A risk-based optimisation strategy for large-scale flood defence systems

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Summary

A method for the optimisation of large-scale water defence systems is described. Minimisation of the life-cycle costs of this type of systems leads to optimisation problems with a high number of dimensions. The proposed method deals with the high dimensionality by dividing the system into appropriate sub-systems. Thus, the method fulfils both the requirements of theoretical soundness and transparency to decision-makers.

Keywords: flood risk, optimisation, water defence structures, life-cycle costs

1. Introduction

In the Netherlands, for many years the design requirements for water defence structures have been defined in the form of prescribed exceedance frequencies of the design water level. In 1996, a new flood defence act was accepted by the parliament. In the new law, the old method of prescribing the design requirements is adopted, but at the same time a transition to a fully risk-based methodology is foreseen.

The main advantage of a fully risk-based design methodology for flood defences is an increased flexibility with respect to the design of the system of flood defences protecting an area. Where in the old methodology every component in the system had to fulfil the same design requirement, the new approach opens the possibility to have an uneven distribution of the failure probability over the components. From earlier studies it is observed that minimisation of the life-cycle costs of a civil structure often leads to such an uneven distribution of failure probabilities. In this paper, an optimisation strategy for large-scale flood defence systems will be shown.

2. Problem outline

For a consistent flood-defence policy, a method has to be found to prescribe the design requirements for flood-retaining structures. In the past, this has been done by prescribing the exceedance probability of the design water level. The design exceedance probabilities of the water level were prescribed in the Delta law as early as 1958. Since then, a considerable development of reliability-based design methods has taken place.

Most importantly, the reliability-based design methods are now able to take into account more than one random variable. Furthermore, reliability analysis of large-scale systems is now possible (see Ditlevsen and Madsen (1996) for an overview). The application of these methods to flood-defences leads to failure probabilities that deviate considerably from the prescribed exceedance probabilities of the water level (TAW, 2000). Though the deviation can be rationally explained, still the question of the acceptability of the occurring failure probabilities is asked by society. Therefore, tools for the analysis of acceptable failure probabilities have to be developed.

3. Design philosophy

In a research project conducted at Delft University, risk-based optimisation is adopted as the main principle on which to base an analysis of acceptable flooding risk. This type of optimisation has been applied successfully in several earlier studies in coastal engineering. Reference is made to van Dantzig (1956), Burcharth et al (1996), Vrijling et al (1998) and Voortman et al (1998). The basic form of risk-based optimisation is economic optimisation that is aimed at minimisation of the lifetime cost of the flood-defence system:

$$C_{life}(\mathbf{p},\mathbf{x}) = I(\mathbf{p}) + R(\mathbf{p},\mathbf{x}) \tag{1}$$

Where: $\mathbf{p}$: Vector of design variables;
$\mathbf{x}$: Vector of random variables;
$I(\mathbf{p})$: Investment in the structure or system;
$R(\mathbf{p},\mathbf{x})$: Monetary risk.

The monetary risk in its basic form is given as the expected value of the monetary damage in case of flooding:

$$R(\mathbf{p},\mathbf{x}) = P_{flood}(\mathbf{p},\mathbf{x})S \tag{2}$$

Where: P_{flood}: The flooding probability of the area;
S: The monetary value of all inventory of the area.

The basic model may be extended in several ways:

- Constraints can be set on the flooding probability to take account of casualty risk in inhabited areas;
- Refined risk models may be applied, taking into account the influence of several properties of the flooding (duration, maximum water depth in the area) on the resulting risk.

These extensions are not of influence on the structure of the optimisation strategy and will therefore not be dealt with in this paper.

4. Optimisation of large-scale systems

Most areas in the west of the Netherlands are protected by an extensive system of flood defences, consisting of dike sections, dune sections and several special structures. Such a system is called a dike ring. The probability of flooding of an area may be evaluated by using system reliability theory, calculating the reliability of all the components first, followed by an evaluation of the system probability of failure (see Hohenbichler and Rackwitz, 1983). Extending the reliability evaluation with optimisation can be done in two ways, which will be called the top-down approach and the bottom-up approach.

In the top-down approach, lifetime costs of the dike ring are defined in the space of the design variables of the components. Well-known optimisation methods may then be used to find the minimum of the lifetime costs. In practice, this approach leads to a high-dimensional optimisation problem. The number of design variables for one dike ring may well be in the order of 100 to 500.

Since the tool is ultimately aimed at supporting decision-making for the definition of acceptable flooding risk levels, it is important that the tool is transparent for decision-makers and design engineers. It is the opinion of the authors that the top-down approach is too much a black box approach. An alternative is the bottom-up approach. In this approach the lifetime costs of the dike ring are defined in the space of the failure probabilities of the individual components of the ring; in formula:

$$C_{life}(\mathbf{P_f}) = I(\mathbf{P_f}) + R(\mathbf{P_f}) = I(\mathbf{P_f}) + P_{flood}(\mathbf{P_f}, \rho)S \tag{3}$$

Where: $\mathbf{P_f}$: Vector of component failure probabilities;
ρ: Correlation matrix, providing the correlation between components.

In this case, the number of dimensions of the optimisation problem is reduced to the number of individual components in the ring. Generally, this means a reduction of the number of dimensions in the system optimisation by a factor 5 to 10.

Fig. 1: Overview of case study area

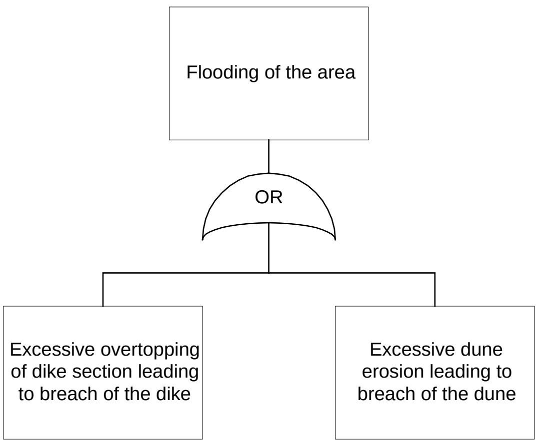

Fig. 2: Fault tree of Rijnvlakte 1

To obtain the optimisation in this form, the functions in the right-hand side of (3) have to be found. System reliability theory provides the flooding probability as a function of the failure probabilities of the components and the correlation matrix. The investment function and the correlation matrix have to be found by a closer analysis of every component.

The result of the optimisation should be independent of the strategy used. It can be proven that a minimum of (3) corresponds to a minimum of (1) if and only if the investment function is defined as the *minimum investment in the component for a given failure probability.* Therefore, the investment function can be found by minimisation of the investment in the section for a number of prescribed failure probabilities.

The correlation matrix is found as a function of the normalised gradients of the reliability index of every component with respect to the basic variables. More details are given in the case study.

5. Case study: safety level of a land reclamation project

5.1 Case description

The concept of bottom-up optimisation is applied to a fictitious land reclamation project, situated in the North Sea near the port of Rotterdam. The terrain is assumed to have a triangular shape. The north shore is protected by a sea dike with a length of 3400 m (see figure 1). The west shore is protected by a dune with a length of 7700 m. The total area is 1125 ha. Bottom-up optimisation is applied to find:

- The economically optimal flooding probability of the area;
- The economically optimal failure probabilities of the dike and the dune.

In this case, failure of the components is described by one failure mode per component only. The fault tree for the top event "flooding of the area" is given in figure 2.

The loading of the water retaining structures is caused by the hydraulic conditions at the North Sea, i.e. the water level, the wave height and the wave period. In a shallow sea, like the North Sea, high wind speeds can cause high wave heights with long wave periods, as well as considerable increases of the water level. Because of this, the loading variables are strongly dependent. The dependency has been described using parametric physical models (see Repko (2000) for details). An overview of all basic variables, including the hydraulic variables described above, is given in table 1.

Table 1: overview of basic variables

Variable	Distr. type	Shift	Scale	Shape	Used in
Water level	W	2.4m	0.19m	0.85	Dune and dike
Model uncertainty wave height	N	0.0m	0.6m	-	Dune and dike
Wave steepness	N	3.8%	0.59%	-	Dune and dike
Model factor overtopping breaking waves	N	1	0.106	-	Dike
Model factor overtopping non-breaking waves	N	1	0.134	-	Dike
Median grain size dune sand	N	0.255mm	0.015mm	-	Dune
Influence factor storm duration	N	0	0.1	-	Dune
Height of gust bump	N	0.4m	0.1m	-	Dune
Model uncertainty dune erosion	N	0	1.0	-	Dune

5.2 Component optimisation

5.2.1 Sea dike

In line with current design practice for sea dikes in the Netherlands, failure of the dike is defined as: *"exceedance of the maximum admissible overtopping discharge"*. The reliability function for this failure mode is written as:

$$M_{overtop} = q_{crit} - q_{occ}$$

Where: q_{crit}: overtopping discharge critical for back slope stability;
q_{occ}: occurring overtopping discharge.

Models for the calculation of the overtopping discharge as a function of the geometry of the dike and the hydraulic loading have been developed in large-scale experiments in the Netherlands (see v.d. Meer and Janssen, 1995). The optimisation problem for the dike section is written as:

$$\min_{h_c, B_b} I(h_c, B_b) = C_{vol} V(h_c, B_b) + C_{cover} A(h_c, B_b)$$
$$s.t. \qquad P_{f;dike}(h_c, B_b) = P_{f;prescr}$$
$$h_c, B_b > 0$$

Where: h_c, B_b: Crest height and berm width of the dike (design variables);
C_{vol}: Cost per volume of body material;
C_{cover}: Cost per area of cover material;
V: Volume of dike body;
A: Outside area of dike body;
$P_{f;dike}$: Failure probability of the dike;
$P_{f;prescr}$: Prescribed failure probability.

By variation of the prescribed failure probability $P_{f;prescr}$ several values of the investment are found. The result is shown in figure 3. The investment can be approximated by a linear function of the log of the failure probability of the dike section.

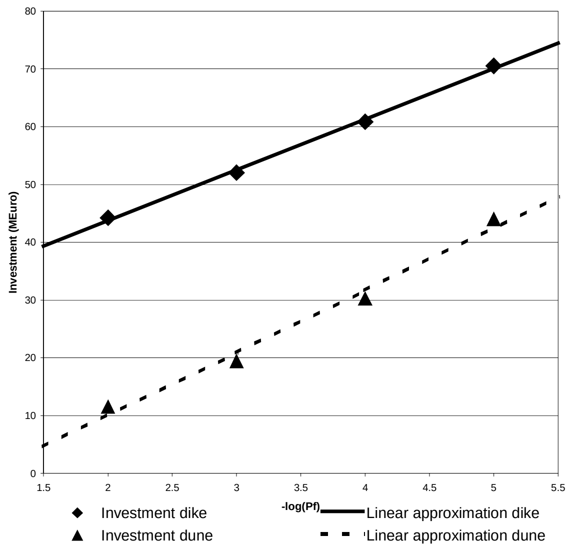

Fig. 3: Investment as a function of failure probability per component

5.2.2 Dune

For the dune section, erosion under storm conditions is considered to be the decisive failure mode. The limit state is defined as: *"Exceedance of the prescribed critical profile"*. Parametric models are available for the description of the shape of the critical profile as a function of the hydraulic loading. The dune will fail if the sediment content necessary for the formation of a storm profile is larger than the available sediment content in the original profile.

In formula:

$$M_{erosion} = V_{available} - V_{storm}$$

Where: $V_{available}$: Sediment content in the normal profile;
V_{storm}: Sediment content necessary for the storm profile.

For simplicity it is assumed that the dune profile is fixed in all respects except for the width of the crest, which is used as a design variable. The optimisation problem for the dune section is written as:

$$\min_{B_c} I(B_c) = C_{vol} V(B_c)$$

$$s.t. \qquad P_{f;dune}(B_c) = P_{f;prescr}$$

$$B_c > 0$$

Where: B_c: Crest width of the dune;
$P_{f;dune}$: Failure probability of the dune.

Also the investment function for the dune can be approximated by a linear function of the log of the failure probability (see figure 3).

5.2.3 Correlation between the components

For the calculation of the flooding probability, the correlation between the values of the reliability function is needed. By storing the values of the normalised gradients that result from the component optimisation, it is possible to describe the correlation coefficient between the components as a function of their respective failure probabilities. The correlation function is used whenever an evaluation of the system probability of failure is necessary.

5.3 System optimisation

Using the results of the component optimisation, the lifetime costs on system level are now given by:

$$C_{life}(P_{f;dike}, P_{f;dune}, S) = I_{dike}(P_{f;dike}) + I_{dune}(P_{f;dune}) + P_{flood}(P_{f;dike}, P_{f;dune})S$$

Optimisation of the system has been performed for three damage levels (S), namely 50 mln Euro, 500 mln Euro and 5000 mln Euro. Figure 4 shows the resulting failure probabilities. Table 2 shows the resulting failure probabilities per component and the corresponding geometry of the structures.

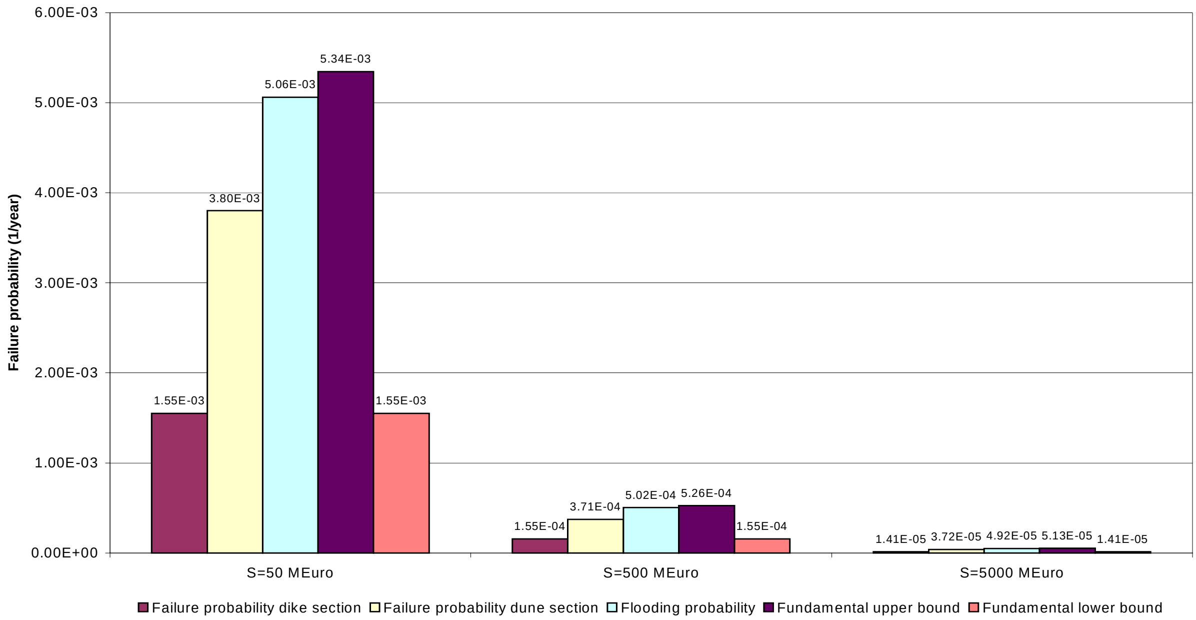

Fig. 4: Failure probabilities resulting from system optimisation

Table 2: geometry of flood defence components resulting from optimisation

Damage level	Failure probability dune (1/year)	Failure probability dike (1/year)	Crest width dune	Crest height dike	Berm width dike
50 MEuro	$3.80 \cdot 10^{-3}$	$1.55 \cdot 10^{-3}$	38.5m	NAP+21.55m	22.45m
500 MEuro	$3.71 \cdot 10^{-4}$	$1.55 \cdot 10^{-4}$	79.9m	NAP+24.20m	24.40m
5000 MEuro	$3.72 \cdot 10^{-5}$	$1.41 \cdot 10^{-5}$	121m	NAP+26.95m	26.40m

6. Discussion and conclusions

An optimisation strategy for risk-based optimisation of systems with a large number of design variables has been shown. The method performs well for the calculation of the optimal safety level of a land reclamation project.

Though the number of failure modes taken into account in the case study is limited, the structure of the method is such that more failure modes, as well as more components can easily be incorporated. The first objective is reached by performing the reliability analysis per component for a system of correlated failure modes within the component. The second objective can be reached by adding investment functions for other components, which are derived in the same way as shown in the paper.

Although somewhat hidden in the optimisation procedure, the description of the failure modes is of ultimate importance to the final result. Economic optimisation should cover the complete analysis from the description of the behaviour of components, the description of (random) input variables, as well as a correct description of the investment and the consequences of failure.

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