is constructed on top of a storm surge barrier, failure is undesirable in the context of transportation function due to potential loss of function and loss of life.

Furthermore, the social perception of structural failure influences the desired level of safety. Storm surge barriers have a landmark value in the Netherlands, if this structure fails, it will have an impact on the political and societal perception of storm surge barriers and flood safety in general. The willingness to prevent such an undesirable event is independent of the actual increase in flood risk that this event eventually causes.

A requirement for structural failure depends on the various functions of the object and the possible consequences of failure. In addition to the consequences of failure, a target reliability for structural failure reflects the relative costs of achieving a certain reliability, accounting for the existence and remaining lifetime of the structure (Steenbergen et al., 2018). This implies that the structural reliability is influenced by an economically optimal strategy to maintain the storm surge barrier.

In summary, different arguments are to be considered in a requirement for structural failure of storm surge barriers. The required level of structural failure is not solely determined by flood risk related aspects. It is necessary to assess the implication of the level of safety of the storm surge barrier within the context of various functions and consequences of structural failure of storm surge barriers. Flood risk must be considered within the applicable conditions.

4. Applying the framework in a generic context

This chapter applies the case study in a generic context. A schematised water level distribution is used for applying the framework. The results of the application are presented and discussed. Further steps to consider in applying the framework are described.

4.1. Introduction to a generic application of the framework

In this chapter, the framework is applied to a schematised water level distribution. This allows for studying the effect of the storm surge barrier failure probability on the dike failure probability without focusing on case-specific aspects. This chapter uses the schematisation described in Section 4.2 as a generic interpretation of storm surge barrier performance. This schematisation translates offshore water levels into estuary water levels using the non-closure probability and the structural failure probability of the storm surge barrier. This schematised water level distribution does not include wind setup within the estuary and the inflow of water into the system. Furthermore, it does not provide the water level distribution as a function of failure of number of gates, the storm surge barrier cannot fail partially.

The framework is applicable to this generic context. However, a translation towards costs is not made in this chapter due to the limited value of generalising investment costs for storm surge barriers and dikes. Instead, this chapter applies the first three steps of the framework presented in Subsection 3.3.2. The focus is on describing the effect of storm surge barrier performance on the dike failure probability per dike failure mechanism. A system is not described exactly; the focus is on the effects of variations in hydraulic load and dike resistance on the dike failure probability.

4.2. Schematisation of storm surge barrier performance

For describing the effect of storm surge barrier performance in terms of resulting water levels, efforts are made in schematising storm surge barrier performance. As for providing insights, it is not convenient to make a complete model for deriving hydraulic boundary conditions. Such a schematisation is presented in Jongejan (2015) and Mooyaart et al. (2025). This schematisation is a generic description of the method used for describing the water level behind the Maeslant Barrier (Maeslantkering, a storm surge barrier near Rotterdam) in Janssen & Jorissen (1992).

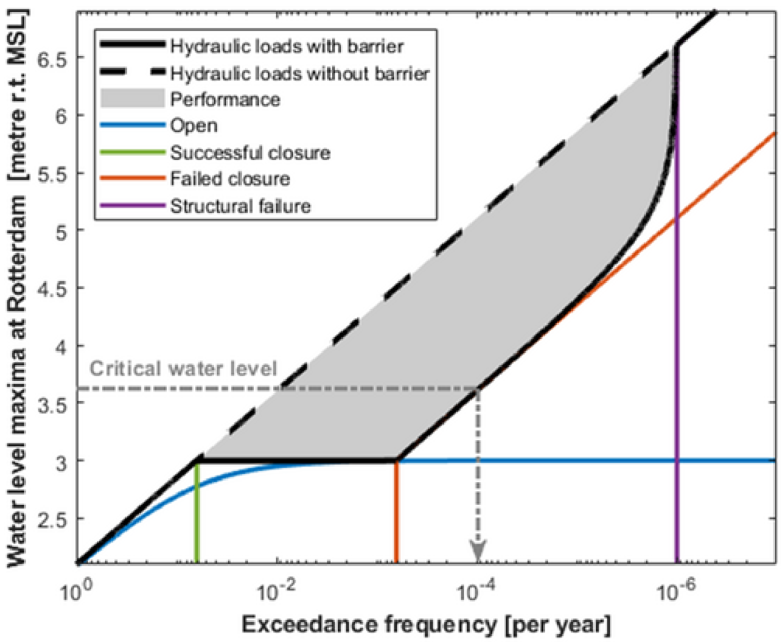


Figure 19: Graphical representation of storm surge barrier performance (Mooyaart et al., 2025).

Figure 19 presents the schematisation in Mooyaart et al. (2025), of which the aspects are described. The exceedance curve (in black) is the water level distribution resulting from the aspects described. The schematisation uses the Maeslant Barrier as a reference case, the principles are applicable in general.

- **Performance (grey area):** The performance of the storm surge barrier is defined as the difference between the water level distribution with and without a storm surge barrier.
- **Water level for no storm surge barrier (black dotted):** The offshore water level is assumed to be exponentially distributed.
- **Closure decision level (green):** Closing procedures are started when this water level is predicted. The storm surge barrier influences the water level distribution when the offshore water level exceeds this level. A perfect storm surge barrier implies no probability density for water levels larger than the closure decision level.
- **Probability of non-closure (red):** Limits the performance of the storm surge barrier. Non-closure results in a shift of the offshore water level towards the right. The exceedance probability per offshore water level is multiplied by a factor corresponding to the probability of non-closure on demand.
- **Structural failure probability (purple):** Structural failure is assumed if the corresponding water level is exceeded. For a structurally failed barrier, the offshore water level describes the estuary water level.
- **Critical water level (grey dotted):** Indicates the water level corresponding to a certain return period, which is a function of storm surge barrier performance.

Two considerations are drawn based on the schematisation presented.

- The non-closure probability is independent of the water level, while structural failure depends on the water level distribution.
- Deterministic behaviour is assumed. In reality, structural failure does not happen exactly when a certain water level is exceeded. Furthermore, closure of the barrier does not result in the estuary water level being exactly equal to the closure decision level. These aspects are included in a probabilistic approach for describing storm surge barrier performance in Mooyaart et al. (2025) but are not discussed in this study.

4.3. Dike failure probability as a function of storm surge barrier performance

This section describes the assumptions and input used for calculating the dike failure probability as a function of storm surge barrier performance. The findings are presented and discussed. The calculations are performed via notebooks, as described in Appendix F.

4.3.1. Assumptions made in applying the framework

The following assumptions are made in applying the framework.

- Storm surge barrier performance is represented in terms of resulting water levels according to the schematisation described in Section 4.2.
- Calculations are performed for three dike failure mechanisms.
- Calculations are performed for the cross section illustrated in Figure 15.

4.3.2. Input framework

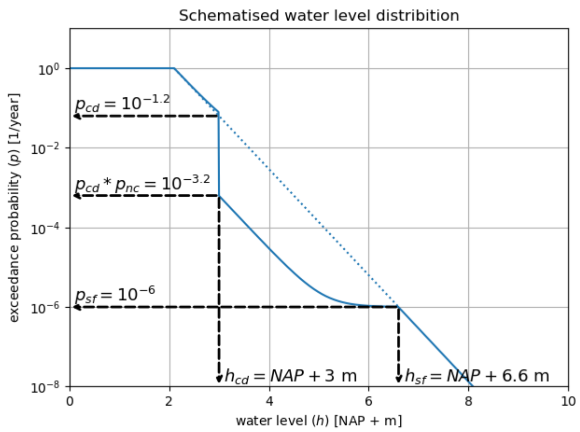
The water level distribution described in Section 4.2 is modelled via Equation 16 and illustrated in Figure 20. The parameters of this distribution are varied while calculating the dike failure probability.

Equation 16

$$f(h) = -\frac{dp(h)}{dh} = -\frac{d\left(p_{nc} * 10^{\left(\frac{a-h}{b}\right)}\right)}{dh} = \frac{\ln(10) * p_{nc}}{b} * 10^{\left(\frac{a-h}{b}\right)}$$

- h [NAP + m]: Water level.
- $f(h)$ [1/year/m]: Probability density function (PDF) water level distribution.
- $p(h)$ [1/year]: Exceedance probability (1-CDF) water level distribution.
- $a = 2.1$ [NAP + m]: Location parameter of the offshore water level distribution.
- $b = 0.75$ [m]: Scale parameter of the offshore water level distribution.
- p_{nc} [1/demand]: Non-closure probability storm surge barrier: the number of demanded closures that includes one occasion of non-closure.

  This non-closure probability is modelled to be smaller than 1 if the closure decision level is exceeded and if the water level is not too large to initiate structural failure.
  - $p_{nc} \neq 1$ for $h_{cd} < h < (a - b * log_{10}(p_{sf}))$.
  - $h_{cd} = 3$ [NAP + m]: Closure decision level.
  - p_{sf} [1/year]: Structural failure probability storm surge barrier.



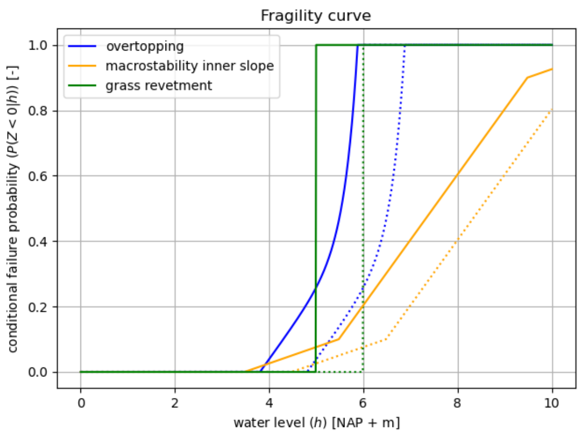


Figure 20 [Left]: Schematised water level distribution for $p_{nc} = 10^{-2}$ and $p_{sf} = 10^{-6}$. Figure 21 [Right]: Fragility curves for three dike failure mechanisms, and their mean values shifted by 1 metre.

The fragility curves described in Appendix B and shown in Figure B.1 are used. The purpose of the fragility curves is to calculate the dike failure probability using dike failure mechanisms with a different response to variations in the water level distribution. Variations in dike strength are simulated by shifting the mean value of the fragility curves by one metre, this approach is illustrated in Figure 21. The three failure mechanisms included in the calculations are listed.

- **Overtopping:** Represents a failure mechanism of which the failure probability is relatively sensitive to the water level distribution.
- **Macrostability inner slope:** Represents a failure mechanism of which the failure probability is relatively insensitive to the water level distribution.
- **Grass revetment failure:** Represents a failure mechanism that is completely driven by the water level. The grass revetment fails if the water level reaches the grass revetment on the outer slope of the dike.

4.3.3. Output framework

The results of the calculations are shown in Figure 22. The output shows the dike failure probability at cross section level per failure mechanism calculated for varying structural failure probabilities. Different non-closure probabilities are depicted by the curves with different colours. The limit values of the calculations are depicted by the black curves; they indicate the dike failure probability that can be achieved theoretically by adjusting storm surge barrier performance.

- **The upper limit** is calculated for a storm surge barrier that fails when the closure decision level is exceeded. The dike failure probability never exceeds this value.
- **The lower limit** represents a storm surge barrier that closes perfectly. This curve is determined by the fragility curve according to Equation 11.

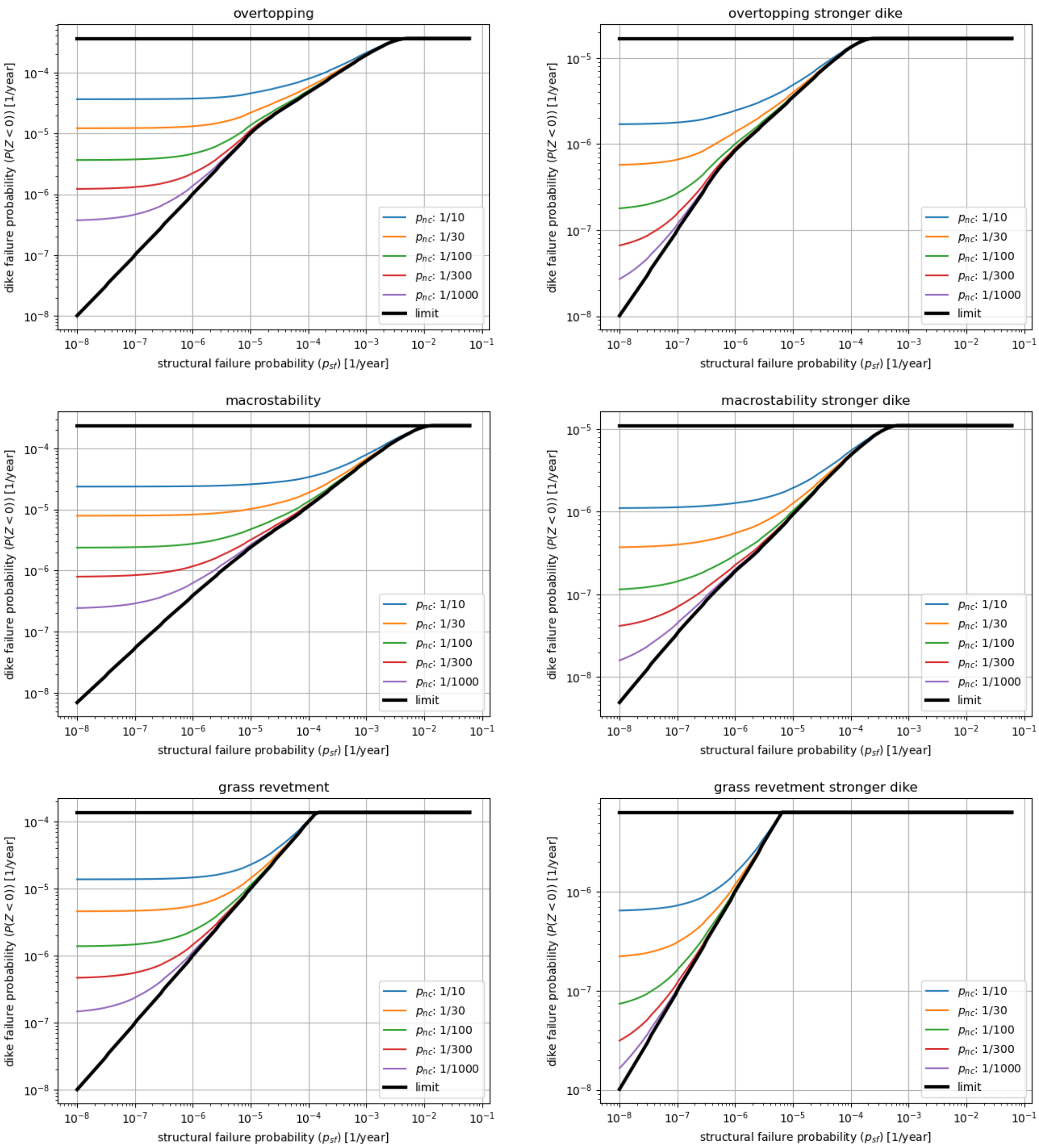


Figure 22 [a-f]: Dike failure probability at cross section level calculated for three failure mechanisms, including a stronger dike configuration.

In short, improving storm surge barrier performance, exemplified by reducing the structural failure probability and the non-closure probability, reduces the dike failure probability. The coloured curves show how the actual performance deviates from the two limit curves.

4.3.4. Discussion of results

Based on the output of the framework, the factors that influence the dike failure probability are identified. These factors relate to the strength of both dike and storm surge barrier.

Relationship between operational failure and structural failure of storm surge barrier
Storm surge barrier performance is influenced by operational failure, structural failure, and the interaction between the two. If one of the two failure probabilities is high, the dike failure probability reduction that can be achieved by reducing the other failure probability is small. This finding is illustrated in Figure 22 by the horizontal segments of the coloured curves. The higher the probability of non-closure, the higher the structural failure probability beyond which the dike failure probability cannot be reduced further. In other words, a further reduction of the structural failure probability has a relatively small influence on the total dike failure probability.

Influence of dike failure mechanism on dike failure probability
The curves shown in Figure 22 are influenced by the fragility curves presented in Figure 21. The increase in dike failure probability resulting from an increase in structural failure probability is greater for a higher conditional failure probability of the dike. This is exemplified by the varying shapes of the curves shown in Figure 22 for the three dike failure mechanisms. The lower limit curve for grass revetment failure has a slope equal to one, whereas the slopes of the lower limit curves for the other two failure mechanisms increase as the structural failure probability decreases according to the shape of the fragility curve.

Influence of dike strength on dike failure probability
Stronger dikes have a lower dike failure probability. Their failure probability is influenced by higher water levels. This implies that for stronger dikes, small structural failure probabilities influence the results. There is a larger range of water levels for which the dike does not fail, which is simulated by shifting the fragility curve. This is depicted in Figure 22 by the limit curves intersecting at lower structural failure probabilities.

It is noted that the effectiveness of improving storm surge barrier performance depends on the dike strength. If the dike fails for water levels lower than the closure decision level, the reduction in dike failure probability that can be achieved by improving storm surge barrier performance is limited. The findings presented in this subsection, which are based on Figure 22, are made for a dike that has no conditional failure probability for water levels below the closure decision level.

4.4. Further steps in applying the framework

The framework is based on generic steps, these steps can be applied to any case study, although making assumptions is required. The aim of this section is twofold: it outlines the steps that can be taken based on the calculations presented in Section 4.3, and it provides an outlook into case-specific aspects for different flood protection systems to consider in applying the framework.

4.4.1. Further steps in interpreting failure probability calculations

This subsection discusses further steps that can be taken in processing the results presented in Section 4.3.

Calculating the total failure probability

The dike failure probability at trajectory level is calculated by summing the contributions of the three failure mechanisms using Equation 12 and the corresponding length effects in Table B.1. Figure 23 shows the dike failure probability calculated per storm surge barrier structural failure probability. Macrostability inner slope is the dominating failure mechanism in this calculation, as it determines the assembled failure probability. In the framework, the calculated dike failure probability is verified against the safety standard after the computation of this failure probability at trajectory level.

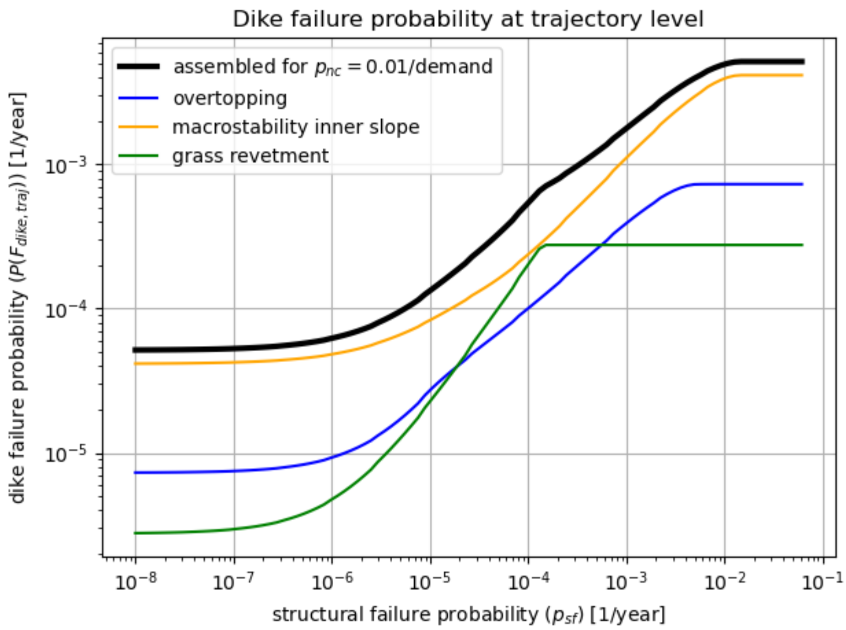


Figure 23: Dike failure probability at trajectory level as a function of the storm surge barrier structural failure probability.

Calculating an economic optimum

The dike failure probability is calculated in this chapter. A requirement based on an economic optimisation requires translating failure probabilities into costs. The effect of varying operational failure probability is included in Equation 17. Including this parameter requires the costs to maintain the storm surge barrier to be expressed in terms of both the non-closure probability and the structural failure probability of the storm surge barrier.

$$C_{invest,tot}^{opt} = \min_{p_{sf},p_{nc}} \left(C_{invest,SSB}(p_{sf},p_{nc}) + \sum_{s=s_1}^{s_n} C_{invest,dike,s}(p_{sf},p_{nc})\right)$$ *Equation 17*

- p_{sf} [1/year]: Structural failure probability storm surge barrier.
- p_{nc} [1/demand]: Non-closure probability storm surge barrier.
- s_i [-]: Dike section along the estuary.
- $C_{invest,tot}^{opt}$ [€]: The optimal and thus minimum costs corresponding to the optimal storm surge barrier performance ($p_{sf}^{opt}, p_{nc}^{opt}$).
- $C_{invest,SSB}$ [€]: The investment to maintain a certain performance of the storm surge barrier (SSB).
- $C_{invest,dike,s}$ [€]: The investment required to reinforce a dike section along the estuary.

Reducing flood risk at flood protection system level
Three measures are identified that reduce the dike failure probability; a combination of the three measures can be applied when such a reduction is needed.

- **Reducing the structural failure probability of the storm surge barrier** reduces the dike failure probability, effectiveness is limited by the fragility curves.
- **Reducing the non-closure probability of the storm surge barrier** reduces the dike failure probability, effectiveness is limited by the structural failure probability.
- **Increasing the dike strength** reduces the dike failure probability, the upper limit of the dike failure probability is lowered.

4.4.2. Case-specific aspects to include in applying the framework
This subsection describes the aspects to consider in applying the framework. These aspects are examined by discussing three case studies, demonstrating that the aspects to include in the framework are case-specific. These case studies are located in the southwestern part of the Netherlands, as shown in Figure 24.

Figure 24: Flood defences in the southwestern part of the Netherlands that are part of the Deltawerken (Rijkswaterstaat, n.d.a).

Maeslant Barrier
As noted in Section 4.2, the schematised water level distribution is used for describing the water levels behind the Maeslant Barrier (Maeslantkering, Figure 25). The water levels at the river behind the storm surge barrier are influenced by both the performance of the storm surge barrier and the river discharge. Calculating an economic optimum requires considering the length of river branches influenced by the performance of the storm surge barrier. The schematisation of the water level distribution can be improved further. For example, Mooyaart et al. (2025) considers the influence of the river discharge behind the Maeslant Barrier on the river water levels as an extension of the model described in Section 4.2.

Figure 25 [Left]: Maeslant Barrier (van Houdt, 2007). Figure 26 [Right]: Haringvliet Sluices (van Houdt, 2008).

Eastern Scheldt Barrier

The water level distribution used in this chapter assumes a unique relationship between the structural failure probability, the operational failure probability, and the resulting water levels. This unique relationship can, however, not be assumed for storm surge barriers with multiple gates, such as the Eastern Scheldt Barrier (Oosterscheldekering, Figure 2). This is illustrated in Figure 27, as the more gates that fail, the higher the hydraulic loads behind the storm surge barrier. In other words, it is difficult to generalise the effect of failure of the storm surge barrier as a function of failure of each of the sixty-two gates on the water level distribution. The approach taken in Prespeil is therefore considered for the Eastern Scheldt Barrier, as discussed in Subsection 2.3.1, and applied in Chapter 5.

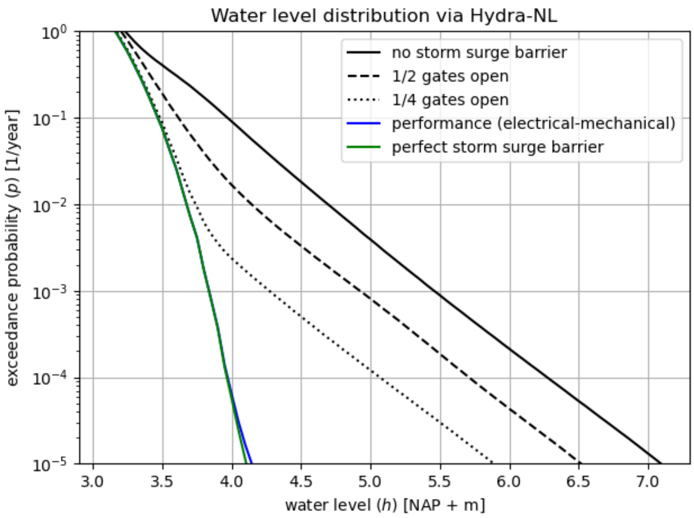


Figure 27: Water level distribution calculated for different numbers of gates that fail. Hydra-NL calculations for a location at the Eastern Scheldt, near the Oesterdam.

Haringvliet Sluices

The dam closing off the Haringvliet (Haringvlietdam, Figure 26) is a storm surge barrier located in the southwestern part of the Netherlands. The Haringvliet Sluices are closed during normal conditions; water is discharged from the river into the North Sea during high river discharges. The framework can be applied to flood protection systems with multiple lines of flood defences; the storm surge barrier does not necessarily have to close during high water. The framework is applicable to cases where the first line of the flood protection system can fail and thereby increase the hydraulic loads on the second line of the flood protection system. For the Haringvliet Sluices, a model that calculates the water levels at the Haringvliet is considered. The water levels at locations behind the Haringvliet Sluices are correspondingly assessed (Rijkswaterstaat, 2022b). This is a similar approach as used for assessing the performance of the Eastern Scheldt Barrier, this approach is described in Subsection 2.3.1.

5. Applying the framework to the case study

The framework described in Subsection 3.3.2 is applied to the case study. The Eastern Scheldt is described first, before a schematised representation of this flood protection system is used to apply the framework. The results of the calculations and the current requirements for the Eastern Scheldt Barrier are presented and discussed.

5.1. Introduction case study

The Eastern Scheldt (Oosterschelde, Figure 28) is a flood protection system with a storm surge barrier. The Eastern Scheldt Barrier (Oosterscheldekering, Figure 2) is a storm surge barrier located in the southwestern part of the Netherlands, at the transition between the North Sea and the Eastern Scheldt. The Eastern Scheldt Barrier is built to prevent flooding of the province of Zeeland, which is the main function of the structure.

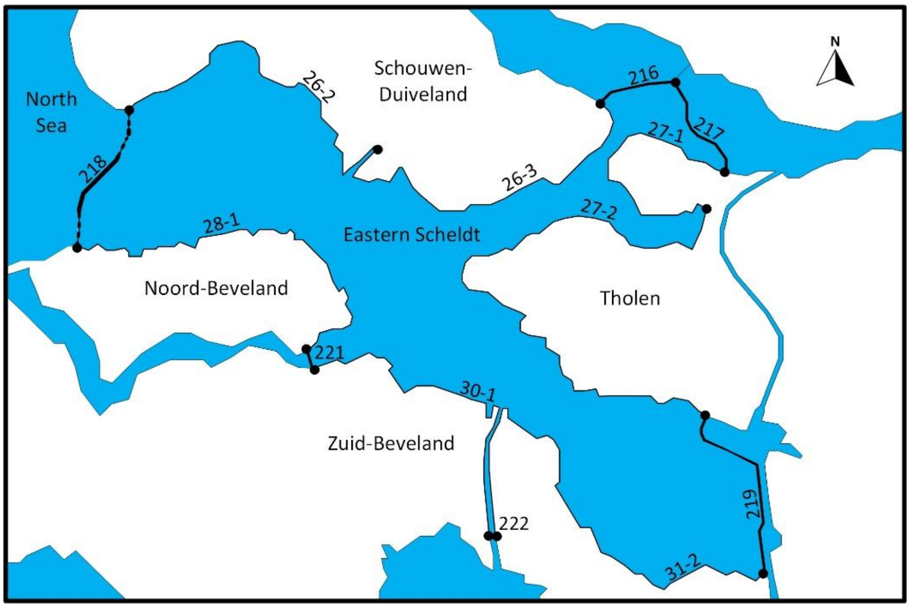


Figure 28: Map of Eastern Scheldt and its flood defence trajectories. The Eastern Scheldt Barrier is indicated by trajectory 218.

This report focuses on the flood risk related aspects of the storm surge barrier. However, it is important to note that ecological considerations, supported by local fishers and nature conservation organisations, led to the current design, whereas the barrier was originally proposed as a dam, a non-moveable barrier. The moveable sections of the barrier allow for tidal exchange, which serves environmental and ecological values (Rijkswaterstaat, 1986). The flood risk related aspects are thus influencing and influenced by other functions and values of the Eastern Scheldt.

The Eastern Scheldt is defined as a closed system, inflow and outflow of water are possible when the Eastern Scheldt Barrier is opened. The flood protection system consists of three elements.

- **Eastern Scheldt Barrier:** Defined as flood defence trajectory 218. It consists of both moveable sections (i.e., Roompot, Schaar, and Hammen) and non-moveable sections (i.e., dam sections and Roompotsluis). The flood defence trajectory is indicated in purple in Figure 29.
- **Dike trajectories:** Seven dike trajectories defend the hinterland directly. These trajectories are indicated in Figure 28: 26-2, 26-3, 27-1, 27-2, 28-1, 30-1, and 31-2.

- **Closure dam trajectories:** The estuary is closed by closure dams; they are the second line of flood defence behind the Eastern Scheldt Barrier. The dams prevent interaction with other water bodies; they close off the estuary. These trajectories are indicated in Figure 28: 216, 217, 219, 221, and 222.

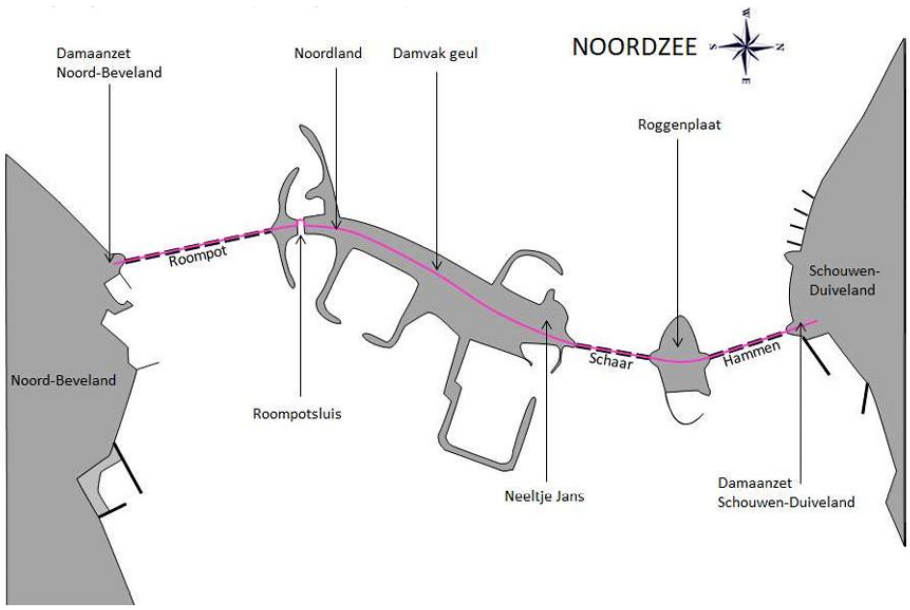


Figure 29: Map of the Eastern Scheldt Barrier (OBT, 2022).

5.2. Results of assessment of Eastern Scheldt flood defences

This section describes the assessment of flood defences as part of the case study. The safety assessment of storm surge barrier and dike trajectories is performed separately. Storm surge barriers are assessed by, or on behalf of, Rijkswaterstaat. Water boards assess dike trajectories.

5.2.1. Results of assessment of Eastern Scheldt Barrier

This subsection discusses the assessment of the Eastern Scheldt Barrier. This assessment has been conducted according to both the old and the new safety standards. Two requirements are used in the recent assessment of the Eastern Scheldt Barrier.

Assessment of the Eastern Scheldt Barrier according to old safety standards

The Eastern Scheldt Barrier was assessed in van der Want (2010). Calculations and inspections were used to assess the failure mechanisms. This assessment was performed according to the old safety standards. This means that the different parts and failure mechanisms of the flood defence trajectory were verified against the hydraulic boundary conditions corresponding to the safety standard (i.e., 4000-year return period). This assessment showed that the storm surge barrier was up to standard at that time. The structural failure probability was categorised between the safety standard and one per cent of this standard, which corresponds to the requirements defined in Table 1.

Assessment of the Eastern Scheldt Barrier according to new safety standards

The Eastern Scheldt Barrier was assessed following the new safety standards in OBT (2022), consisting of the derivation of the failure probability in closed state of the flood defence trajectory. This failure probability in closed state consists of failure of non-moveable sections and failure of structural components of the moveable sections (la Gasse et al., 2020). Components with a non-negligible share with respect to the failure probability of the trajectory (i.e., a failure probability smaller than 1 per cent of the safety standard) were included in the derivation of the quantitative results.

Five components of the moveable parts of the barrier were identified with a non-negligible share in the assembled failure probability. The failure probabilities of these five components were calculated, as depicted in Figure 30. Four of these five components significantly contribute to the assembled failure probability. The assembled failure probability of the trajectory was calculated after integrating over the different storm events. The failure probabilities per storm event are integrated in the water level distribution via Prespeil. These estuary water levels were used to assess the performance of all storm surge barrier failure mechanisms, as discussed in Subsection 2.3.1.

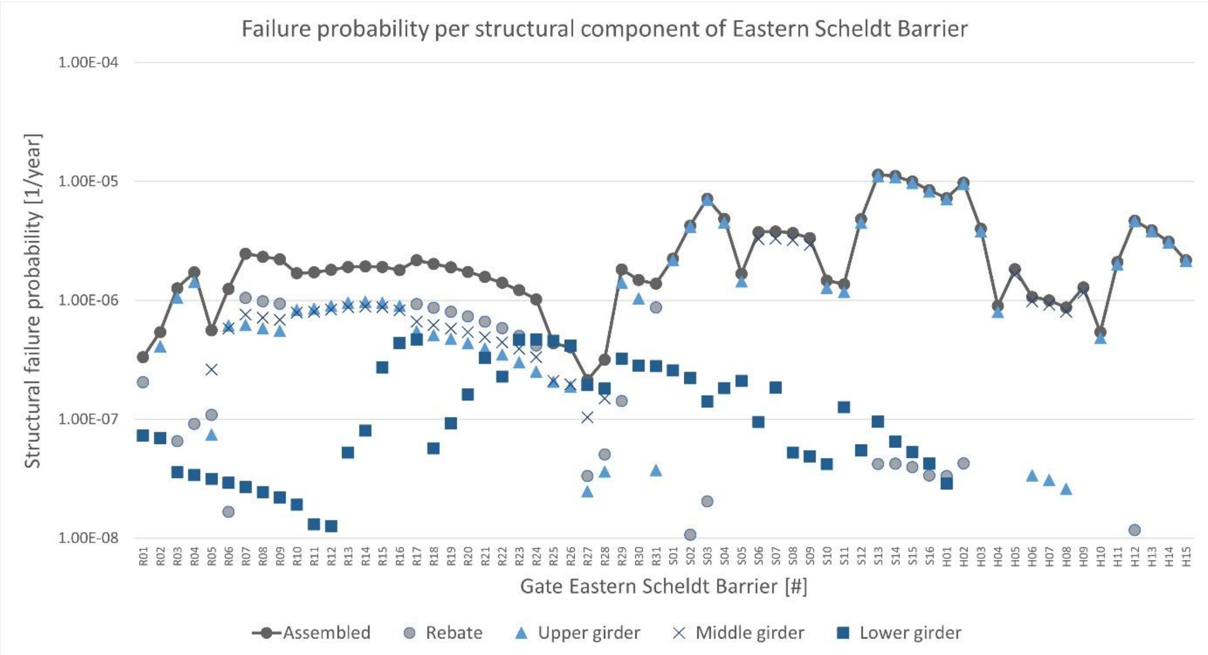


Figure 30: The structural failure probability per gate of the Eastern Scheldt Barrier resulting from the contributing structural components (Vuik et al., 2024).

The Eastern Scheldt Barrier was in OBT (2022) assessed based on two requirements.

- **The first requirement** relates to failure in closed state, as described in Section 2.2. OBT (2022) shows that the assembled failure probability in closed state is smaller than the allowed failure probability as derived in Equation 6 (i.e., 1/10,000), as this failure probability is approximately equal to 1/13,000. This implies that the failure probability in closed state has a negligible effect on the dike failure probability.
- **The second requirement** relates to water levels as described in Subsection 2.3.1. OBT (2022) reports that all locations along the estuary comply with this requirement. For the normative dike location, an increase in water level of 1.36 metres is calculated. This is equivalent to a margin of 8.64 centimetres compared to the agreed maximum allowed increase in water level of 10 centimetres.

5.2.2. Results of assessment of dike and dam trajectories

The dike trajectories and closure dam trajectories all have different requirements because the consequences of failure differ per location. An overview of flood defence trajectories and their assessment with respect to the current requirements, including the assessment of different dike failure mechanisms, is provided in Appendix A.

5.3. Dike failure probability for non-perfect storm surge barrier

This section describes the calculation of dike failure probability as a function of the performance of the Eastern Scheldt Barrier. The calculations are performed via notebooks, as described in Appendix F.

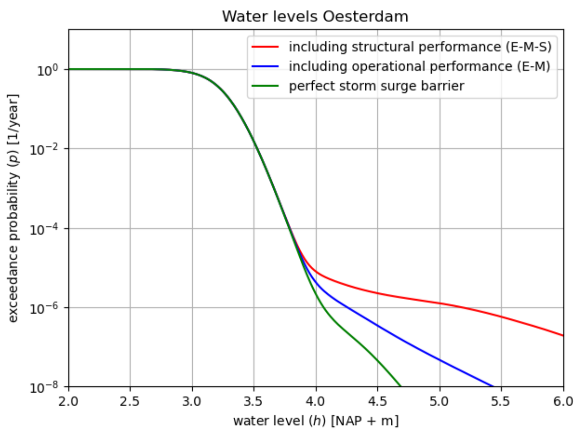
5.3.1. Assumptions made in applying the framework

The following assumptions are made in applying the framework.

- It is assumed that all relevant storm surge barrier failure mechanisms are described by and implemented in Prespeil.
- Three dike failure mechanisms are used for describing the Eastern Scheldt. These failure mechanisms represent failure of both dike trajectories and closure dam trajectories. The closure dam trajectories are included as part of the second line of flood defences.
- The framework is applied to one cross section in this section; this cross section is considered representative for the flood defence trajectories along the estuary. The cross section considers the elements illustrated in Figure 15.

5.3.2. Input framework

The water level distributions calculated using Prespeil for the Oesterdam that are shown in Figure 31 are used as input. A description of the dike failure mechanisms is given in Appendix B. The dike failure mechanisms are presented through the fragility curves illustrated in Figure 32. The same failure mechanisms are used in Chapter 4.



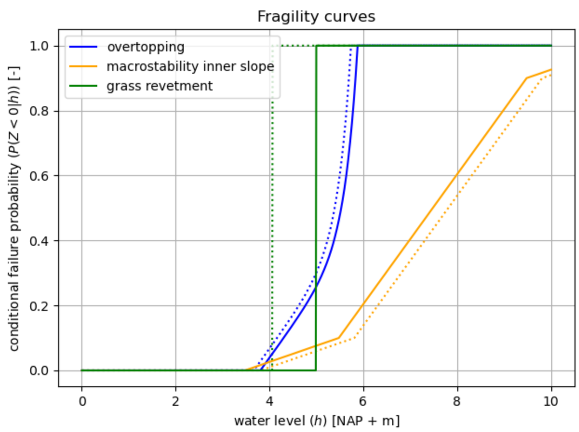


Figure 31 [Left]: Water level distribution at Oesterdam via Prespeil. Figure 32 [Right]: Fragility curves for a dike that is governed by macrostability failure, and the mean values shifted to represent a dike according to distribution factors.

Differences in dike strength are simulated by shifting the fragility curves, as illustrated by the dotted curves in Figure 32. A dike that complies with a safety standard equal to 10^{-4} is simulated by constructing each dike failure mechanism at the maximum allowed annual probability of failure per dike failure mechanism, thus including the distribution factors prescribed in Figure 6, according to Equation 3. This schematisation considers a dike that is designed while accounting for operational failure of the storm surge barrier. This difference in dike strength allows for studying the results for a dike that has a reduced probability of failure for macrostability.

5.3.3. Output Framework

The input of the framework is used for calculating the dike failure probability for the three different water level distributions illustrated in Figure 31. The failure probability calculations at trajectory level are shown in Table 4. Clearly, the fragility curves are constructed such that macrostability is the dominant failure mechanism. Therefore, the calculated dike failure probabilities for the two other failure mechanisms do not contribute to the total failure probability.

Table 4: Failure probability at trajectory level for a perfect storm surge barrier (SSB) and for taking into account electrical (E), mechanical (M), and structural (S) failure.

Failure probability per mechanism	perfect SSB [1/year]	E-M failure [1/year]	E-M-S failure [1/year]
Overtopping	1.71E-06	2.19E-06	4.16E-06
Macrostability	1.13E-03	1.13E-03	1.14E-03
Grass revetment	1.34E-09	9.63E-08	2.54E-06
Total	1.13E-03	1.13E-03	1.14E-03

The results in Table 5 are calculated for the dike fitted according to the distribution factors. The dike failure probability is lower, as this dike has a greater resistance against failure due to macrostability of the inner slope. Furthermore, the total dike failure probability is influenced by all three failure mechanisms, it is not dominated by one failure mechanism.

Table 5: Failure probability at trajectory level for a dike fitted for the distribution factors per dike failure mechanism.

Failure probability per mechanism	Distribution factor (ω) [-]	perfect SSB [1/year]	E-M failure [1/year]	E-M-S failure [1/year]
Overtopping	0.24	2.24E-05	2.33E-05	2.57E-05
Macrostability	0.04	2.97E-06	3.97E-06	7.43E-06
Grass revetment	0.05	1.97E-06	5.22E-06	1.20E-05
Total	0.33/1	2.74E-05	3.24E-05	4.51E-05

5.3.4. Discussion of results

The inclusion of the structural failure probability in the calculations for the Eastern Scheldt Barrier results in an increase in dike failure probability, which is depicted in Table 6. For the 'distribution factor dike', the factor of the increase in dike failure probability, the relative increase, is larger than for the 'macrostability dike'. However, the absolute increase in dike failure probability is still small. So, the maximum allowed annual failure probability is not underestimated by a large factor, an absolute increase in the order of magnitude of 10 per cent relative to the strictest dike safety standard along the Eastern Scheldt is calculated.

Table 6: Difference in dike failure probability resulting from including the effect of structural failure.

Increase in dike failure probability	E-M failure [1/year]	E-M-S failure [1/year]	Absolute increase [1/year]	Relative increase [-]
Macrostability dike	1.13E-03	1.14E-03	9.87E-6	1.01
Distribution factor dike	3.24E-05	4.51E-05	1.27E-5	1.39

Table 7 shows the increase in dike failure probability relative to a perfect storm surge barrier, thus relative to a perfectly closing Eastern Scheldt Barrier. The increase in dike failure probability is larger than as shown in Table 6, however it is still in the same order of magnitude.

Table 7: Difference in dike failure probability compared to a perfect storm surge barrier.

Increase in dike failure probability	Perfect SSB [1/year]	E-M-S failure [1/year]	Absolute increase [1/year]	Relative increase [-]
Macrostability dike	1.13E-03	1.14E-03	1.41E-5	1.01
Distribution factor dike	2.74E-05	4.51E-05	1.77E-5	1.65

The findings thus depend on the assumed strength of the dike. Assuming that a dike will not be less strong than its current state results in the conclusion that the absolute increase in dike failure probability resulting from including the effect of storm surge barrier performance is not larger than order of magnitude 10^{-5}. This is concluded based on the assumption that the conditional dike failure probability per water level, which is modelled via fragility curves, does not increase for a stronger dike.

There are two aspects identified that contribute to differences in the calculated dike failure probability when including storm surge barrier performance.

- **For macrostability failure,** the failure probability is assessed at a low failure probability at cross section level (i.e., order of magnitude 10^{-7}). A large length effect amplifies the effect of small increments in dike failure probability at cross section level when translating to trajectory level, which is exemplified by Equation 12. The uncertainty in dike strength along the dike trajectory is reflected in a lower demanded failure probability at cross section level. The uncertainty on the ability of the dike to resist water levels with higher return periods, the water levels influenced by storm surge barrier performance, is higher.
- **For revetment failure,** the fragility curve is modelled as a step function. This means that the calculations solely depend on the load (i.e., the water level distribution), the fragility curve is not distorted by the strength of the dike. The failure probability calculations in Appendix C (C.1) show that the structural failure probability influences the results, the magnitude of this influence depends on the strength of the dike.

5.4. An economically optimal structural failure probability

This section describes the steps to calculate a requirement for structural failure of the Eastern Scheldt Barrier by performing an economic optimisation. The calculations are performed via notebooks, as described in Appendix F.

5.4.1. Assumptions made in applying the framework

The same assumptions as those listed in Subsection 5.3.1 are made, implying that the costs at flood protection level are calculated using one representative cross section. One dike cross section is considered representative for the complete length of flood defence along the estuary.

5.4.2. Input framework

For deriving a requirement, an assumption is needed regarding the effect of varying structural failure probability of the Eastern Scheldt Barrier on the resulting water levels. For reference, the calculations performed in Nicolai & Vuik (2025) are used; these results are shown by the blue dotted curves in Figure 33. This figure shows the resulting water levels for an assumed uniform reduction in failure probability; the same factor in failure probability reduction is applied to all gates. The calculations are performed for the Oesterdam and include a sea level rise of 50 centimetres.

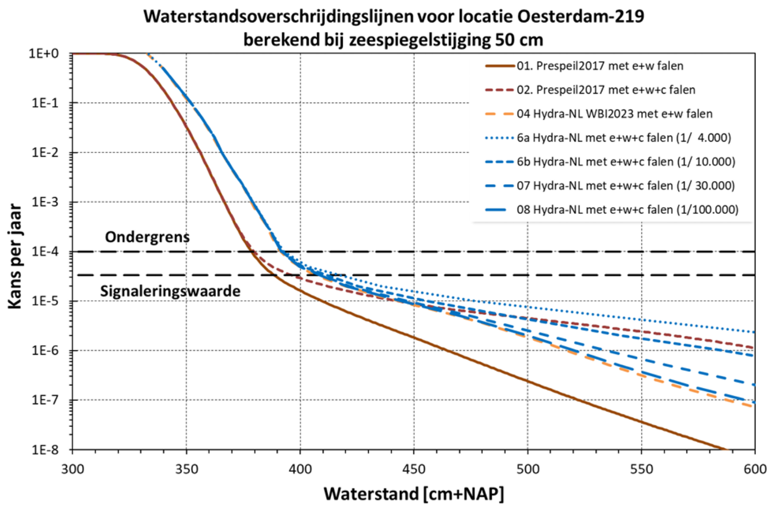
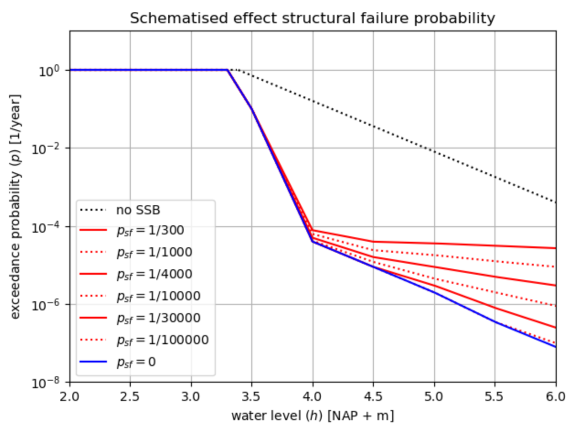


Figure 33: Water level distribution at Oesterdam calculated for different structural failure probabilities (Nicolai & Vuik, 2025).

A discretised approximation of Figure 33 is shown in Figure 34. This approximation illustrates how hydraulic loads increase due to an increase in structural failure probability. The higher the water level, the greater the difference in exceedance probability between the different curves. This approximation is used in this section to estimate the effect of different structural failure probabilities. In this schematisation, structural failure is defined as loss of water-retaining of at least one of the sixty-two gates of the Eastern Scheldt Barrier. The operational failure probability is not optimised in this chapter. It is assumed that the current non-closure probability represents the optimal non-closure probability.

The results in Figure 33 are extrapolated in two ways. First, the slope of the curve is extended towards water levels with larger return periods. This extrapolation is performed for water levels smaller than those corresponding to the offshore water level, as the estuary water level does not exceed the water level corresponding to a situation without a storm surge barrier. The offshore water level distribution is shown in Figure 27, a sea level rise of 50 centimetres is added to the assumed exponential distribution. Second, the slope of the curve is extrapolated to examine the effect of higher structural failure probabilities. As part of this extrapolation, the same increase in exceedance probability per water level is assumed for an increase in structural failure probability by the same factor.



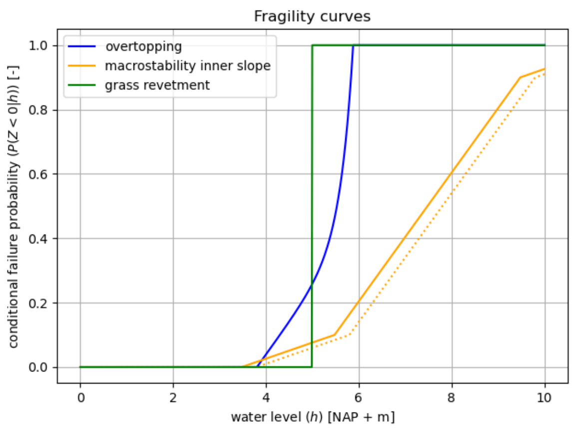


Figure 34 [Left]: Assumed water level distribution for different structural failure probabilities. Figure 35 [Right]: Fragility curves with a reduced failure probability for macrostability to represent a dike that just meets the safety standard.

The fragility curves are fitted to represent a dike that just complies with the dike safety standard for a negligible storm surge barrier structural failure probability. This is done by reducing the failure probability for macrostability, as shown in Figure 35. It is reasoned that the dike is designed while accounting for a negligible structural failure probability, in other words, the dike safety standards consider a negligible effect of structural failure on the dike failure probability. The dike is strengthened to account for the increase in dike failure probability resulting from decreasing storm surge barrier performance.

The dike investment function is calculated using Equation 13 and shown in Figure 18 [3a]. This function is used for evaluating the costs associated with small variations in dike failure probability. The dike costs are calculated for varying storm surge barrier structural failure probabilities. The following parameters are used as input for this function.

- $L_{estuary} = 196$ [km]: Total length of dike and dam trajectories along the estuary, as identified from Appendix A.
- $C_{dike,fact10} = 2 * 10^6$ [€/km]: Dike investment to reduce the dike failure probability by a factor of 10. A representative value for the Eastern Scheldt is estimated using Slootjes & Wagenaar (2016).
- $P_{req,dike} = 10^{-4}$ [1/year]: Maximum allowable annual probability of dike failure. The strictest safety standard of the flood defences along the Eastern Scheldt is used (see Appendix A).
- $C_{dike,base} = 0$ [€/km]: Costs to initiate dike reinforcement are not considered.

The required investment to guarantee a certain structural failure probability for the Eastern Scheldt Barrier is estimated using Equation D.2, which is described in Appendix D. The resulting function is shown in Figure D.1. The costs associated with a variation in structural failure probability by a factor of 10 are used for analysing the sensitivity of the storm surge barrier investment function with respect to the calculated economic optimum.

5.4.3. Output framework

As a first step, the dike failure probability is calculated. As shown in Table 8, the dike failure probability increases for a higher probability of structural failure. For the calculations in Table 8, an increase in dike failure probability in the order of magnitude 10^{-4} is calculated relative to the assumption of a storm surge barrier that does not fail structurally.

Table 8: Dike failure probability at trajectory level ($P(F_{dike,traj})$) per storm surge barrier structural failure probability (p_{sf}).

p_{sf} [1/year]	Negligible	$\frac{1}{100{,}000}$	$\frac{1}{30{,}000}$	$\frac{1}{10{,}000}$	$\frac{1}{4{,}000}$	$\frac{1}{1{,}000}$	$\frac{1}{300}$
$P(F_{dike,traj})$ [1/year]	9.25E-05	9.26E-05	9.65E-05	1.10E-04	1.51E-04	2.42E-04	4.40E-04

The input of the framework is used to calculate an economic optimum. The calculated investment costs are presented in Figure 36, the economically optimum structural failure probability is calculated to be 10^{-3}. The sensitivity of this result with respect to the parameters used as input for the framework is discussed in Subsection 5.4.4.

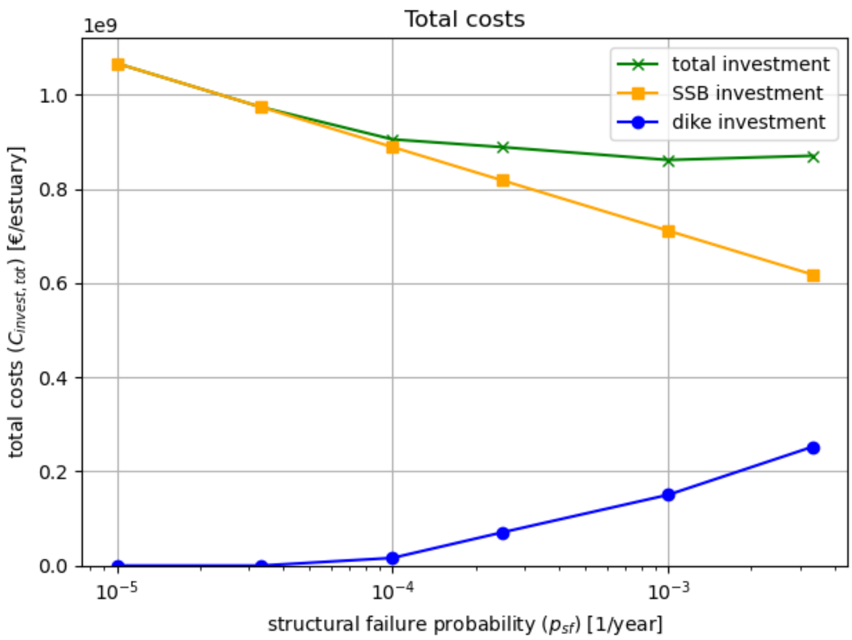


Figure 36: Total costs as a result of dike and storm surge barrier costs for different structural failure probabilities of storm surge barrier (p_{sf}).

5.4.4. Discussion of results

An economic optimum is calculated and presented in Figure 36, based on the assumed parameters, which are summarised in Appendix E. Two aspects determine the structural failure that is calculated in Figure 36.

- **The dike failure probability as a function of storm surge barrier performance.** The economic optimum is determined by the variation in dike failure probability for a certain increment in structural failure probability. The aspects influencing this relationship are discussed in Subsection 4.3.4 and Subsection 5.3.4. It is noted that the dike investment function uses the relative increase in dike failure probability, a factor of ten increase in failure probability, therefore the dike costs are most sensitive to absolute variations in dike failure probability when the initial dike failure probability is small.
- **The storm surge barrier investment function relative to the dike investment function.** The economic optimum is determined by the variation in storm surge barrier costs compared to the variation in dike investment costs. In other words, the justified investment to be spent on improving storm surge barrier performance is determined by the variation in dike costs. The sensitivity of the parameters influencing this relationship is discussed in this subsection.

Figure 37 illustrates the sensitivity of the parameters used in describing the investment functions and how these parameters influence the economically optimal structural failure probability.

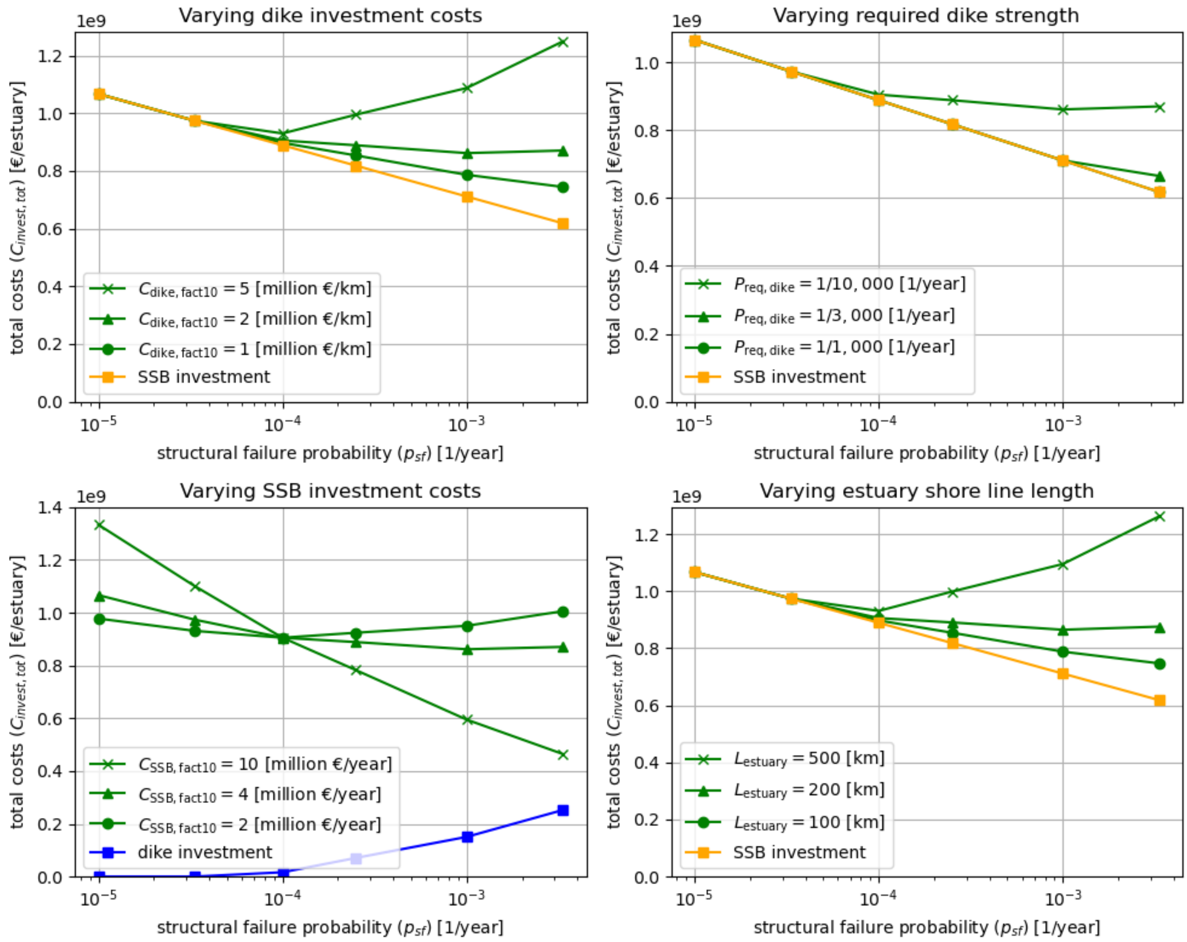


Figure 37 [a-d]: Sensitivity of the parameters influencing the investment functions. The total costs at estuary level depicted in green are calculated for varying magnitudes of the parameters.

The following conclusions are drawn from Figure 37.

- The dikes and the storm surge barrier must be maintained in all considered options. These base costs do therefore not influence the calculated economic optimum.
- A lower economically optimal structural failure probability is calculated when the variation in dike investment costs is large with respect to the variation in storm surge barrier investment costs.
- The required dike strength determines the required dike reinforcement. No dike reinforcement is required when the dike failure probability is lower than required.
- Physical parameters, such as the total length of dike along the estuary, influence the variation in costs. A variation in estuary shoreline length is equivalent to the same variation in the dike costs described by a factor of ten. The greater the total length of dike, the higher the variation in dike costs relative to the variation in storm surge barrier costs.
- The case-specific results indicate a low justified investment in strengthening the Eastern Scheldt Barrier. This is a result of both the dike investment costs per kilometre and the increase in dike failure probability for a varying structural failure probability.

5.5. Discussion of safety standards for structural failure of the Eastern Scheldt Barrier

For studying safety standards for structural failure of the Eastern Scheldt Barrier, the dike failure probability is calculated for different hydraulic boundary conditions in this study. The theory demonstrates that the dike failure probability depends on the water levels on the dikes and that this failure probability is higher for higher structural failure probabilities of the storm surge barrier.

The calculations show that the increase in dike failure probability resulting from including the current estimation of failure in closed state via water levels is small. In fact, the increase in dike failure probability for including both failure mechanisms, operational failure and structural failure, is small. This is in line with the limited increase in water levels resulting from including the effect of storm surge barrier performance along the Eastern Scheldt, as described in Subsection 5.2.1.

These findings do not account for the repair time of the structural components of the Eastern Scheldt Barrier. Therefore, these findings hold under the assumption that the repair time of these structural components is limited and does not significantly influence the hydraulic loads behind the storm surge barrier.

The findings align with an approach that includes the effect of both failure mechanisms in a criterion that assesses the maximum allowable increase in dike failure probability. For the dike trajectories along the Eastern Scheldt, individual risk was the most critical criterion in deriving dike safety standards, as concluded from Slootjes & Wagenaar (2016). Therefore, the maximum allowed increase in dike failure probability relates to the maximum allowed increase in individual risk.

It is noted that this approach does not necessarily lead to an economically optimal flood protection system. Although, the calculations indicate that a small increase in dike failure probability does not result in large variations in dike investment costs. Therefore, a large deviation between the maximum allowable structural failure probability and the economically optimal structural failure probability is not expected, unless the storm surge barrier costs are relatively insensitive to the required structural failure probability compared to the dike costs.

Deriving the water level distribution as a function of storm surge barrier performance, and subsequently calculating the resulting dike failure probabilities, is important, as the interpretation of the requirement for failure in closed state suggests that this effect may almost not be neglected. As presented in Subsection 5.2.1, the estimated failure probability in closed state is almost equal to the maximum annual probability of failure. Applying this requirement strictly leads to a different conclusion than that based on the assessment of the criterion that considers water levels behind the storm surge barrier, as it indicates the need to improve the structural reliability of the Eastern Scheldt Barrier.

This assessment is based on a high conditional probability of dike failure given storm surge barrier failure for a small increase in water level behind the storm surge barrier. Failure of the Eastern Scheldt Barrier is assumed for failure of at least one of the sixty-two gates, which is associated with a probability of one in three that a dike fails given failure of the storm surge barrier. However, Vuik et al. (2024) reports that failure of one gate has no substantial effect on the water levels behind the storm surge barrier. This suggests that this assessment considers a conservative interpretation of the definition, and associated conditional failure probability, of failure in closed state of the Eastern Scheldt Barrier.

6. Discussion

This chapter discusses the steps taken in applying the framework, these steps are discussed per element of the flood protection system. It is discussed that applying the framework, and thus deriving a safety standard for storm surge barriers, requires making assumptions regarding the schematisation of the elements of the flood protection system.

Schematisation of storm surge barrier performance

Storm surge barrier performance is part of the derived water level distributions for the Eastern Scheldt. These water level distributions depend on the data, models, and assumptions used to derive the hydraulic boundary conditions. This is exemplified by the different findings presented in this report. The findings depend on the consulted model and, therefore, on the assumptions made in constructing the model.

- van Manen (2008) reported an 8 cm increase in water level resulting from accounting for storm surge barrier performance at Stavenisse, while Duits & Vuik (2022) reported a 1 cm difference at the same location for a higher return period (10,000 years versus 4,000 years).
- Hydra-NL predicts a more conservative water level distribution than Prespeil. Figure 38 illustrates that Hydra-NL predicts a higher water level for the complete range of exceedance probabilities.

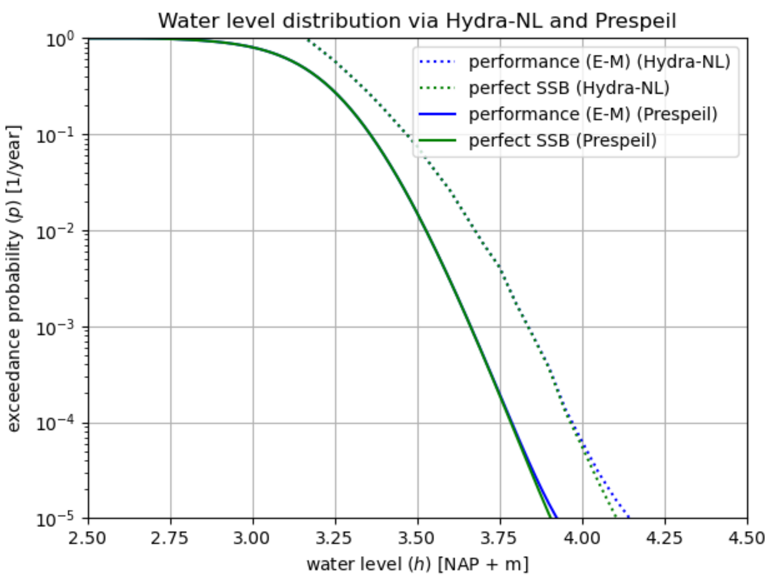


Figure 38: Water level distributions calculated using Prespeil and Hydra-NL.

The schematisation of estuary water levels made using Prespeil is used as input for the framework. Several aspects are included in Prespeil, for example, Prespeil includes the effect of operational failure possibly leading to structural failure of gates of the Eastern Scheldt Barrier. This cascade effect considers that failure of the bed protection, which is caused by non-closure of a certain gate, leads to loss of stability of parts of the structure (Vuik et al., 2021).

The repair time of the structural components of the Eastern Scheldt Barrier is not explicitly considered in the safety assessment. The repair time determines the state of the storm surge barrier at the start of the next storm. This is associated with the probability that the failed structural components have not been repaired before the next closure of the storm surge barrier. The repair time therefore influences the resulting water levels behind the storm surge barrier significantly if the repair time is not limited.

Discretisation of storm surge barrier performance
The structural failure probability is assembled into one value in the framework, as exemplified by Equation 14. Such an approach is suitable for storm surge barriers with fewer gates, as a unique relationship between storm surge barrier performance and resulting water levels is estimated. For the Eastern Scheldt Barrier, multiple configurations of different gates not fulfilling their water-retaining function result in the same structural failure probability. The translation towards water levels is for these configurations not necessarily the same.

This implies that applying the framework requires making assumptions about the relationship between the storm surge barrier structural failure probability and the resulting water level distribution in order to avoid iteration over small variations in the water level distribution. This is exemplified by Figure 33, the assembled failure probability is reduced by applying the same reduction in structural failure probability to all gates of the Eastern Scheldt Barrier.

Changing hydraulic boundary conditions
This report focuses on the effect of storm surge barrier performance on the estuary hydraulic boundary conditions. The influence of variations in water level can be analysed using the framework. For example, by varying the parameters of the schematised water level distribution described in Equation 16. This approach can be followed to study the effect of sea level rise. This report does not consider sea level rise and its effect on the risk of flooding. This is however inevitable when keeping in mind the lifetime of flood defences.

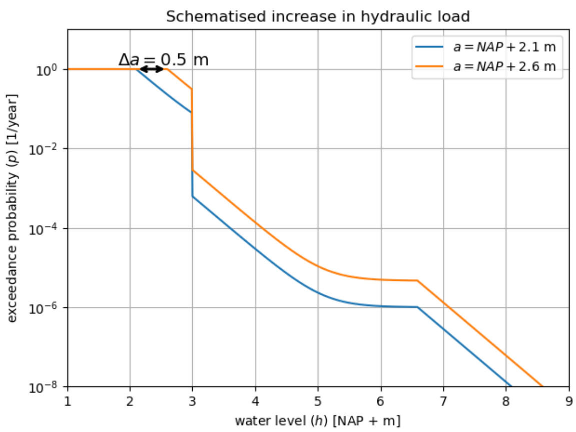
Due to sea level rise, the hydraulic loads on flood defences increase. Consequently, the structural failure probability of the storm surge barrier increases. The Eastern Scheldt was designed while accounting for a rise in water level; a safety margin of 30 centimetres was included in the design to account for the effects of both subsidence and sea level rise (Verbruggen et al., 2012).

Duits et al. (2024) calculated that the requirements for the Eastern Scheldt Barrier discussed in Subsection 5.2.1 are no longer met for a certain rise in water level. The requirement for failure in closed state is no longer met for an estimated water level rise of 5 to 10 cm. For the requirement regarding water levels, exceedance of the maximum allowed increase in water level is expected for 70 to 100 cm sea level rise for the normative dike locations.

The impact of sea level rise is amplified by the closure decision level that is increased to limit the number of closures needed. Such a measure is expected, as the number of closures per year must be limited to maintain tidal exchange and thus preserve environmental and ecological values. The hydraulic loads on dikes increase due to an increasing closure decision level.

The dike failure probability increases for higher hydraulic loads. This is exemplified by increasing the location parameter (α in Equation 16) of the water level distribution by 50 cm, while maintaining the same water level corresponding to structural failure, as depicted in Figure 39. The resulting calculations are shown in Figure 40.

These calculations show that the increase in the location parameter results in an increase of the dike failure probability by the same factor for all storm surge barrier structural failure probabilities, which exemplifies that the density of the water level distribution has increased by the same ratio for all water levels. Furthermore, it is concluded that an increase in hydraulic loads results in an increase in both storm surge barrier failure probability and dike failure probability.



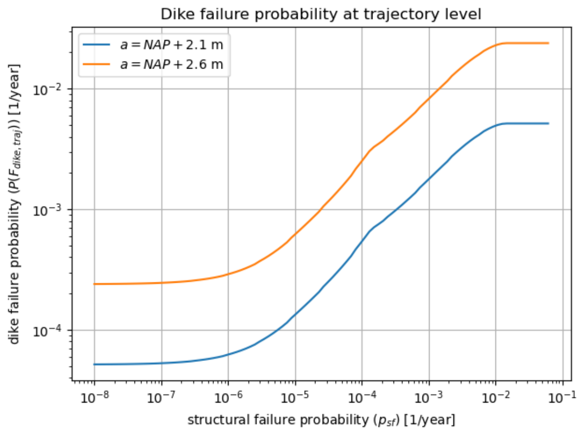


Figure 39 [Left]: Schematisation of increase in hydraulic loads. Figure 40 [Right]: Dike failure probability at trajectory level for increase in hydraulic loads with respect to the calculations in Figure 23.

Schematisation of dike strength

The resistance of dikes to failure is schematised using fragility curves, which provide a method to assess the sensitivity of a dike to variations in the water level distribution resulting from varying storm surge barrier performance. This study assumes the shape of the fragility curves; it does not provide a mathematical description of the physical processes leading to failure. Furthermore, it is assumed that the three dike failure mechanisms are independent. This assumption does not consider that dike failure mechanisms are influenced by the same water level on the dike during a certain event. Finally, a limited number of dike failure mechanisms is included in the calculations.

Not all dike failure mechanisms can be accurately represented using fragility curves. For example, overtopping failure depends on the wave height and the water level in front of the flood defence. It is not straightforward to capture the correlation between the two hydraulic boundary conditions using a fragility curve.

This is the main reason for the conceptual approach that is taken for deriving fragility curves. As part of this conceptual approach, the shapes of the fragility curves for macrostability and overtopping are derived by examining the results of typical calculation methods, such as overtopping discharge formulas and dike stability calculations. In practice, fragility curves, in particular fragility curves for overtopping, were not used and derived during safety assessment. Fragility curves for failure mechanisms such as macrostability and piping are more common and depend on geotechnical parameters.

When applying the framework, the methods and models that are used to calculate dike failure probabilities for varying hydraulic loads must be chosen. In other words, it is not strictly necessary to use fragility curves for applying the framework, as exemplified by the generic steps outlined in Subsection 3.3.1.

The correlation between dike failure mechanisms is especially relevant for the dependency between overtopping failure and grass revetment failure. Overtopping most likely occurs when the water level is above the start of the grass revetment, indicating a strong correlation between these two failure mechanisms. These two failure mechanisms are assumed to be independent in the framework, which implies that a conservative assumption is made for calculating both the dike failure probability and the influence of storm surge barrier performance on the dike failure probability. Figure 41 illustrates the fragility curve for assuming that the two failure mechanisms are fully correlated. This assumption results in a lower dike failure probability than the sum of the two individual contributions.

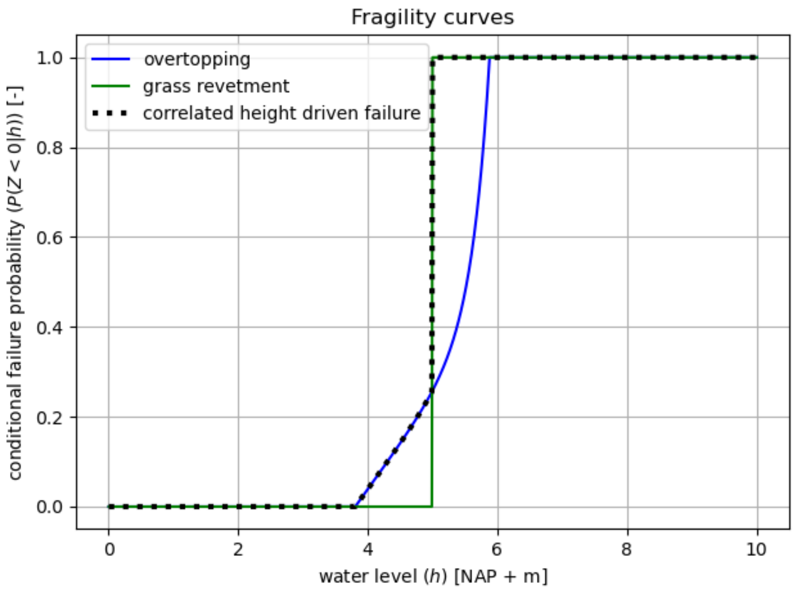


Figure 41: Fragility curves for overtopping and grass revetment failure. The fragility curve that assumes the two failure mechanisms to be fully correlated is shown by the black-dotted line.

Three dike failure mechanisms are included in the calculations. These failure mechanisms relate to geotechnical sections that are vulnerable to variations in water level. Specific structures within a dike trajectory and dike failure mechanisms insensitive to variations in water level are not considered. Piping failure is not included, as it is not considered as an important failure mechanism for describing the effect of storm surge barrier performance on the dikes along the Eastern Scheldt.

The dike probability is most vulnerable to storm surge barrier performance when the conditional dike failure probability is high for a relatively low water level on the dike. Erosion of grass revetment is an example of a failure mechanism that includes this characteristic. The failure probability of this failure mechanism is determined solely by the water level distribution, as discussed in Appendix C. The example of failure due to erosion of grass revetment is generalised to outline similar failure mechanisms that include this characteristic.

- Grass revetment failure models a dike that fails suddenly for a low water level on the dike, which is a simplified schematisation of failure due to overflow of a low dike.
- The correlated height driven failure mechanism in Figure 41 models a dike that fails for a water level that exceeds the height of the outer slope berm. This is a conservative schematisation of the wave reduction by outer berms of dikes. The higher the water level relative to the height of the outer berm, the smaller the reduction in wave height (EurOtop, 2007). Accounting for a smaller reduction in wave height increases the conditional failure probability of overtopping for water levels above the height of the outer berm.

Discretisation of flood protection system
The calculations have been applied to one cross section in this study. When deriving a requirement for flood defences, the effect of storm surge barrier performance on all relevant dike sections must be considered. It must be checked that the requirements are met for all selected locations along the estuary.

In case an optimisation problem is consulted, a distinction of different dike sections is needed. This allows for considering differences in load and resistance per location along the estuary. Equation 18 shows the problem that is solved in this study. The only change with respect to Equation 14 is the representative length of dike, or in other words, the number of dike sections considered. A distinction of dike sections also allows for specifying the dike investment function per section.

$$C_{invest,tot}^{opt} = \min_{p_{sf}}(C_{invest,SSB}(p_{sf}) + C_{invest,dike}(p_{sf})) \quad \textit{Equation 18}$$

- p_{sf} [1/year]: Structural failure probability storm surge barrier.
- $C_{invest,tot}^{opt}$ [€]: The optimal and thus minimum costs corresponding to the optimal storm surge barrier structural failure probability (p_{sf}^{opt}).
- $C_{invest,SSB}$ [€]: The investment to maintain a certain structural failure probability of the storm surge barrier (SSB).
- $C_{invest,dike}$ [€]: The investment required to reinforce the dikes along the estuary.

Estimation of investment functions
In this study, the dike failure probability is directly translated into costs, as exemplified by Equation 13. Translating failure probability to the required design geometry of a dike, and then calculating the costs to strengthen the dike, provides more detail. In that case, measures are identified per dike failure mechanism and included in the optimisation problem, as indicated by the green arrows in Figure 42.

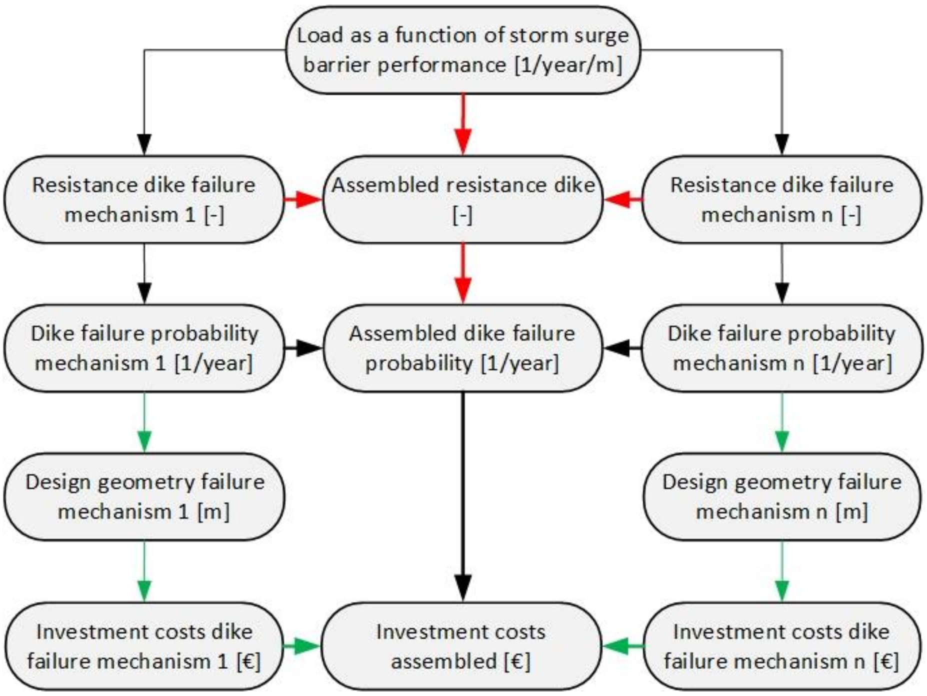


Figure 42: Steps to calculate the investment costs. The black arrows indicate the steps taken in this study. The red arrows represent dike strength by means of one function (e.g., one fragility curve). The green arrows calculate the required measures per dike failure mechanism.

Appendix C (C.2), for example, shows that the investment costs are lower when considering case-specific aspects. The costs to heighten revetment blocks on the outer slope of a dam are estimated to be lower than the costs based on the ratio between the actual and the required dike failure probability via Equation 13. Including a higher level of detail in the investment functions is desirable, examples are given for specifying the investment for a dike failure mechanism and for the structural failure probability of the storm surge barrier.

- **For the dike investment function,** the costs to reduce the failure probability of macrostability inner slope depend on the measure taken. The costs of a hard measure (e.g., a diaphragm wall) differ from the costs of a soft measure (e.g., a stability berm). Therefore, the investment costs depend on the available space per dike section, as a soft measure is applicable when enough space is available.
- **For the storm surge barrier investment function,** a concrete plan on how a certain structural failure probability is achieved and maintained is of interest. For the Eastern Scheldt Barrier, this consists of the costs to reduce the structural failure probability of the gates. This is achieved by increasing the strength of a certain structural component. The investment function presented in Figure D.1 is used to analyse the sensitivity of the parameters influencing this function.

7. Conclusions and recommendations

7.1. Conclusions

The first research question considers the criteria that have been used in safety standards for storm surge barriers, which have developed over time. It is important to understand the assessment of storm surge barriers with respect to the governing safety standards. Under the old safety standards in the Netherlands, the criteria and corresponding definitions were based on a maximum allowed estuary water level. The new safety standards follow approaches that assess whether the effect of storm surge barrier performance on flood risk may be considered negligible. If this is not the case, storm surge barrier performance must be modelled in the estuary hydraulic boundary conditions.

Furthermore, separate standards have been established for the different failure mechanisms of storm surge barriers. Additional requirements have been established for structural failure; these requirements are stricter than those for operational failure of storm surge barriers. The consequences in terms of flood risk associated with structural failure of storm surge barriers differ between safety standards, which is reflected in specific criteria for structural failure.

The framework presented in this study calculates the dike failure probability as a function of storm surge barrier performance. This is possible by accounting for storm surge barrier performance when schematising the water level distribution in front of dikes. The resistance of dikes to failure is in this study schematised using fragility curves.

Two approaches are identified to calculate a requirement for structural failure of storm surge barriers based on these failure probability calculations, which encompasses the objective of this study. The investment costs differ between flood protection systems designed based on an economic optimisation and systems designed using a conservative approach. Additional steps are necessary to perform an optimisation approach, as it requires the estimation of investment costs. An optimisation approach is relevant to assess the costs associated with a conservative approach.

- **An optimisation approach** considers the costs at the level of the flood protection system. A safety standard for storm surge barriers is derived by considering the investment in increasing the strength of dike and storm surge barrier to comply with the dike safety standards. When designing and assessing dikes, there is accounted for storm surge barrier performance by means of hydraulic loads. These hydraulic loads correspond to the optimal system configuration.
- **A conservative approach** does not account for storm surge barrier performance while designing and assessing dikes. A requirement is established so that the dike safety assessment does not need to be adjusted when the effect of storm surge barrier performance on the dike failure probability is accounted for. In other words, the maximum allowable consequences of dike failure are not exceeded when the effect of storm surge barrier performance is accounted for. There are two approaches to comply with this criterion: increasing the performance of the storm surge barrier and strengthening the dikes. Both measures lead to a lower dike failure probability; this exemplifies the system approach that is studied.

  It is noted that this approach corresponds to a negligible effect on dike failure probability and consequences of flooding. It does not imply that accounting for this negligible effect when designing and assessing dikes using hydraulic boundary conditions that describe the effect of storm surge barrier performance does not result in a substantial difference in dike geometry. This is exemplified using the calculations shown in Appendix C, a large difference in required design geometry does not correspond with a large absolute difference in dike failure probability.

The criteria that should be considered in safety standards for storm surge barriers are identified by applying the framework in a generic context and to the case study. The same criteria were identified in the two chapters presenting these applications. This is a result of the description of the flood protection system that is used for building the framework.

The aspects that describe the effect of storm surge barrier performance on flood risk are determined by the failure probabilities of flood defences, including both dike and storm surge barrier. These failure probabilities depend on the hydraulic loads, the resistance of flood defence defences, and the consequences of failure. It is concluded that an increase in storm surge barrier failure probability results in an increase in water level, an increase in dike failure probability, and consequently an increase in flood risk. These relationships that answer the second research question are included in the derivation of a requirement for storm surge barrier failure via the framework.

The criteria that should be considered in safety standards for storm surge barriers based on these relationships are listed to formulate an answer to the main research question. An elaboration of the relationships that determine these criteria is provided.

- **A definition of storm surge barrier failure.** The strength of the storm surge barrier influences the significance of the reduction in hydraulic loads. The strength and the number of structural components and gates influence the resulting hydraulic boundary conditions.
- **The influence of varying storm surge barrier performance**. The dike strength determines the required performance of the storm surge barrier. The sensitivity of the dike failure probability to small changes in water level, resulting from varying structural reliabilities of the storm surge barrier, differs per dike failure mechanism and therefore per dike section.
- **The minimum costs at the level of the flood protection system.** The justified investment in strengthening a storm surge barrier depends on the economic optimisation that considers dike and storm surge barrier investment functions.
    - The greater the reduction in dike failure probability achieved by increasing storm surge barrier performance, the higher the justified investment in the storm surge barrier.
    - The larger the length of dike protecting the hinterland, the higher the reduction in flood risk achieved by improving storm surge barrier performance.
- **The maximum allowed consequences of flooding.** The required dike strength is essential for determining the required strength of the storm surge barrier. The required dike strength reflects the consequences of dike failure for the hinterland.

The third research question addresses the criteria that should be considered in a requirement for structural failure of the Eastern Scheldt Barrier. For this case study, two aspects are in particular of relevance in addition to the generic criteria identified by addressing the main research question.

- Structural failure of the storm surge barrier should be expressed as a function of the number of gates that fail per storm event, which in Prespeil is represented in terms of estuary water levels.
- In terms of flood risk, the consequences for the hinterland should be considered. Individual risk is the most relevant indicator for the Eastern Scheldt dikes. This implies that an economic optimisation does not fully determine a requirement for storm surge barrier performance. A criterion that assesses the individual risk for the hinterland is necessary.

7.2. Recommendations

A framework is proposed to derive a requirement for storm surge barriers based on the relationship between storm surge barrier performance and dike failure probability. The following recommendations relate to the use of the framework.

- A limited number of calculations are performed in this study. Varying the input functions provides insights into the sensitivity of the results. Furthermore, it is necessary to perform calculations for multiple locations and dike cross sections when analysing the complete flood protection system.
- The framework does not include the steps to calculate the consequences of dike failure in terms of individual risk and societal risk. Including these criteria in the calculations allows for verifying that the maximum allowed consequences of flooding are not exceeded.
- A generic description of the steps of the framework is provided in this report. The functions and formulas to be used in applying the framework can be altered based on the available tools for performing the analysis. The tools must be available to calculate the dike failure probability while varying the load on a dike and the dike resistance.

The framework is applied to a case study: the Eastern Scheldt Barrier. The following recommendations are based on the discussions and calculations in this study regarding this case study.

- Structural failure of the Eastern Scheldt Barrier is currently verified using two requirements that evaluate flood safety. The assessment of these two requirements provides two contradicting conclusions. Therefore, it is relevant to reflect on the approaches that are used in safety assessment using the failure definitions in Besluit kwaliteit leefomgeving (2025).
- For the Eastern Scheldt Barrier, a criterion that assesses whether the effect of storm surge barrier performance on the consequences of flooding may be considered negligible is suitable. This approach does not require the investment functions and the effect of different dike safety standards to be considered, which reduces the effort in performing the calculations.
- The dike failure probability, and thus the risk of flooding, increases for increasing structural failure probability. It is recommended to check whether this effect is of interest regarding non flood risk related aspects. It is not checked in this study which increase in structural failure probability is accepted when considering the Building Decree and the repair time of structural components.

Appendix A. Overview of assessment of Eastern Scheldt flood defences

This appendix gives an overview of the assessment of flood defence trajectories along the Eastern Scheldt; these flood defence trajectories are presented in Figure 28. Section A.1 discusses the methods used in assessing flood defences. The characteristics of the dike trajectories are summarised in Section A.2. The characteristics of the closure dams along the estuary are presented in Section A.3. These characteristics are used for schematising the fragility curves for the Eastern Scheldt in Appendix B.

A.1. Methods for assessing flood defences

Flood defences are verified against safety standards, the maximum allowed failure probability and the signal value, as depicted in Table A.1. The minimum required dike strength is represented by the maximum allowable annual probability of failure, the signal value is used to decide whether reinforcement is necessary. The maximum allowable annual probability of failure is never stricter than the signal value.

Table A.1: Assessment categories for flood defences (IHW, n.d.).

Assessment Category	Description
A+	Complies with signal value by a large margin.
A	Complies with signal value.
B	Complies with maximum allowable failure probability, not with signal value.
C	Does not comply with both maximum allowable failure probability and signal value.
D	Does not comply with maximum allowable failure probability by a large margin.

Flood defences are assessed using calculations per cross section and per failure mechanism. The failure probability of a cross section is determined by summing the failure probabilities of the individual failure mechanisms, thus assuming that the different failure mechanisms are independent. The failure probability per cross section is translated to trajectory level, this failure probability is verified against the maximum allowable annual probability of failure per dike trajectory.

Table A.2 presents an example of dike failure probability calculations for a dike trajectory along the Eastern Scheldt (i.e., dike trajectory 28-1). For this dike trajectory, the calculated failure probability (i.e., 1/790) is lower than the maximum allowed failure probability (i.e., 1/300).

Table A.2: Failure probability calculations for dike trajectory 28-1 (Waterschap Scheldestromen, 2022).

Failure mechanism	Failure probability [1/year]	Share of total [%]
Overtopping	6.42E-7	0.1
Piping	1.07E-4	8.4
Macrostability	1.16E-3	91.5
Failure of structure	4.31E-7	≈0
Total	1.27E-3	100

A.2. Overview of assessment of dike trajectories

The dike trajectories protect the hinterland directly against flooding. The required strength of the dike trajectories is expressed via safety standards. Seven dike trajectories are defined along the Eastern Scheldt.

Table A.3: Summary of characteristics of dike trajectories along the Eastern Scheldt (IHW, n.d.).

Trajec-tory [#]	Trajectory length [km]	Maximum allowed failure probability [1/year]	Dominating failure mechanism	Assess-ment
26-2	20.7	1/1,000	Macro stability inner slope (STBI) Shearing grass cover inner slope (GABI)	C
26-3	21.9	1/3,000	Macro stability inner slope (STBI) Shearing grass cover inner slope (GABI) Piping failure of structure (PKW)	C
27-1	16.2	1/3,000	Macro stability inner slope (STBI) Shearing grass cover inner slope (GABI)	C
27-2	36.9	1/10,000	Macro stability inner slope (STBI)	D
28-1	23.9	1/300	Macro stability inner slope (STBI)	B
30-1	22.6	1/1,000	Stability block revetment (ZST)	D
31-2	28.6	1/3,000	Macro stability inner slope (STBI) Strength and stability of water-retaining structure (STKWl)	C

The dominating failure mechanism, the failure mechanism that determines the assessment category, differs per dike trajectory, as concluded from Table A.3. Failure due to macro instability of the inner slope is important for all dike trajectories. Other important failure mechanisms relate to a specific structure that is part of the flood defence trajectory or to the quality of the revetment of the dikes.

In this study, the failure probability of dike failure mechanisms is calculated using the water level on the dike. Table A.4 shows that macro stability inner slope is the most important failure mechanism for describing the dikes along the Eastern Scheldt regarding the failure mechanisms driven by the water level.

Table A.4: Minimum and maximum failure probabilities at trajectory level of the seven dike trajectories (IHW, n.d.).

Failure probability per mechanism	Overtopping failure	Macro stability inner slope failure	Piping failure
Minimum failure probability [1/year]	3.24E-07	9.03E-04	1.15E-05
Maximum failure probability [1/year]	1.56E-04	1.64E-02	1.63E-04

A.3. Overview of assessment of closure dam trajectories

The Eastern Scheldt is closed off by dams. These closure dams are designed to separate bodies of water. Closure dams are flood defences before another line of the flood protection system (voorliggende keringen), just like storm surge barriers. Their function is to reduce the hydraulic loads behind the dam; they do not protect the hinterland directly. The five trajectories corresponding to the dams and their characteristics are outlined in Table A.5.

Table A.5: Summary of characteristics of closure dam trajectories along the Eastern Scheldt (IHW, n.d.).

Trajectory [#]	Trajectory [-]	Trajectory length [km]	Maximum allowed failure probability [1/year]	Assessment
216	Grevelingendam	4.4	1/1,000	A
217	Philipsdam	7.8	1/10,000	B
219	Oesterdam	11.5	1/10,000	D
221	Zandkreekdam	0.9	1/3,000	A
222	Sluizen kanaal door Zuid-Beveland	0.1	1/10,000	A

Currently, only the Oesterdam does not comply with the safety standards, assessment category D is assigned to this trajectory. The failure mechanisms related to the resistance of the outer slope revetment are the reason for no improved assessment for both the Oesterdam and the Philipsdam.

Appendix B. Fragility curves for the Eastern Scheldt

The framework uses fragility curves to represent the strength of a dike cross section. Three relevant failure mechanisms for the Eastern Scheldt are represented by fragility curves. The fragility curves are conceptual; an exact mathematical description is not provided. This appendix discusses three failure mechanisms and their corresponding fragility curves.

B.1. Description of fragility curves

Fragility curves represent the failure probability of a failure mechanism given a certain load; in this study the load is represented by the water level. A fragility curve is constructed by calculating the failure probability per water level. The fragility curve represents the resistance to failure, the higher the resistance to failure, the lower the failure probability given a certain load. The conditional failure probability, the failure probability given a certain water level, increases for increasing water level.

B.2. Overview of failure mechanisms used in this study

Three failure mechanisms are used to describe the flood defences along the Eastern Scheldt.

- **Overtopping failure** is included, as this failure mechanism is more driven by water levels than geotechnical dike failure mechanisms.
- **Macrostability of inner slope** is an important failure mechanism for dikes along the Eastern Scheldt, as derived from Appendix A, and is therefore essential for describing the Eastern Scheldt dikes.
- **Failure due to erosion of the outer slope** is largely dependent on the quality of the revetment. The example of failure due to erosion of the outer slope grass revetment for the Oesterdam is used as an example of a revetment failure mechanism that is determined by water levels.

Figure B.1 illustrates the fragility curves of the considered failure mechanisms. Equation B.1 and Table B.1 provide the length effect calculations corresponding to these failure mechanisms. The parameters are representative for the case study. The three following sections describe the failure mechanisms.

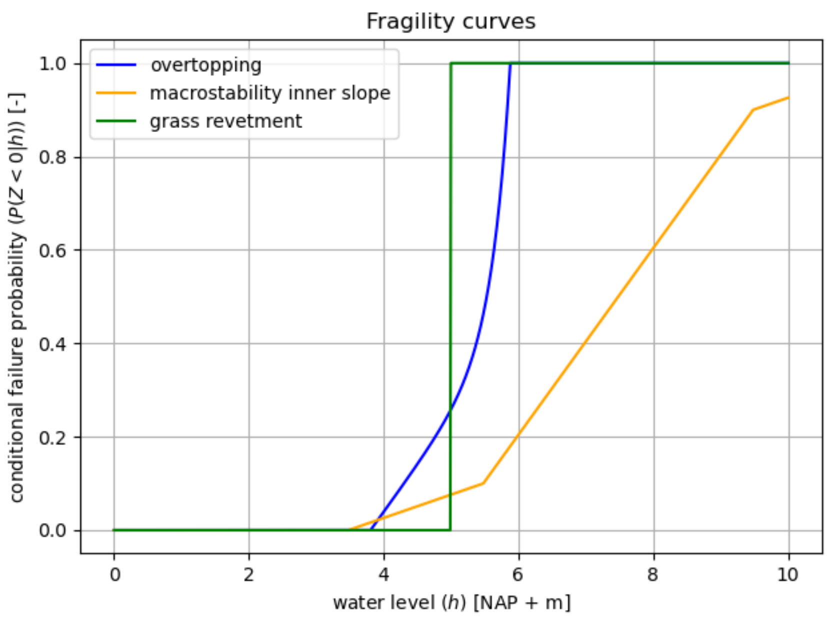


Figure B.1: Fragility curves for a dike with three failure mechanisms.

$$N = 1 + a * \frac{L_{traject}}{b}$$ *Equation B.1*

- N [-]: Length effect.
- a [-]: Fraction of length sensitive to failure mechanism.
- b [m]: Length between independent dike cross sections.
- $L_{traject} = 25{,}000$ [m]: Length of a typical dike trajectory, as identified from Appendix A.

Table B.1: Failure mechanisms with corresponding distribution factor (ω) and length effect (N) (Handreiking ontwerpen met overstromingskansen, 2014).

Failure mechanism	ω [-]	a [-]	b [km]	N [-]
Overtopping	0.24	-	-	2
Macrostability inner slope	0.04	0.033	0.05	17.5
Erosion grass revetment	0.05	-	-	2 (Rijkwaterstaat, 2022a)

B.3. Overtopping

Water topping over a flood defence leading to erosion of the inner slope. Failure is defined when an excessive discharge flows over a flood defence. Failure mechanism depends on estuary water level. The Eastern Scheldt is characterised by high flood defences, thus the failure probability for overtopping of dikes is low, as shown in Appendix A.

The fragility curve is characterised by a relatively steep slope, indicating that a small increase in water level increases the conditional probability of dike failure significantly. The mean value of the fragility curve is fitted to represent a typical failure probability for a dike along the Eastern Scheldt (i.e., order of magnitude 10^{-6}/year at trajectory level).

B.4. Macrostability inner slope

Instability of the inner slope leading to sliding of parts of the flood defence. Failure is defined if the external moment is larger than the resisting moment. The conditional dike failure probability is relatively insensitive to small changes in water level. Macrostability of the inner slope is an important failure mechanism for dike trajectories along the Eastern Scheldt, as shown in Appendix A.

The fragility curve is characterised by a relatively mild slope, indicating that failure is influenced by a relatively large range of water levels. The mean value of the fragility curve is fitted to represent a typical dike cross section along the Eastern Scheldt (i.e., order of magnitude 10^{-3}/year at trajectory level).

B.5. Erosion grass revetment outer slope

Loads on outer slope that initiate erosion of the outer slope. Failure is initiated by instability of outer slope revetment. Failure mechanism is mostly dependent on wave loading. Erosion of the grass revetment of the Oesterdam is an example of failure due to erosion of the outer slope of a flood defence.

This example considers dam failure due to failure and erosion of revetment. Specifically, failure of grass revetment due to erosion of the grass layer is considered. To prevent erosion of revetment, it is common practice to use revetment that is capable of withstanding wave impact. In general, grass revetment is not suitable to use in the wave impact zone, block revetment is used instead.

Klerk & Jongejan (2016) describes an approach for determining the wave impact zone. This zone is defined below the water level corresponding to the return period of the failure mechanism at cross section level according to Equation 3, which is illustrated in Figure B.2. Above this transition, wave run-up takes place, and applying grass revetment is not problematic.

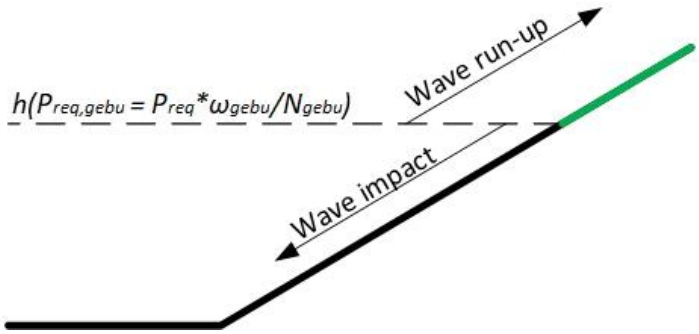


Figure B.2: Wave impact and wave run-up on outer slope flood defence.

This failure mechanism is relevant for the Oesterdam, a dam along the Eastern Scheldt, indicated as flood defence trajectory 219 in Figure 28. The Oesterdam is a closure dam with grass revetment on the outer slope of the cross section, as shown in Figure B.3. The grass revetment is rejected when the theoretical transition level exceeds the transition level on the dam cross section (Rijkswaterstaat, 2022a).

Figure B.3: Oesterdam (van Houdt, 2011).

This failure mechanism is schematised by assuming conditional failure if the water level is above the start of the grass revetment on the dam's outer slope. It is assumed that the revetment has no residual strength, it fails after the start of erosion of the outer slope. This is illustrated by a sudden jump in the fragility curve, a step function. The jump is schematised at a typical start of the grass cover on the outer slope for a cross section of the Oesterdam (i.e., NAP + 5 m).

Appendix C. Calculations grass revetment failure Oesterdam

This appendix presents calculations for grass revetment failure. This failure mechanism is relevant for the Oesterdam and is described in Appendix B (B.5). A characteristic of this dike failure mechanism is that it is completely driven by the load, the failure probability is described fully by the water level distribution. This implies that the required design level of the start of the grass revetment on the dam's outer slope is read directly from Figure C.1. The required strength, the design level, depends on Equation 3.

$$P_{req,gebu} = \frac{P_{req,dike} * \omega_{gebu}}{N_{gebu}} = \frac{10^{-4} * 0.05}{2} = 2.5E - 6 \quad \textit{Equation 3}$$

- $P_{req,gebu}$ [1/year]: Maximum allowed failure probability of grass revetment (GEBU) at cross section level.
- $P_{req,dike} = 10^{-4}$ [1/year]: Maximum allowed annual probability of failure of the Oesterdam (see Table A.5).
- $\omega_{gebu} = 0.05$ [-]: Distribution factor grass revetment failure (see Table B.1).
- $N_{gebu} = 2$ [-]: Length effect failure grass revetment (see Table B.1).

Subsequently, the required transition level is determined at NAP + 4.44 metres for taking into account storm surge barrier performance. This is 0.44 metres higher than the required design level for assuming a perfect storm surge barrier. This implies that the required transition level depends on the structural failure probability of the storm surge barrier.

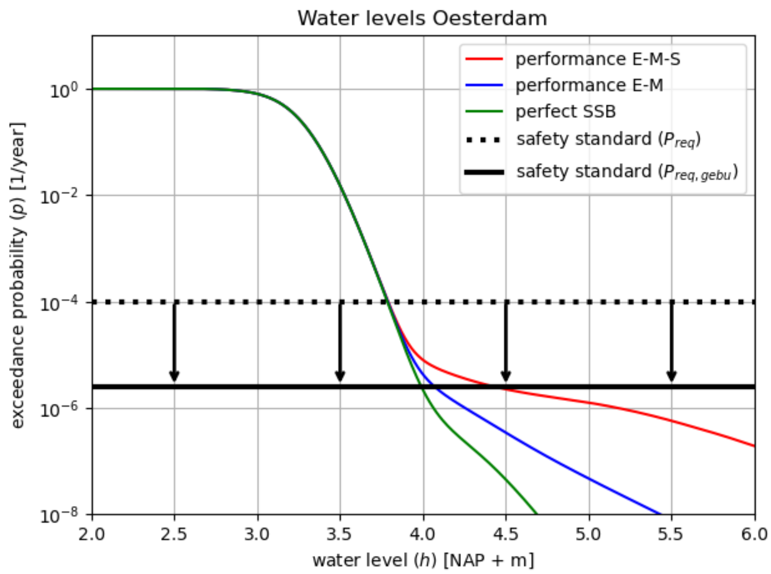


Figure C.1: Prespeil output for Oesterdam read at exceedance probability corresponding to failure of grass revetment.

C.1. Calculation of design levels and failure probabilities for grass revetment failure

The required strength of the dam, the required height of the transition level, is sensitive to small changes in exceedance probability. In practice, the required height is adjusted via the distribution factor. Two options are presented in Table C.1.

1. The effect of storm surge barrier performance on the design level is reduced by increasing the failure budget (e.g., $\omega_{gebu} = 2 * 0.05$).
2. The contribution of this failure mechanism relative to the safety standard, and thus relative to other dike failure mechanisms, is reduced (e.g., $\omega_{gebu} = 0.1 * 0.05$).

Table C.1: Calculations for failure grass revetment for different failure budgets (ω_{gebu}). Design levels (h_d) and failure probabilities at trajectory level per design level for taking into account storm surge barrier performance (E-M-S) ($p_{df|h_d}$).

	$\omega_{gebu} = 0.05$		$\omega_{gebu} = 0.1$		$\omega_{gebu} = 0.005$	
	design level (h_d) [NAP + m]	$\mathbf{p}_{df\|h_d}$ **[1/year]**	**design level (h_d) [NAP + m]**	$\mathbf{p}_{df\|h_d}$ **[1/year]**	**design level (h_d) [NAP + m]**	$\mathbf{p}_{df\|h_d}$ **[1/year]**
perfect SSB	4.00	1.60E-05	3.95	2.25E-05	4.25	7.21E-06
performance (E-M)	4.08	1.14E-05	3.99	1.70E-05	4.58	4.03E-06
performance (E-M-S)	4.44	4.96E-06	4.13	9.75E-06	5.90	4.91E-07

The calculations in Table C.1 show how the design level influences the dike failure probability for taking into account storm surge barrier failure (performance E-M-S). If the dike is designed for not taking into account storm surge barrier failure (perfect SSB) or taking into account failure due to non-closure (performance E-M), the failure probability is underestimated. This effect is altered by changing the failure budget, as shown by the two options presented.

1. The design level is lower for a higher failure budget. Furthermore, the absolute increase in required design level when accounting for storm surge barrier performance is smaller for a higher failure budget.
2. The failure probability is lower for a higher design level. Furthermore, the absolute increase in failure probability when accounting for storm surge barrier performance is smaller for a higher design level.

C.2. Estimation of costs to reduce the failure probability of grass revetment

To show the implications of the results presented in Table C.1, the results are translated into costs. The required investment to account for the effect of storm surge barrier failure (E-M-S), instead of assuming a perfect storm surge barrier, is calculated in Table C.2. The calculations are assumed to be representative for the complete length of the Oesterdam (i.e., 11.5 kilometres, see Table A.5).

The costs are calculated for two approaches.

- C_{pf}: Investment based on a difference in dike failure probability, calculated using Equation 13, with parameters defined in Subsection 5.4.2.
- C_{h_d}: Investment based on the difference in design level. The costs to place rock revetment are estimated at 100 €$*$m^{-2} (HWBP, n.d.). For assuming a 1 in 4 slope of the dam, the costs to place block revetment are estimated at €500/metre height/metre width.

Table C.2: Costs required to heighten the transition level to take into account storm surge barrier performance. Costs are calculated for two approaches for calculating investment and for three different failure budgets.

	$\omega_{gebu} = 0.05$	$\omega_{gebu} = 0.1$	$\omega_{gebu} = 0.005$
C_{pf} **[million €]**	11.7	8.3	26.8
C_{h_d} **[million €]**	2.5	1.0	9.5

The calculations show that it is possible to translate between a difference in failure probability, design height, and costs. Furthermore, the costs are calculated lower when estimating the costs for this specific failure mechanism (C_{h_d}), instead of using generalised costs of dike strengthening per kilometre (C_{p_f}).

Appendix D. Description of storm surge barrier investment function

This appendix outlines the principles that are used for describing the storm surge barrier investment function. This function quantifies the costs associated with maintaining a certain structural failure probability of the Eastern Scheldt Barrier.

The storm surge barrier investment function is estimated, as the relationship between costs and the structural failure probability of the Eastern Scheldt Barrier is not available. Based on Figure 30, it is assumed that the structural failure probability is determined by the gates (schuiven) and the support structure of the gates (schuifaanslagen). Three maintenance tasks are identified for these components.

- Preservation of the gates.
- Replacement of the gate supports.
- Replacement of the gates.

The first two tasks are currently part of the maintenance of the structure. The total maintenance costs of the Eastern Scheldt Barrier are approximately equal to 30-40 million euros per year, of which about 10 million euros is associated with these tasks, as concluded after contact with Rijkswaterstaat. The third task, the replacement of the gates, is not planned within the near future.

For describing the investment function, the following assumptions are made on the maintenance of these three tasks.

- The frequency of maintenance on the storm surge barrier, and therefore the annual expenditure, increases if a lower structural failure probability is required. The frequency of maintenance, an expression for the number of gates maintained per year, determines the investment costs.
- The replacement of the gates is needed to guarantee a lower structural failure probability but is currently not part of the maintenance tasks. Including this task is expected to increase the maintenance budget significantly. This is interpreted as at least a doubling of the maintenance costs for structural failure.

It is assumed that the costs are determined by the annual investment required to maintain the gates and their support structure. The discount rate is used to convert these annual costs to total costs, which is needed to ensure the same unit of costs for the dike and storm surge barrier investment functions. Equation D.1 provides the approximation of the total maintenance costs over the lifetime of the structure. This approximation is valid for a long reference period and is assumed to be applicable to the lifetime of the Eastern Scheldt Barrier, which has been defined as 200 years in Rijkswaterstaat (1986).

$$C_{lifetime} = C_{yearly} * \left[\sum_{t=1}^{\infty} \frac{1}{(1+r)^t}\right] = \frac{C_{yearly}}{r}$$

Equation D.1

- C_{yearly} [€/year]: The annual maintenance costs.
- $C_{lifetime}$ [€]: The total maintenance costs over the lifetime of the structure.
- r [-]: Discount rate used to determine the present value of costs.
- t [year]: Number of years relative to the reference year.

The estimation of the storm surge barrier costs is given for the current operation of the storm surge barrier, which corresponds to the present structural failure probability (i.e., $p_{sf} \approx 10^{-4}$/year). The costs associated with an increment in structural failure probability are described by the costs associated with a factor ten difference in probability. This approach is used for analysing the sensitivity of the investment function with respect to the calculations presented in Section 5.4. The investment function is shown in Figure D.1 and described by Equation D.2.

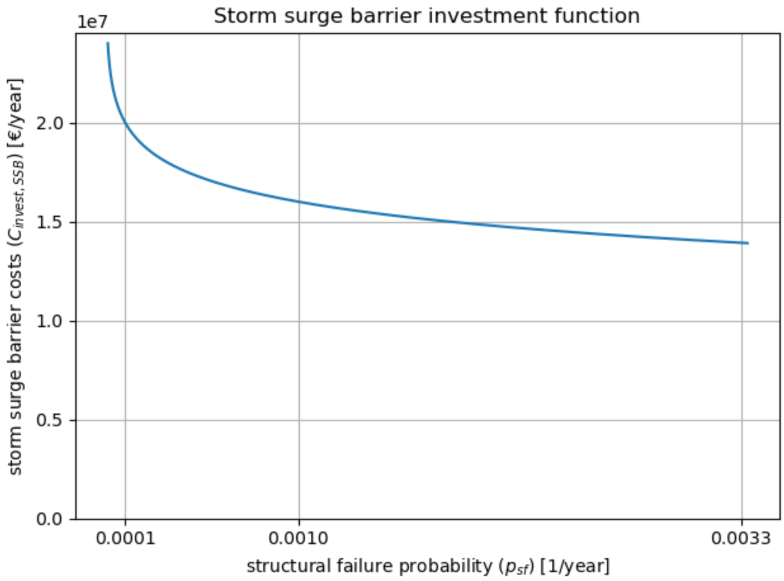


Figure D.1: Storm surge barrier investment function.

Equation D.2

$$C_{invest,SSB} * r = C_{SSB,fact10} * \log_{10}\left(\frac{10^{-4}}{p_{sf}}\right) + C_{SSB,base}$$

- p_{sf} [1/year]: Structural failure probability storm surge barrier.
- $C_{invest,SSB}$ [€]: The investment to maintain a certain structural failure probability of the storm surge barrier (SSB).
- $r = 0.0225$ [-]: Discount rate via Rijkswaterstaat (n.d.b).
- $C_{SSB,fact10} = 4 * 10^6$ [€/year]: SSB investment to vary the structural failure probability by a factor of 10. The sensitivity of this parameter with respect to the calculation of an economic optimum is discussed in Subsection 5.4.4.
- $C_{SSB,base} = 20 * 10^6$ [€/year]: The estimated annual maintenance costs related to structural failure.

Appendix E. Parameters used for calculating a requirement for structural failure

An overview of the parameters considered in the application of the framework to the case study is provided in Table E.1. The parameters are listed according to the generic steps for calculating an economic optimum, as outlined in Subsection 3.3.1.

Table E.1: Parameters included in calculating an economically optimal structural failure probability.

Parameters used for performing the steps of the framework		
Parameter included in calculating the dike failure probability		
1	$f(h)$ [1/year/m]: Probability density function (PDF) water level distribution.	p_{sf} [1/year]: Structural failure probability storm surge barrier. p_{nc} [1/demand]: Non-closure probability storm surge barrier.
2	$P(Z < 0\|h)$ [-]: Fragility curve providing the failure probability of a dike failure mechanism per water level.	$\mu_{P(Z<0\|h)}$ [NAP + m]: Mean value of the fragility curve. $\sigma_{P(Z<0\|h)}$ [m]: Shape of the fragility curve.
3	$P(F_{dike,traj})$ [1/year]: Dike failure probability at trajectory level.	N [-]: Length effect corresponding to dike failure mechanism.
Parameters included in the investment functions		
4	$C_{invest,dike}$ [€]: The investment required to reinforce the dikes along the estuary.	$L_{estuary} = 196$ [km]: Total length of dike and dam trajectories along the estuary. $C_{dike,fact10} = 2 * 10^6$ [€/km]: Dike investment to reduce the dike failure probability by a factor of 10. $P_{req,dike} = 10^{-4}$ [1/year]: Maximum allowable annual probability of dike failure.
5	$C_{invest,SSB}$ [€]: The investment to maintain a certain structural failure probability of the storm surge barrier (SSB).	$r = 0.0225$ [-]: Discount rate. $C_{SSB,fact10} = 4 * 10^6$ [€/year]: SSB investment to vary the dike failure probability by a factor of 10.
6	$C_{invest,tot}$ [€]: The total investment costs, the sum of the two contributions.	p_{sf}^{opt} [1/year]: Optimal structural failure probability storm surge barrier.

Appendix F. Description of notebook calculations

The calculations in this report are performed using Python notebooks. The notebooks follow the steps outlined in the report. Output is generated by varying the code within the notebook. Three notebooks are written; the content of these notebooks is described concisely.

F.1. Hydra-NL

This notebook uses the hydraulic loads calculated with Hydra-NL to illustrate the effect of storm surge barrier performance on the hydraulic loads. The notebook describes the location used in the calculations and the approach to modify the reliability of the Eastern Scheldt Barrier in Hydra-NL.

F.2. Framework Generalised

This notebook follows the steps in Subsection 3.3.2 to calculate the results presented in Chapter 4. This includes deriving the schematised water level distribution and providing functions for calculating the output per fragility curve for different hydraulic loads.

F.3. Framework Case

This notebook follows the steps in Subsection 3.3.2 to calculate the results presented in Chapter 5. The input is provided in MS Excel files. Figures and tables outline the steps in the calculations. Calculations for grass revetment failure, presented in Appendix C, are included in the notebook.

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