CHAPTER 94

Safety philosophy for dike design in The Netherlands

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Abstract

This paper describes the history and present state of the art with respect to safety philosophy for flood defence systems in the Netherlands. It is explained that present day philosophy is based on a so called dike-ring approach and on a probabilistic treatment of all load and strength parameters. Both target safety levels as well as verification procedures are discussed. Simplification rules for application in every day practice are given.

1. Introduction

In the past decades, the design of dikes and flood-defences has developed from a traditional craft to a scientific approach. Traditionally the crest of the dike was built 1 m above the highest water level known so far. In the late 1930's it was recognized that water levels are statistical quantities and that dike design should be based upon water level exceedence frequencies. The first step from a deterministic to a probabilistic design approach was taken. The next step is to extend this idea to other load and strength parameters, the so called full probabilistic design. This paper describes the main developments in this field and the present state of the art.

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2. Floods and flood defence strategies, a historical overview

In 1916 a storm surge flooded the land around the former Zuiderzee (see Figure 1). This inundation led to the decision to close the Zuiderzee, by means of a dam, the Afsluitdijk, and thus creating the IJssel-meer. The Afsluitdijk was completed in 1932. For the design only historical data were taken into account. The dike height was based on the rule that it should be able to withstand the highest known storm level in history.

For the next 20 years, Holland seemed to be safe. Then, on the first of February 1953, a severe storm surge struck the south western coast and drove the water into the delta of the Rhine, Schelde and Meuse, up to an unprecedented level. A great number of dikes collapsed, large parts of land were flooded and over 1800 people drowned.

After this disaster the so called Delta-committee was formed to prevent such a tragedy to ever happen again. The Delta-plan was developed and executed. This meant a 700 km shortening of the coastline, by the closure of all major estuaries, and strengthening of the dikes.

In the preceding decades it was discovered that the observed storm levels plotted on probability paper against their probability of exceedence formed nearly a straight line. Now it was possible to extrapolate this line and base the dike design on a storm level with a chosen probability of exceedence.

The acceptable return-period for the waterlevel that the dikes should still withstand was set by the Delta-committee on 10,000 years for central-Holland and 4,000 years for the other parts of Holland, with less inhabitants and less investments. Also a economical study was carried out, trying to balance the investments in flood defences against the probability of failure and the consequential damage. That study pointed in the same direction for the choice of the return period.

The Delta-plan was still under construction when the next event happened. In 1960 an inland polder dike failed and the polder Tuindorp-Oostzaan, an urban area near Amsterdam, was flooded. After the investigation of the cause of this event it was concluded that it would be better not to wait for the next disaster and then form an other committee of investigation, but to have a permanent committee to safeguard the safety against inundation.

This led to the formation of the Technical Advisory Committee on Water Defences (TAW) by the Minister of Transport and Public Works. The first task of this committee is to advise the minister on all technical-scientific aspects of water defences and of the protected areas. To do so this committee coordinates research and publishes guides for the design and maintenance of water defence works.

In the early seventies the acceptable return period for river dikes became a matter of discussion. In this case the figures given by the Delta Committee seemed to be too strict. In 1975 the Becht Committee advised a return period of 1250 years for the design water level of the river dikes.
This recommendation was based on the following distinction between river and sea hazards:

- inundation by fresh water causes less damage than inundation by salt water;
- high water level on rivers can be predicted earlier and appropriate measures can be taken;
- the areas threatened by rivers are above mean water level, which means that after the flooding the water disappears and gaps can easily be closed.

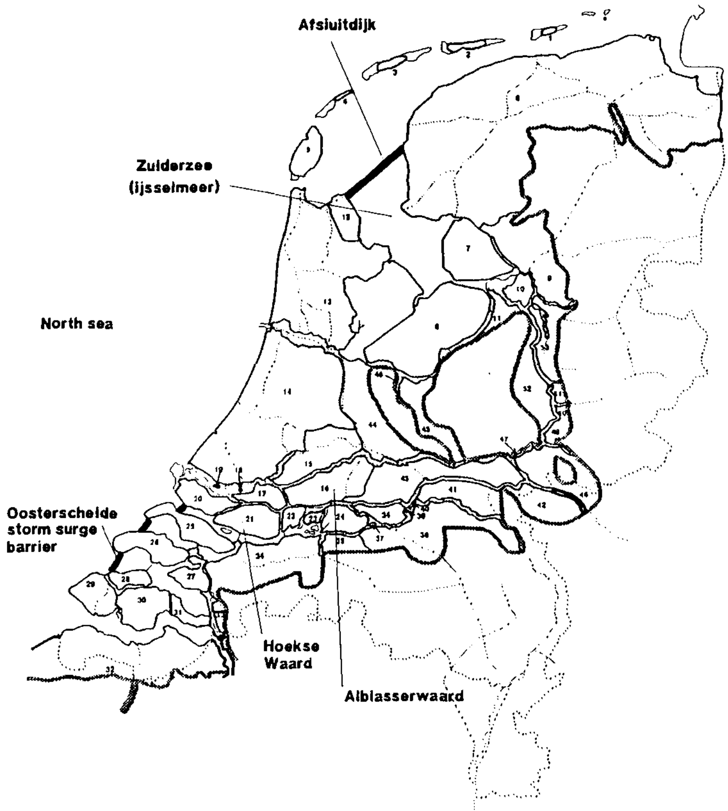

Figure 1: Map of the Netherlands

As a part of the Delta Plan the Eastern Schelde Storm Surge Barrier was build in the period 1980-1988 (see Figure 1). During design it was recognised that probabilistic treatment of the water level should be extended to other load parameters (wind, waves), but also to resistance parameters (soil) and operational factors (electric power, human factors). After this rather succesful introduction of probabilistic methods into practice, other applications followed.

Recently, in 1989, the TAW published the Guide for the Design of River Dikes, especially dealing with tidal-river dikes. This design guide is based on probabilistic starting points and the dike-ring concept (see section 3). It is however stressed that this does not imply that it is possible to actually calculate the probability of inundation.

In 1991 a new Law in Flood Protection is expected to pass the Dutch Houses of Parliament. Target of the new law is to maintain the safety that has been obtained by years of construction, consuming large sums of money. To do so a five-yearly check of the primary waterdefences has to be carried out and a report on the provided safety should be given. The TAW is now working on a guidance document how to carry out this safety-check.

3. Basic concepts of Probabilistic Design

In the Netherlands a polder is often bordered by water on many sides. Therefore the expression "dike-ring" is introduced for refering to the protecting ring of water retaining structures bordering the area (see Figure 2). An important point is that this protecting ring should be considered as a coherent system and not as an arbitrary set of individual elements. If for the time being equal consequences for the failure of all parts of the ring are assumed, the basic safety requirement for the dike-ring can be formulated as:

$$P\{F\} < P\{\text{target}\} \qquad (1)$$

In here $P\{F\}$ is the failure probability or probability of inundation for the dike ring (per year) and $P\{\text{target}\}$ is the accepted value. The design problem now can be subdivided into two distinguished parts:

(1) to determine the target failure probability;
(2) to judge wether a given dike system (existing or designed) fulfils the basic requirement.

Item (1) is partly a technical matter and partly a matter of political decision. The technical part is related to questions as: what will be the consequences of a dike failure in terms of inundation, loss of property and loss

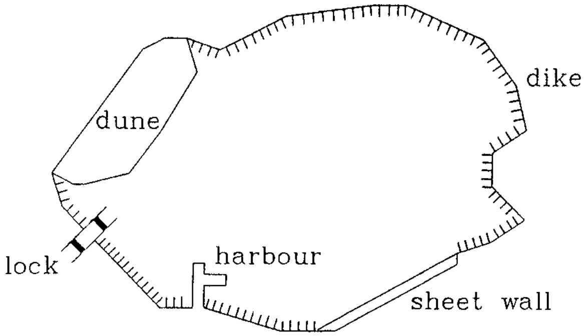

Figure 2: A dike-ring is an area surrounded by a system of water retaining elements as dunes, sheel walls, locks and so on.

of life. Politicians should answer questions as to what losses can be accepted.

Item (2) is a typical technical problem. It is effective to distinguish two different lines of approach. The first line of approach is bottom up: based on physical models for all failure mechanisms and based on statistical models for all random variables, one may calculate the failure probability for the complete system. The second line is top down: starting from a given target probability for the system, one derives targets for individual mechanisms and elements; from there on one derives requirements for the design variables.

As long as all mechanisms are known and full information on all statistical properties exists, both approaches are entirely equivalent. However, as this is not the case, the first approach is deemed to fail at present: the system failure probability for a complete dike-ring simply cannot be calculated. Taking the second approach however, it is possible to deal at least with a substantial part of the design problem, even if not all mechanisms can be treated. As research goes on, the part that can be dealt with using these techniques, will increase.

4. Target reliability

In Figure 3 the flow chart for a target reliability estimation has been indicated. Based on the hydraulic conditions at the river, sea or lake on one side and the gap growth characteristics for the failing dike element on the other, the discharge through the breach can be calculated. Given the resulting inundation pattern, the material losses and the losses of human lives must be estimated. An example is shown in Figure 4.

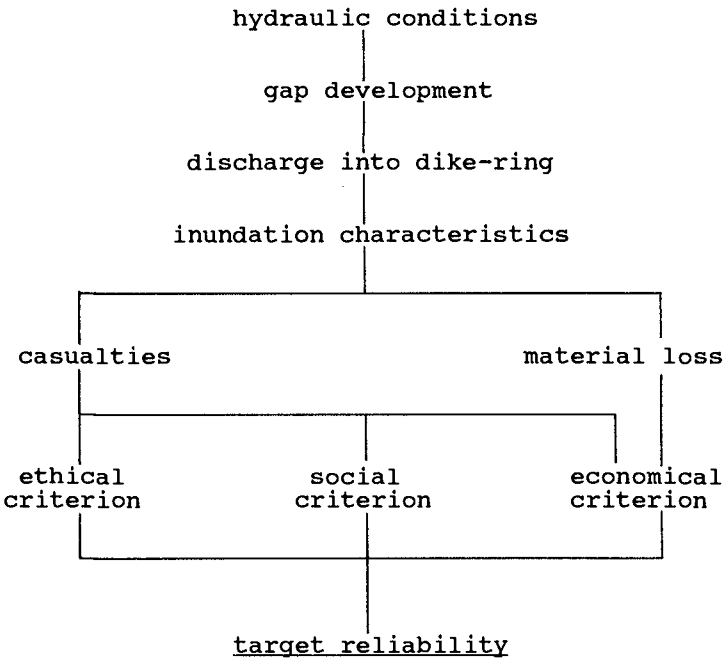

Figure 3: Determination of target reliability

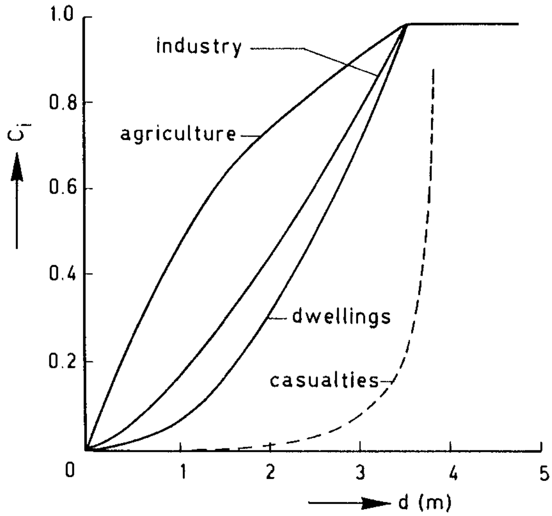

Figure 4: Material loss and number of casualties as a function of the inundation depth (examples)

These losses should give indications for target reliabilities. In the Netherlands a three criterion system is under development:

1. An ethical or personal risk criterion. According to this criterion it is not allowed to let an arbitrary person run a risk for drowning which is substantially higher than the risk for an accident in normal life;
2. A socially accepted risk, which is concerned with the aversion a society has against large accidents including many casualties;
3. An economic criterion: the cost of improving a dike system should (at least) be balanced by the save of losses.

For further information the reader is referred to [TAW]. An interesting application, involving also time dependency and maintenance aspects is presented in [Vrijling]. If the three criteria give different answers, as they usually do, a possible strategy is to maintain the most severe requirement as the governing one. However, as said before, in matters of this kind the last word is to politicians.

Alblasserwaard case

In order to check the usefulness of the criteria mentioned and the adequacy of the calculation tools, one of the dike rings in the lower Rhine area has been analysed [Vrouwenvelder, Wubs]. The dike ring chosen was the Alblasserwaard which stretches from a river dominated regime at the east to a mixed sea river regime at the west side, see Figure 1. A more detailed map is presented in Figure 5. Figure 6 presents a schematic cross section.

For breaches on various locations along the dikes, the resulting water levels within the dike ring have been calculated (Figure 7). These water levels depend highly on the location of the breach: the most severe inundation occurs when the dike fails at Gorinchem. In that case the water level equals 3.70 m above average sea level, which means inundation depths varying from 1.70 m to 5.20 m. A breach at Alblasserdam, located at the most western point of the dike ring, leads to an inundation depth of no more than 1.5 m; parts of the dike ring even will remain dry.

These results show that it may be necessary to have a safety differentiation within one dike ring. At present this is not common practice. Following this line of thought, safety targets were derived for every location based on inundation depth versus loss diagrams (Figure 4) and the criteria presented before.
For Alblasserdam a target value for the inundation return period of 3,500 years resulted, which almost equals the present value. For Gorinchem this value varied from 8,000

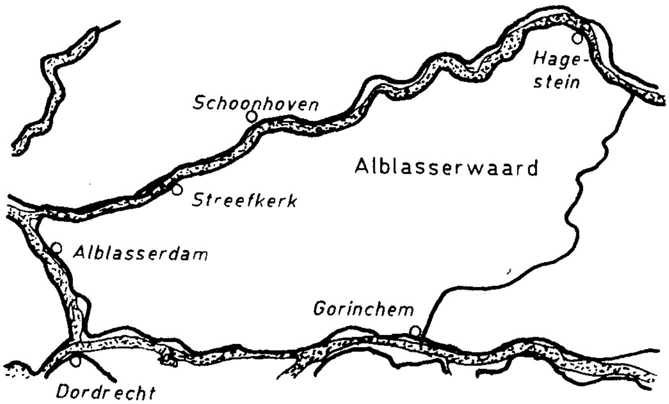

Figure 5: Dike ring Alblasserwaard

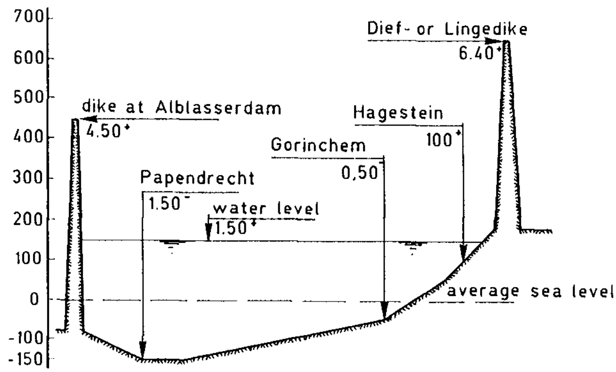

Figure 6: Schematic cross section of Alblasserwaard

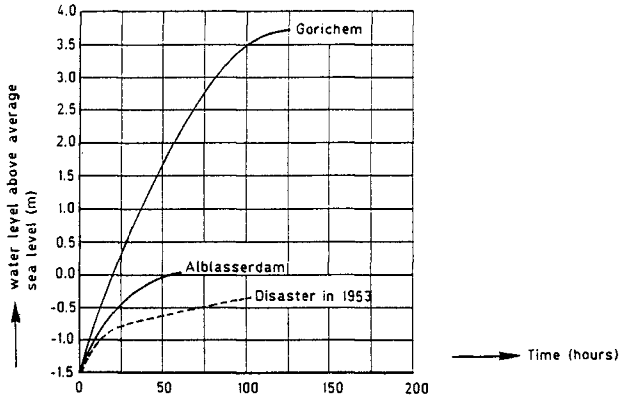

Figure 7: Inundation depth versus time curves for breaches on various locations

to 600,000 years, depending on the casualty-inundation depth relationship. It should be stressed that this relationship is highly uncertain. On the other hand, it is only necessary to oversize the dikes at Gorinchem slightly compared to other ones to reach a very high local safety level.

5. Assessment of a given dike-ring

As mentioned in section 3, a useful strategy is to start from the accepted general failure probability and break it down into acceptable failure probabilities for the various mechanisms and elements (top-down-approach). A demonstration of such a break down is presented in Figure 8. This failure tree shows the dominant failure modes and (by way of example) corresponding individual failure probabilities per mode. All modes have been assumed to be stochastically independent, which is conservative.

Within one mode one might continue the break down and split up the total failure probability for the mode under consideration between all elements of the dike-ring. As an alternative it is sometimes possible to use for one mechanism a bottom up procedure, and calculate the failure probability of the system. This depends on the characteristics of the failure mode, the elements involved and the system properties (serial system, parallel system or mixed). Both procedures will be discussed later on.

Special attention in the analysis of a dike-ring has to be given to structural components as locks and storm surge barriers. In the first place, these structures may give rise to additional mechanisms, resulting from discontinuities in the water retaining system. A second point is that these structures may contain moving parts, which may fail because of jamming, faults in electrical and hydraulic systems, human errors, and so on. The basic philosophy and assessment tools for these types of events can, however, be the same as for natural failure modes.

- Top Down procedures

For discrete elements forming a purely serial system, the break down within one mode can be performed in the same manner as for the break down between the modes; if necessary again independency between the elements or modes can be assumed. So in the case of N elements one has to fulfill:

$$\Sigma\, P(F_i) = P(F_1 \text{ or } F_2 \ldots \text{ or } F_N) \geq P\{F_{system}\} \qquad (2)$$

where $P\{Fi\}$ = Failure probability of element i for the failure mode under consideration (e.g. overtopping or sliding) and $P\{Fsystem\}$ = Target system failure probability for the mode under consideration.

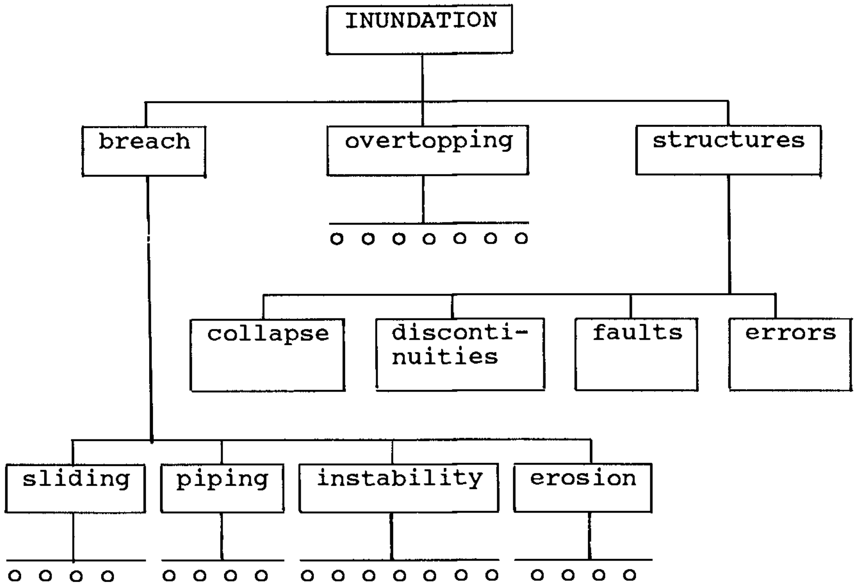

Figure 8: Failure Tree for a Dike-ring

Most straightforward of course is to take equal failure probabilities for all members. However, from the economical point of view some other distribution may be preferred. If there is correlation between the members, one might use some equivalent number of members (see [Vrouwenvelder]).

In the case of <u>continuous</u> elements the concept of the equivalent independent dike section can often be used. As an example consider the mechanism of slope instability. It can be proven [Calle] that the dike may be conceived as a system of independent sections, each section having a lenght of 30 - 100 m. This length coincides almost with the length of a sliding surface. The probability of failure for a single sliding surface can be found from a standard FORM analysis [TAW]. In the same way the mechanism of piping can be analysed [Calle].

- <u>Bottom Up Procedures</u>

It is sometimes possible to calculate the failure probability of the complete system for the specific mode. Three methods can be distinghuished: (1) Monte Carlo, (2) Numerical Integration and (3) First Order Methods.

Monte Carlo may be considered as an appropriate for relatively simple systems. The point is that the number of simulations should be large in order to get a reliable result. However, there are promising developments going on into new techniques as for instance importance sampling and directional sampling [Bjerager].

Numerical integration is feasable as long as the number of random variables is small (say less then 5), or when some special structure of the mathematical problem makes it possible to break the multiple integral into a number of smaller integrals. The model defining the failure domain should not be too complicated.

An example where the technique of numerical integration has been applied with great succes is the mechanism of wave overtopping: for all elements of a dike ring this mechanism may depend on the same sea water level, river discharge, wind velocity and wind direction. This enables the evaluation for the dike-ring failure probability by means of a multi dimensional integral. Based on this principle the computer program DIJKRING has been developed [Niemeijer, Volker, Vrouwenvelder]. Consider as an example the dike ring Hoekse Waard (Figure 9), which can be subdived into 18 dike segments. DIJKRING needs a specification of the orientation, location and geometry for all dike segments. Next, for every combination of the four random variables DIJKRING checks all dike segments for overtopping failure. The resulting failure probability was calculated as once per 600 year. After the construction of a storm surge barrier near Rotterdam this number will be improved.

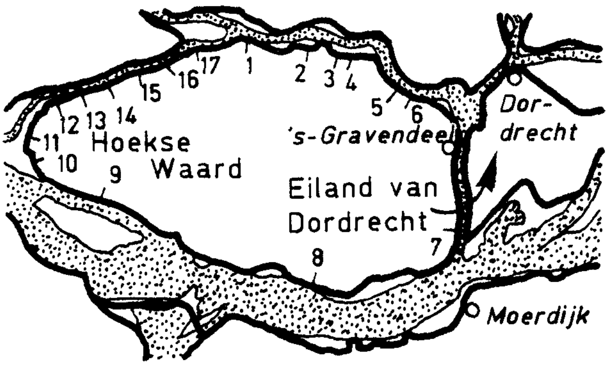

Figure 9: Dike ring Hoekse Waard, subdivision into 18 elements

Especially in structural engineering the method of First Order Methods is very popular. As a first step the individual failure modes are analysed using the FORM or level II procedures [TAW]. Next the combination of failure modes of failure sequences are evaluated using the first order approximation according to [Hohenbichler/Rackwitz], [Ditlevsen] or [Stevenson/Moses]. For this method the number of modes and the correlation between the failure modes should not be too large.

6. Every day practice/code development

Although the basic philosophy for the safety assessment should "always" be a probabilistic one, it is not desirable to perform detailed probabilistic analyses for all mechanisms and all dike-rings. There is a need for simple design methods for the every day practice. Standard procedures to derive simple rules from probabilistic considerations have been developped in the past decades and can be found in the international literature.

The basic idea is that one uses "design values" for the random variables. A design value X_d is the value that one uses in the safety check formulas, and corresponds to a probability of being lower (for strenght parameters) or higher (for load parameters) of:

$$P\ [X < X_d] = \Phi(-\alpha\beta) \quad \text{(for resistance)} \tag{3}$$

$$P\ [X > X_d] = \Phi(+\alpha\beta) \quad \text{(for load)} \tag{4}$$

Here β is the so called reliability index (corresponding roughly to - log P(target)) and the coefficient α ($0 < \alpha < 1$) indicates the relative importance of the variable and can be found from a FORM (First Order Reliability Method) or level II analysis. In many codes these α-values have been standardized in the following way:

- leading resistance parameter: $\alpha = 0.80$
- leading load parameter : $\alpha = 0.70$
- other resistance parameters : $\alpha = 0.32$
- other load parameters : $\alpha = 0.28$

In practice, design values are often calculated as the product of characteristic values and partial safety factors. Assuming the characteristic values to equal the mean value and a normal distribution, the partial safety factor is given by:

$$\gamma = 1 + \alpha\ \beta\ V \tag{5}$$

V is the coefficient of variation for the variable under consideration. For other distributions similar expressions are available. The concept of "design values", characteristic values and partial safety factors have also found its way into the TAW guides for river dike design and dune reliability assessment.

7. Conclusion

Based on the probabilistic principles and methods outlined in this paper, it is possible to judge in a rational manner the safety of a complete dike system. Consistent assessment on various levels of sophistication is possible. In practice the degree of refinement will depend on the state of the knowledge about the mechanisms under consideration and/or on the economic consequences of nonoptimal solutions.

In the present situation already many basic ideas of the probabilistic design philosophy have found their way into practice, either by design guides, or in the design of specific structures. There is a tendency towards more applications in specific projects. This has to do with the fact that the most difficult parts of the River dike construction works still have to be carried out. Especially the cases with conflicting interests have been postponed until the last stage. These are for instance dikes in cities or through valuable landscapes.

Problems of that type demand extra skills and ingenuity, to take all aspects in account and to find the best possible design. In these cases an integrated approach and an open discussion is necessary to achieve an optimal and generally accepted solution. For large projects, such as the Storm Surge Barrier in the Eastern Schelde, this is already good practice, but smaller projects may also demand the same approach. It may be necessary to change the historically approved opinion that only a water defence system consisting of sand and clay is a good one. Probabilistic methods will help to prove that other solutions can be considered as equivalent reliable alternatives.

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